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Scintillators for nondestructive assay in industrial and security applications

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Summary

1. NUCLEAR MEASUREMENT LAB
2. X-RAY IMAGING
3. GAMMA-RAY SPECTROSCOPY
4. NEUTRON MEASUREMENTS
5. NEUTRON & PHOTON ACTIVATION
6. CONCLUSION & PROSPECTS

1. Introduction

The Nuclear Measurement Laboratory

- CEA, DES Energy Division, IRESNE institute at CEA Cadarache
- 25-30 permanent staff + 5-10 PhD, trainees, temporary contracts
- 50 - 60 projects or collaborations on R&D and applications

Non-destructive Nuclear Measurements

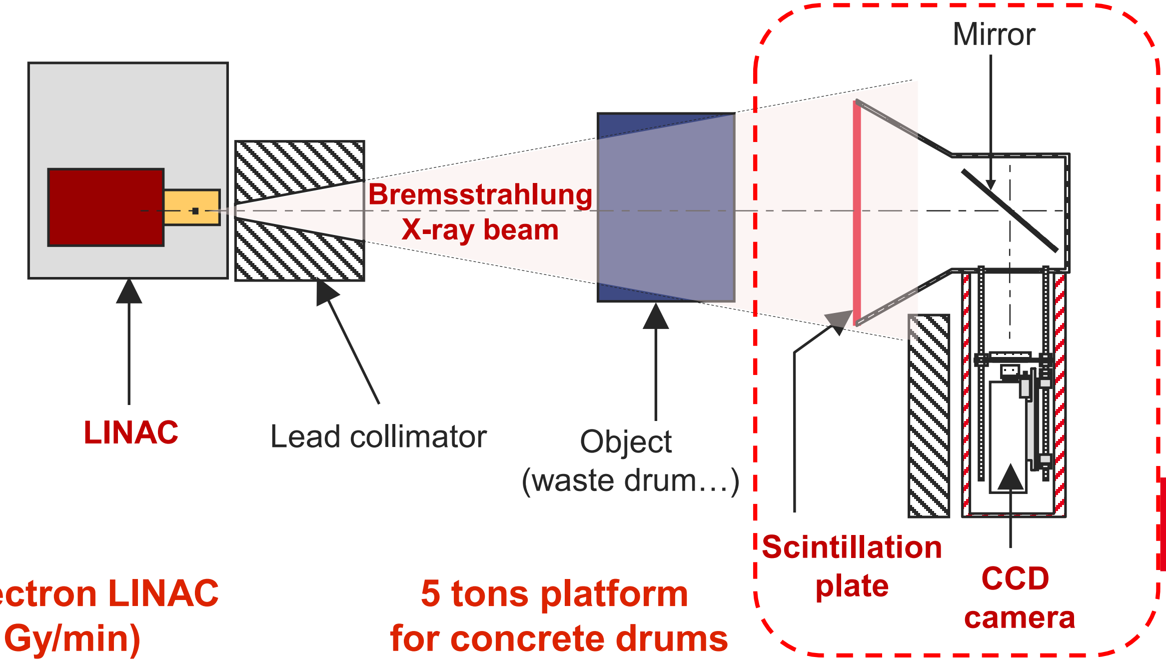
- **Radiological characterization**
  - ✓ Gamma-ray spectroscopy
  - ✓ Passive and active neutron measurements
  - ✓ Photofission
- **Physical characterization**
  - ✓ Photon radiography and tomography
  - ✓ Neutron radiography
- **Elemental characterization**
  - ✓ Thermal neutron activation analysis
  - ✓ Fast neutron activation analysis

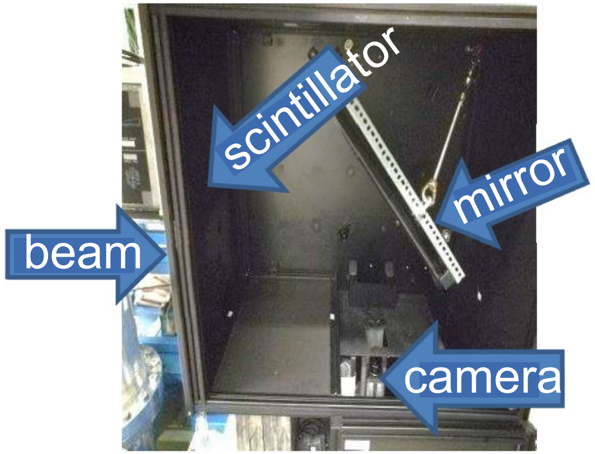
Applications

- **Nuclear fuel cycle**
  - ✓ Uranium mining, enrichment, fuel fabrication & reprocessing
  - ✓ Radioactive waste characterization
  - ✓ Dismantling and decommissioning
- **Reactors**
  - ✓ Non-destructive exams for Jules Horowitz Reactor
  - ✓ Nuclear accident studies and monitoring
- **Homeland Security and Safeguards**
  - ✓ CBRNE threats detection
  - ✓ Nuclear material controls
- **Waste recycling**
  - ✓ Characterization of valuable materials

2. Scintillators for X-ray imaging

High energy X-ray imaging in CINPHONIE casemate





Scintillation plate 800 x 600 mm²

Gadox Gd_2O_2S thickness 1.5 mm

15-20 MeV electron LINAC (up to 65 Gy/min)

5 tons platform for concrete drums

N. Estre, D. Eck, J-L. Pettier, E. Payan, et al. High-Energy X-Ray Imaging Applied to Non Destructive Characterization of Large Nuclear Waste Drums, DOI:10.1109/ANIMMA.2013.6727987

High energy X-ray imaging of large concrete drums

Concrete waste package

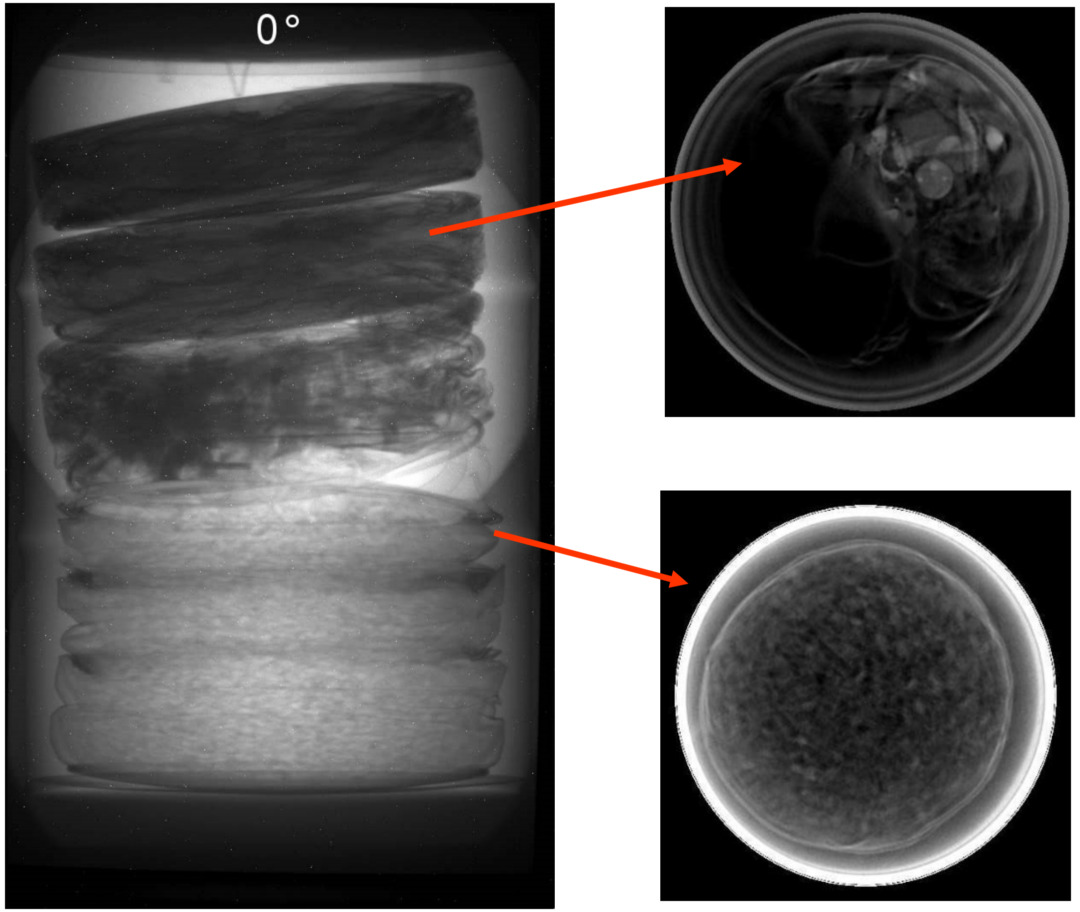
- Density > 2 g/cm^3
- Mass > 1,2 ton
- H = 120 cm
- ∅ = 84 cm

<< 1 s per radiography

but due to mechanical movements

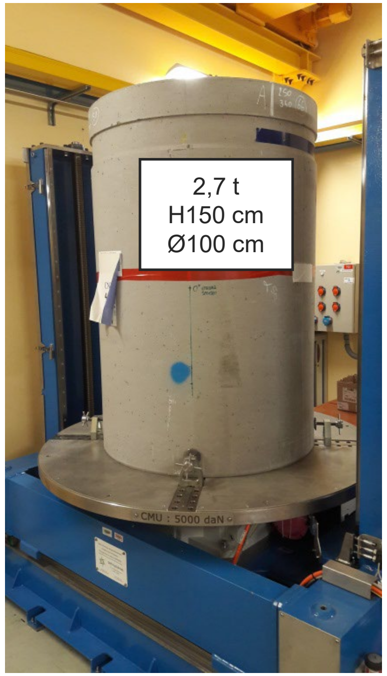
- ➢ Radiography ≈ 10 min
- ➢ Tomography ≈ 25 min

Radiography **Tomography**

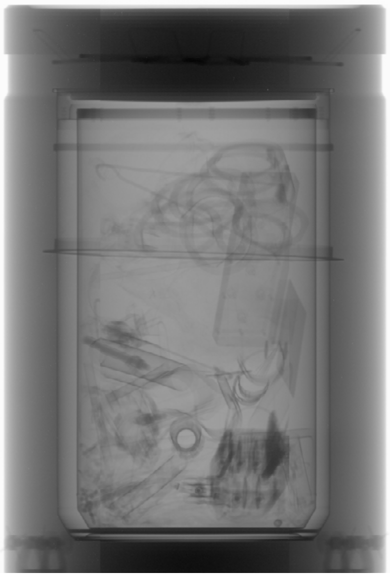


Detailed expertise of a large concrete drum

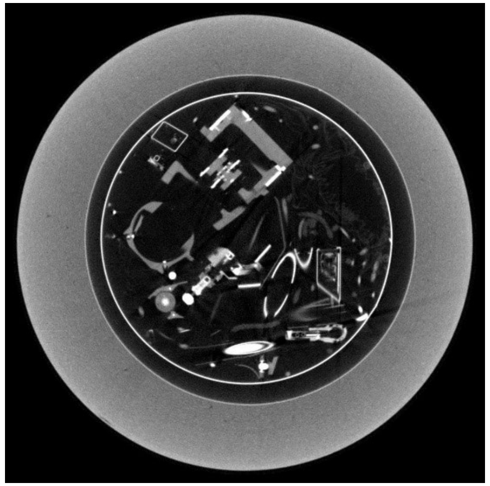
500 l waste blocked in a concrete matrix
(external volume 1.2 m³)

