A high resolution γ-ray imaging spectrometer for radioactive waste characterization

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Outline

Introduction.

- Electricity production based on nuclear energy.
- i-TED concept.

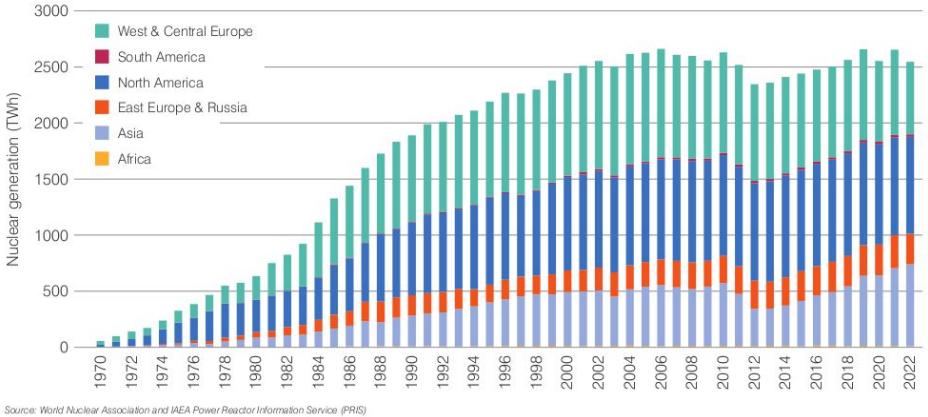
Radioactive waste classification at El Cabril.

- Experimental setup.
- Results

Nuclear energy

Continued growth of the electricity production based on uranium fission (nuclear energy):

- Main advantage: reduction of greenhouse emissions.
- Main drawbacks: production and subsequent storage of radioactive waste.



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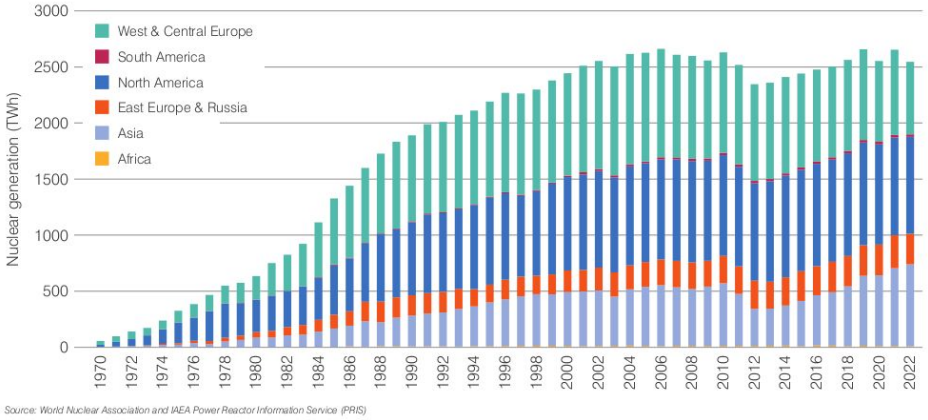

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- High-level waste: primarily uranium spent fuel.
- Very low-, low- and intermediate-level waste: contaminated protective shoe covers and clothing, filters, reactor water treatment residues, equipment and tools…

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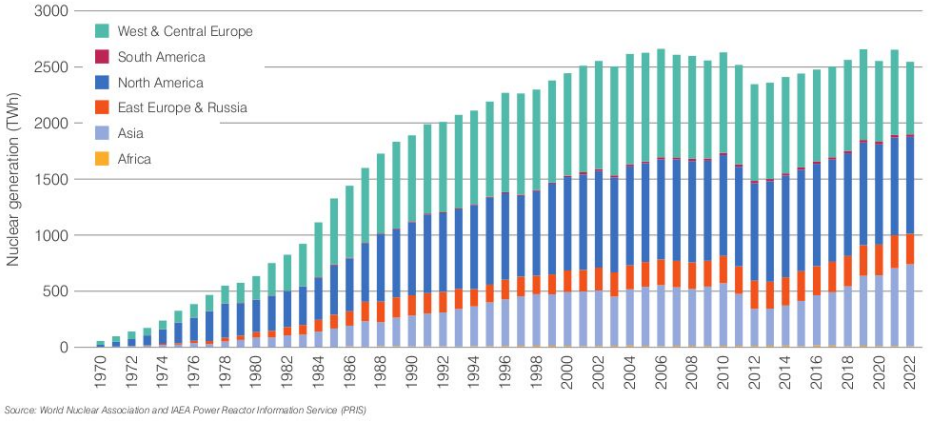

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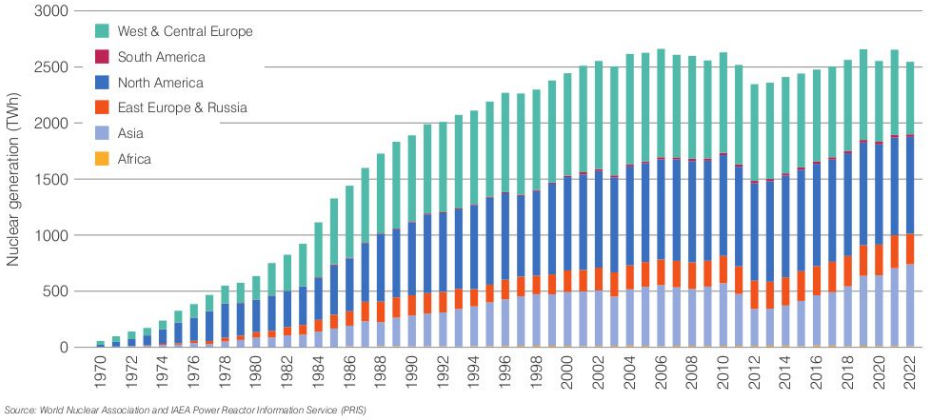

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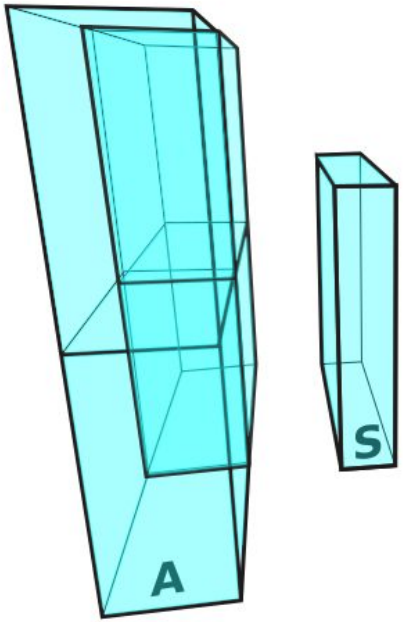
A good classification is mandatory to minimize the radioactive waste and optimice the limited disposal space:

- We propose the use of the high resolution γ-ray imaging spectrometer i-TED, for radioactive waste characterization.

i-TED concept

i-TED (imaging-Total Energy Detector) is a portable and scalable Compton camera with **large Field of View** and **high detection efficiency**.



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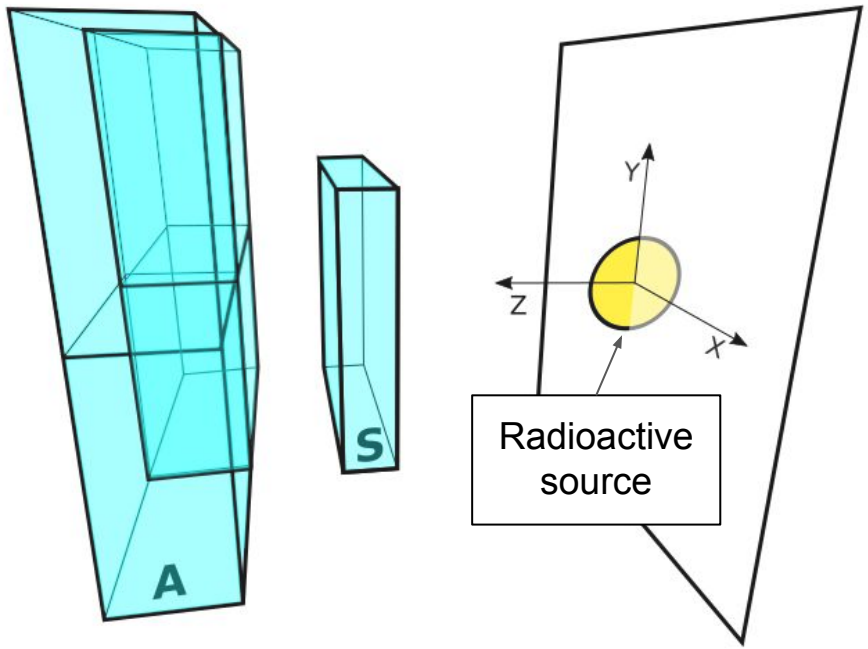

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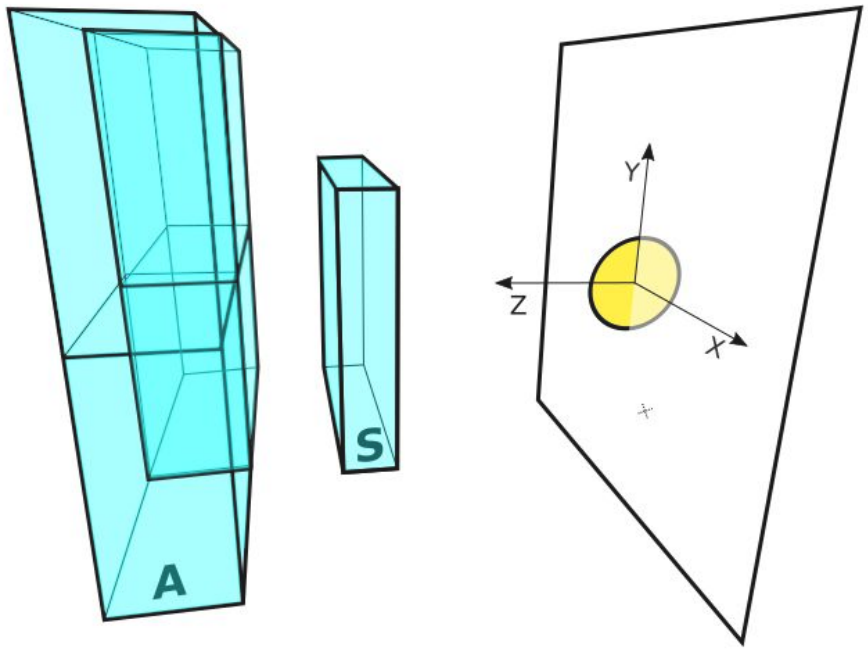

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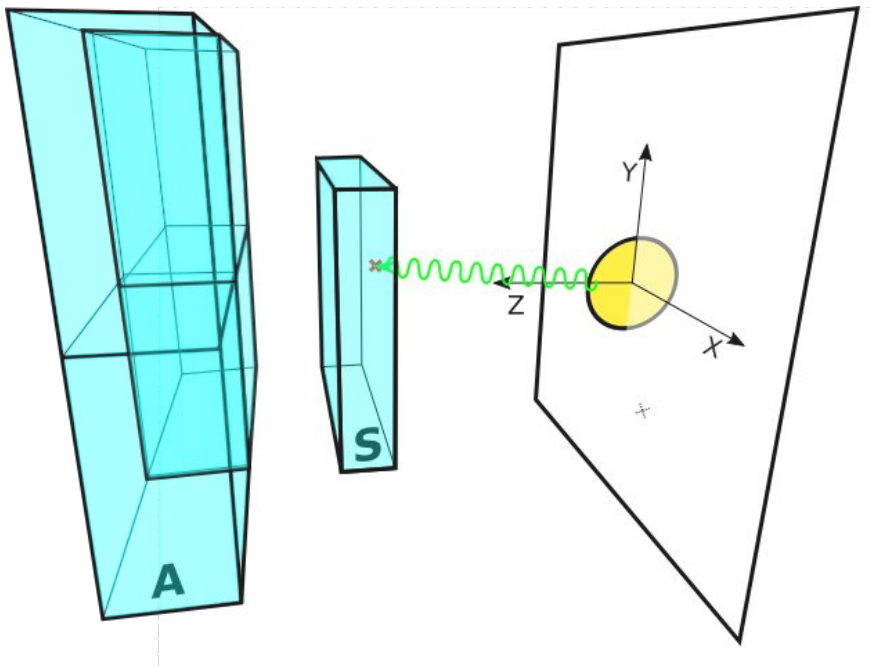

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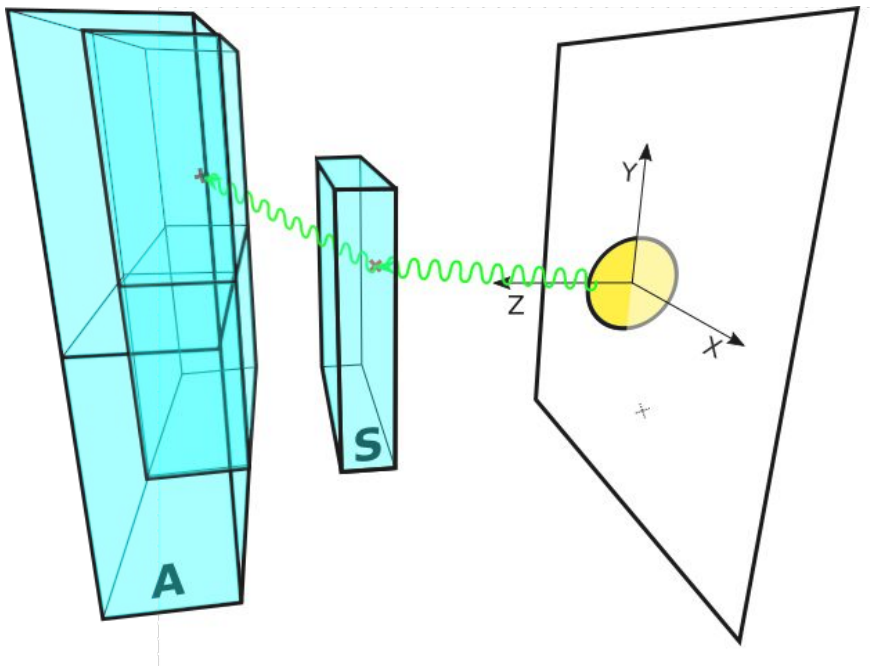

