A gamma-ray imaging camera for NORM radioactivity detection

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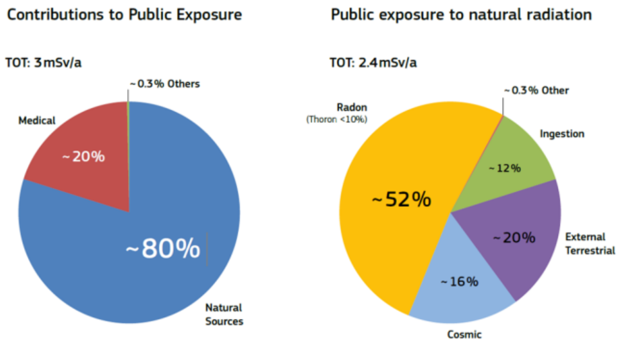
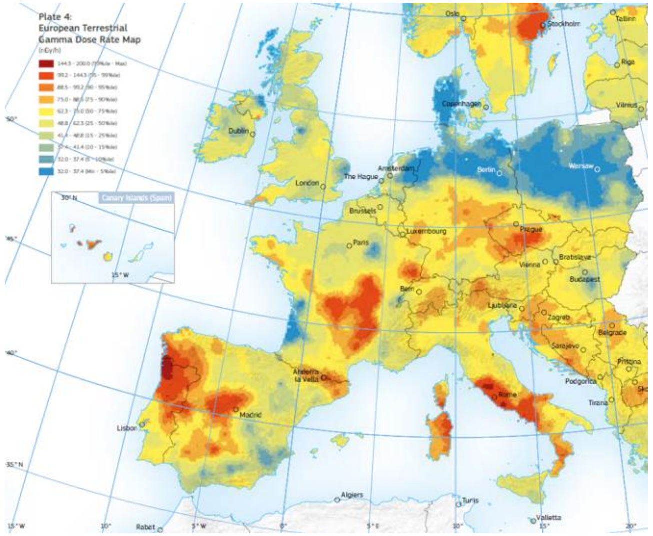
NORM and TENORM

NORM (Naturally Occurring Radioactive Materials) and **TENORM** (Technologically Enhanced Naturally Occurring Radioactive Materials) consists of material, usually <u>industrial wastes</u> or <u>by-products</u> enriched with <u>radioactive elements</u> found in the environment. **NORM** and **TENORM** can cause dangerous increment of the natural radioactivity and increase the public exposure.





Many **TENORM** are generated from industrial processes that exploit natural resources such as <u>coal combustion</u>, <u>fertilizers production</u>, <u>processing metal</u>, <u>oil mineral ores extraction</u>, …

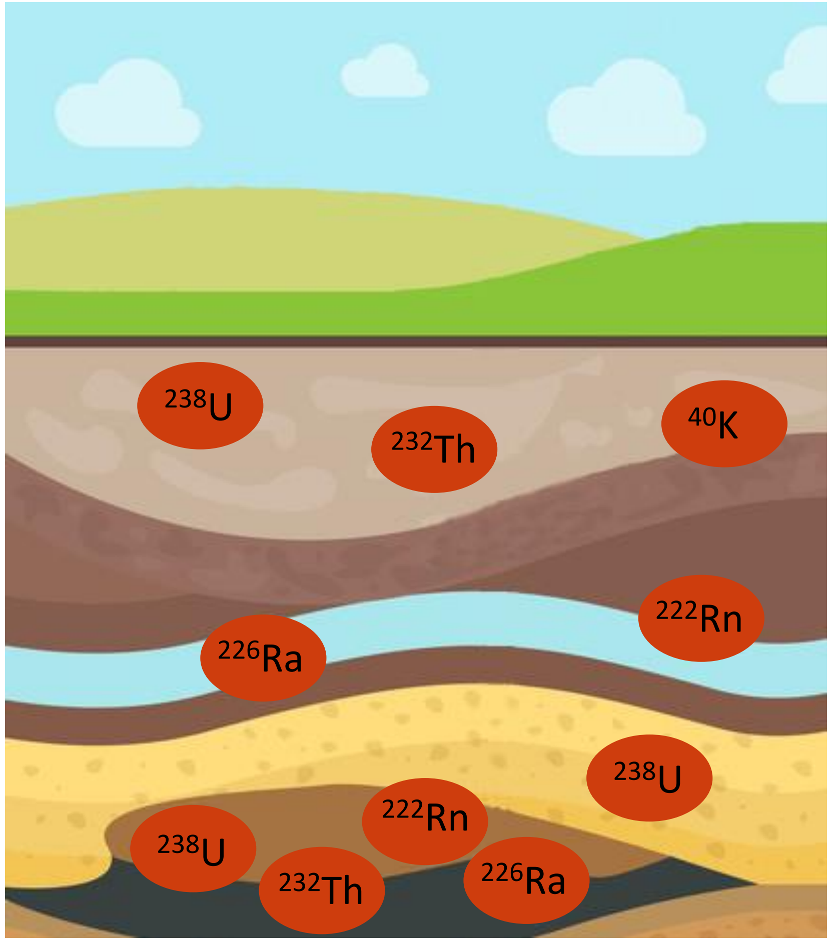
To monitoring the ambient radioactivity and public exposure special skills and new instruments are needed:

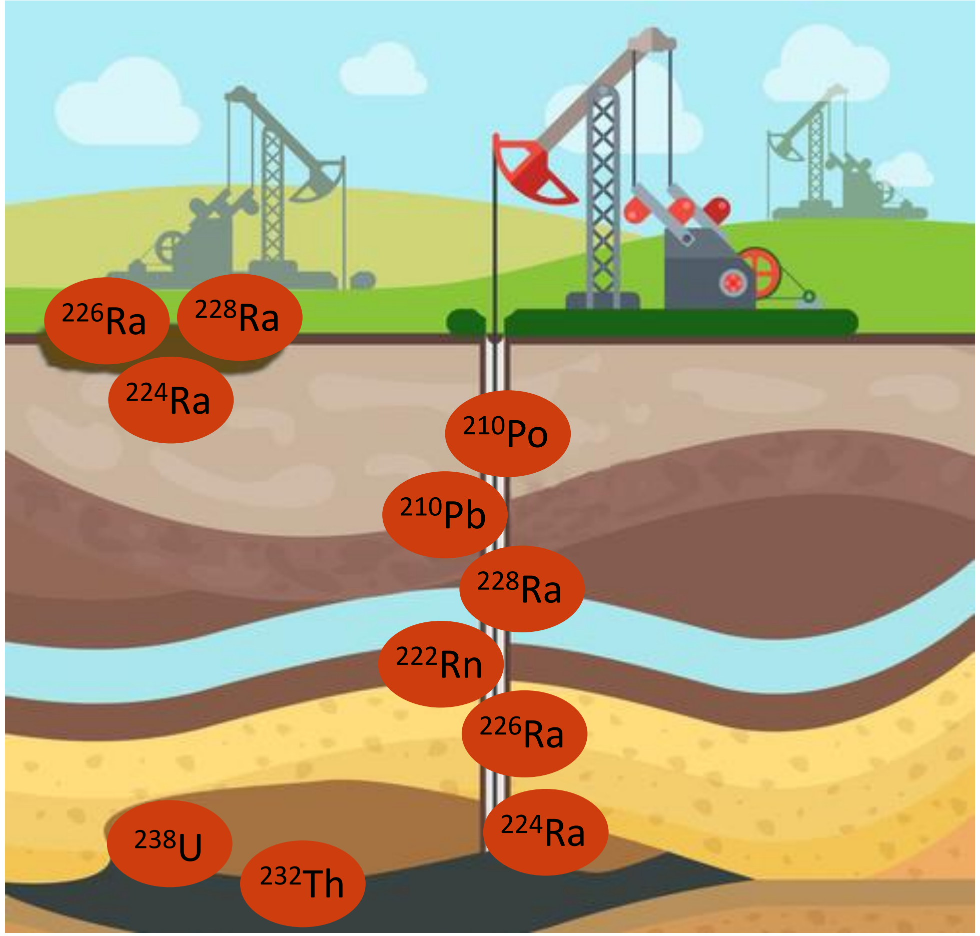
- <u>In-situ</u> and <u>real time</u> acquisition
- Localization and source shaping
- High sensitivity to gamma radiation
- Wide gamma energy range (**100-3000 keV**)
- Possibility to make acquisition on the go.

NORM and TENORM

NORM
- ^{238}U and ^{232}Th decay chains and ^{40}K
- **Undisturbed** as a result of human activities
- **NOT exposed** to accessible environment

TENORM
- **NORM concentrated** and **exposed**
- ^{238}U and ^{232}Th **not soluble**
- Increase of external exposure to workers and population





Gamma camera purpose


Fly coal ash (example of TENORM)

Set-Up:
- 4X4 scintillator array made of CsI(Tl) $3x3x10cm^3$ coupled with 16 Photomultiplier tubes.