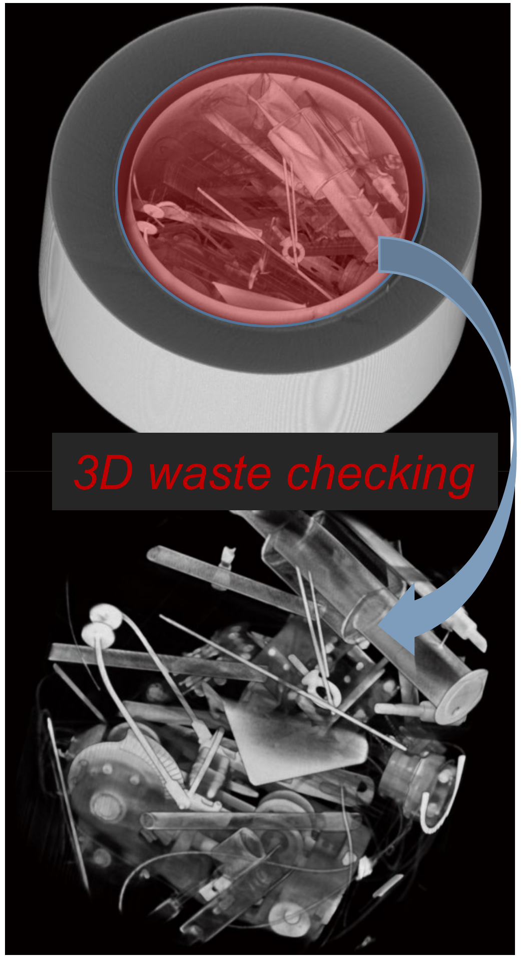


Radiographies
(duration 10 min)



2D/3D Tomographies
(duration 30 min)





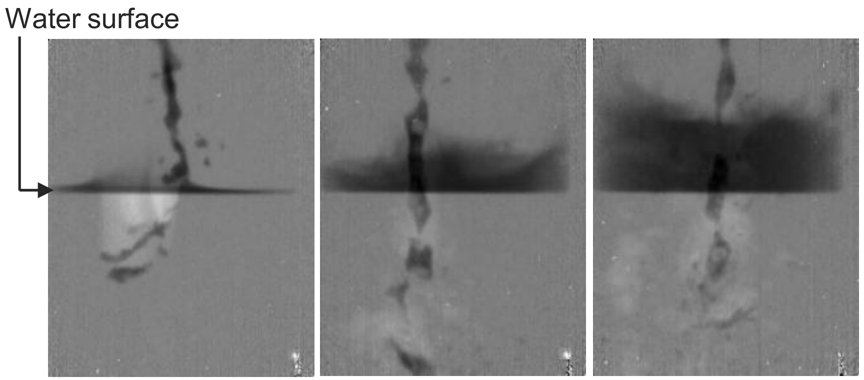
High energy X-ray radioscopy

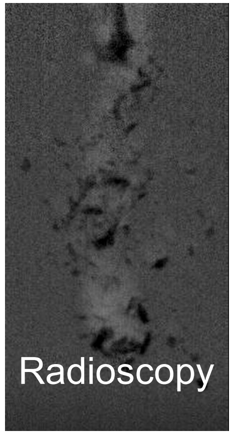
Dynamic radiography

- ➢ Original camera 50 pictures / sec – 230 × 240 pixels
- ➢ With 4 modern cameras ⇨ up to 200 pict/s – 2560 × 2160 pixels

Application to corium / water interaction

⇨ MC3D code validation (nuclear accident studies)





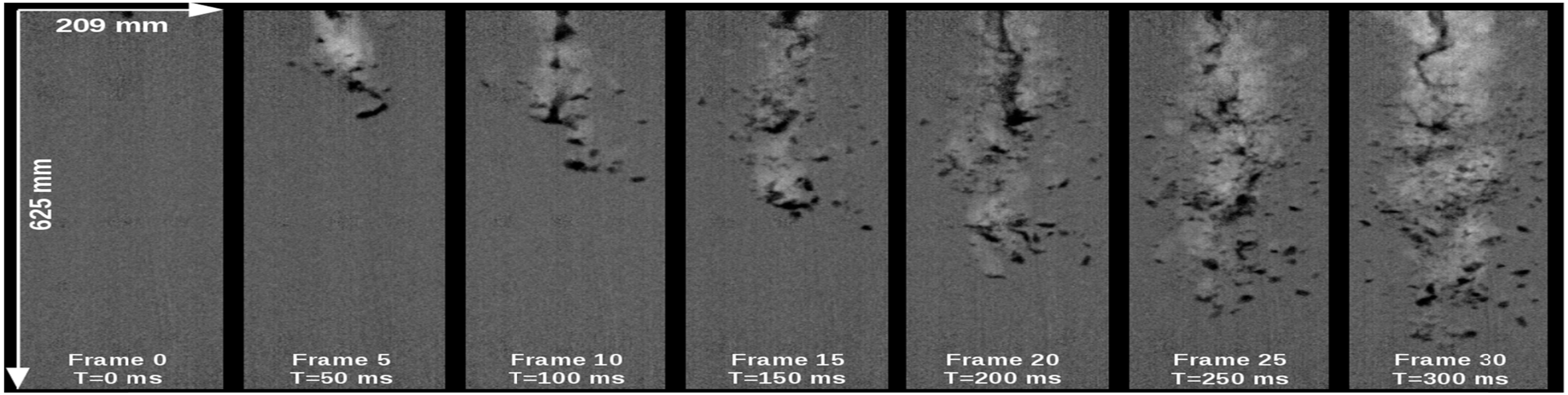
KROTOS facility

In yellow: 9 MeV LINAC
In black : imaging plate

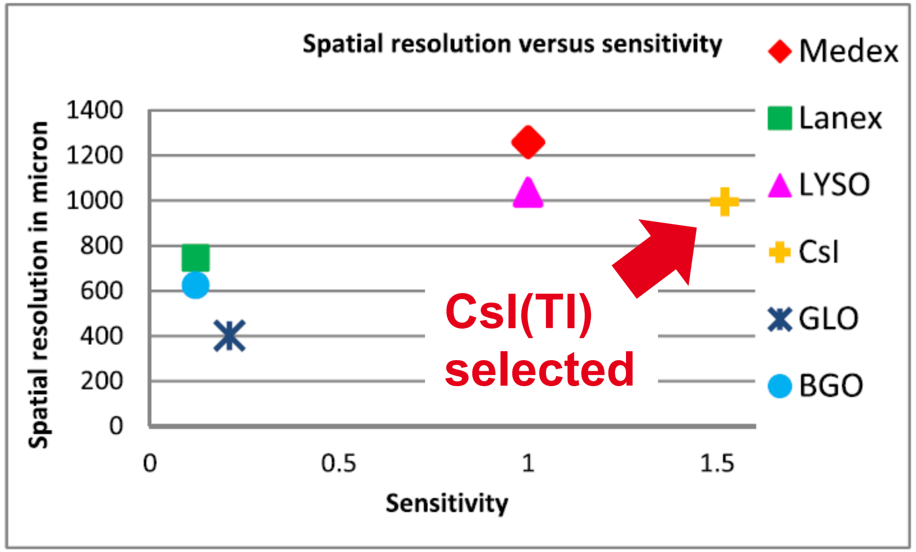
« ICE » Project on Water-Corium Interaction

N. Estre, E. Payan, L. Berge, Fast Megavoltage X-Rays Radioscopy ,Nuclear Science Symposium, 29 Oct. – 4 Nov. 2016, Strasbourg, France
D. Tisseur et al. Detector Upgrade for Fast MeV X-Ray Imaging for Severe Accidents Experiments, IEEE TNS, VOL. 67, NO. 7, JULY 2020

R&D on high resolution fast scintillation screens



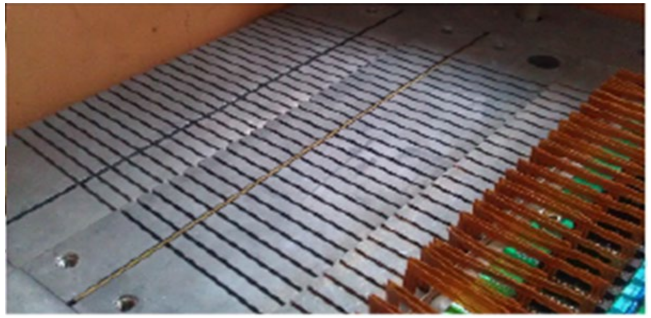
Scintillator	Density (g/cm^3)	Thickness (mm)	Surface density (mg/cm^2)	Average Light yield (photons/MeV)	Wavelength Peak (nm)
Medex (GOS)	4.45	0.780	347	65000	545
Lanex (GOS)	4.62	0.290	134	65000	545
CsI:Tl	4.51	2	902	54000	546
BGO	7.13	3	2139	9000	480
LYSO	7.25	20	14500	30000	420
GLO	9.10	1.58	1438	55000	589

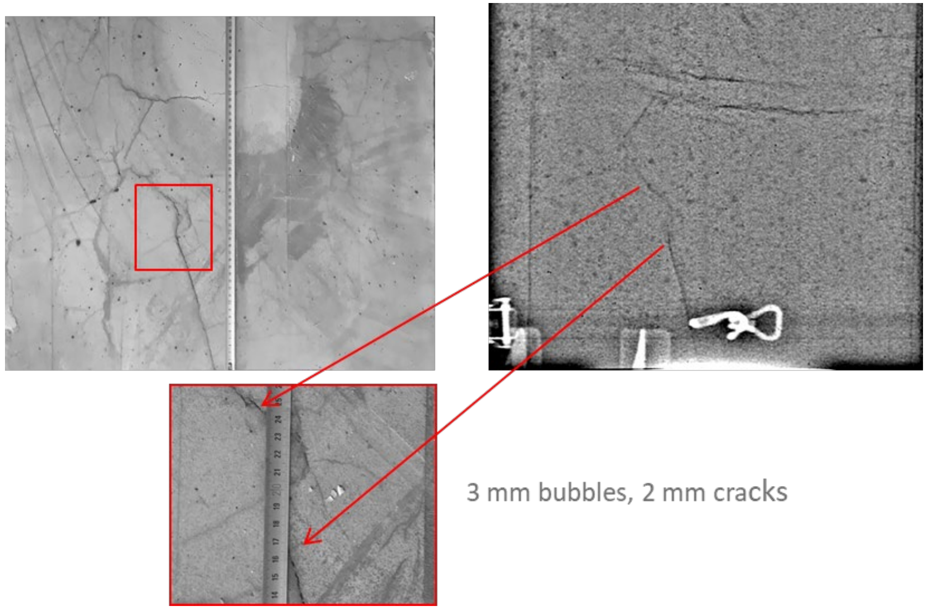


D. Tisseur et al. Detector Upgrade for Fast MeV X-Ray Imaging for Severe Accidents Experiments, IEEE TNS, VOL. 67, NO. 7, JULY 2020

R&D on high resolution linear detectors

Historical system = 25 CdTe collimated detectors





3 mm bubbles, 2 mm cracks

Scintillators typically used in imaging systems: CsI(Tl), $CdWO_4$, Gadox (GOS GD_2O_2S:Tb)