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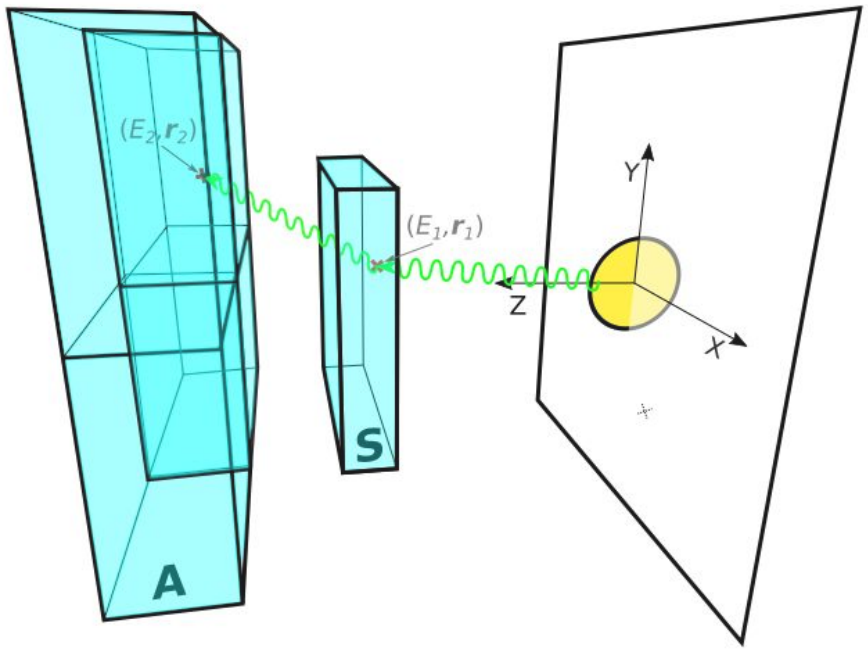

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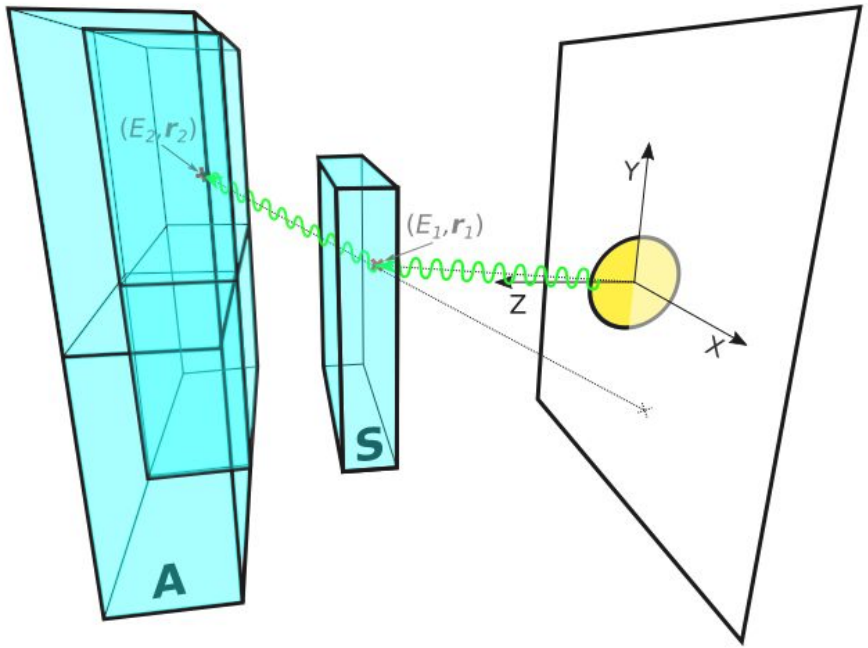

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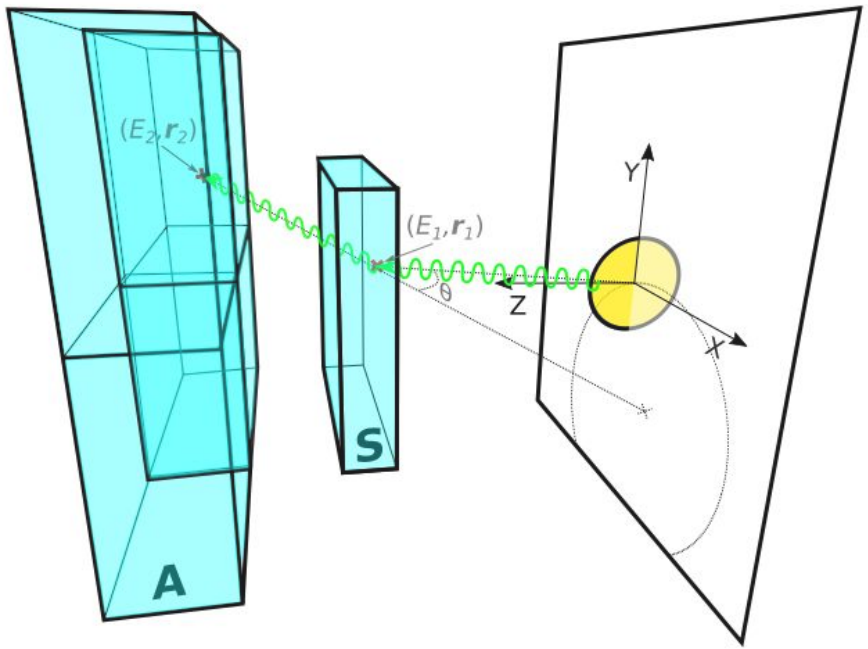
- Position interactions draw the axis of a cone, whose aperture angle (θ) depends on the interaction energies E_1 and E_2.

$$\theta = arccos\left[1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_\gamma}\right)\right]$$

$$E_\gamma = E_1 + E_2$$



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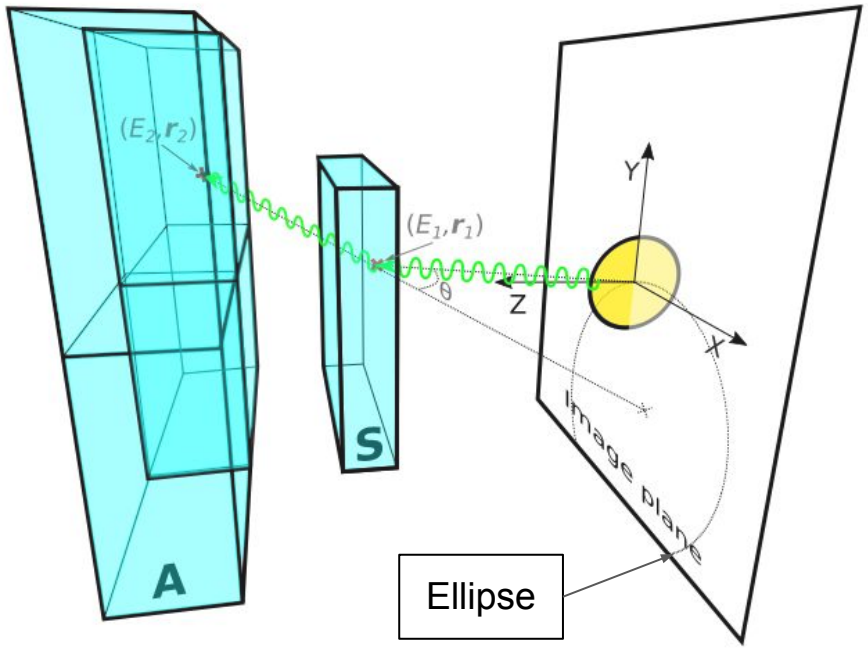

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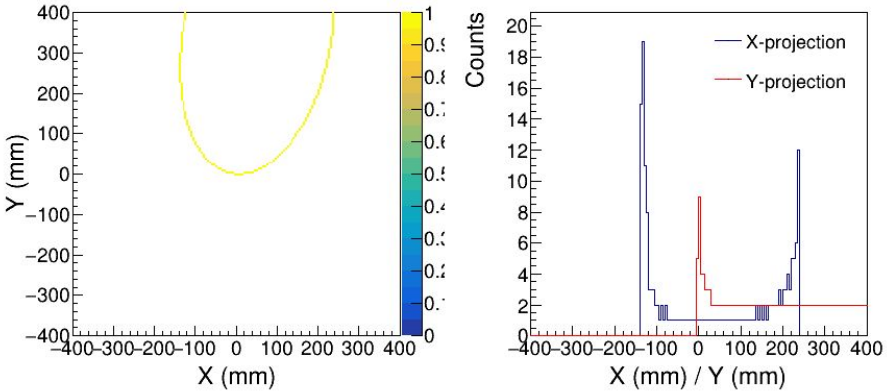
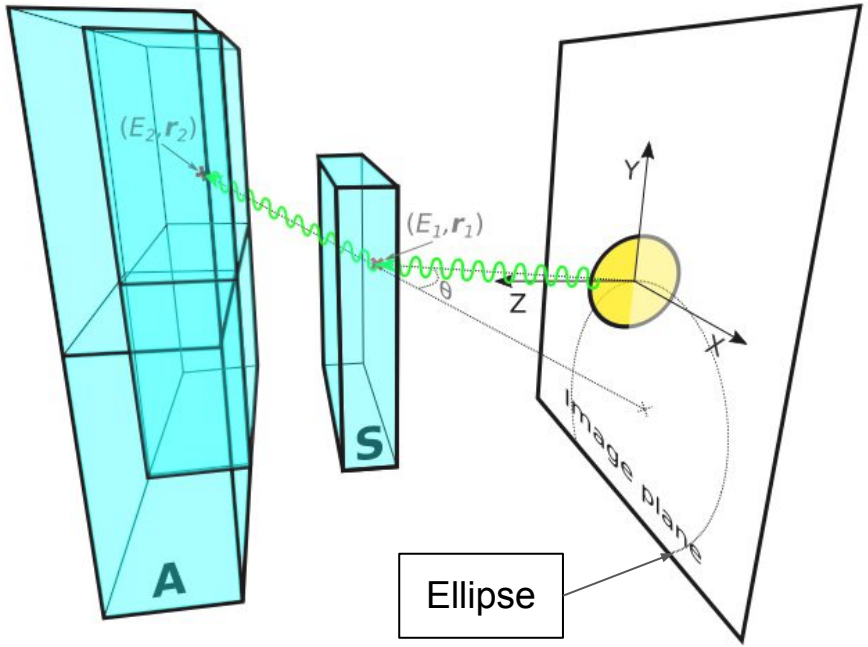
i-TED (imaging-Total Energy Detector) is a portable and scalable Compton camera with high Field of View (FoV) and high detection efficiency.

Compton imaging technique:

- The accumulation of the ellipses in the image plane results in the Compton image.





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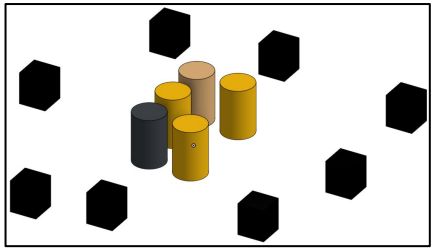
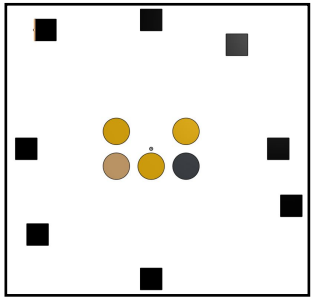
- Five radioactive barrels arranged in an specific configuration.
- i-TED placed at eight different positions for data collection.