Signal read-out:
- CAEN digitizer V1725, 14-bit @ 250 MS/s

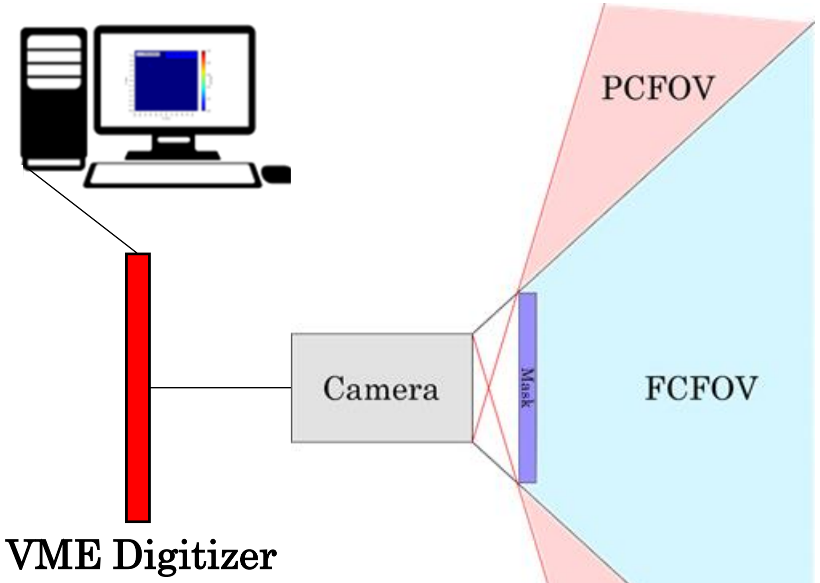
Skills (real time and in-situ):
- Gamma spectra analysis and source recognition (*gamma spectroscopy 100-3000 keV*)
- Gamma source localization (*gamma imaging*)

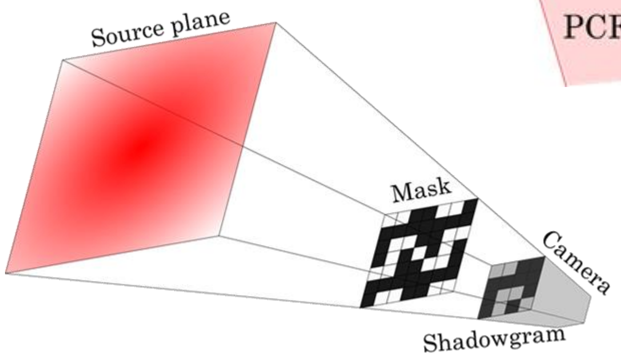
Aim:
- NORM and TENORM environmental monitoring
- Homeland security
- Safety control in industrial environment

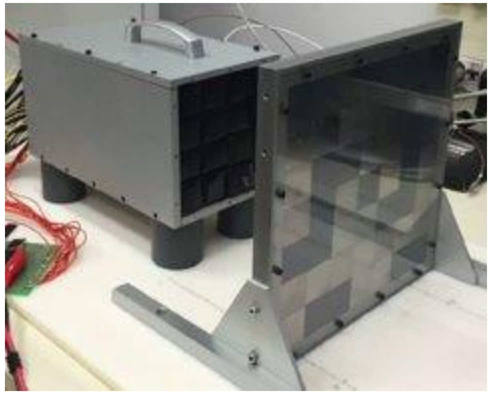

Oil&Gas industry (example of TENORM)

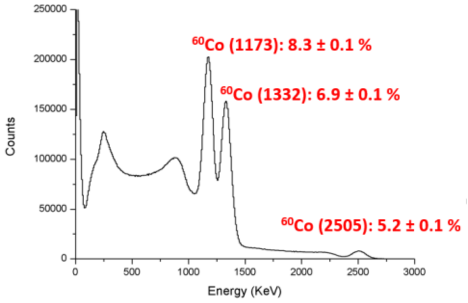

Gate monitoring for homeland security

Prototype







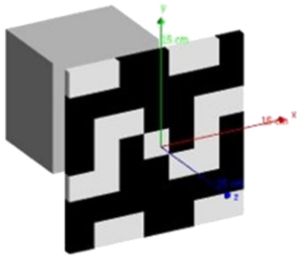


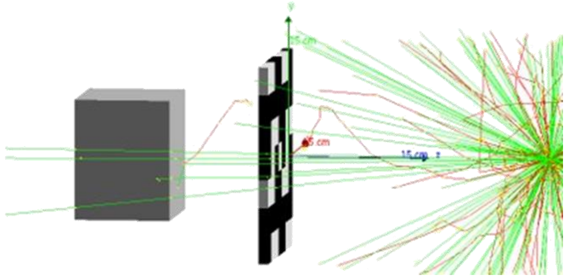
•Gamma sources are detected and identified by spectra. Then, the position is reconstructed by algorithms based on coded mask technique.

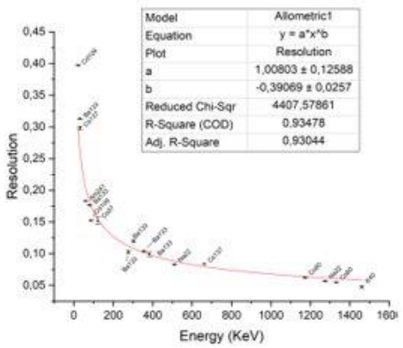
•All the sources emission in the Full Coded Field of View **(FCFOV)** are coded by mask and acquired by camera.

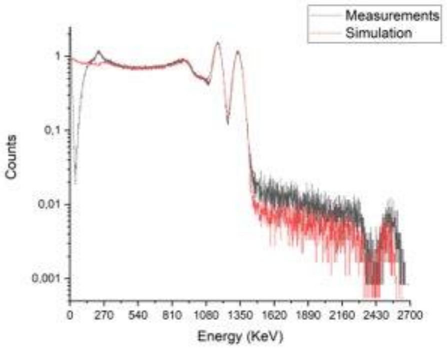
•The camera is composed by a 4x4 CsI(Tl) scintillators array (3x3x10 cm^3 each crystal), coupled with PMTs and the outcoming signal is digitalized by a digitizer CAEN V1725 14-bit 250 MS/s.

Monte Carlo simulation





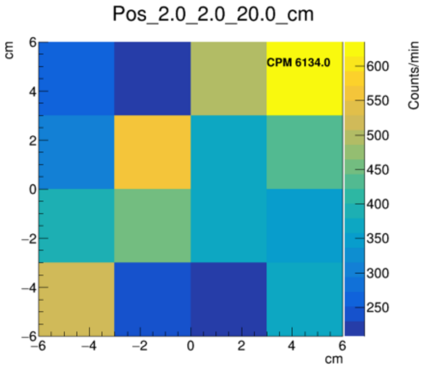




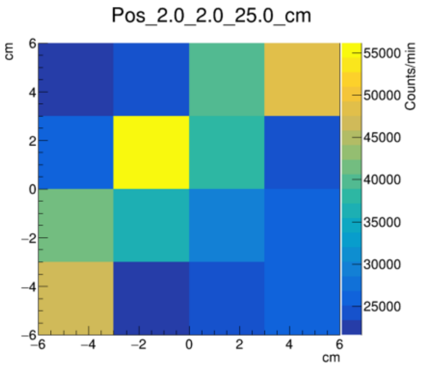
Toy Monte Carlo

- A Toy Monte Carlo was developed as a first simulation step to test reconstruction algorithm without radiation-matter interaction. Each gamma ray is tracked and can be only absorbed by mask or counted by Camera on the hit channel.