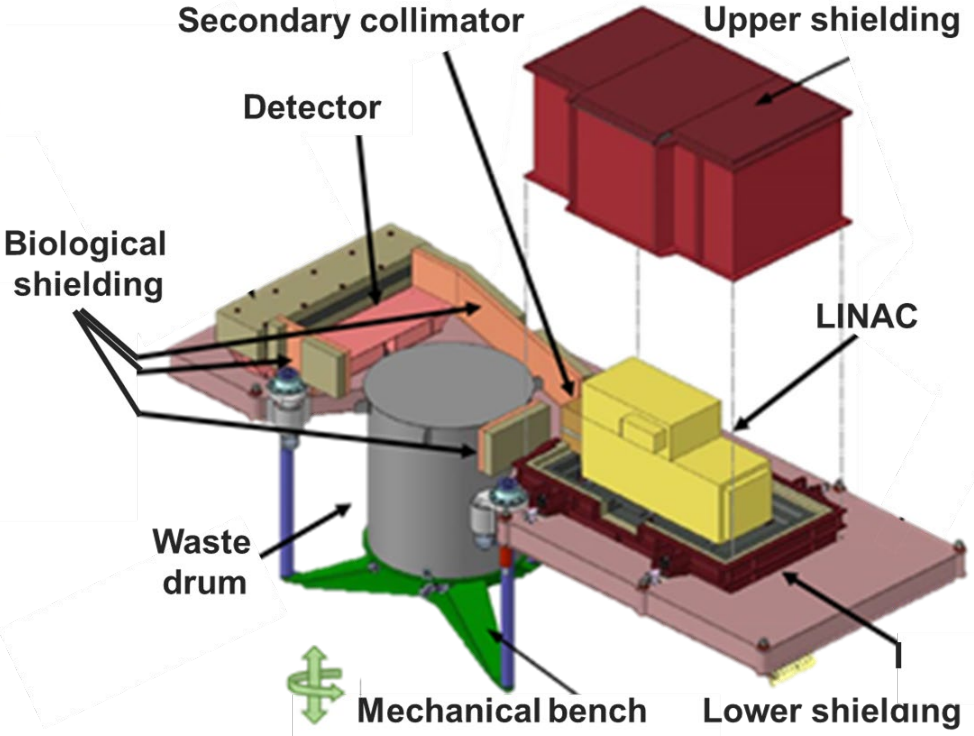
Scintillator	**density ρ *(g/cm^3)***	***Photon yield (ph/MeV)***
GLO ($GD_{0,3}Lu_{1,6}Eu_{0,1}O_3$)	9.1	55 000
CsI(Tl)	4.5	54 000
$CdWO_4$	7.9	20 000
Gadox (GOS GD_2O_2S:Tb)	4.5	55 000

- ❑ **Objective: high resolution imaging 200 µm**
- ❑ Analysis of small objects and defects (bubbles, cracks…)
- ❑ Comparative study of linear detectors to replace the collimated CdTe detectors ⇨ reduced acquisition time

⇨ **GLO (if available), $CdWO_4$ or CsI(Tl) scintillators**

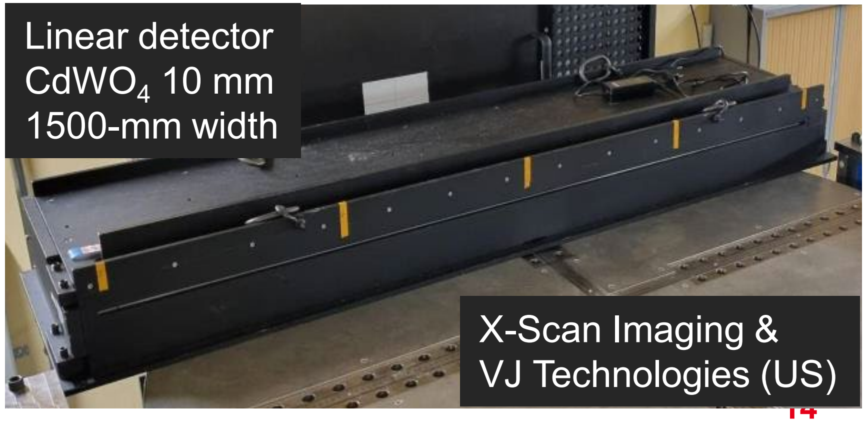
M. Maulin et al., Design of a High-Energy and High-Resolution detector for X-ray computed tomography, EPJ Web of Conferences, ANIMMA2021

TOMIS mobile high-energy tomography

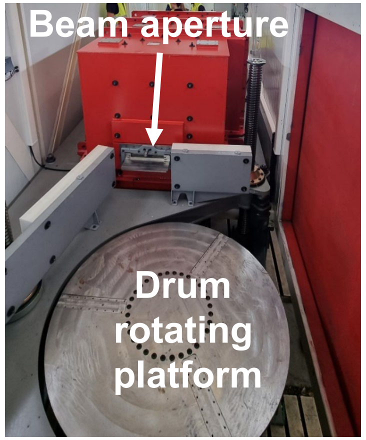


- ❑ 9 MeV LINAC, 30 Gy/min @ 1 m
- ❑ Integration in a 40 feet sea container
- ❑ **High performance $CdWO_4$ linear detector**
- ❑ 5.5 tons mechanical bench, up to 1.8 m^3
- ❑ Self-shielded LINAC ⇨ small footprint (restricted area)

⇨ In situ imaging of legacy concrete waste packages



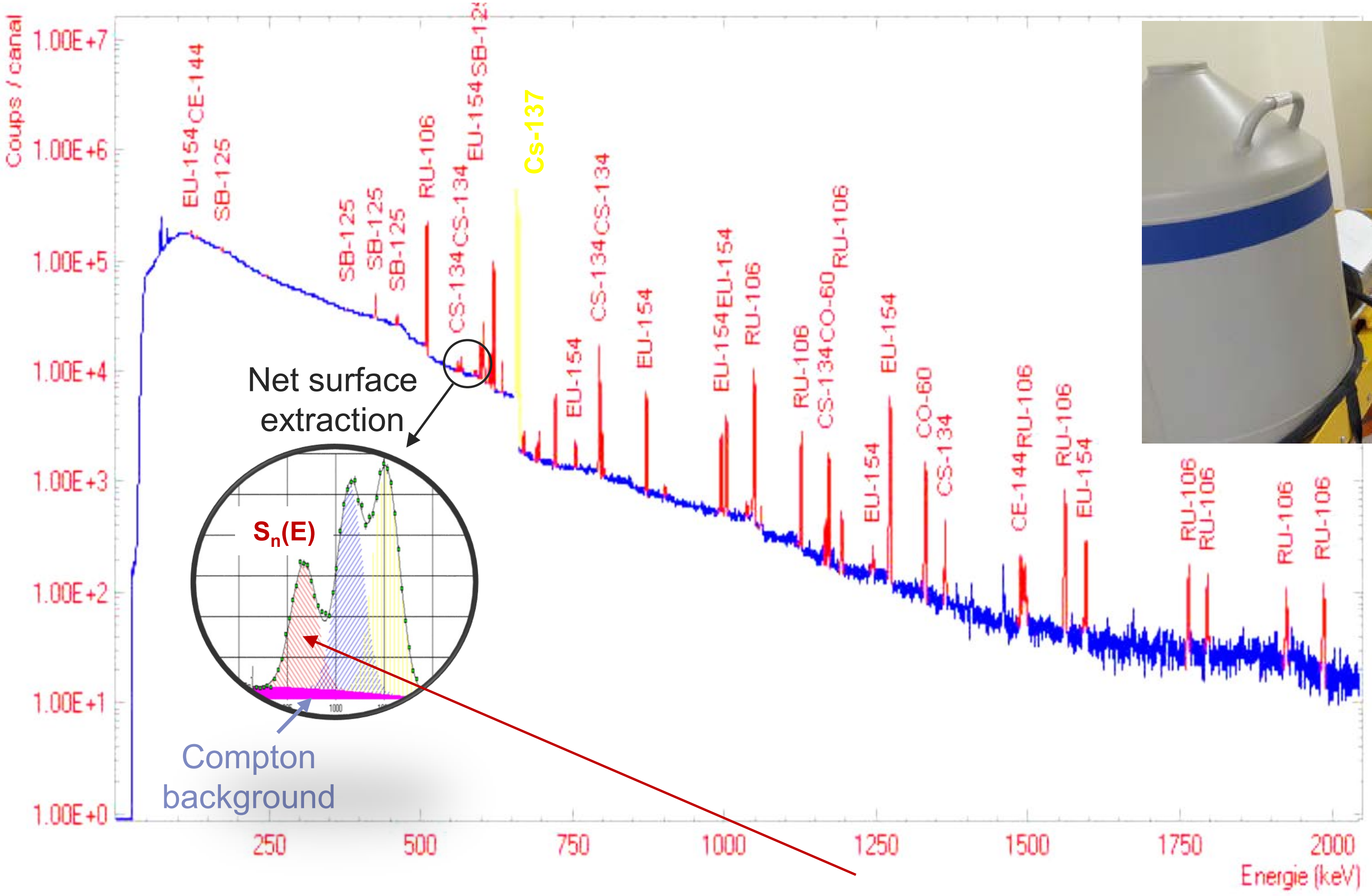
TOMIS in situ implementation



Commissioning and first measurements in 2024

3. Scintillators for gamma-ray spectroscopy

HPGe ⇨ gold standard in gamma spectroscopy



Radionuclide activities:

$$A(E) = \frac{Sn(E)}{\varepsilon(E) \times \underbrace{I(E)} \times T}$$

Detection efficiency

Gamma-ray intensity

Measurement time

But many other gamma detectors are available

Liquid nitrogen cooled HP Ge

Portable HP Ge (electric cooling)

CdTe, CdZnTe

NaI(Tl)

BGO ($Bi_4Ge_3O_{12}$)

$CeBr_3$

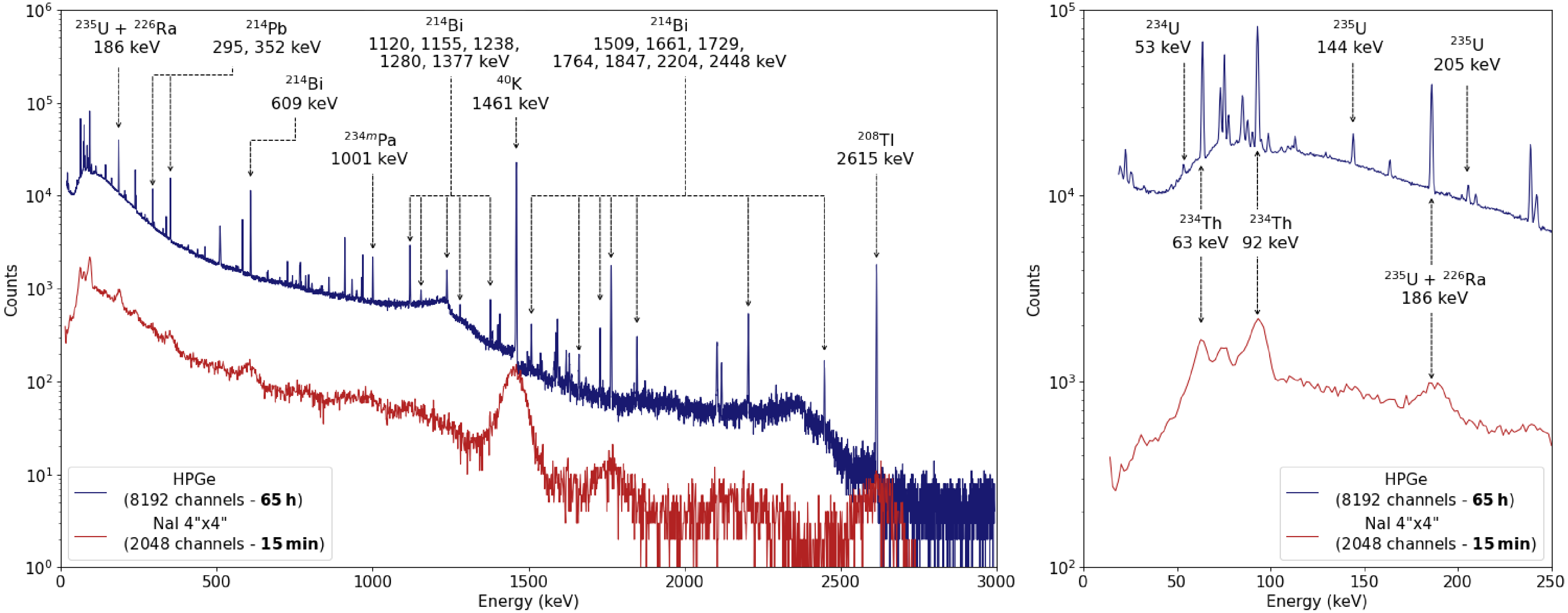
$LaBr_3$(Ce)