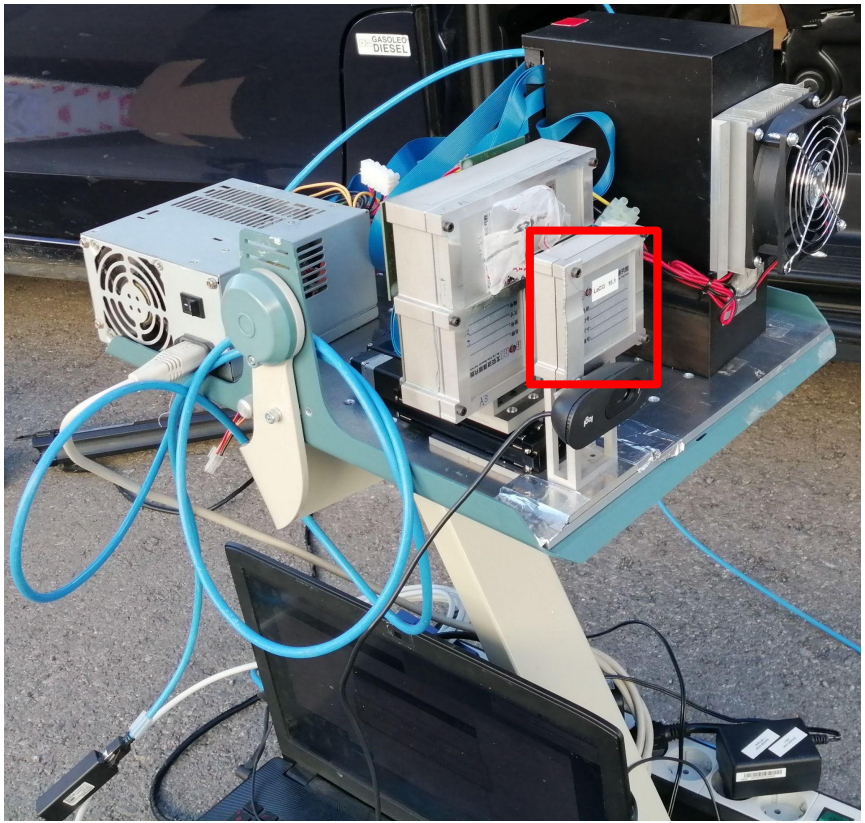




Experimental setup - i-TED apparatus

Materials:

- **Scatterer plane**: 1 Position Sensitive Detector (PSD)



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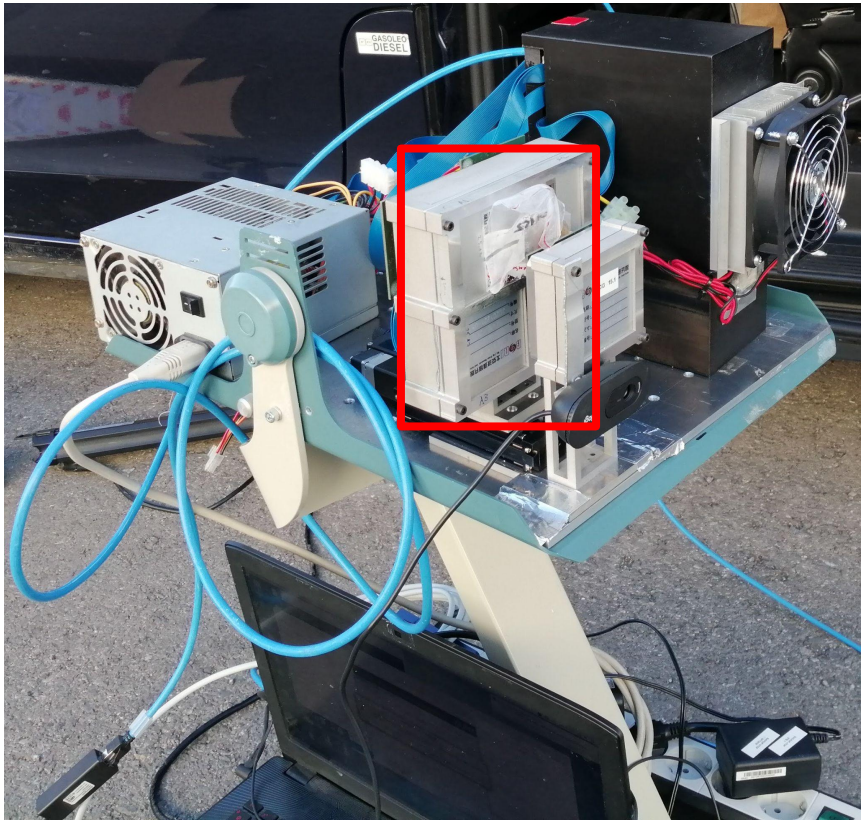

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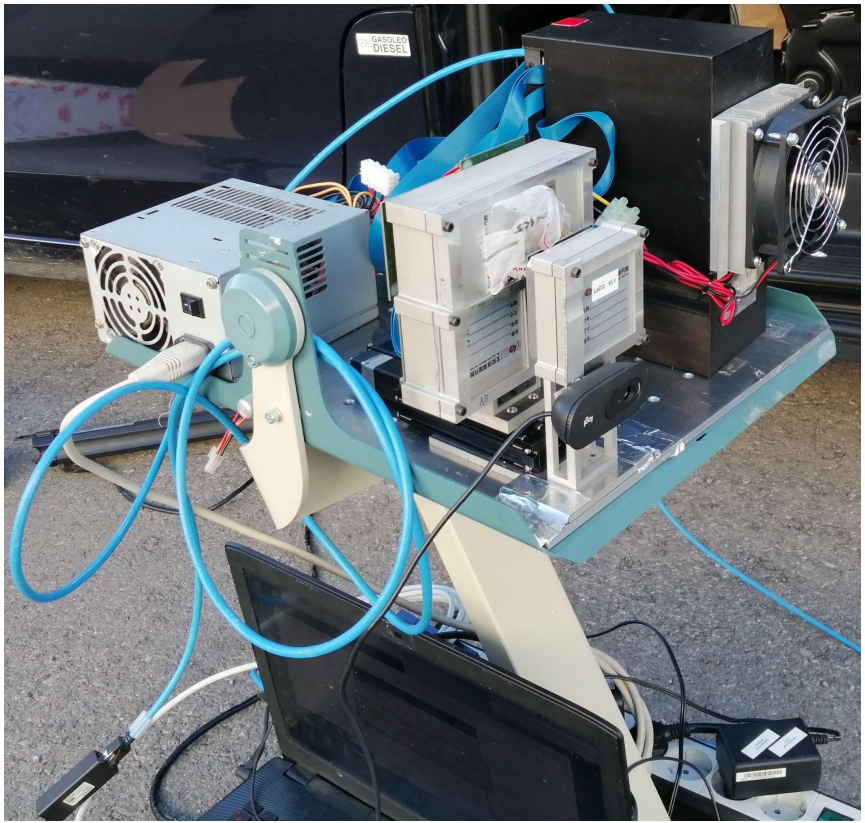

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Materials:

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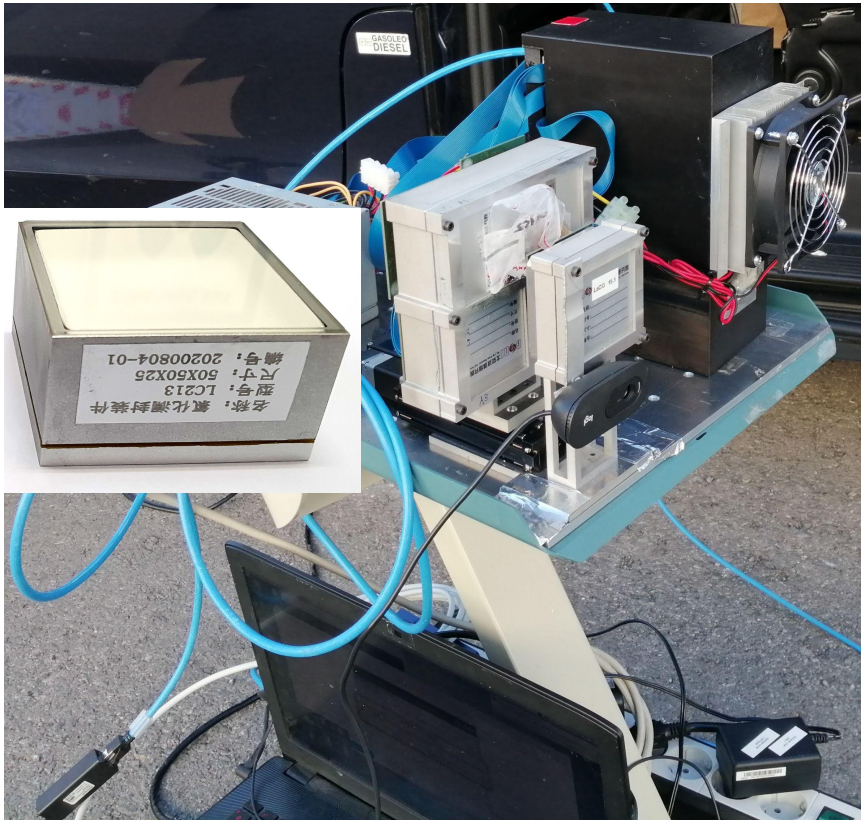
Each PSD:

- LaCl3(Ce) scintillation crystal of 50x50 mm2 square face and 15 mm (S) and 25 mm (A) thickness.



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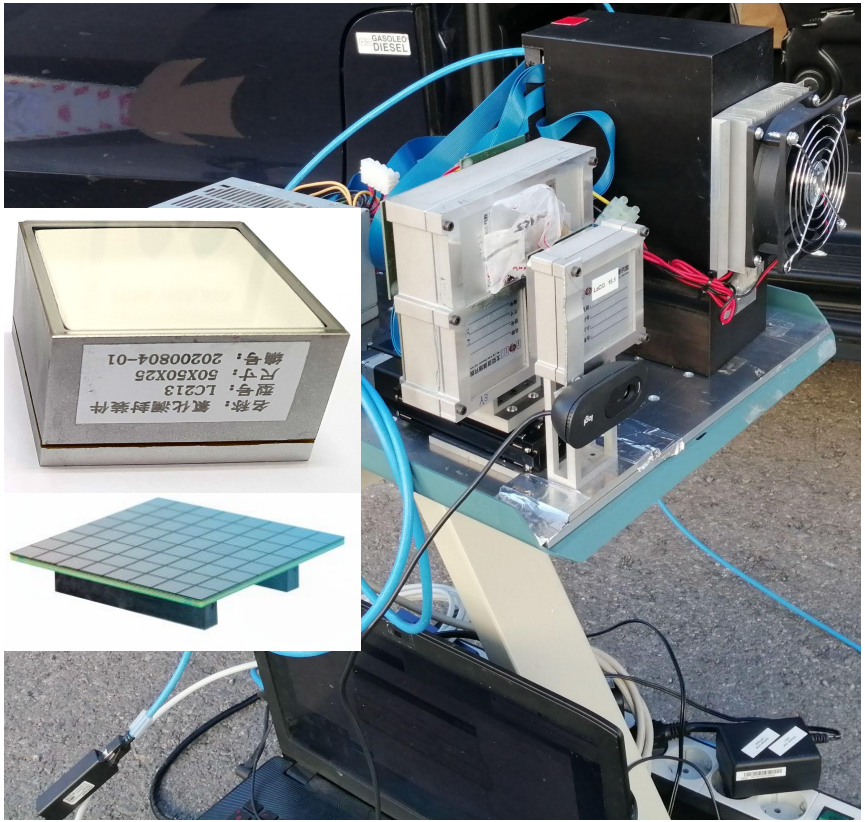

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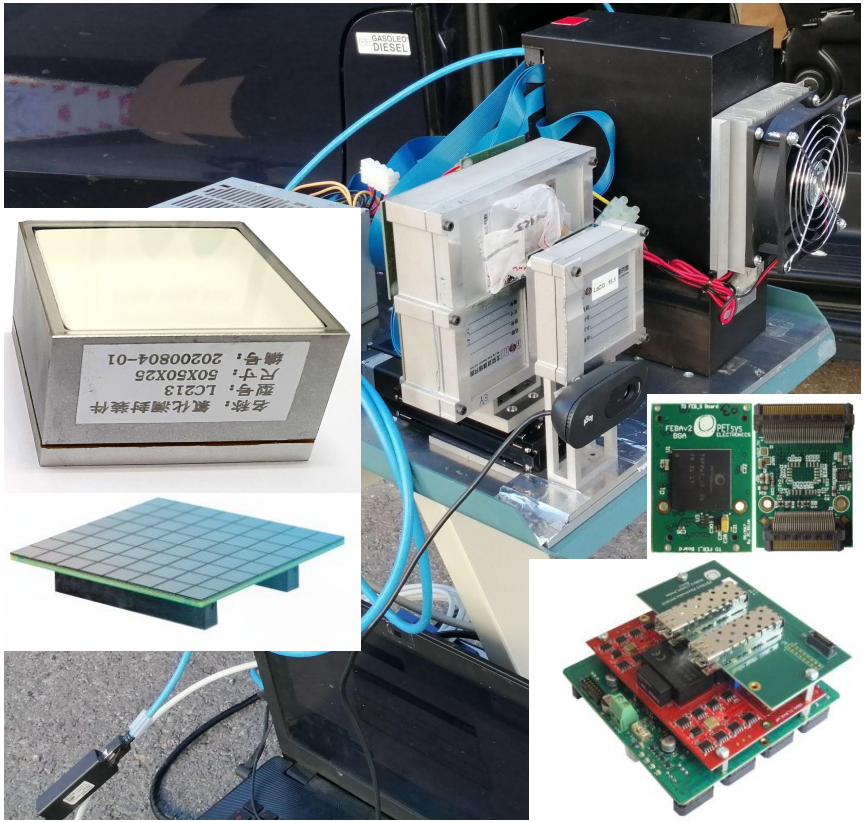