Measurements



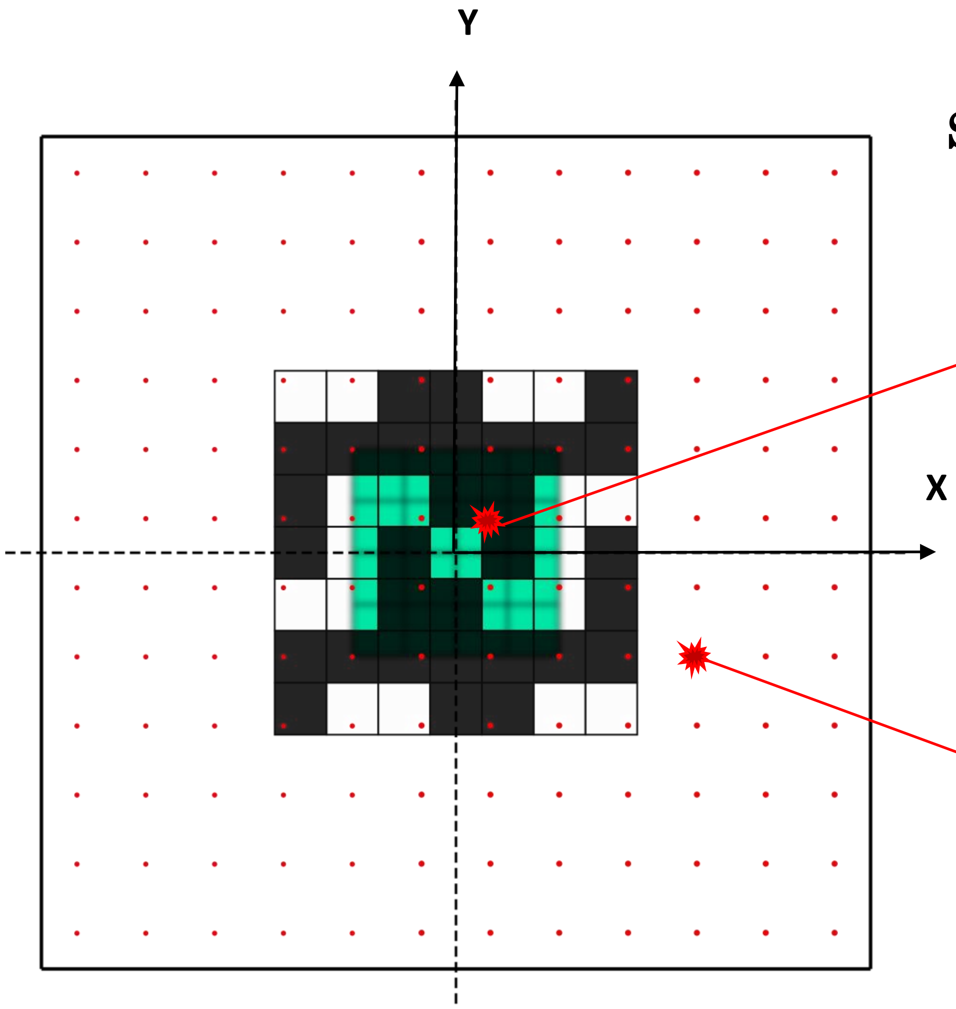
Simulation



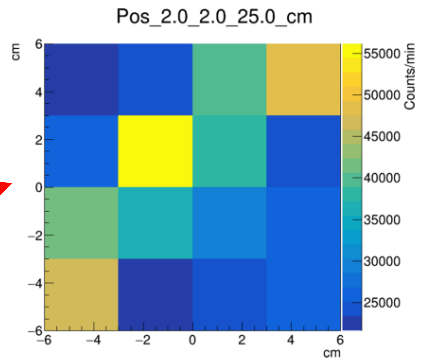
Monte Carlo G4 Based

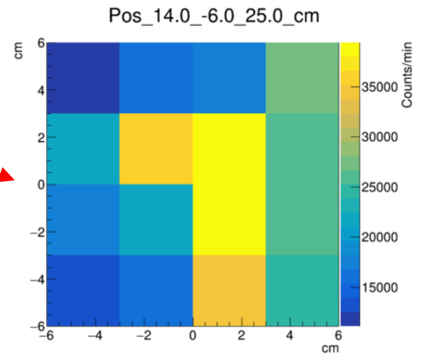
- A Monte Carlo simulation based on GEANT4 was developed.
- To simulate the instrument spectra broadening was used data acquired with different sources using the gamma camera crystal (CsI), and the trend was fitted.
- Spectra visualization was compared between simulation and data acquisition and a good agreement was obtained.
- Count maps come from simulation show the same coded pattern of the measurements.
- Gamma imaging reconstruction algorithm can be deeply studied taking into account also the radiation-matter interactions.
- In this work two sources are simulated and compared: ^{60}Co, ^{137}Cs.

Image reconstruction

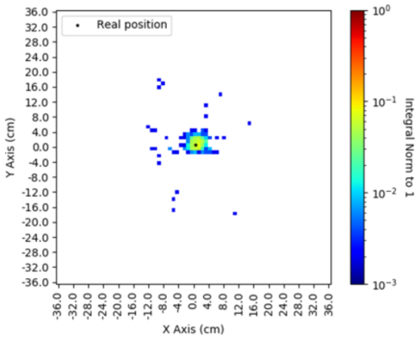


Scintillators count map

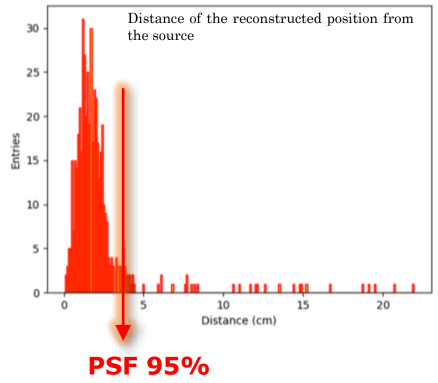




- Imaging algorithm is based on a two-dimensional Kolmogorov-Smirnov test generalization (KS2D-test).
- A database of counting maps (in cpm) is recorded during calibration and used for comparison along KS2D-test.
- To test the goodness of algorithm, a series of sources in random places was reconstructed and the resulting distances from real positions are binned and plotted in a histogram. Its Point Spread Function (quantile at 68% and 95%) is the figure of merit used for tests.

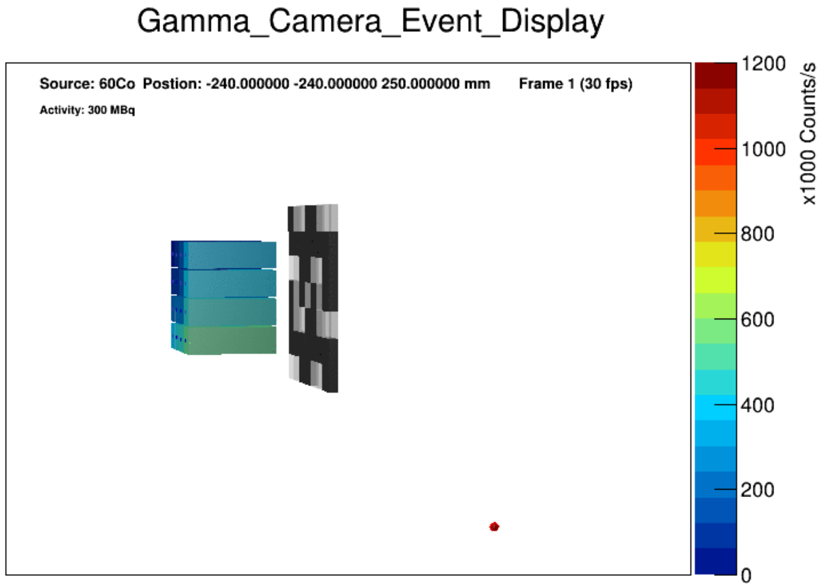


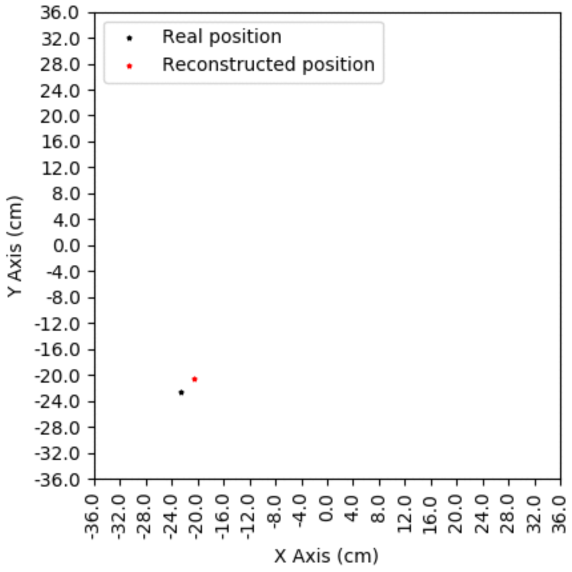
Black point show the real position of the source (random position normalized to center), the binned data the reconstructed positions. Data come from simulation.