Scintillators

Energy resolution vs. efficiency

- ❑ **HPGe is the standard of gamma spectroscopy**
  ⇨ Pu isotopic composition, spent fuel, nuclear accidents, etc. (many peaks)

- ❑ **But scintillators are preferred in many instances** for their robustness, efficiency/cost ratio, fast timing…
  ⇨ radioactive waste (few peaks), cleaning and dismantling, uranium mining, online analysis, security…

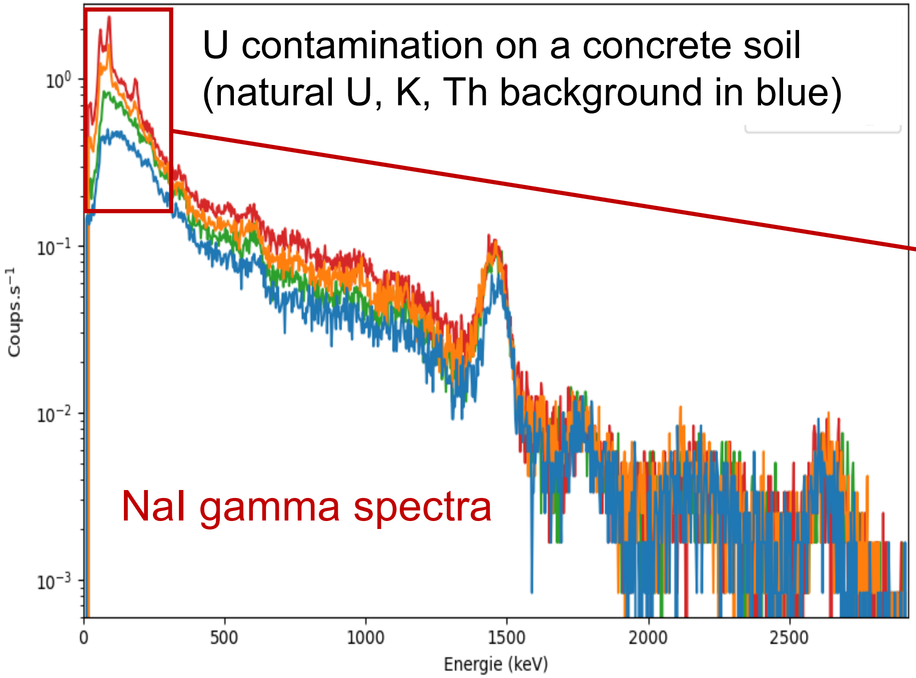


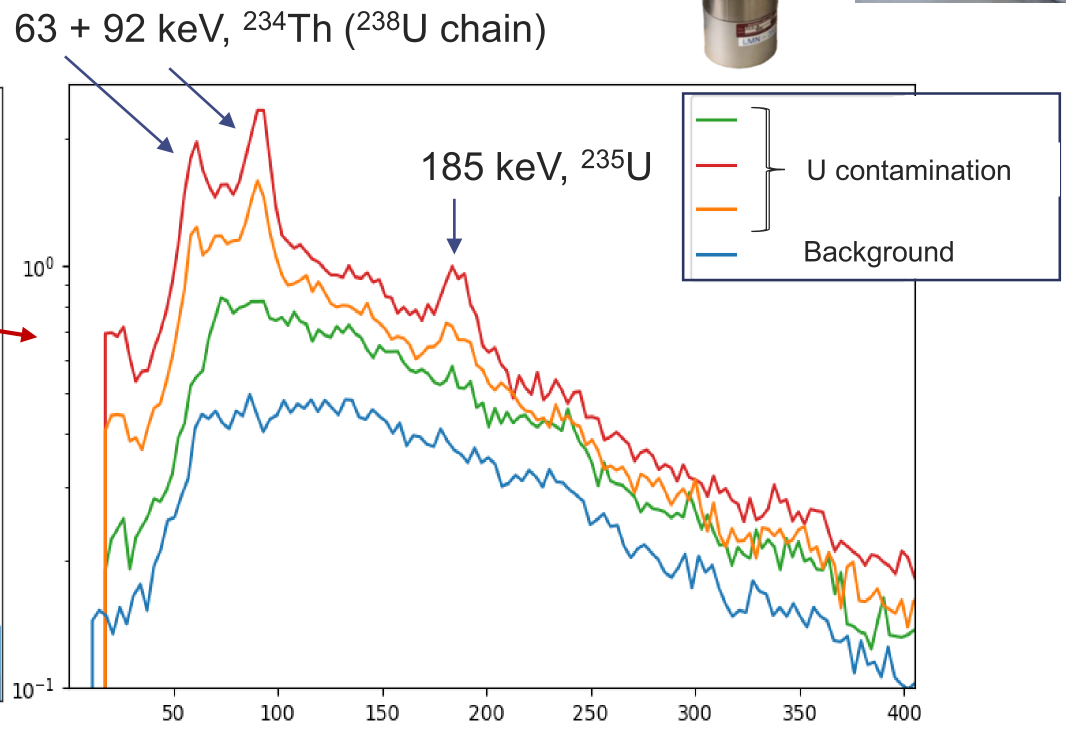
Salvador et al., Low and high resolution gamma-ray spectroscopy for the characterization of uranium contamination, submitted to NIM A, NIMA-D-24-00254

Alpha-beta-gamma scintillators for D&D

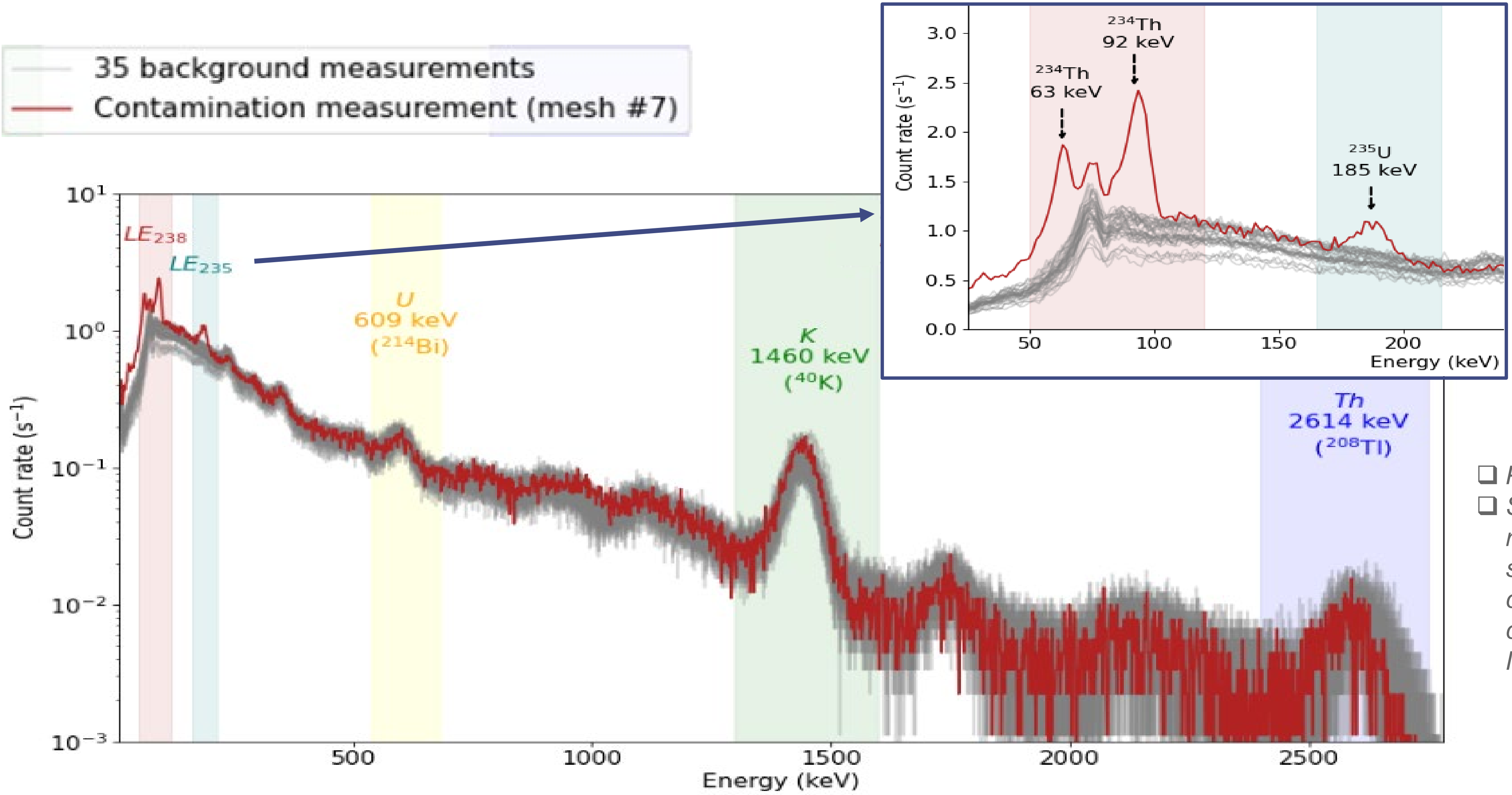
ZnS(Ag) scintillator

- Fast alpha and beta detection (a few min) of uranium contamination deposited on concrete soil with **ZnS(Ag) and plastic PVT scintillators**
- Shielded **NaI(Tl) scintillator** close to the ground to confirm the activity within about 15 min





NaI(Tl) spectrum analysis with energy bands



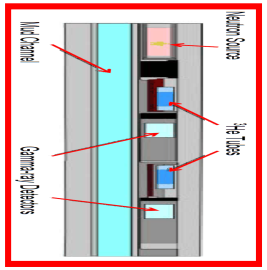
- Patent application FR2210553
- Salvador et al., Low and high resolution gamma-ray spectroscopy for the characterization of uranium contamination, submitted to NIM A, NIMA-D-24-00254

	HPGe (reference)	NaI(Tl)
Acquisition time	**64 h**	**15 min**
U surface activity	(7.47 ± 0.75) Bq.cm^{-2}	(9.8 ± 1.4) Bq.cm^{-2}
U enrichment	(0.83 ± 0.07) %	(0.73 ± 0.15) %

Uranium mining ⇨ gamma scintillators for samples, logging probes, truck portal monitors, conveyor belts