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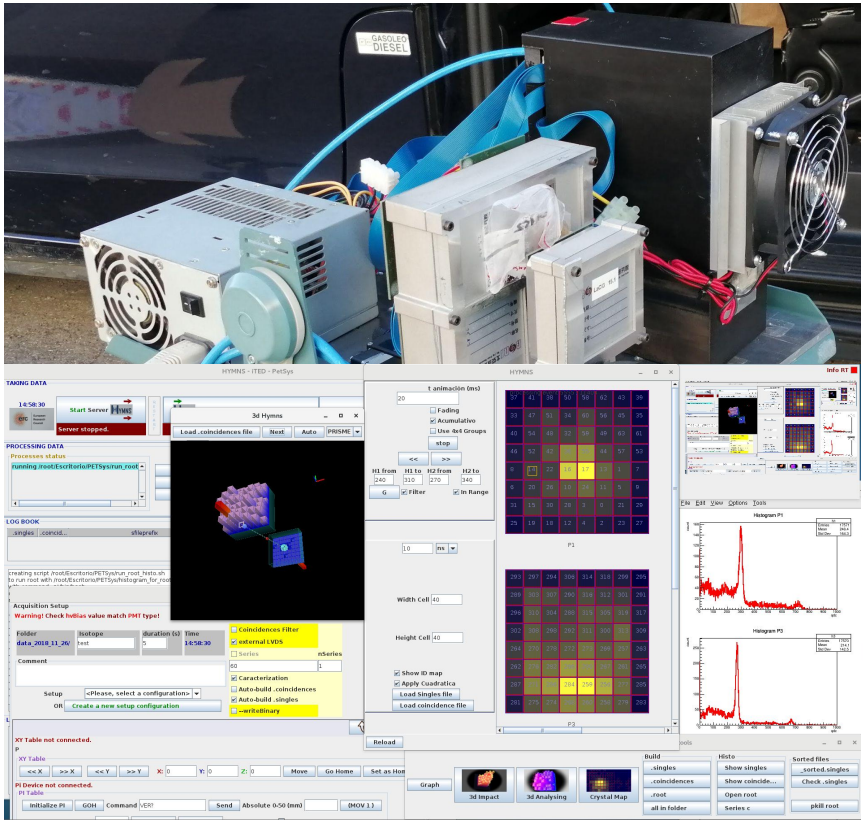
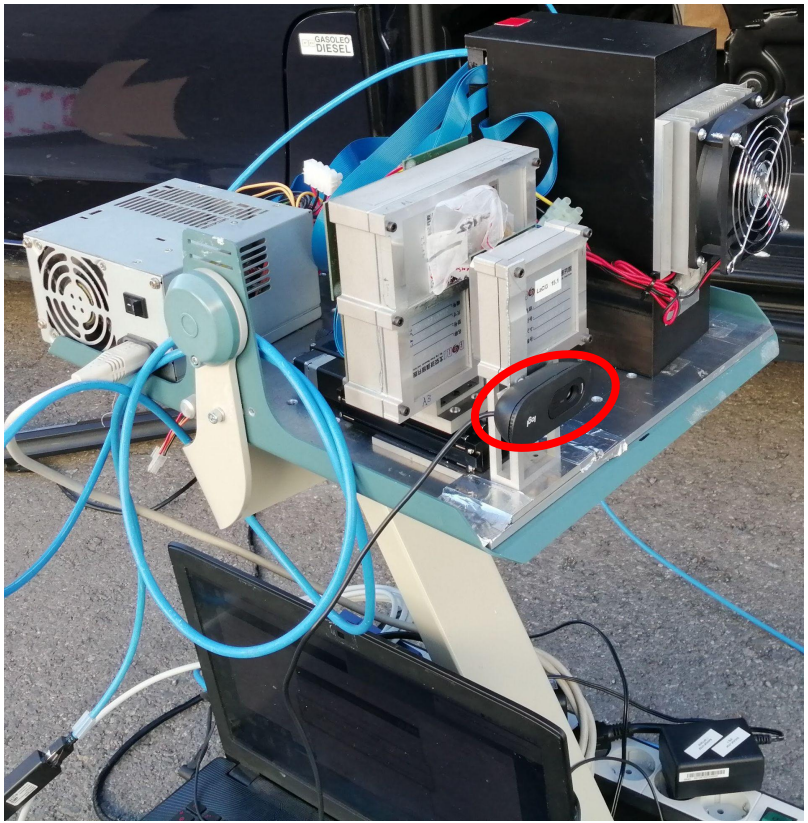
A custom GUI run on a PC included for taking data.



Experimental setup - Computer vision

A commercial RGB camera attached to i-TED:

- Allows to mix visual information of the scene with radioactive one.



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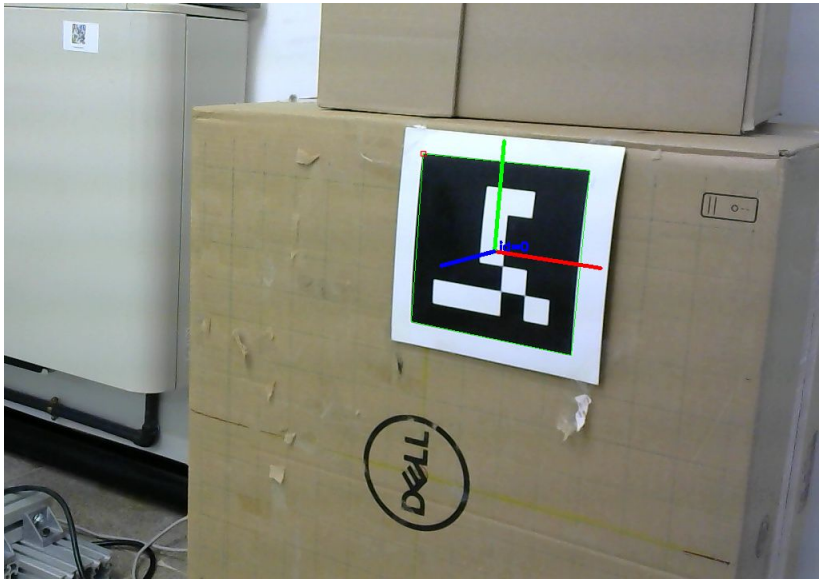
  - Provides information about distance and pose of i-TED with respect to the residues.




```
Pose (m): 0.17 x; -0.04 y; 1.05 z;
→ Distance camera-marker:
     1.06 m
→ Angle camera-marker:
     -170° X; -36° Y; -3° Z
```

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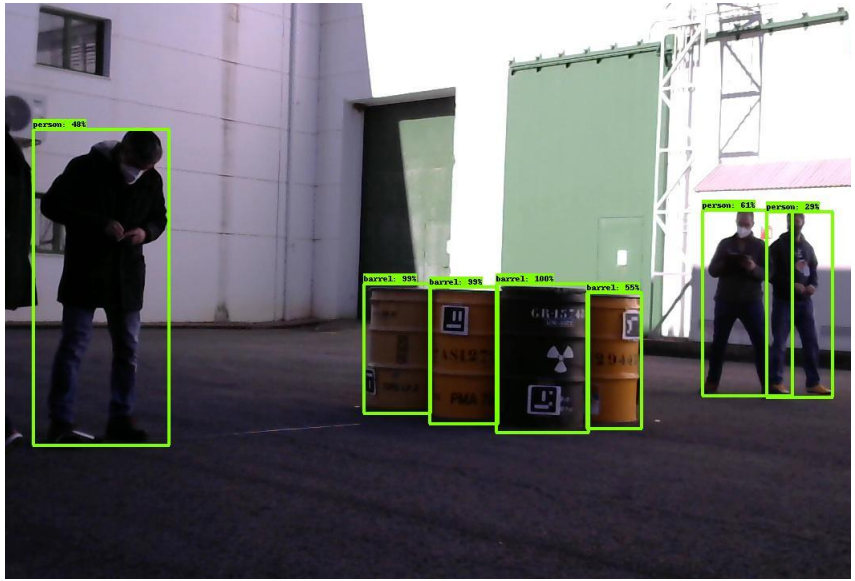
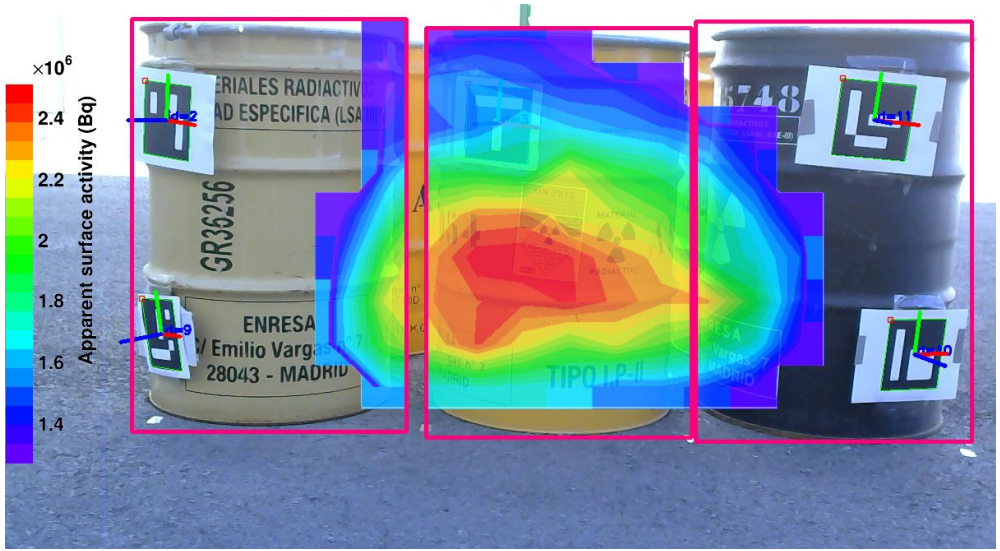
- Detection of fiducial markers: ARUCO:
  - Provides information about distance and pose of i-TED with respect to the residues.
- Segmentation: AI tools by Tensorflow.
  - Identify radioactive objects.
  - Resolve Compton image only for required objects.
  - Cross check for the measurement of the distance.



Results - Position #1

A single picture contains all the provided information:



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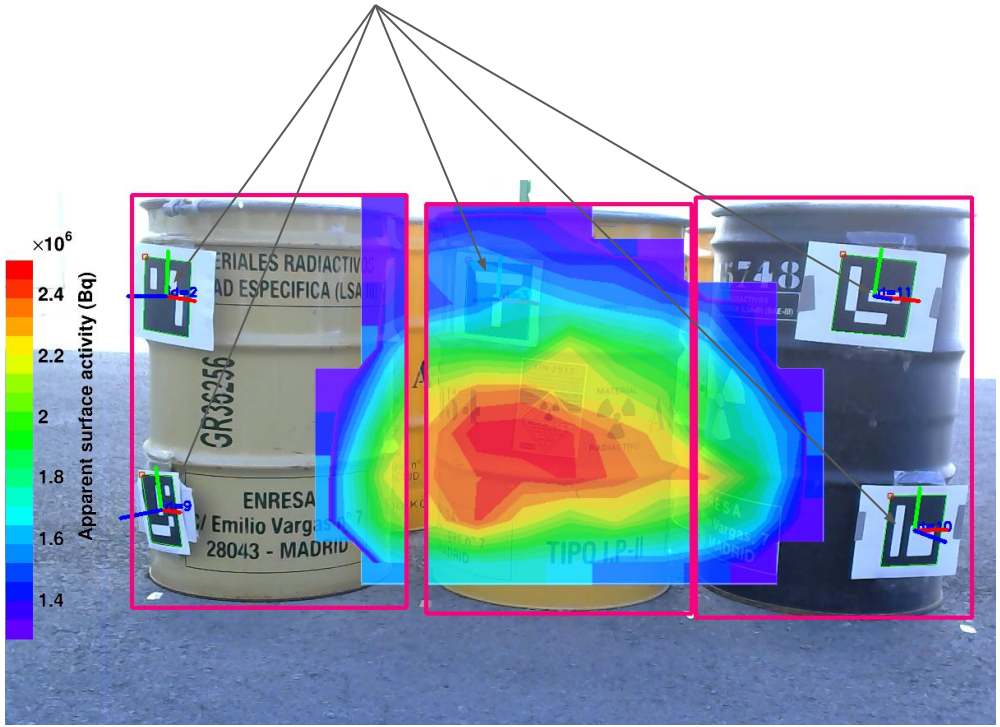

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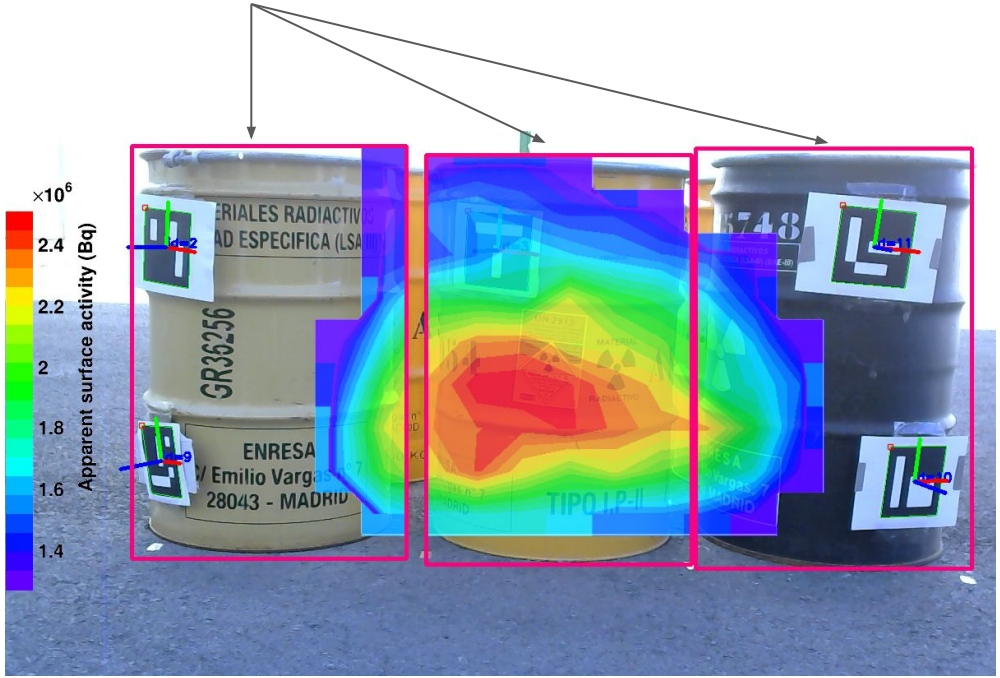