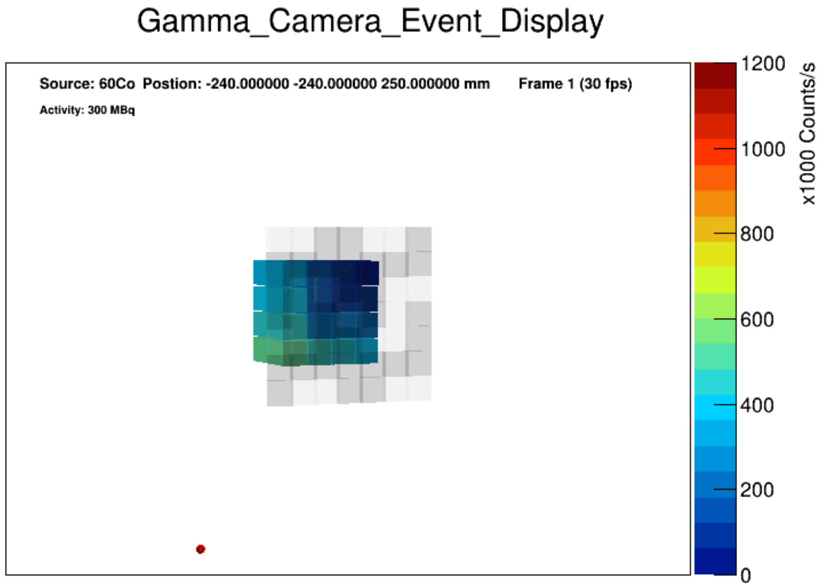


Monte Carlo simulation

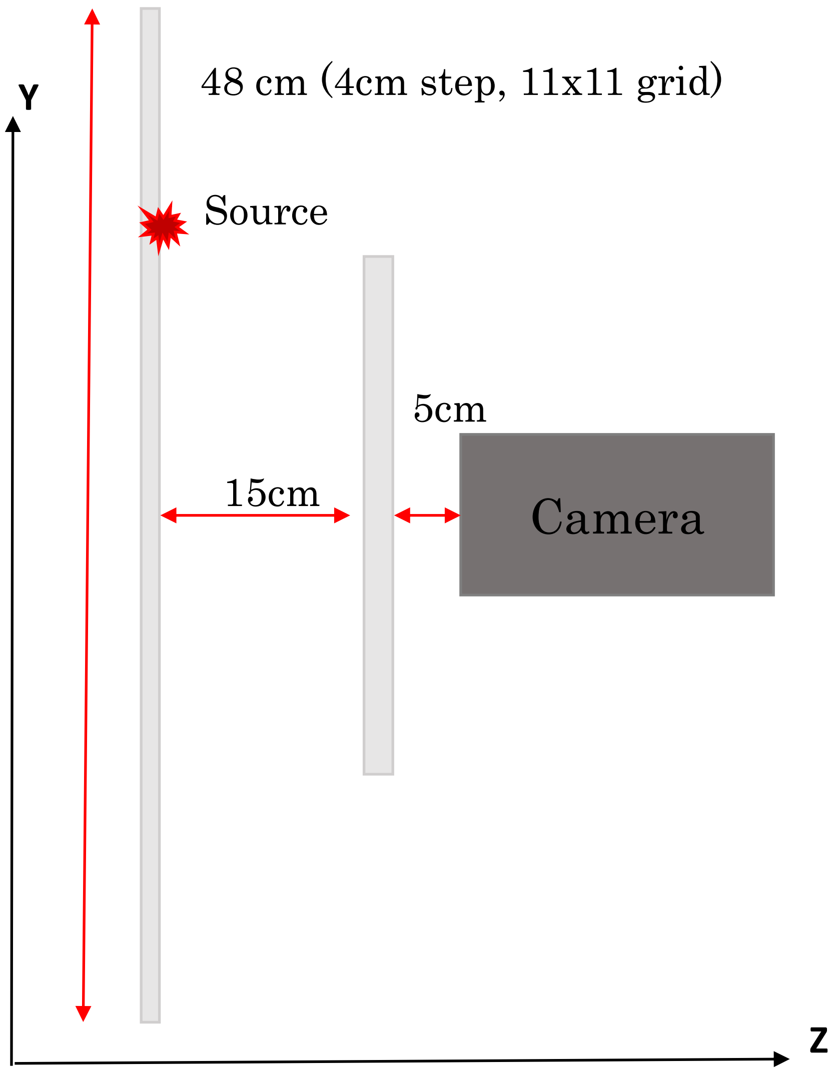
Simulation of a real-time acquisition (^{60}Co source with an activity of 300 MBq at 20 cm from the Camera)

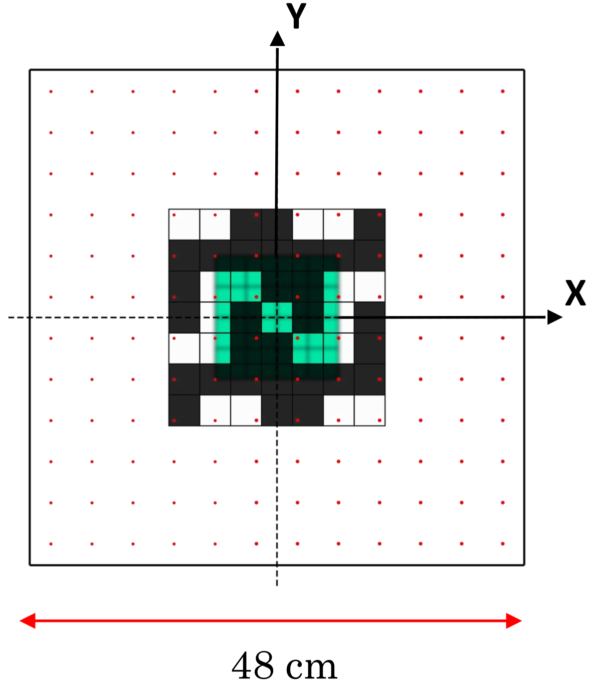






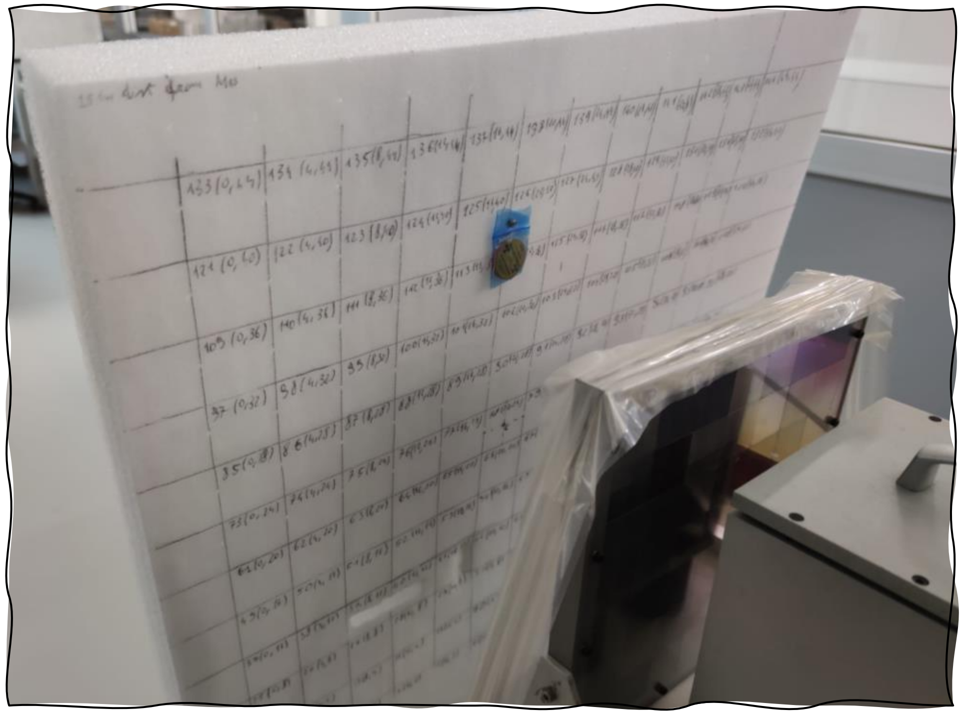
Data acquisition configuration





Field of view

48x48 cm^2 @ 20 cm 1.8π sr
Step Size 4 cm = 144 calibration points



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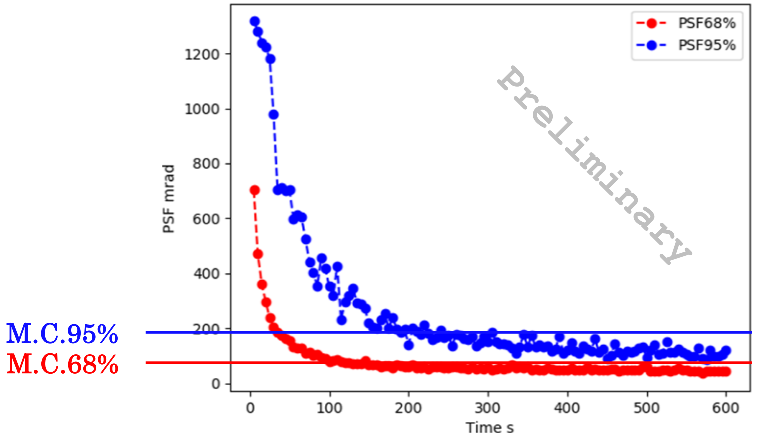
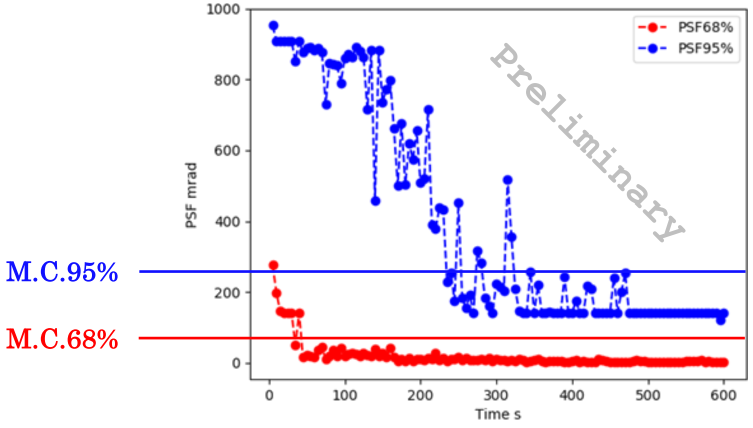
Data reconstruction results