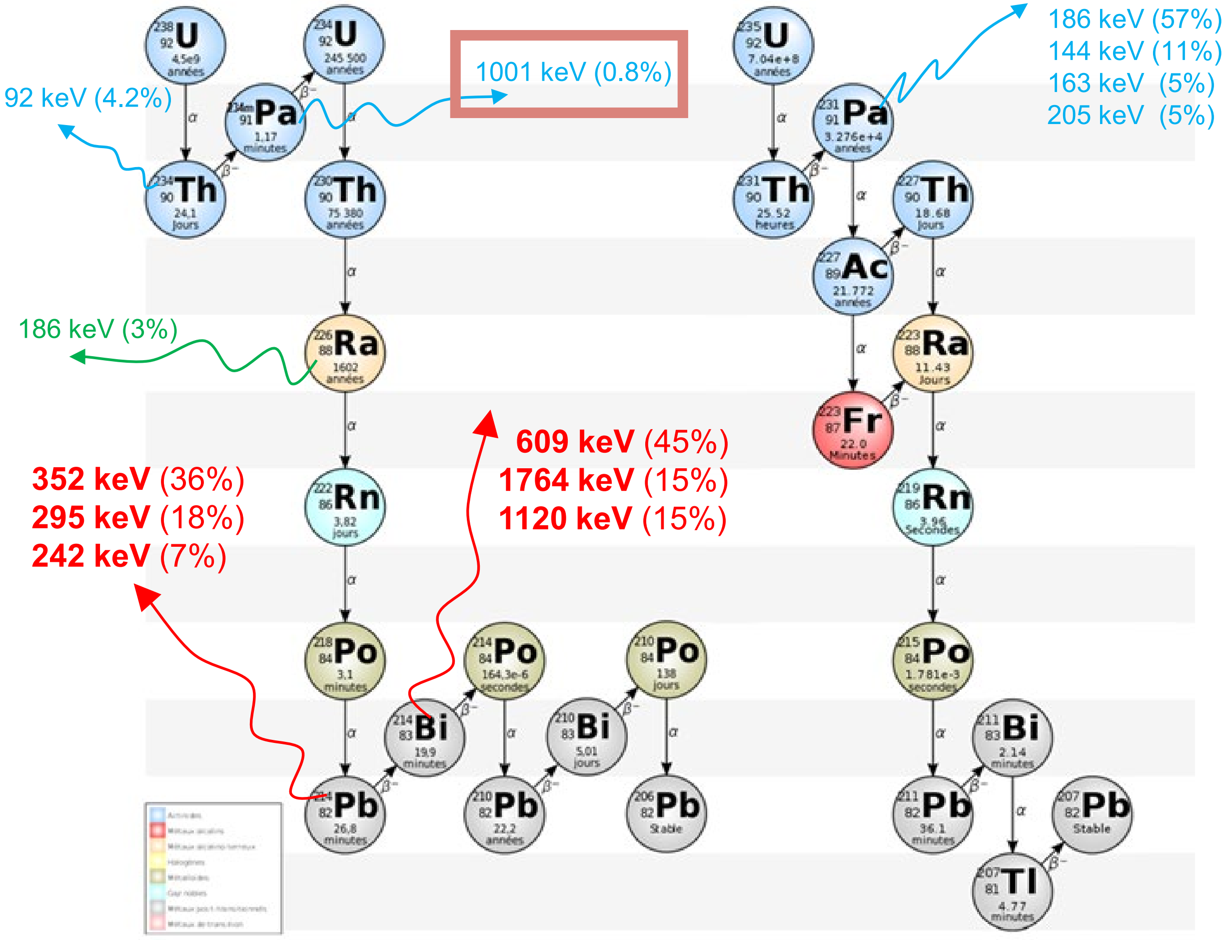
Characterization of uranium content

- *Spectrophotometry* — Liquid measurement, sample measurements
- *Beta / gamma ratio* — Thommeret system, disequilibrium measurement, sample measurement
- *Gamma spectroscopy* — Disequilibrium expertise measurement, core sample measurement, ^{226}Ra
- *Gamma counting* — Gamma-ray logging, Handheld measurements, on shovel, Gantry for truck, Conveyor belt
- *X-ray fluorescence spectrometry* — Handheld measurements, quick, surface measurement (few mm)
- *Neutron measurement* — ^{235}U, Conveyor belt, destructive method

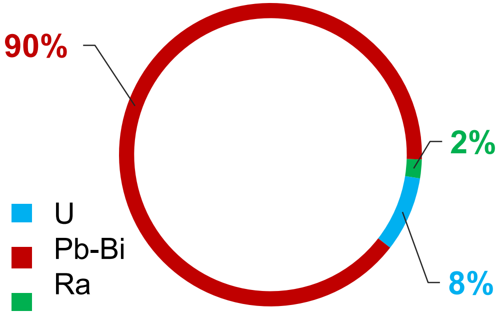


Non-destructive Measurements

Uranium chain gamma emissions



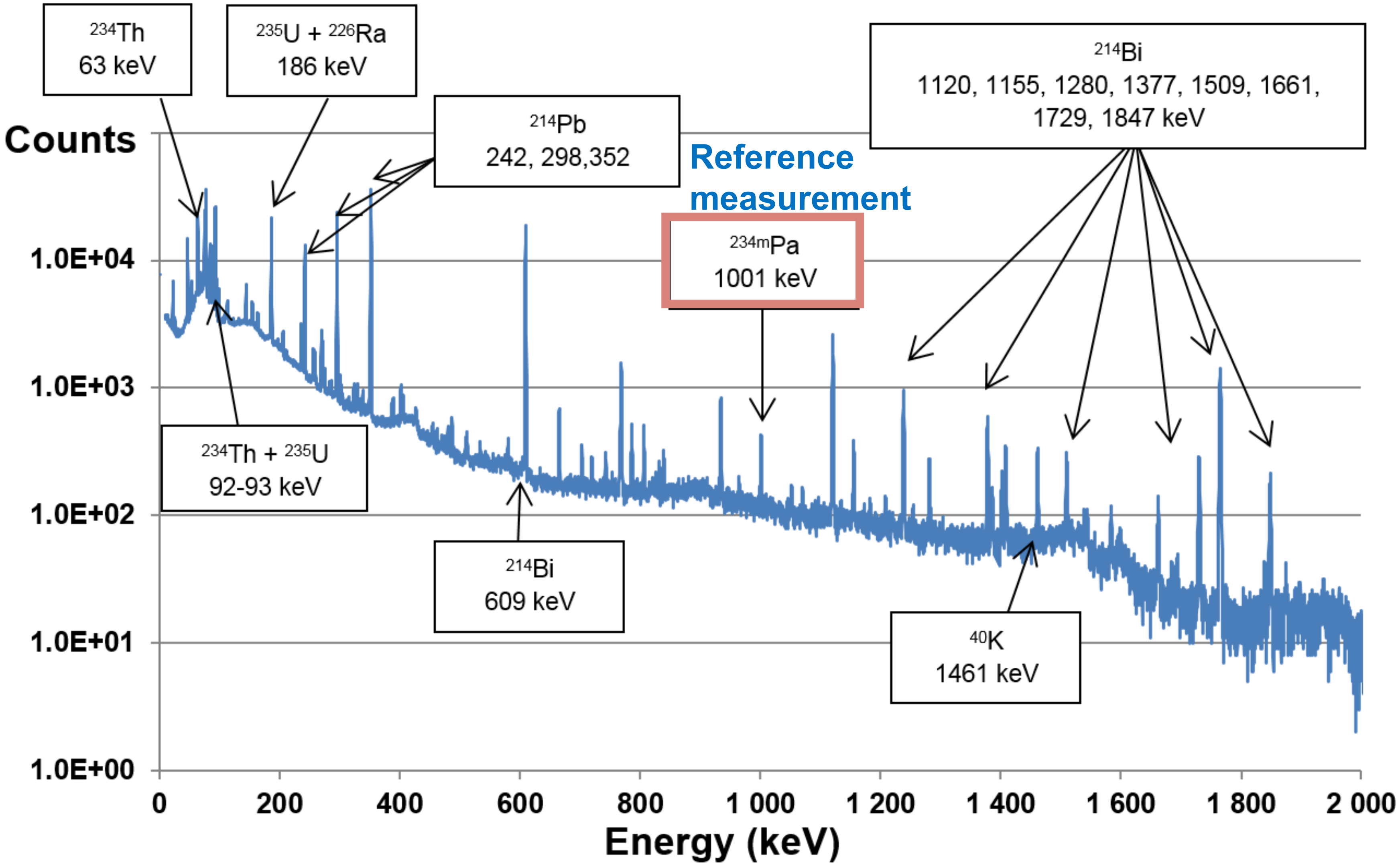
Origin of gamma rays



Disequilibria in U chain (U vs. Ra differential leaching in roll fronts)

⇨ U grade over/under estimated by total gamma counting

Disequilibrium ⇨ HPGe spectroscopy in the lab



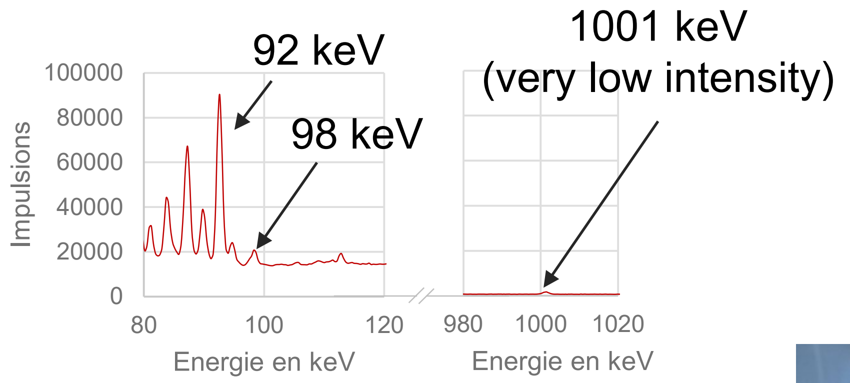
Low intensity of the 1001 keV ray ⇨ long measurement (hours)

Low energy of ^{234}Th gamma rays ⇨ large attenuation effects

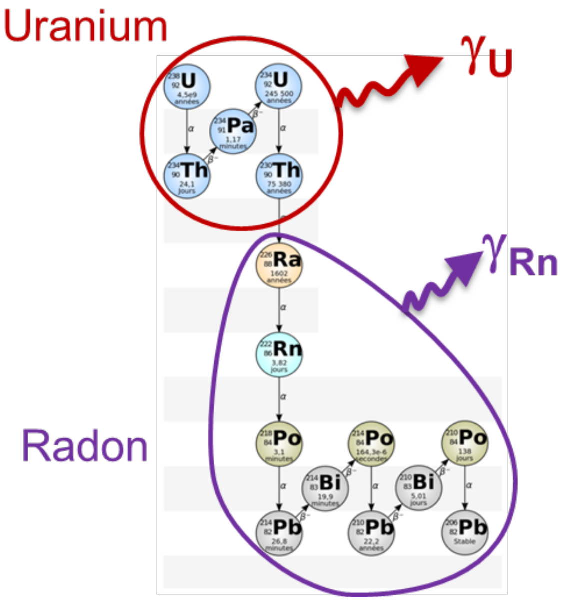
Gamma spectroscopy on samples: from Ge to NaI

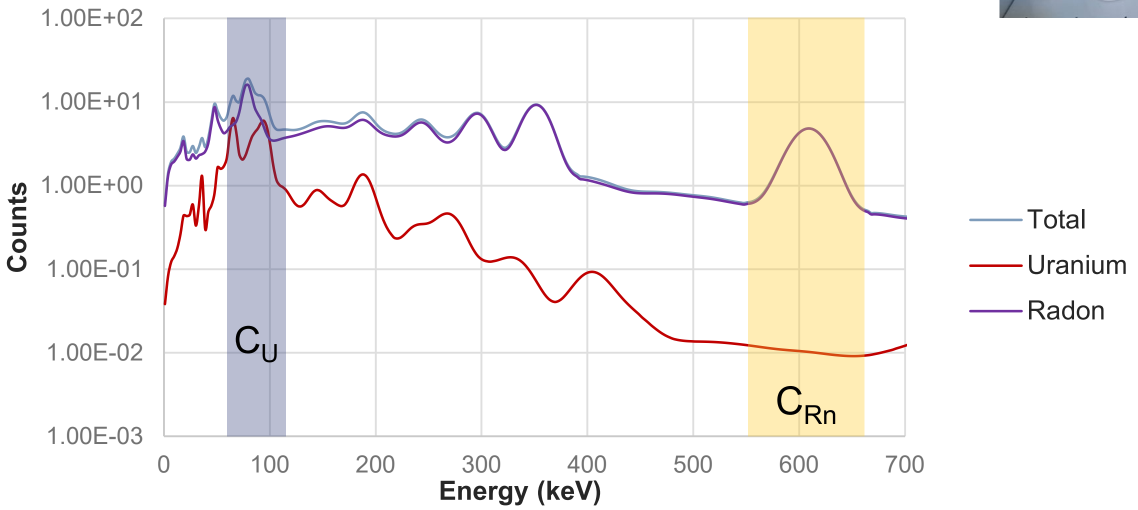
New U-grade measurements (faster than with 1001 keV line and HPGe)

1. HPGe high-resolution spectroscopy
   - 92 keV γ-ray of ^{234}Th
   - 98 keV self-induced fluorescence X-ray



2. **NaI(Tl) low-resolution spectroscopy** : count rates in energy bands (C_U and C_{Rn})