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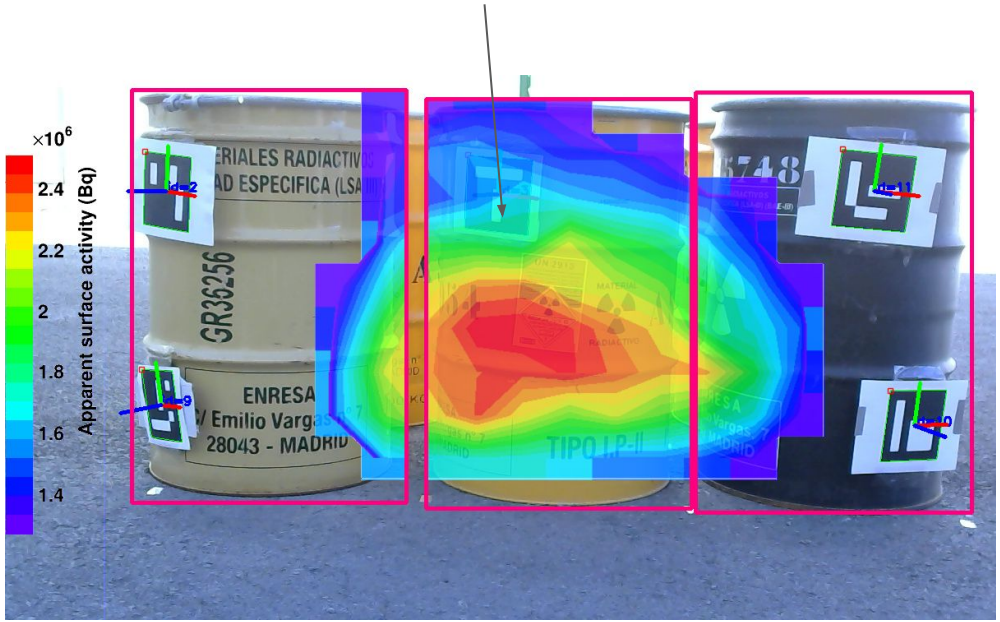
- Compton image -> heat map of ɣ-radiation



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A single picture contains all the provided information:

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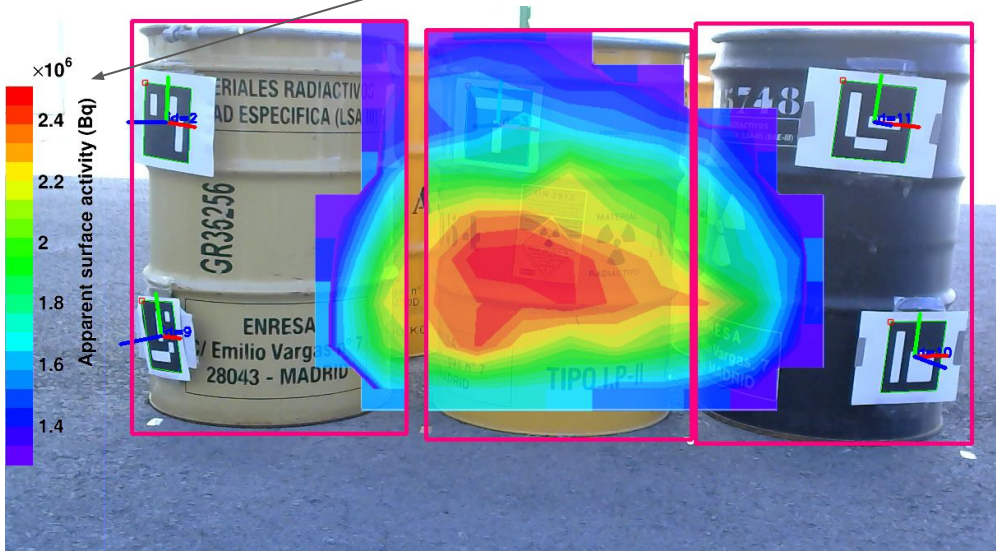
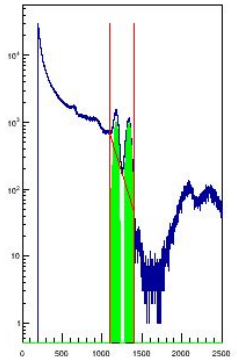
- Compton image -> heat map of ɣ-radiation
- Estimation of the measured activity.

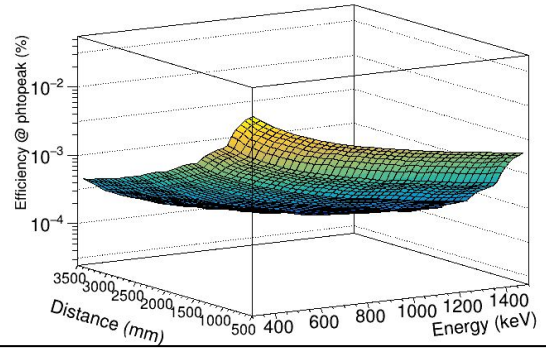


Activity estimation:

- Number of counts detected in photopeak after removing backgrounds quantified.

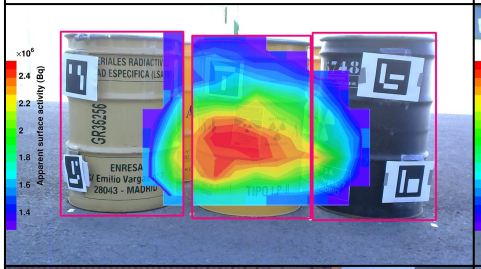
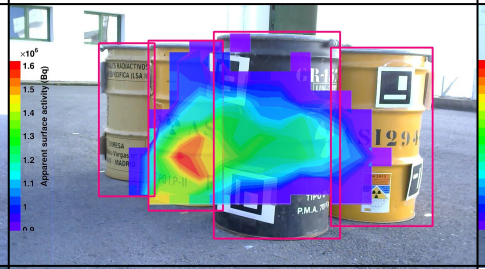
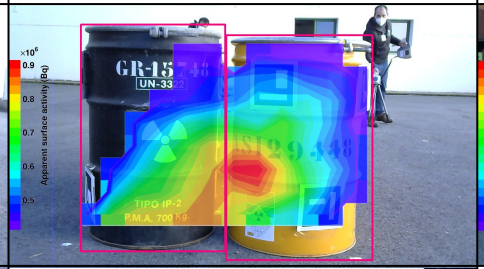
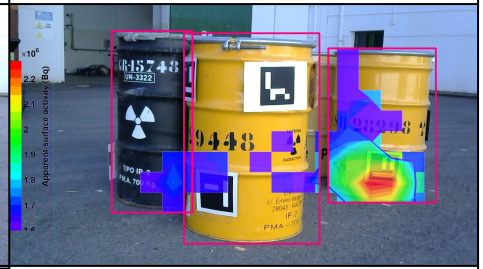
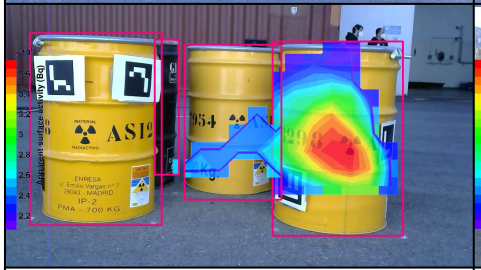
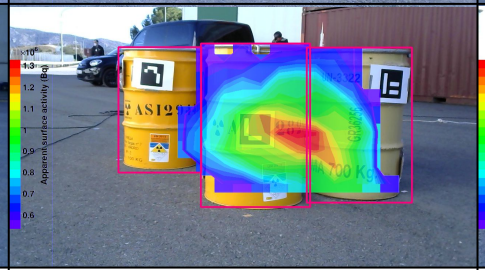
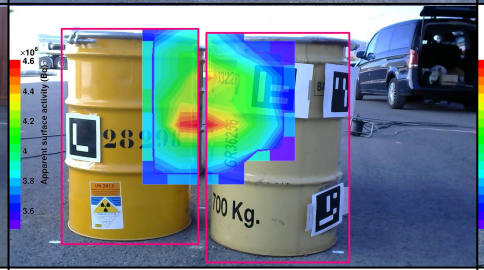
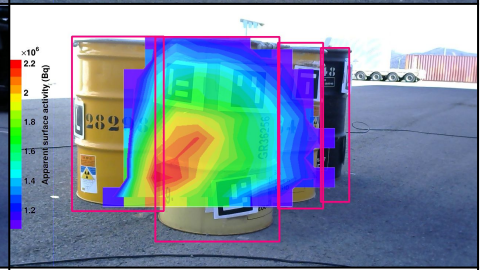


- Weighted by an efficiency factor obtained from MC simulations



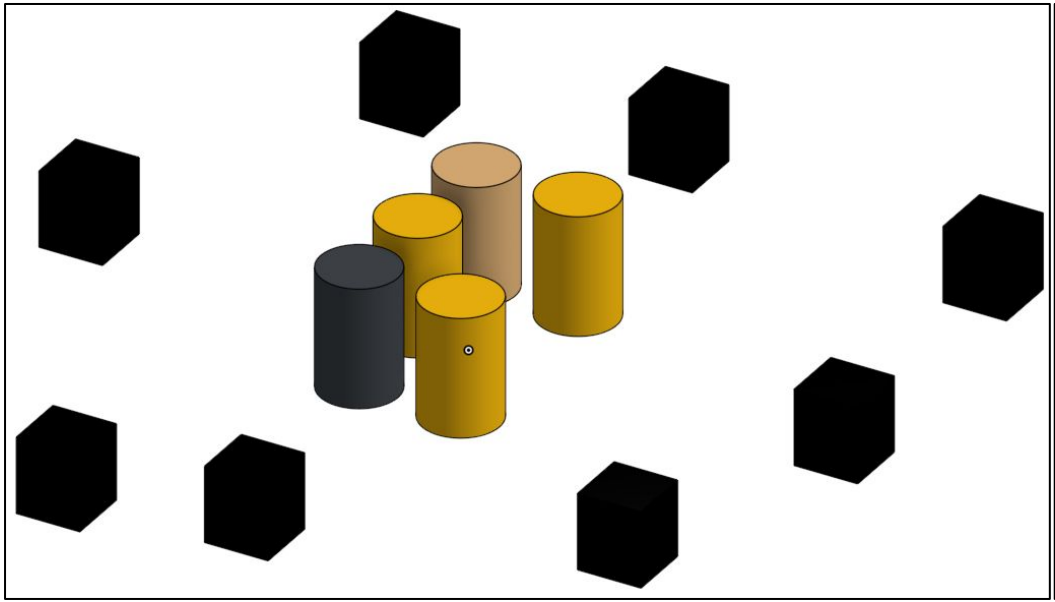
Results - All positions

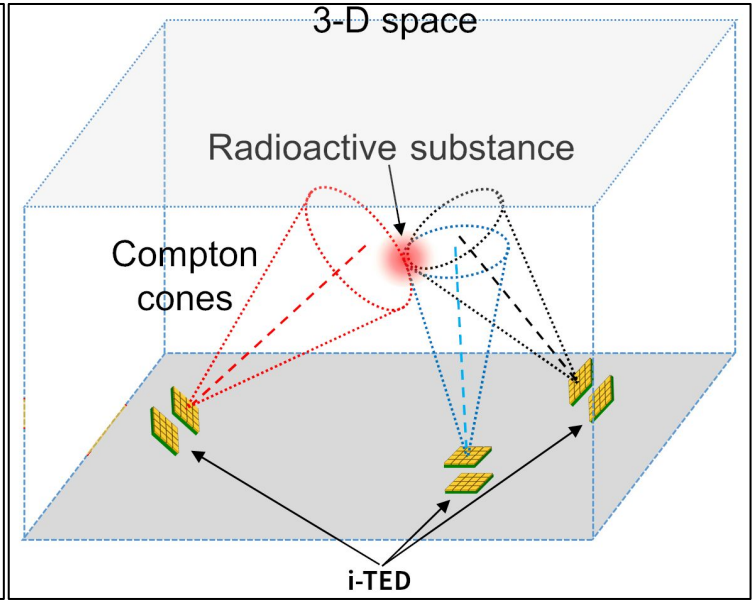
Consistent results:

Position #1	Position #2	Position #3	Position #4
			
			
Position #5	**Position #6**	**Position #7**	**Position #8**

Results - Next future

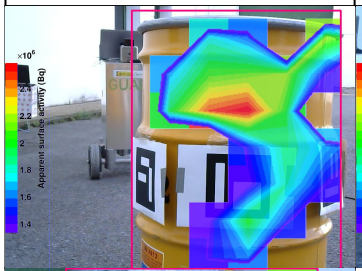
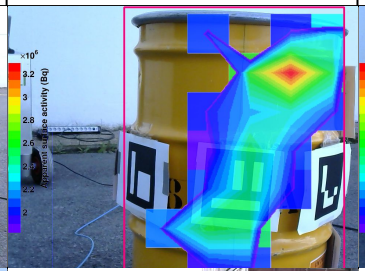
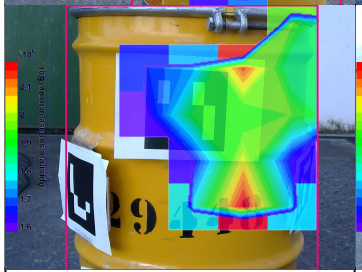
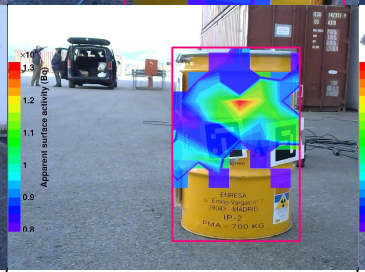
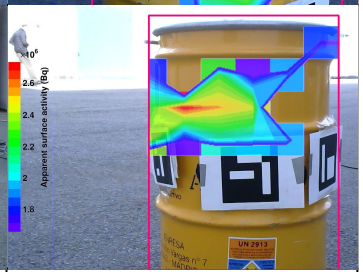
Taking data from different point of views of the same configuration of barrels enables the possibility of resolving the 3D distribution of the ɣ-radiation.