^{137}Cs Source



^{60}Co Source

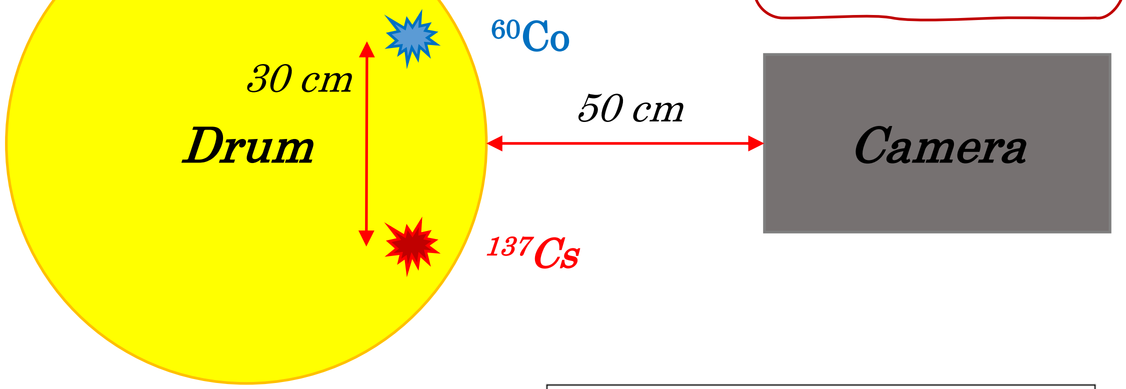


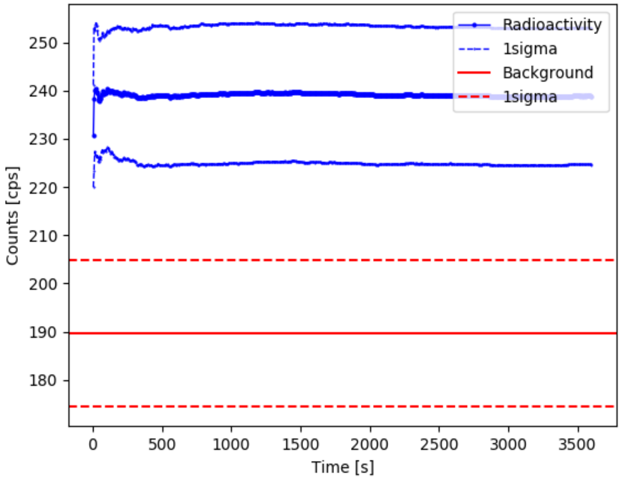
PSF vs Acquisition Time

- We measured the PSF of ^{137}Cs and ^{60}Co with increasing acquisition time in 4 different position randomly chosen.
- We can see e.g. for ^{137}Cs that we need almost 2 minutes to reach the best PSF. After this time we reach a plateau, and no more time is needed to improve reconstruction.
- ^{137}Cs shows a softer convergence than ^{60}Co mainly due to the fact than at low energy (~660 for ^{137}Cs and 1150-1350 for ^{60}Co) the mask tungsten tiles have a better gamma absorption, and the mask works better.
- Those results are compared with Monte Carlo simulation (straight line on plot).

Radioactive drum measurements

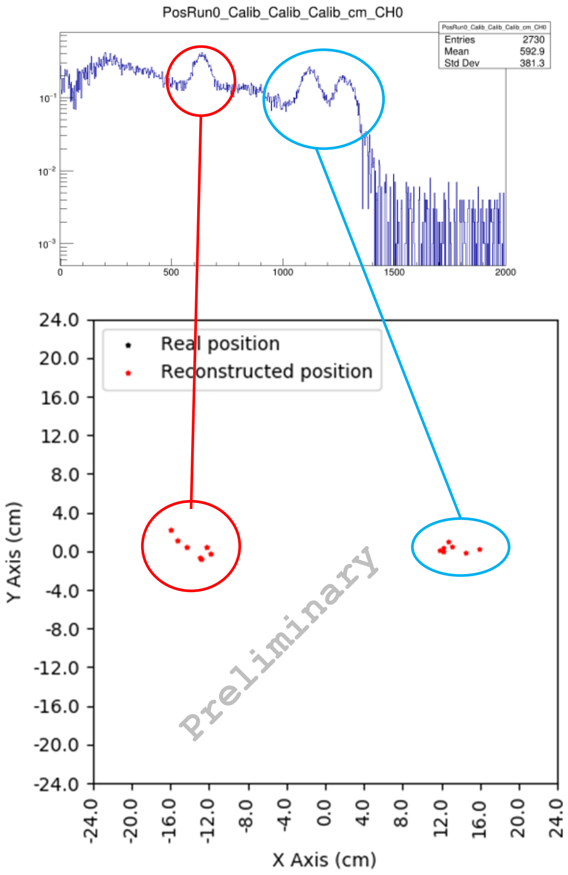
^{60}Co: 37 kBq
^{137}Cs: 9.25 kBq





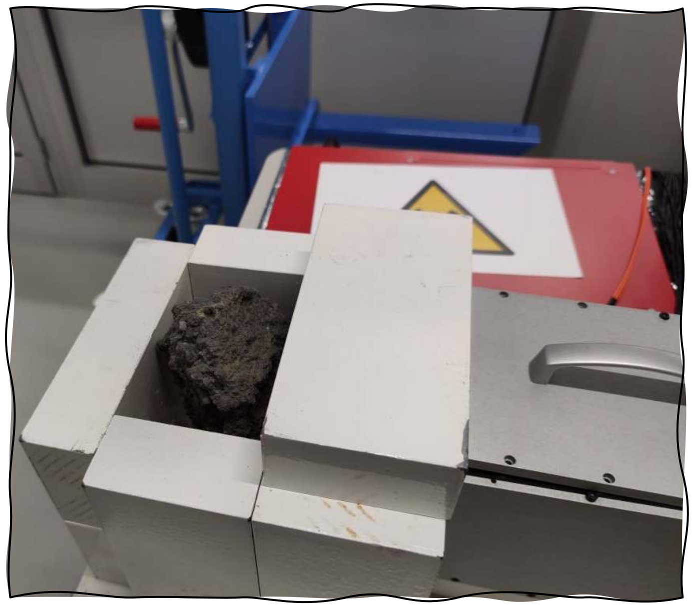
The integral count rate (600-1800 keV) shows a radioactivity over the background and generates an alarm in few seconds.