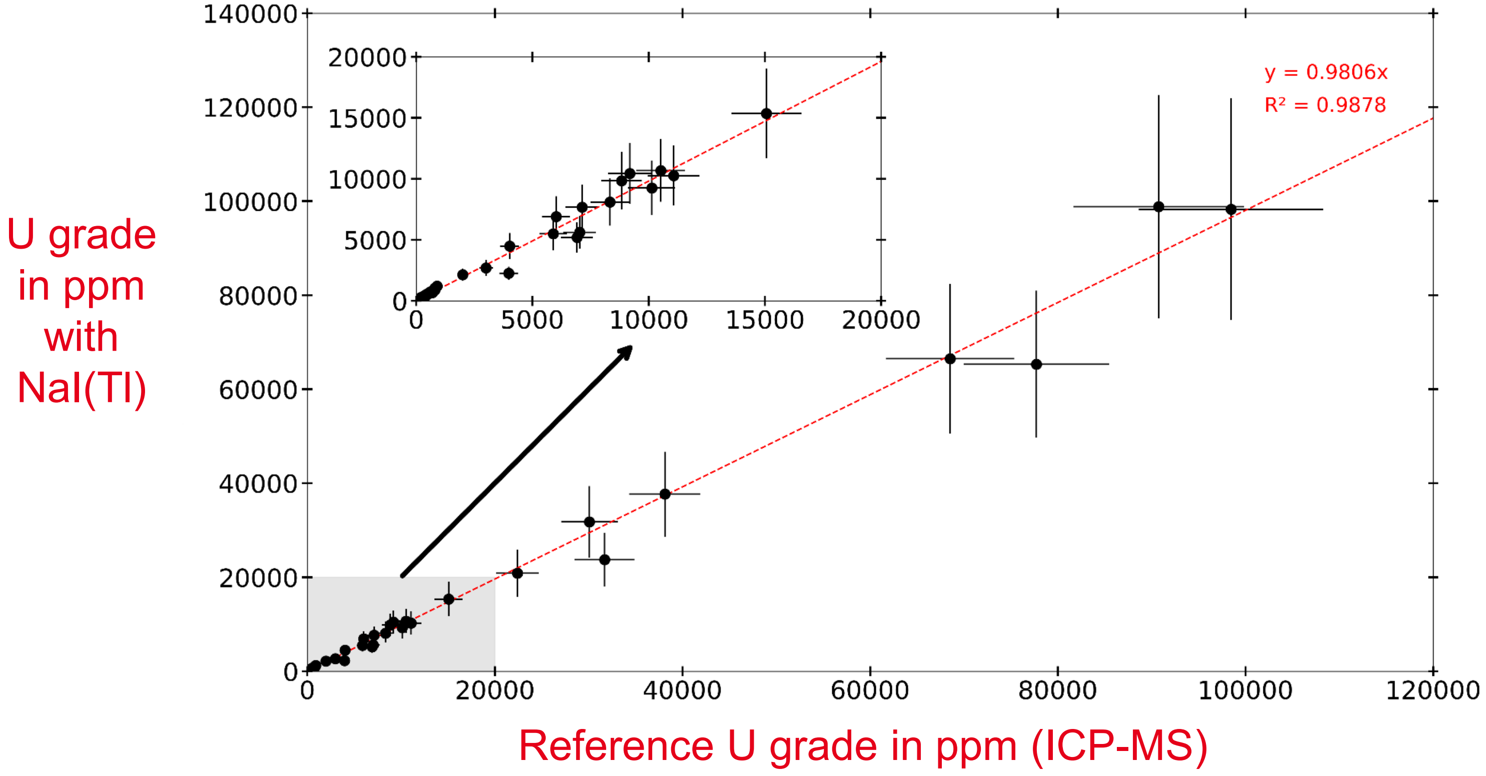


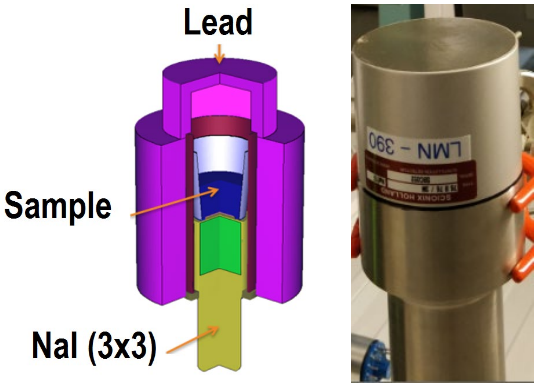
Energy-band approach with NaI(TI)

$$\frac{C_U}{C_{Rn}} = \alpha \frac{A(U)}{A(Rn)} + \beta$$

PATENT FR3088445

- ✓ Method validated with 38 samples
- ✓ Measurement time < 3 min

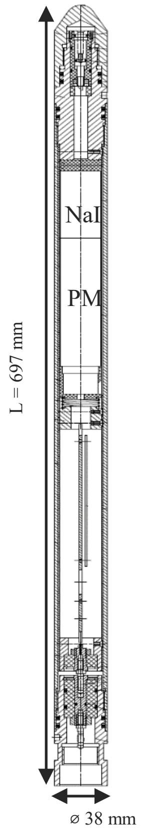


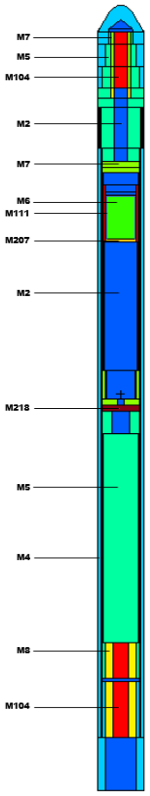


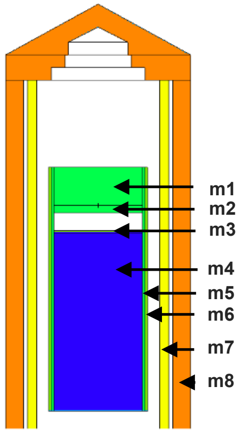
T. Marchais, B. Pérot, C. Carasco, P-G. Allinei, H. Toubon, R. Goupillou, Y. Bensedik, *Low-resolution gamma spectroscopy of uranium ores to determine U concentration and U/Rn imbalance*, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 69, NO. 4, APRIL 2022, DOI 10.1109/TNS.2021.3129343

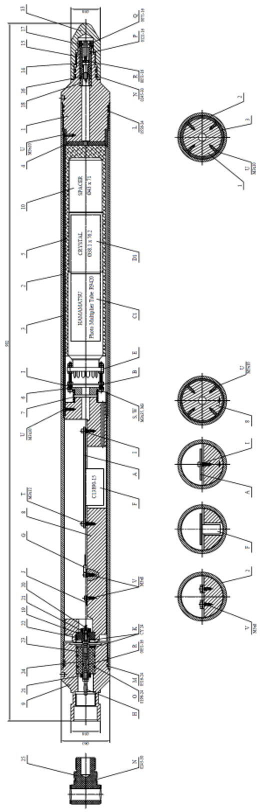
Logging probes with gamma scintillators

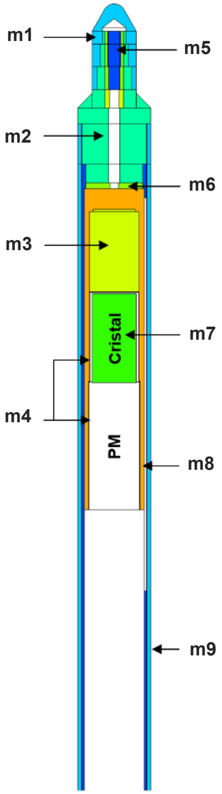
GEOVISTA – NGRS Probe *Total counting*	KOBRA – KSP Probe *Total counting*	GEOVISTA – $LaBr_3(Ce)$ Probe *Spectrometric probe*	ALT Advanced Logic Technology – $CeBr_3$ Probe *Spectrometric probe*
NaI(Tl) 2.4 cm x 3.9 cm	NaI(Tl) 3.0 cm x 7.0 cm	$LaBr_3(Ce)$ 3.81 cm x 7.62 cm	$CeBr_3$ 2.0 cm x 9.6 cm

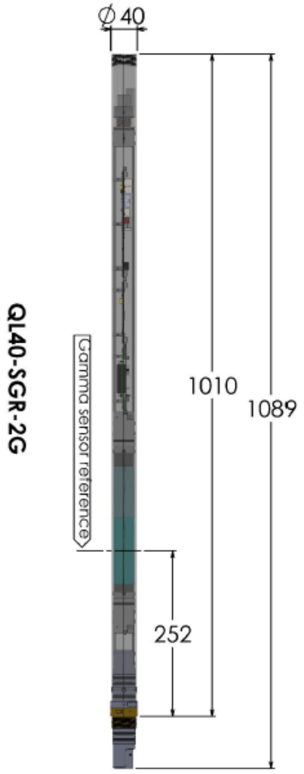


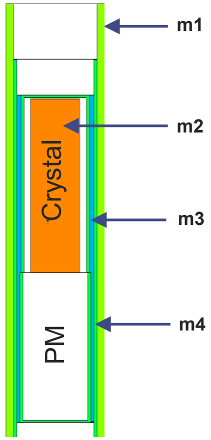






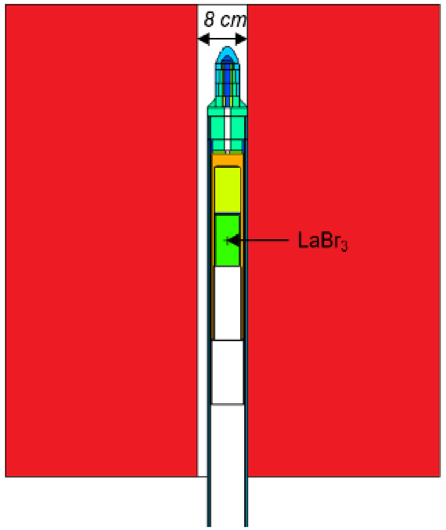






Development of new spectroscopic methods

GEOVISTA



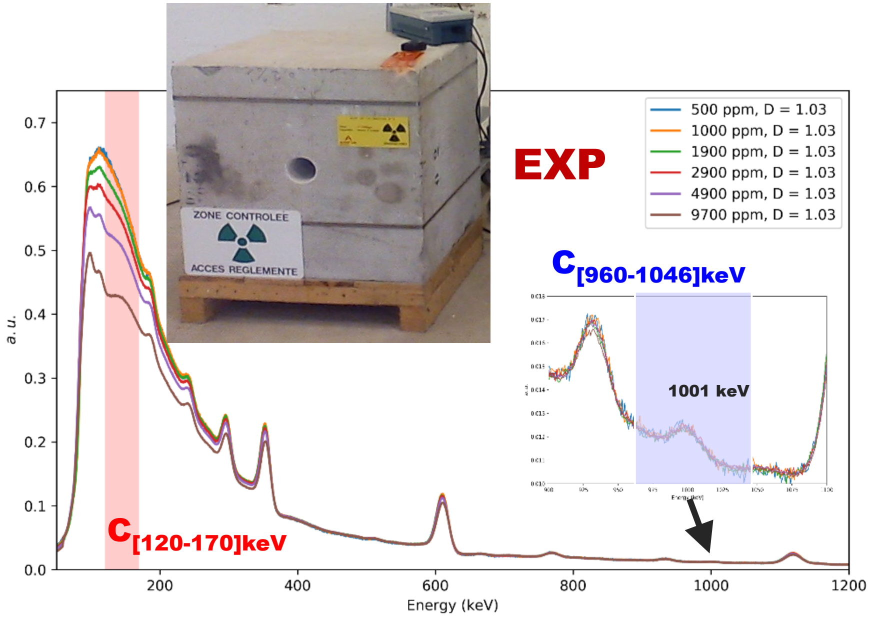
❑ MCNP simulations

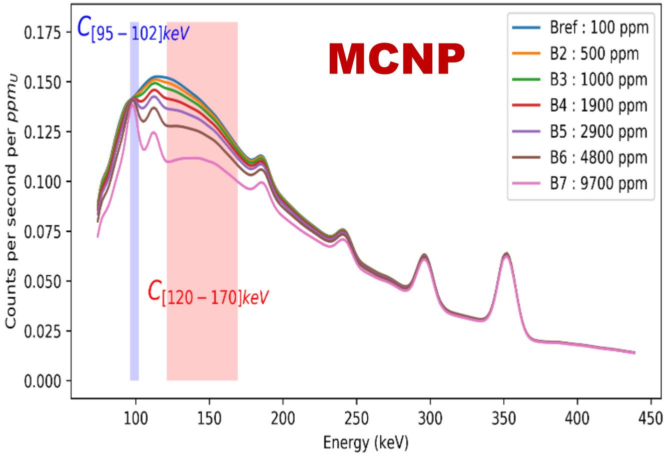
- ✓Compton counts vs. uranium grade (calibration)
- ✓Uncertainties (disequilibrium, density, mineralogy…)