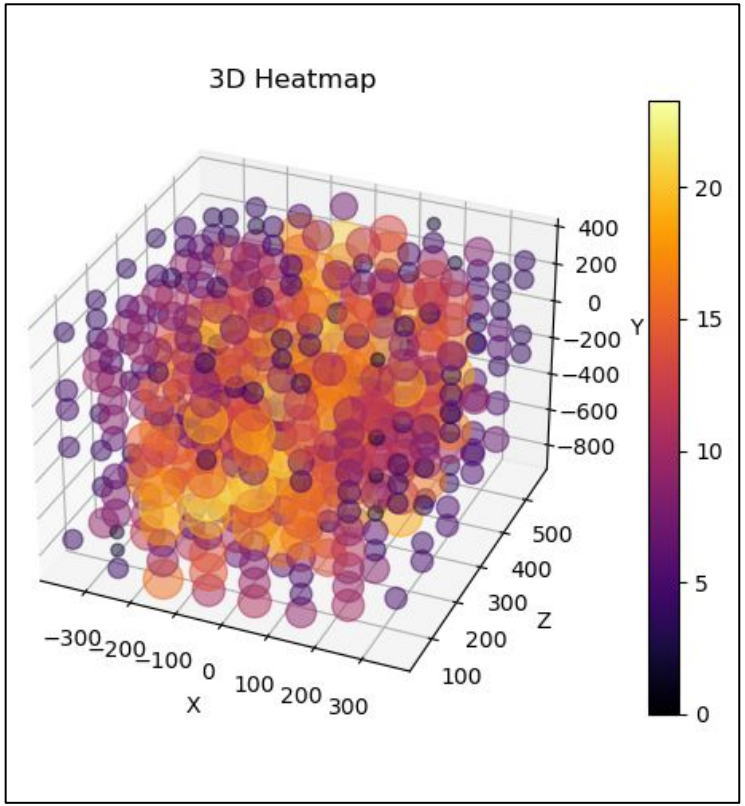




Results - Next future

For the moment… ɣ-ray 3D distribution of a single barrel.

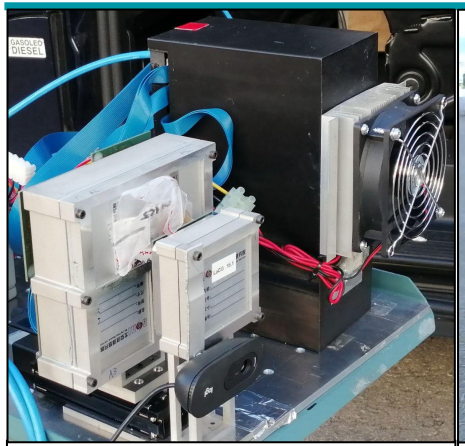
Position #1	Position #2	Position #3
		
		
Position #4	**Position #5**	**Position #6**

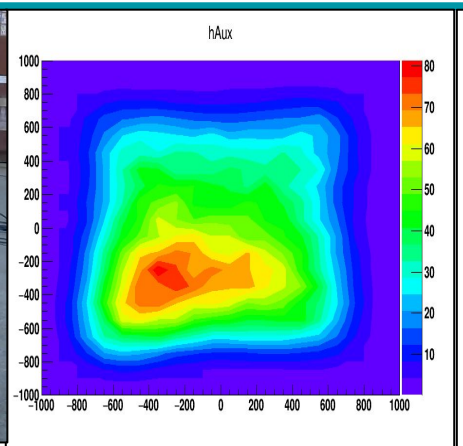


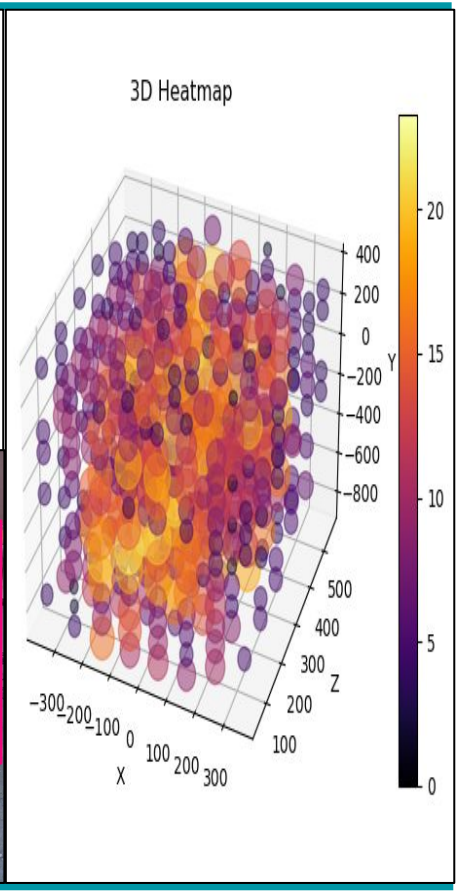
Summary and outlook

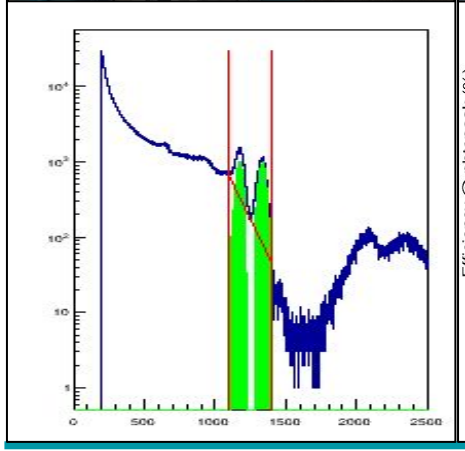
- Materials classified as **radioactive waste** must be **optimized** in order to minimize their space in disposal centers.
- We propose the use of the high resolution γ-ray imaging spectrometer, **i-TED**, for this radioactive **waste characterization**.
- Combining **Compton imaging** and **computer vision techniques**, visual results are provided in one single image.
- **Proof-of-concept** measurements were carried out at **El Cabril** disposal facility (Córdoba - Spain).
- **Results** obtained for different positions are **consistent** with each other.
- Ongoing work: **3D distribution** of γ-radiation.

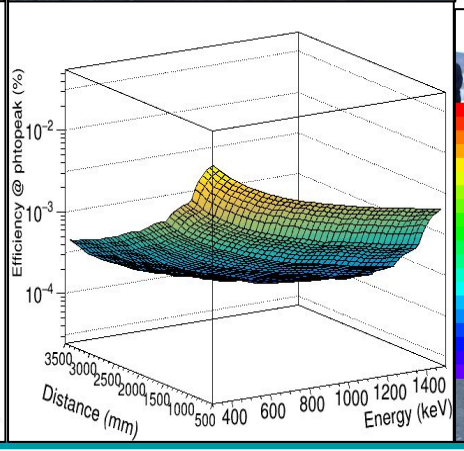
Thanks for your attention

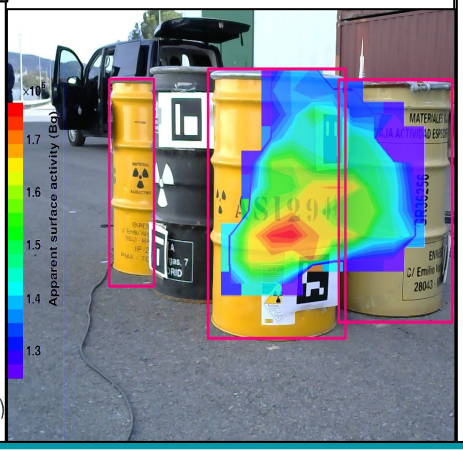










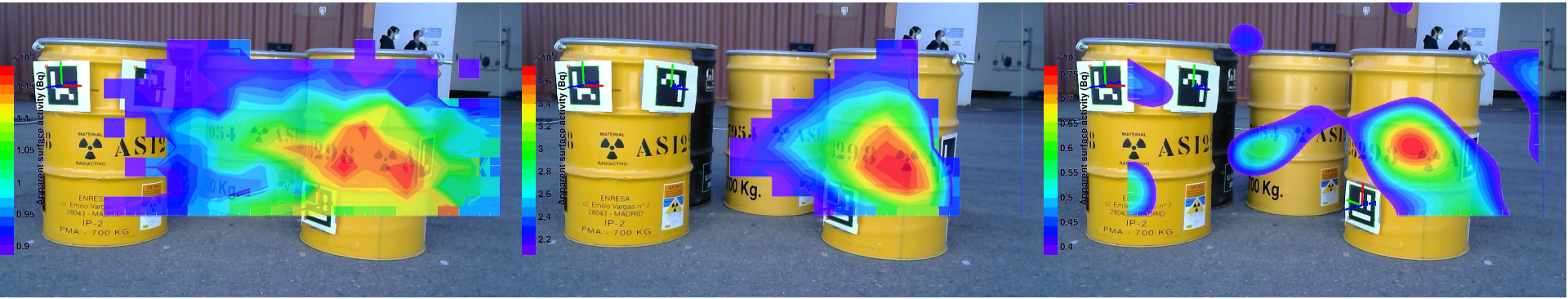


Backup slides

Algorithm comparison

Three different algorithms have been tested:

Backprojection | **Maximimum Likelihood (ML)** | **Analytical**



Results - All datasets

Three different datasets:

01/02/2022

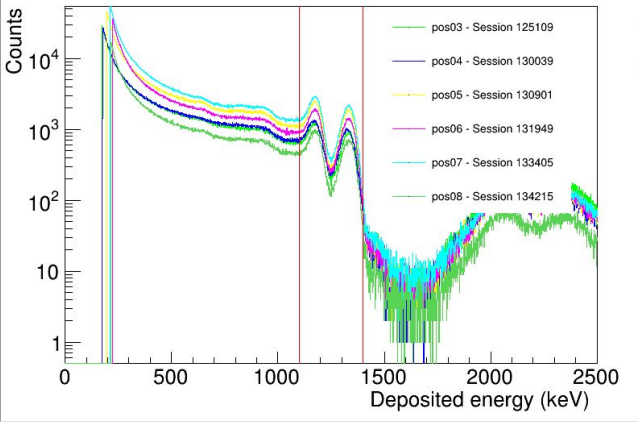
pos06 2.93 m 190 MBq	pos05 2.596 m 190 MBq		pos04 2.481 m 100 MBq
pos07 2.163 m 165 MBq	AS 28298 2.75 mSv/h XXXX		AS 29448 3 mSv/h X
	GR 36256 0.65 mSv/h X	AS 27954 4 mSv/h	GR 15748 0.56 mSv/h
			pos03 2.199 m 60 MBq
pos08 2.443 m 70 MBq			

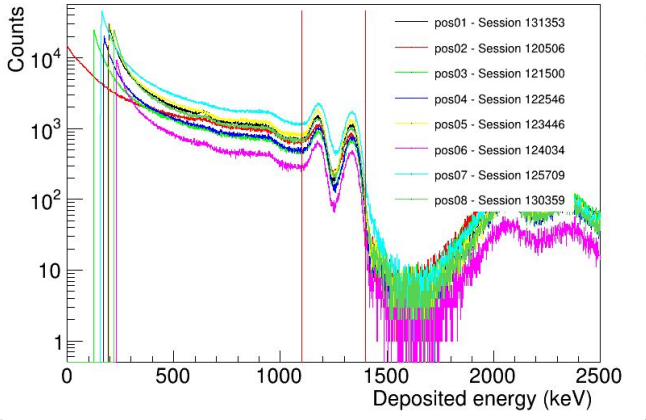
02/02/2022

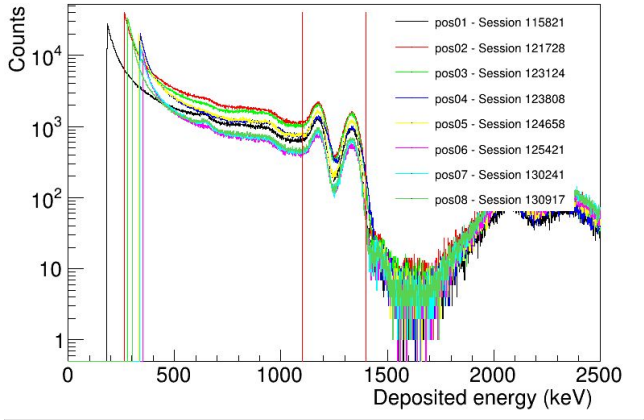
pos06 2.84 m 75 MBq	pos05 2.560 m 180 MBq		pos04 2.310 m 75 MBq
pos07 2.067 m 150 MBq	AS 28298 2.75 mSv/h XXXXX		AS 29448 3 mSv/h X
	GR 36256 0.65 mSv/h	AS 27954 4 mSv/h XX	GR 15748 0.56 mSv/h
			pos03 2.120 m 55 MBq
pos08 2.4 m 125 MBq	pos01 2.585 m 150 MBq		pos02 2.420 m 90 MBq