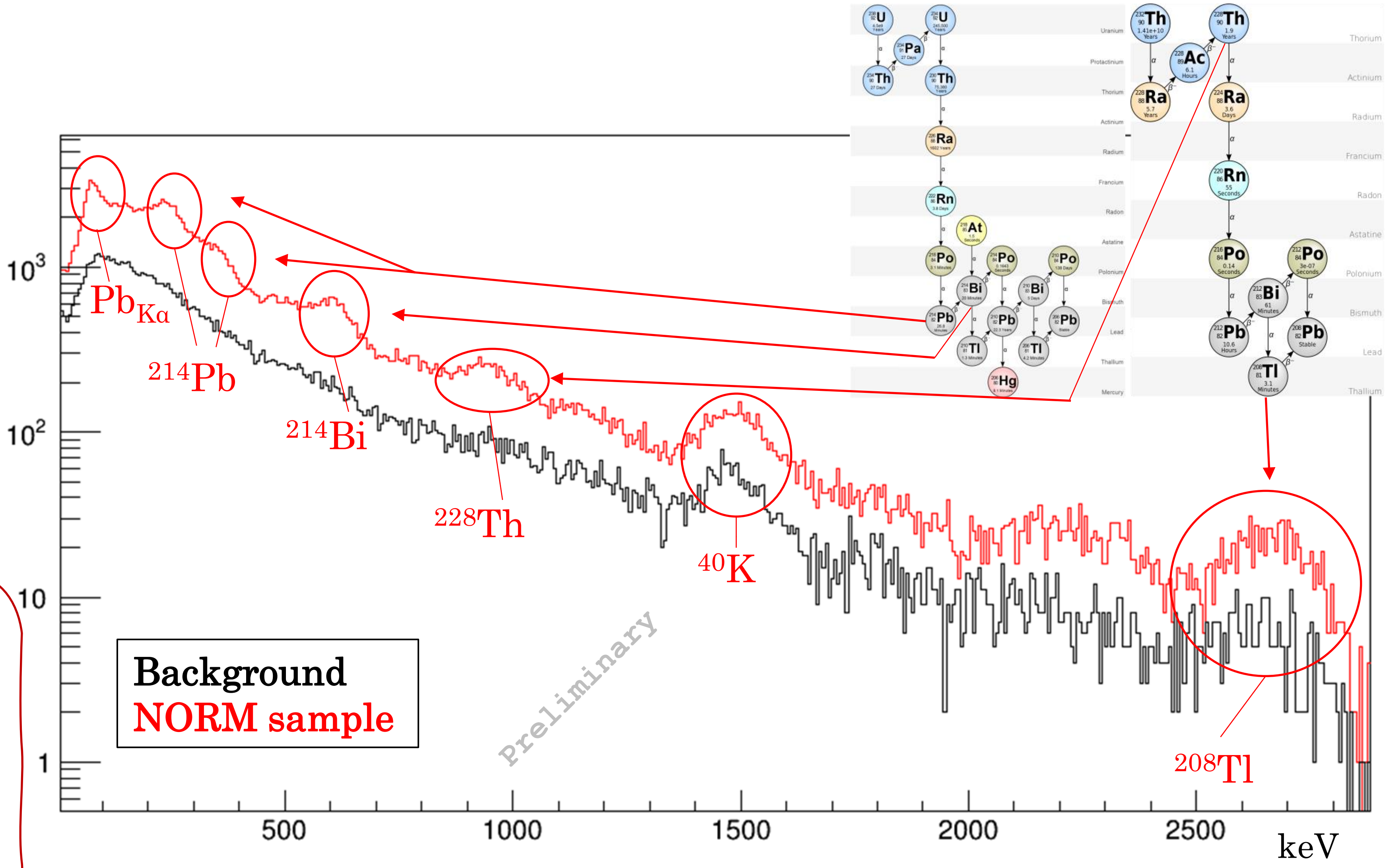
- Using the calibration data it is possible to identify two different sources in the same camera field of view.
- Using the spectra information it is possible to identify the two different source and reconstruct both independently
- It is also possible to identify an alarm rate when the cps rate of the camera exceed a threshold (in this case 1 sigma over the background).



The two sources was reconstructed using the spectrum information and spatial separated.

NORM qualitative analysis

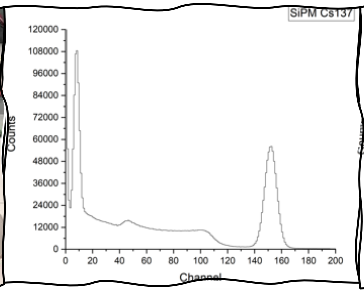


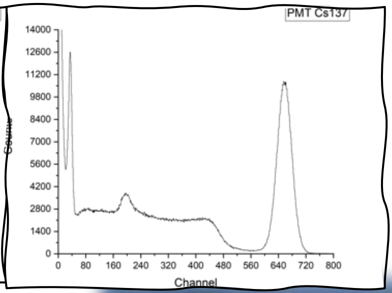


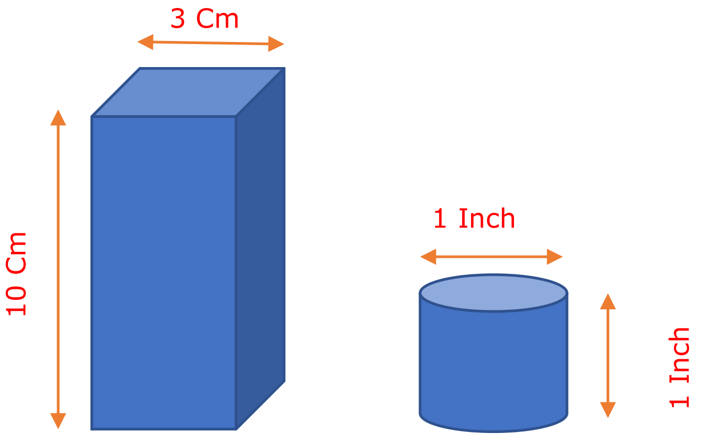
A NORM igneous rock gamma spectrum was acquired with Camera to identify the main natural gamma radioactive peaks. The expected radionuclides was ^{238}U and ^{232}Th decay chains and ^{40}K.

Future improvements

- Develop a NORM quantitative analysis on different geometries.
- Test new algorithms for direct reconstruction.
- Replace Photomultiplier tubes (PMT) with Silicon Photomultiplier (SiPM).
- Change crystal sizes to reduce total camera length.
- Increase number of channel to increase spatial resolution.
- Use a wifi-module to use the camera also in remote mode (robot and drones).





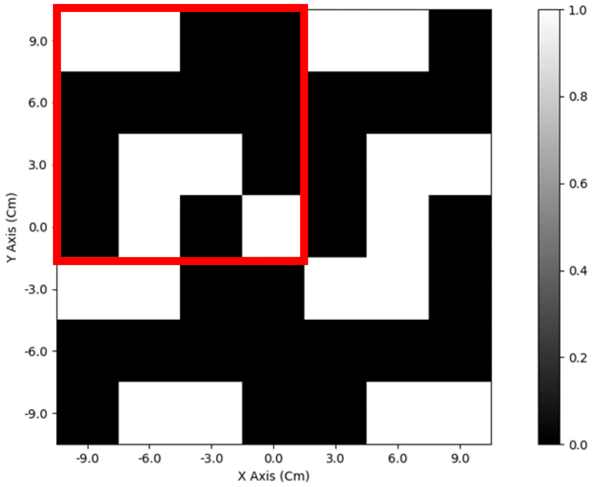


In conclusion…

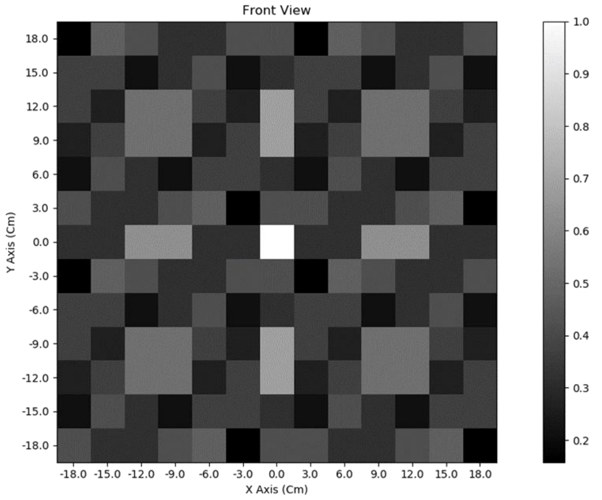
- There are many techniques for gamma imaging one of the most used is the coded mask technique based on the principle of the "*camera obscura*".
- A prototype of Gamma camera was built up using a 4x4 CsI scintillator array and a coded mask 7x7.
- The Gamma camera prototype is also able to localize sources in real time with a spatial PSF at 68% for ^{137}Cs of <u>61 msr</u> (<u>1.5 cm @ 20 cm</u> from camera) and for ^{60}Co of <u>10 msr</u> (<u>0.4 cm @ 20 cm</u> from camera) in 200 seconds of acquisition time.
- The Gamma camera it also able to identify sources with an energy resolution for ^{60}Co of <u>5.8%</u> and for ^{137}Cs of <u>6.2%.</u>
- Gamma camera can identify simultaneously sources in different position using spectrum data and generate a radioactive alarm after few seconds.
- A NORM qualitative analysis is possible in 1 hour in the energy range of interest (<u>100-3000 keV</u>).
- In future we will try to reduce the size and the weight of the camera and increase the number of pixels to increase also the spatial resolution, and test new algorithm as well.