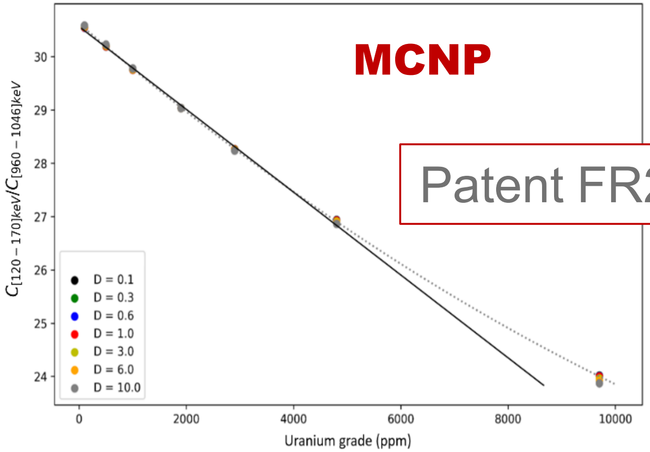
❑ EXP: ORANO CIME calibration station

- ✓ Concrete blocks with U grades up to 10 000 ppm

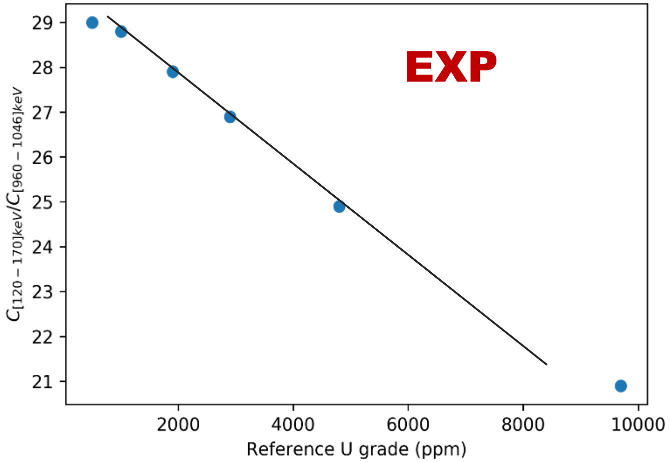
$$U_{ppm} = \frac{\beta_{Comtpon} - \frac{C_{[120-170]keV}}{C_{[960-1046]keV}}}{\alpha_{Comtpon}}$$







Patent FR2109325



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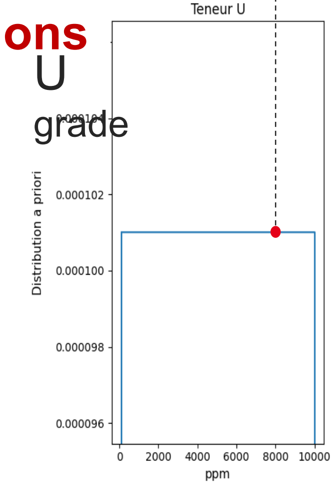
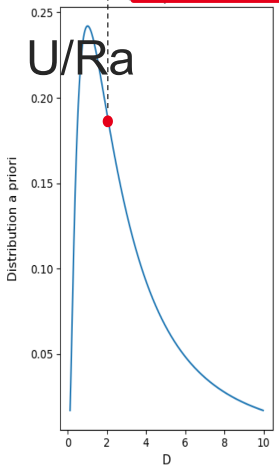
B. Pérot, T. Marchais, P.-G. Allinei, H. Toubon, Y. Bensedik, R. Goupillou, A. Berland, Development of Gamma Spectroscopic Tools for Uranium Ore Samples and Borehole Exploration, 2022 IEEE Nuclear Science Symposium, 5 – 12 November 2022, Milano, Italy

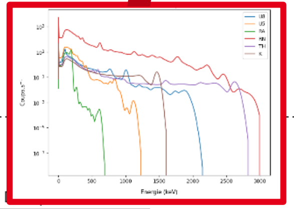
Approaches using the entire spectrum

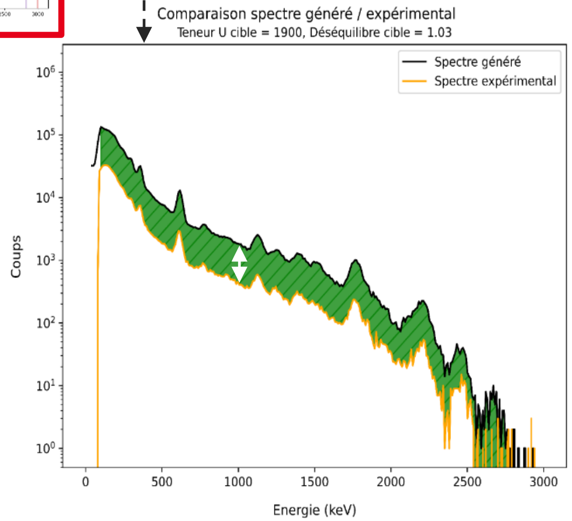
- Unfolding (see further in slide 42)
- Machine Learning, neural networks
- Bayesian inference (here)

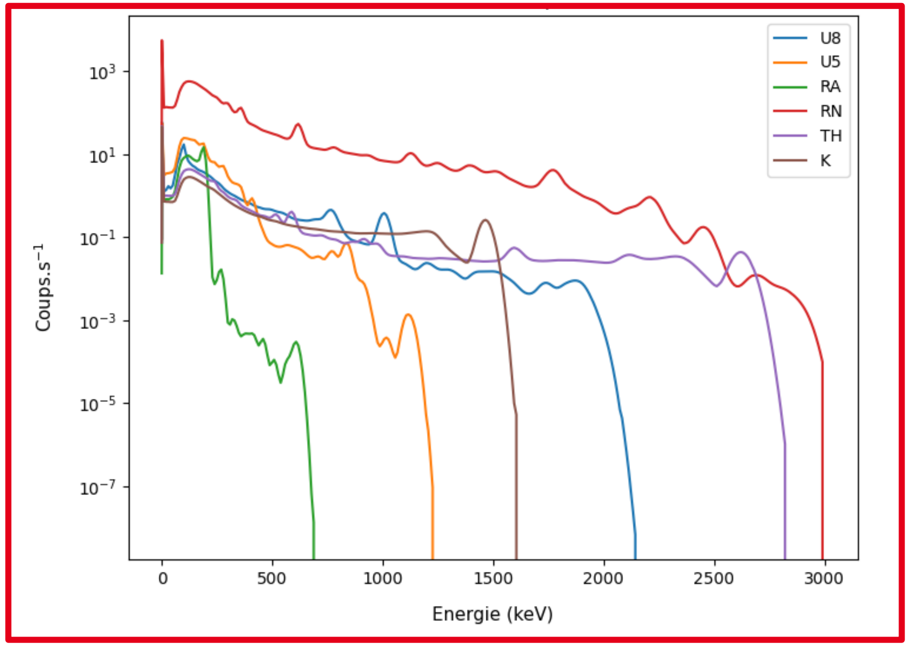
Prior distributions



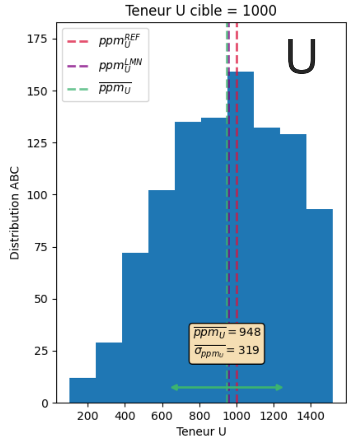


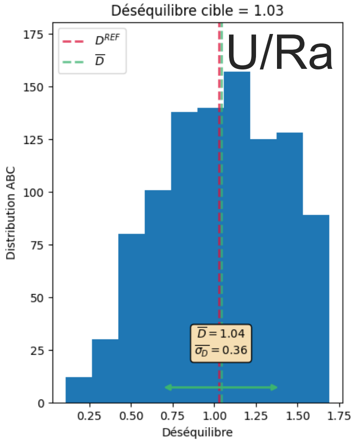






$$distance = \sum_i (canal_i^{EXP} - canal_i^{GEN})^2$$
$$\text{if } distance < \varepsilon$$





Posterior distributions

4. Scintillators for passive neutron coincidence counting

Main neutron detectors

^{3}He proportional counter is the gold standard
in radioactive waste and nuclear material characterization, nuclear process monitoring, homeland security, etc.

Detector Type	Size	Neutron Active Material	Incident Neutron Energy	Neutron Detection Efficiency[a] (%)	Gamma-Ray Sensitivity (R/h)[b]
Plastic scintillator	5 cm thick	^{1}H	1 MeV	78	0.01
Liquid scintillator	5 cm thick	^{1}H	1 MeV	78	0.1
Loaded scintillator	1 mm thick	^{6}Li	thermal	50	1
Hornyak button	1 mm thick	^{1}H	1 MeV	1	1
Methane (7 atm)	5 cm diam	^{1}H	1 MeV	1	1
^{4}He (18 atm)	5 cm diam	^{4}He	1 MeV	1	1
^{3}He (4 atm), Ar (2 atm)	2.5 cm diam	^{3}He	thermal	77	1
^{3}He (4 atm), CO_2 (5%)	2.5 cm diam	^{3}He	thermal	77	10
BF_3 (0.66 atm)	5 cm diam	^{10}B	thermal	29	10
BF_3 (1.18 atm)	5 cm diam	^{10}B	thermal	46	10
^{10}B-lined chamber	0.2 mg/cm^2	^{10}B	thermal	10	10^3
Fission chamber	2.0 mg/cm^2	^{235}U	thermal	0.5	$10^6 - 10^7$

Passive Non Destructive Assay of Nuclear Materials, Los Alamos National Laboratory, NUREG/CR-5550, 1991