03/02/2022

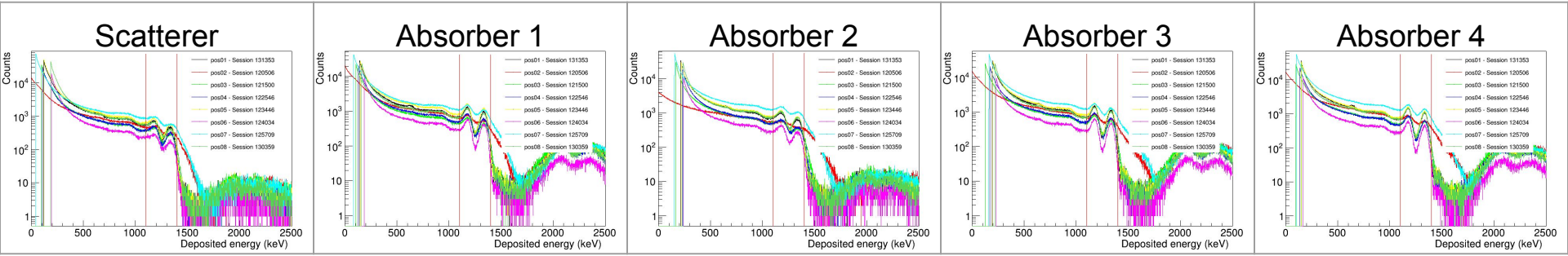
pos06 2.969 m 105 MBq	pos05 2.510 m 165 MBq		pos04 2.304 m 115 MBq
pos07 2.236 m 60 MBq	AS 29448 3 mSv/h X	GR 15748 0.56 mSv/h X	AS 28298 2.75 mSv/h XXX
	GR 36256 0.65 mSv/h XX	AS 27954 4 mSv/h X	
			pos03 2.129 m 135 MBq
pos08 2.487 m 85 MBq	pos01 2.604 m 125 MBq		pos02 2.856 m 260 MBq

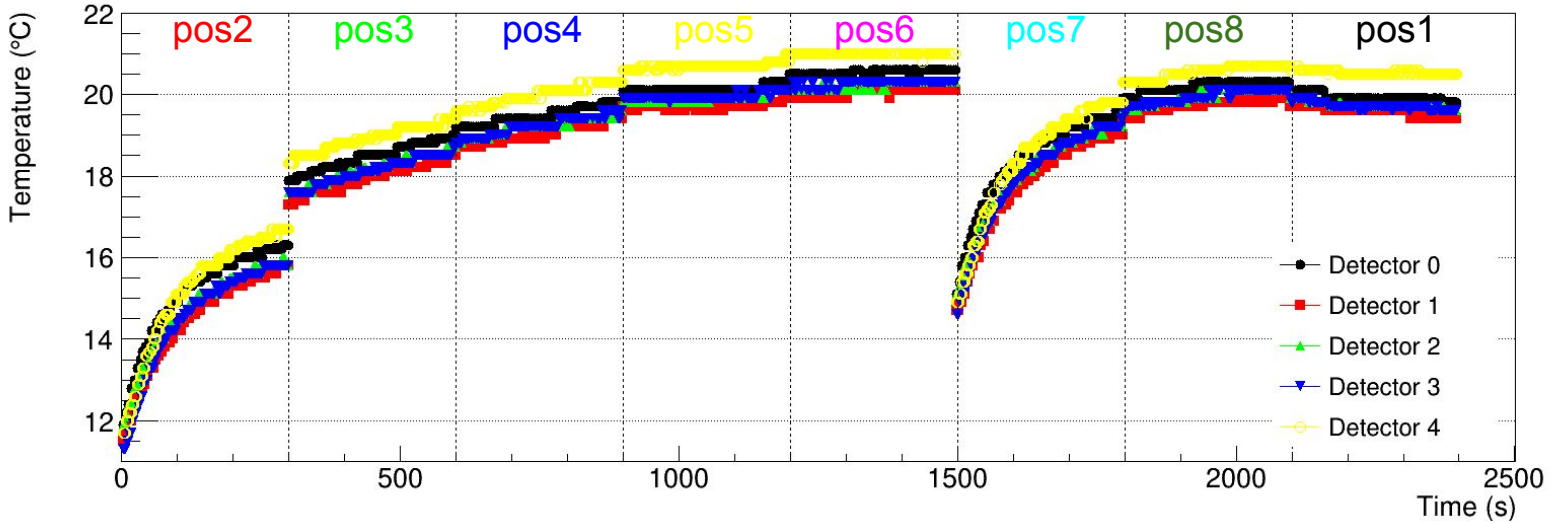






Temperature correction





Temperature correction

Let's take the simplest approximation for the energy calibration in one of the individual detector:

$$\hat{E} = a_0 + a_1 x + a_2 x^2$$

Where x is the ADC registered as the sum of the individual pixels in coincidence. Therefore, if we assume a linear dependence with the temperature we have:

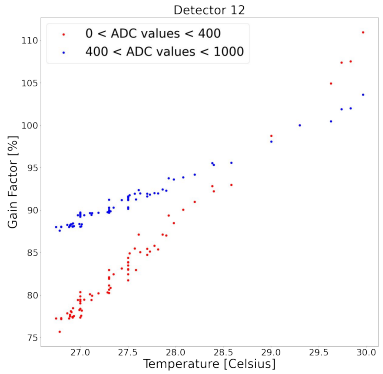
$$x = x_0 \left(1 + \beta * \Delta T\right) = x_0 \left(1 + \beta * (T - T_{ref})\right)$$

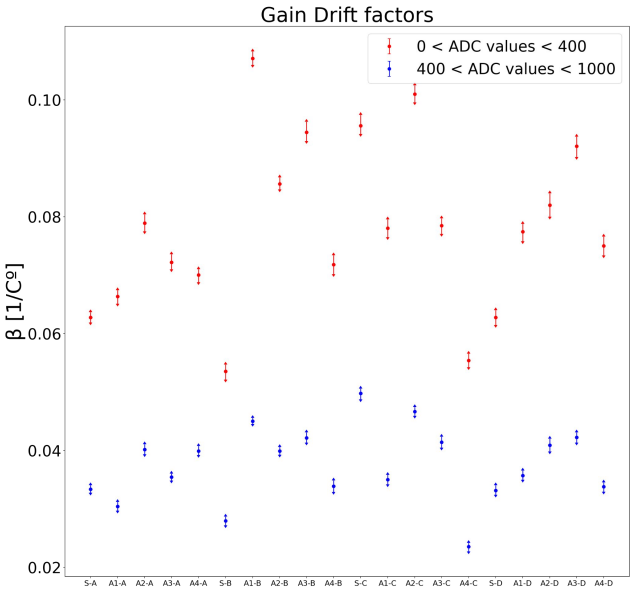
Where β is simply the multiplication factor.

Results coming from our* study:

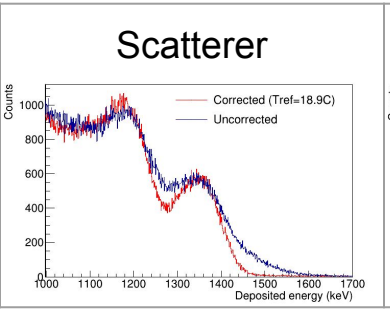
- β ≅ 0.04 (x < 400)
- β ≅ 0.08 (x > 400)

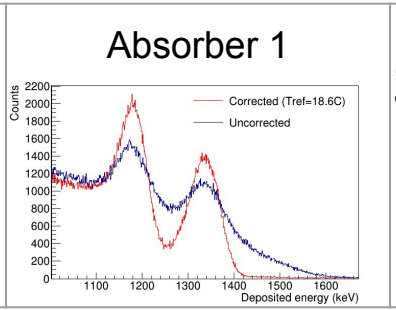
*Thanks to Dr. Balibrea-Correa.

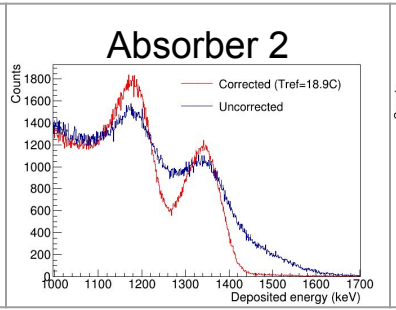


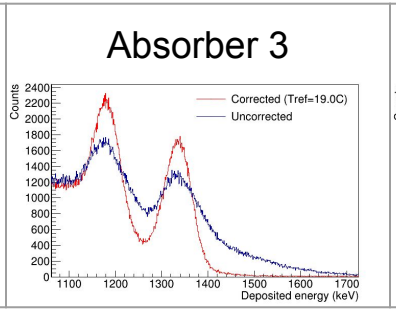


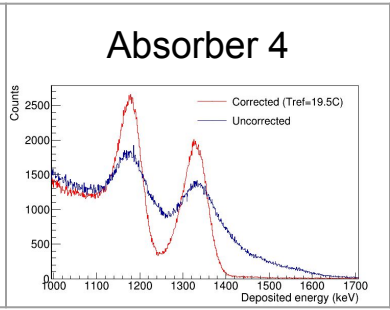
Temperature correction

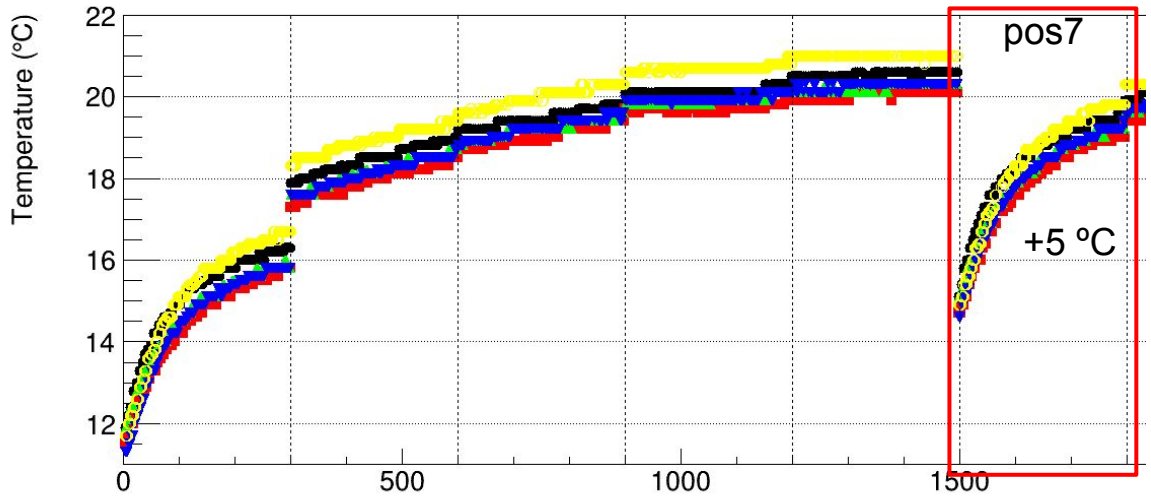


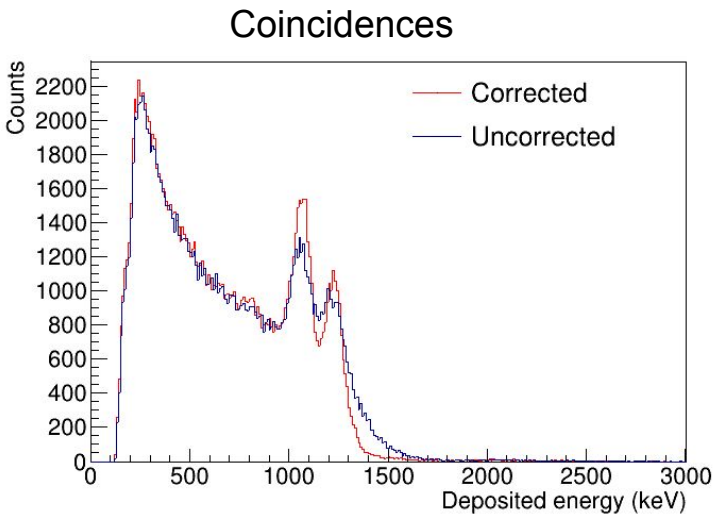








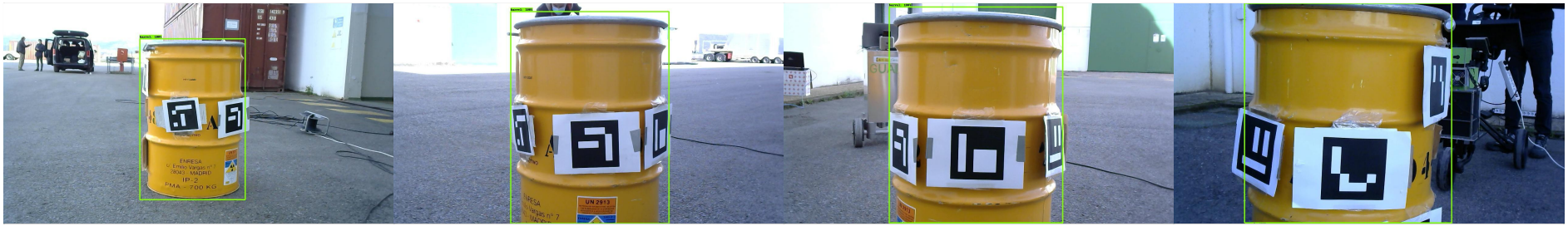




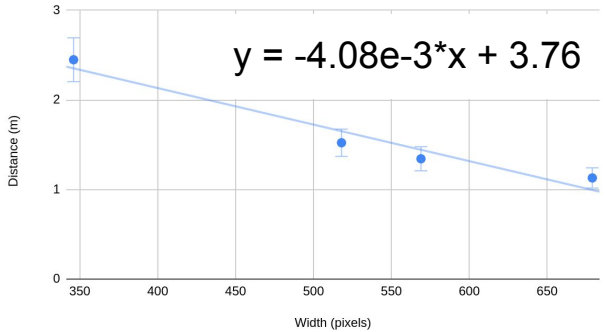
Tensorflow distance cross-check

The object detection feature can be used to obtain the distance to the object.