Backup

Mask



SACF



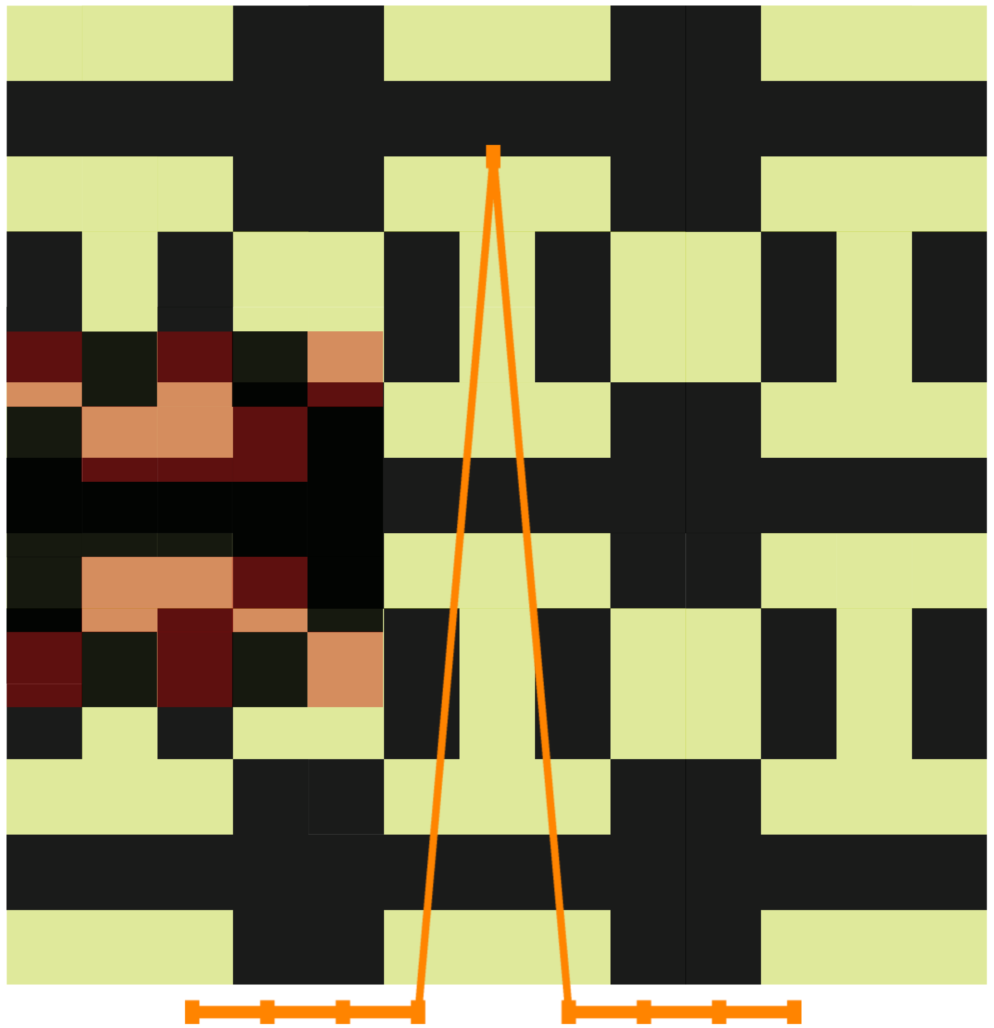
- The <u>mask</u> was assembled with PVC tiles (in white) transparent to gamma radiation and tungsten tiles (black) opaque to gamma radiation.

- The main repetition array is a 4x4 matrix shown in left top figure (red square). The main array was repeated 4 times and the last raw and last column were cut.

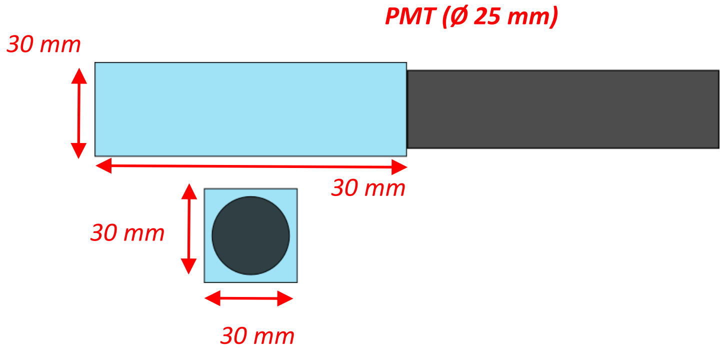
- The left bottom picture shows the SACF (Spatial Auto-Correlation Function) of our mask. The throughput is **38.8%** and the mean lateral lobes value is **0.36.** Those values are very important to qualify the goodness of image reconstruction.

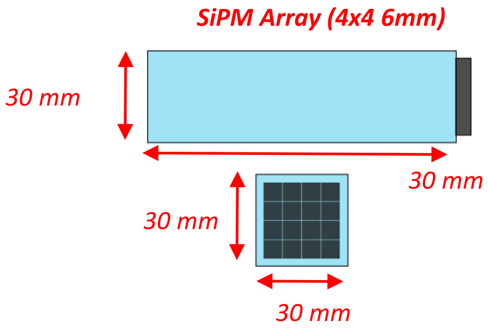
How to measure SACF

Spatial Auto-Correlation Function with Constant Lateral Lobes



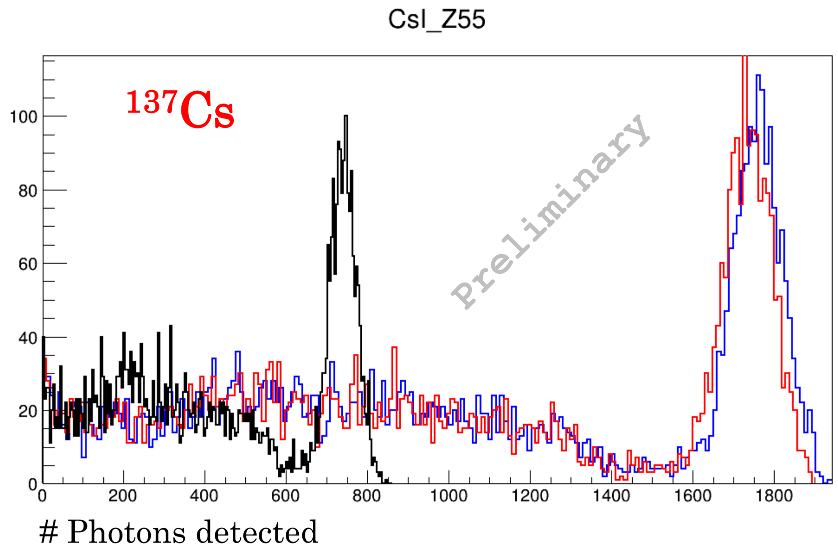
New SiPM configuration

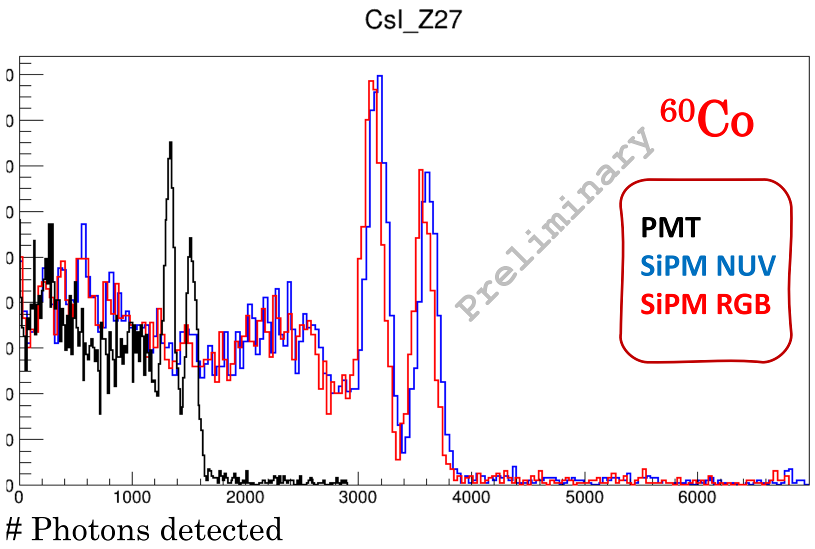


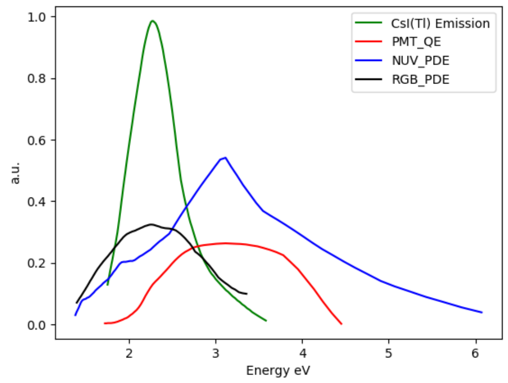


The new SiPM configuration is currently under test, and a new simulation with optical photon tracking was coded.

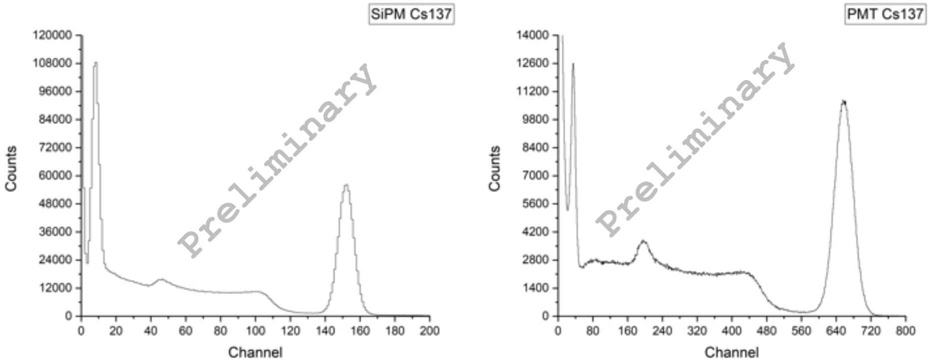
CsI (Tl) Scintillator G4 simulation

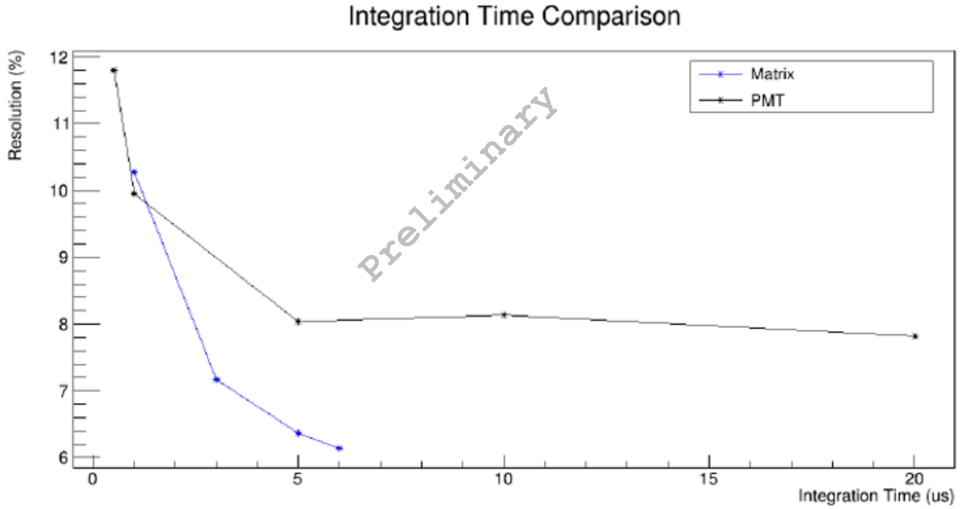






Preliminary SiPM test

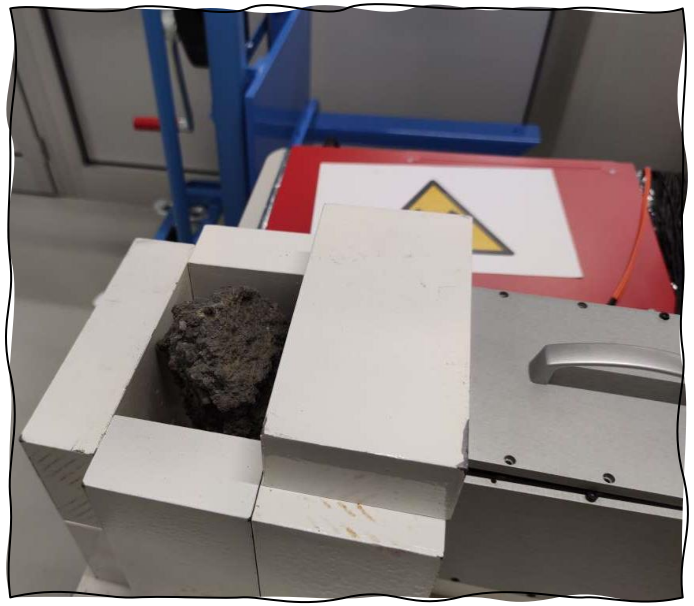


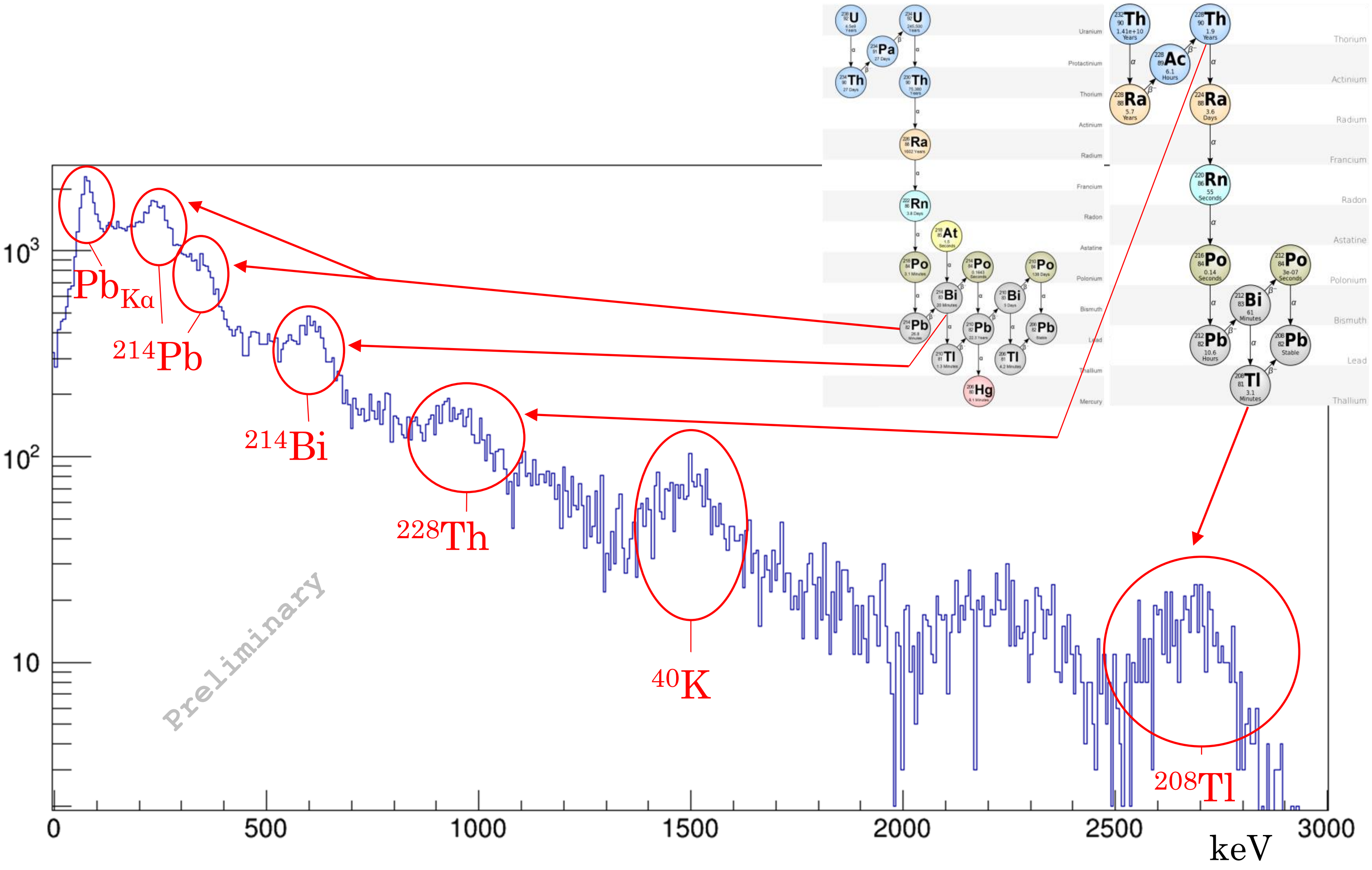


- This preliminary test was carried out using a SiPM array (4x4 4 mm NUV) from FBK
- For long enough integration time the resolution of this ^{137}Cs source increases considerably (remember that CsI(Tl) scintillator has a decay time of 1.22 μs)

Radioisotope	Energy (keV)	PMT Res. (%)	SiPM Res. (%)
^{22}Na	511	8.3	6.8
^{22}Na	1275	5.6	4.5
^{137}Cs	662	8.4	6.2
^{57}Co	122	15.20	12.8
^{60}Co	1173	6.2	5.8
^{60}Co	1332	5.5	5.2
^{241}Am	59.5	18.3	16.0

NORM qualitative analysis





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