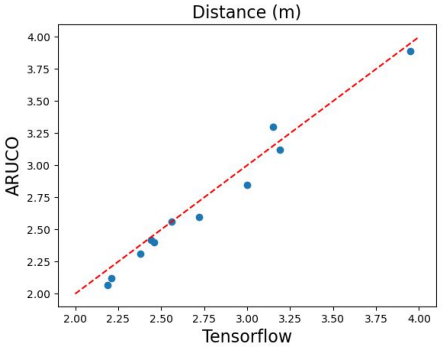
- Pictures of a single barrel to get the distance - size relation.
- The distance is computed at each case using ARUCOS.
- Tensorflow provides the object size in pixels.



- Equivalence:



Comparative:



Dynamic electronic collimation

- Distance between Scatter and Absorber (dSA) planes can be modified to obtain the desired trade-off in efficiency and image resolution.

Efficiency vs dSA

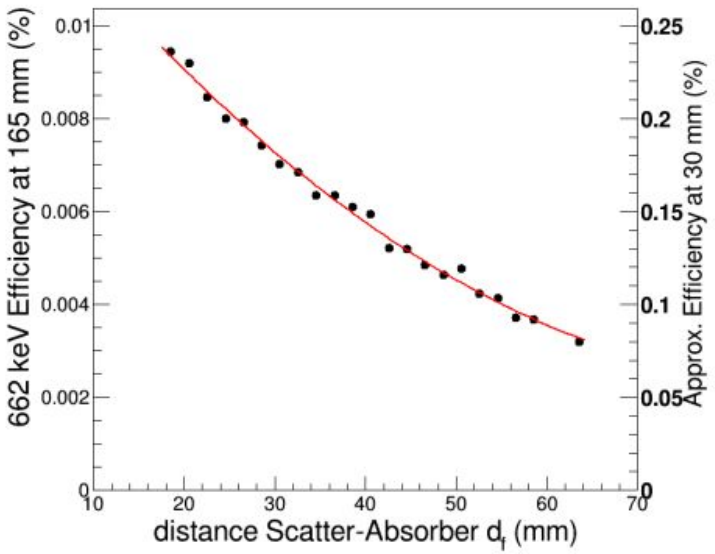
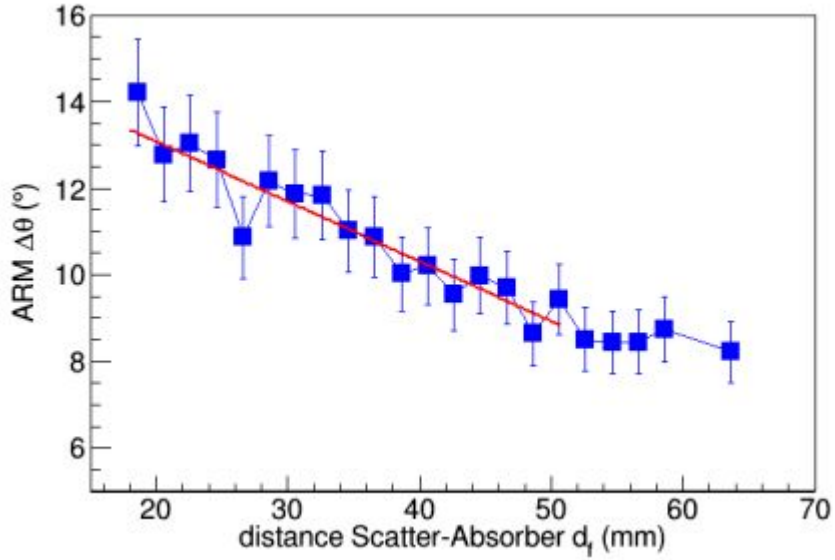
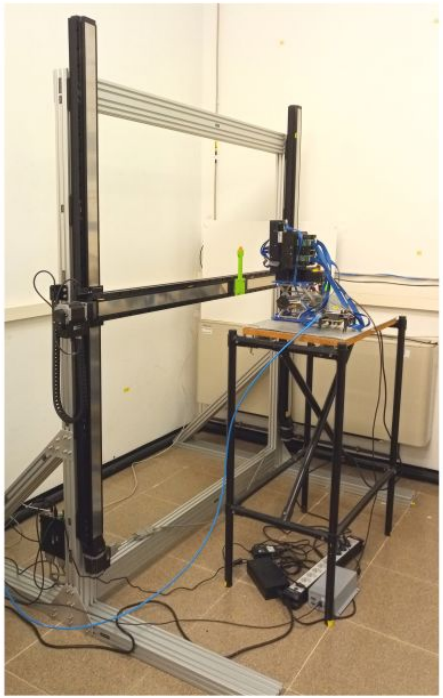


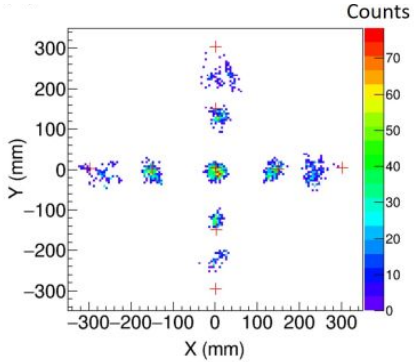
Image resolution vs dSA



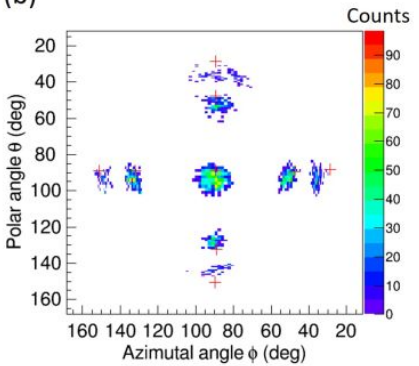
Field of view

- Compton cameras has a field of view of 360 degrees but with a pay in efficiency.

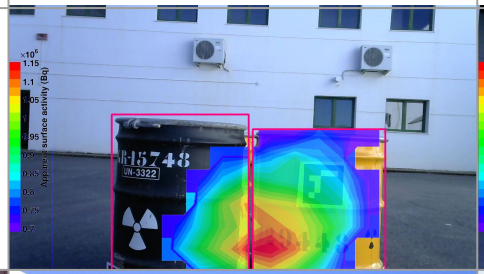
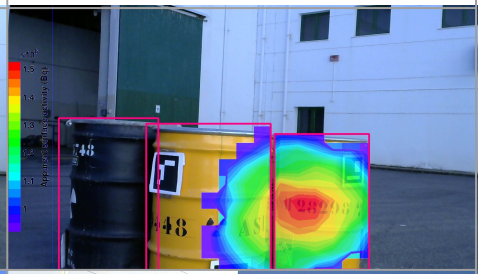
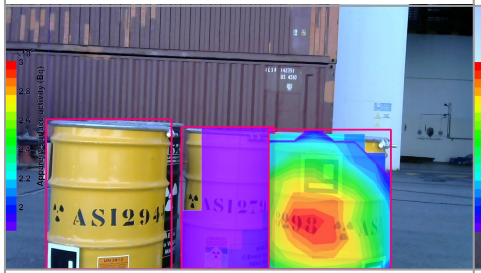
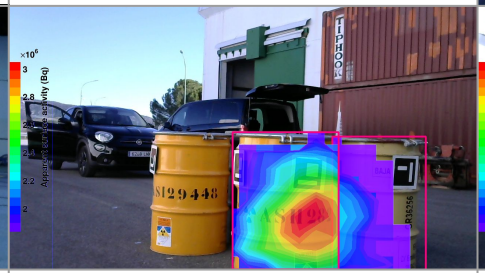
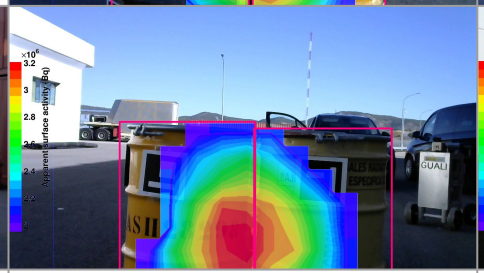
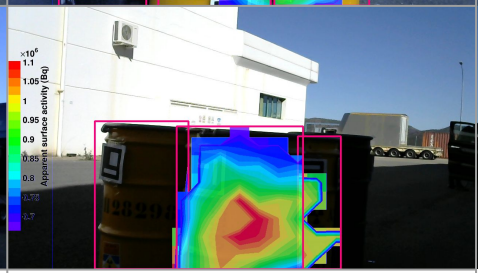




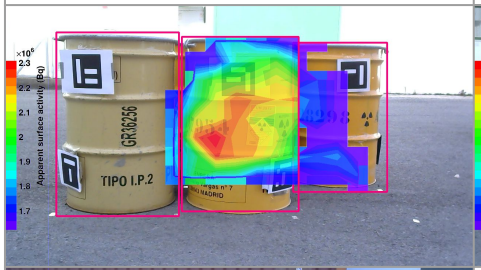
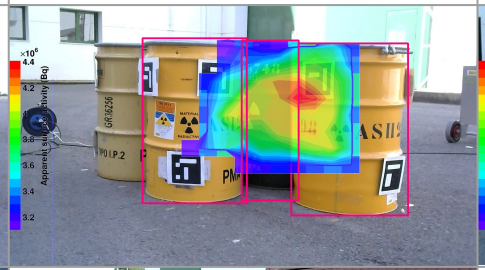
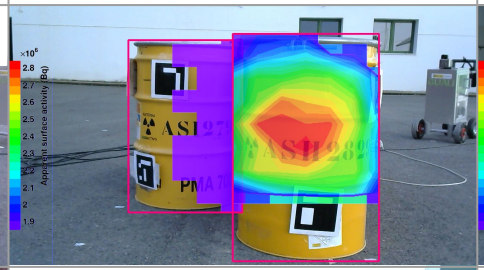
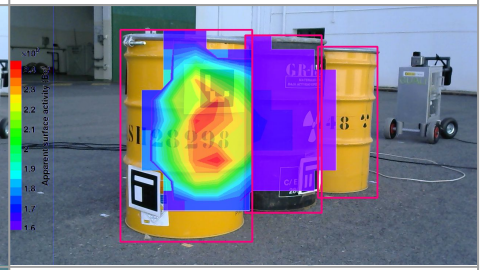
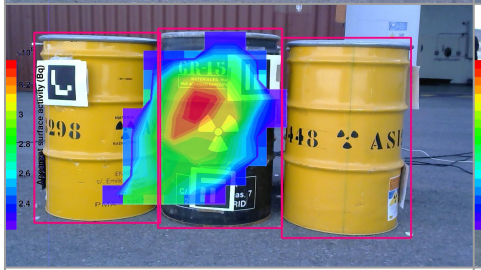
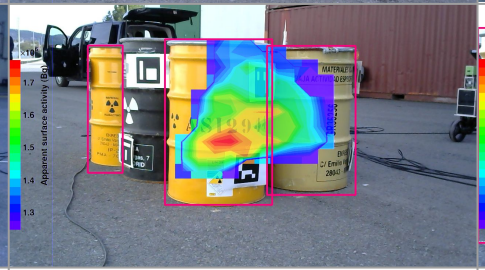
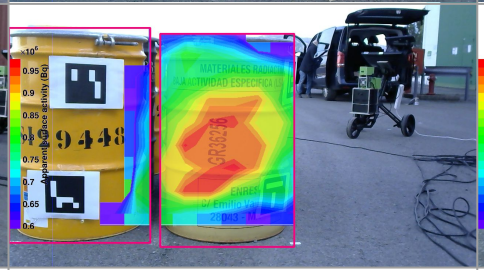
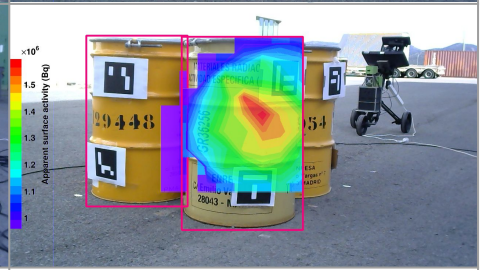
(b)



Results - All positions

Position #1	Position #2	Position #3	Position #4
X	X		
			
Position #5	**Position #6**	**Position #7**	**Position #8**

Results - All positions

Position #1	Position #2	Position #3	Position #4
			
			
Position #5	**Position #6**	**Position #7**	**Position #8**