Passive neutron measurements with ^{3}He counters

❑ Total counting

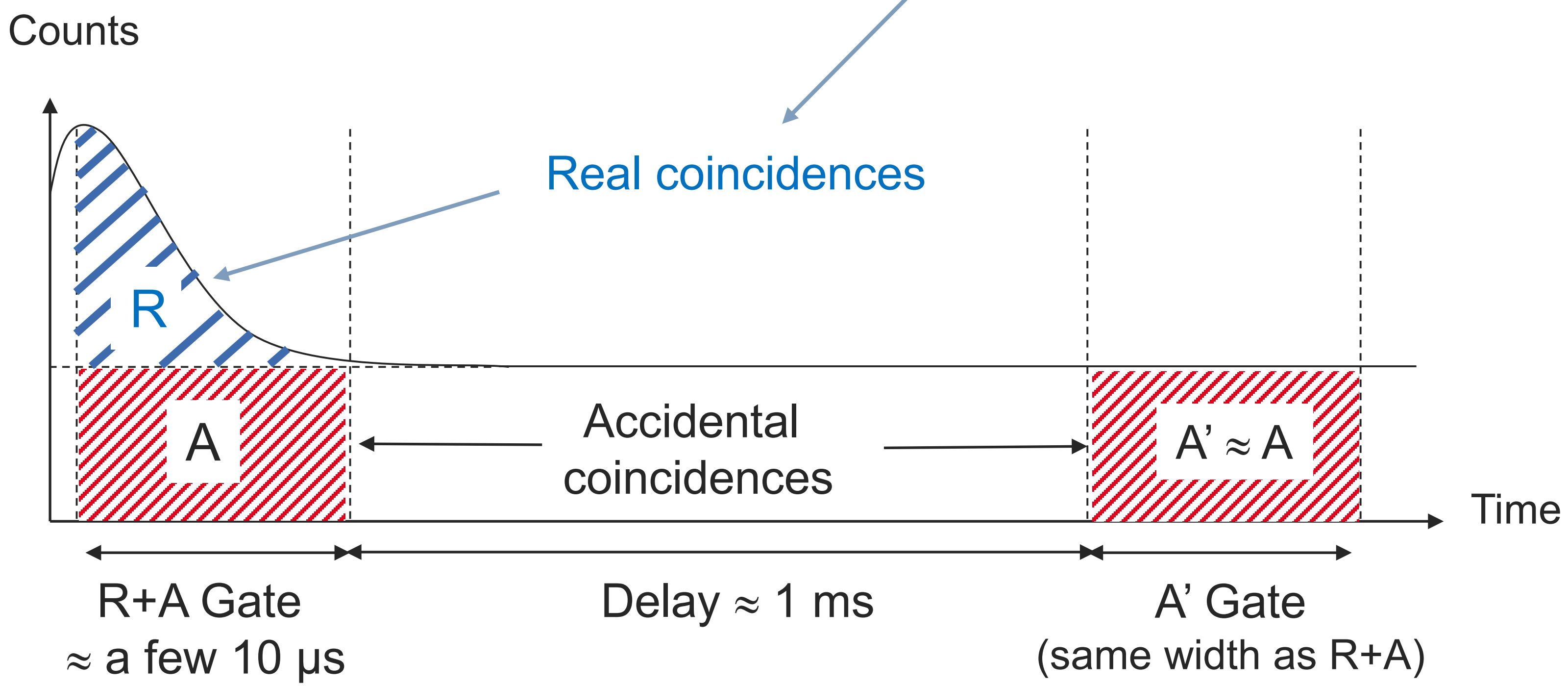
Background: (α,n) neutrons — Useful signal: $^{238, 240 \text{ and } 242}$Pu

Spontaneous fission + (α,n) neutrons ⇨ $^{242 \text{ and } 244}$Cm, $^{238, 240 \text{ and } 242}$Pu, ^{241}Am (+ ^{238}U if mass > kg)

❑ Coincidences counting

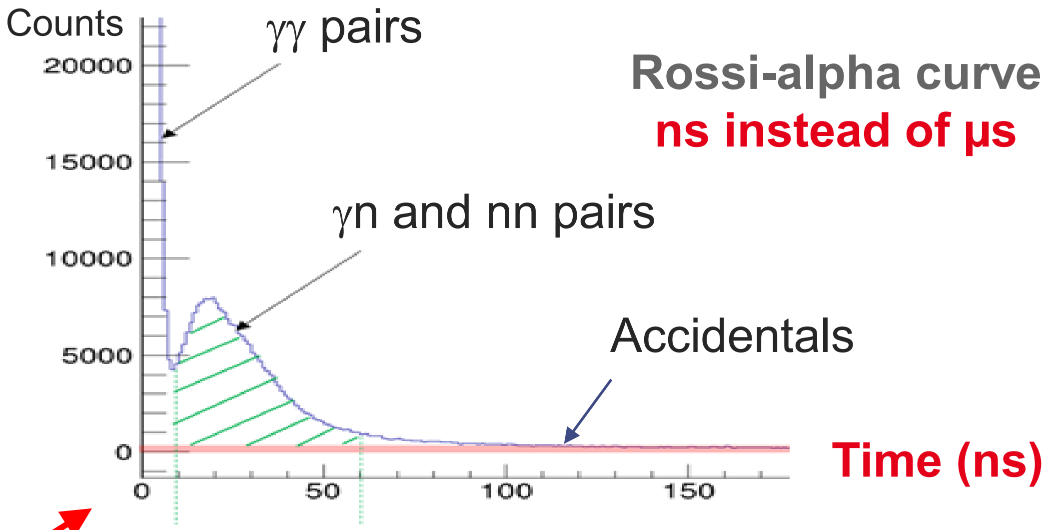
Spontaneous fission neutrons only ⇨ $^{242 \text{ and } 244}$Cm, $^{238, 240 \text{ and } 242}$Pu (+ ^{238}U)

"Rossi-alpha" curve



Alternatives to ^{3}He counters ⇨ PVT plastic scintillators

^{3}He proportional counters	Plastic Scintillators
	
👍 GOOD EFFICIENCY	👍 GOOD EFFICIENCY
👎 EXPENSIVE (since 09/11/2001)	👍 CHEAP (~ factor 5 wrt. ^{3}He)
👎 SLOW RESPONSE (~ µs) (thermalization needed)	👍 FAST RESPONSE (~ ns) (recoil proton)
👍 UNSENSITIVE TO γ RAYS AND CROSS TALK	👎 VERY SENSITIVE TO γ RAYS AND CROSS-TALK



Rossi-alpha curve
ns instead of µs

- 118 L drums with ~ 0.5 g $^{240}Pu_{eq}$
- PVT scintillators + 5 cm Pb shield
- 1500 s acquisition time

MCNPX PoliMi Feasibility study

0.5 g/cm^3 metallic matrix

Multiplicity	Pu only	Am only	Mix (Am, Pu)
0	232,383 ± 482	450,562 ± 671	684,157 ± 827
1	32,356 ± 180	3,675 ± 61	36,287 ± 190
2	2,400 ± 49	9 ± 3	2,365 ± 49
3	66 ± 8	0	66 ± 8

0.2 g/cm^3 organic matrix

Multiplicity	Pu only	Am only	Mix (Am, Pu)
0	178,516 ± 423	299,817 ± 548	478,372 ± 692
1	11,744 ± 108	2,795 ± 53	14,777 ± 122
2	372 ± 19	12 ± 3	365 ± 19

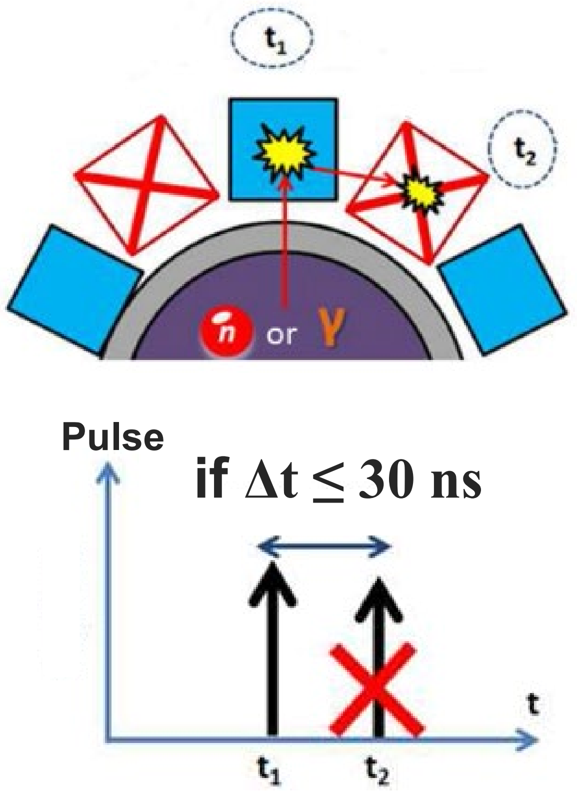
→ At least 3 coincident pulses within 100 ns

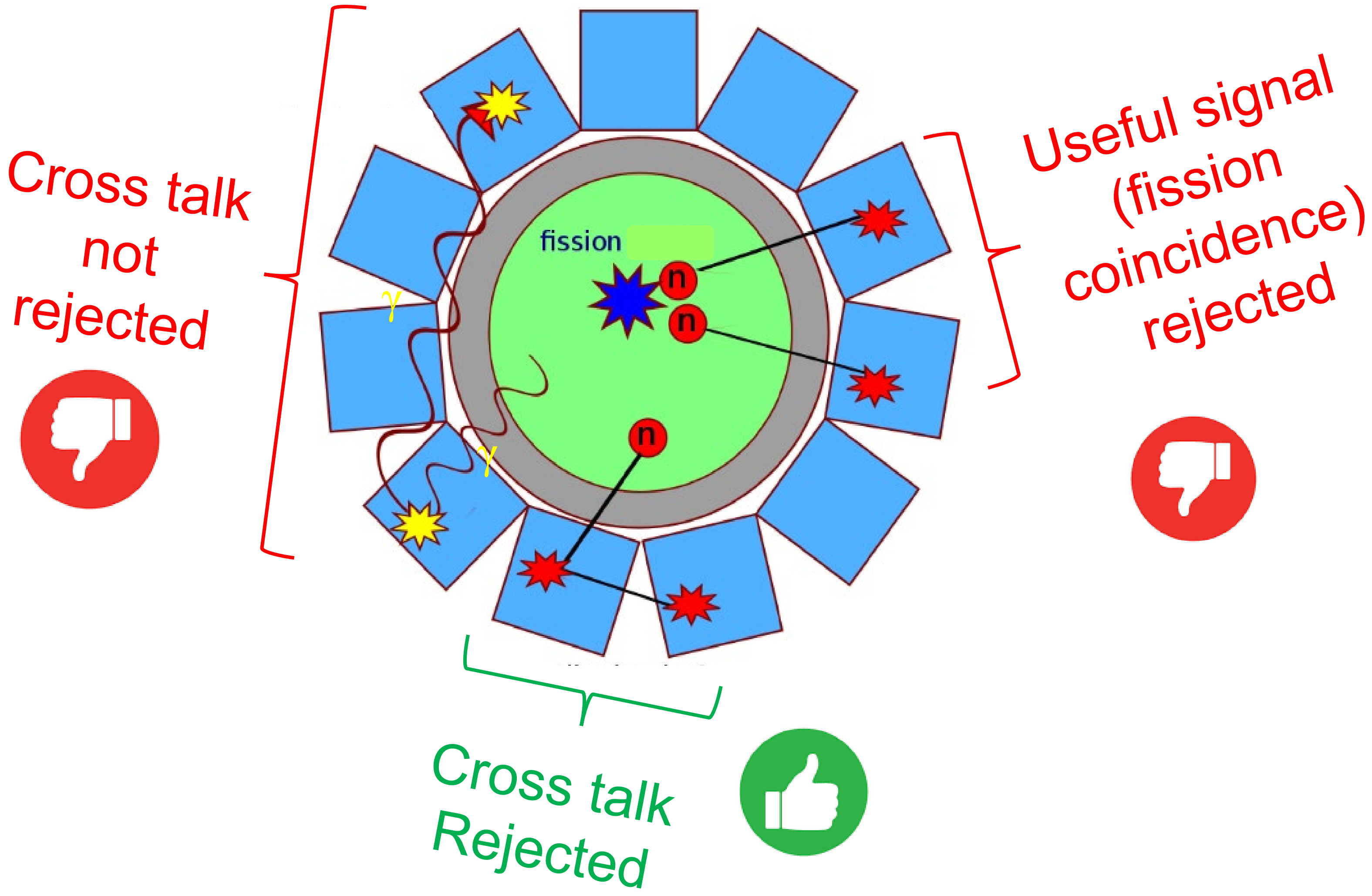
B. Simony, C. Deyglun, B. Pérot, C. Carasco, N. Saurel, S. Colas, J. Collot, Cross-talk characterization in passive neutron coincidence counting of radioactive waste drums with plastic scintillators, IEEE Transactions on Nuclear Science, Vol. 63, No. 3, June 2016

Scattering cross talk mitigation

Principle

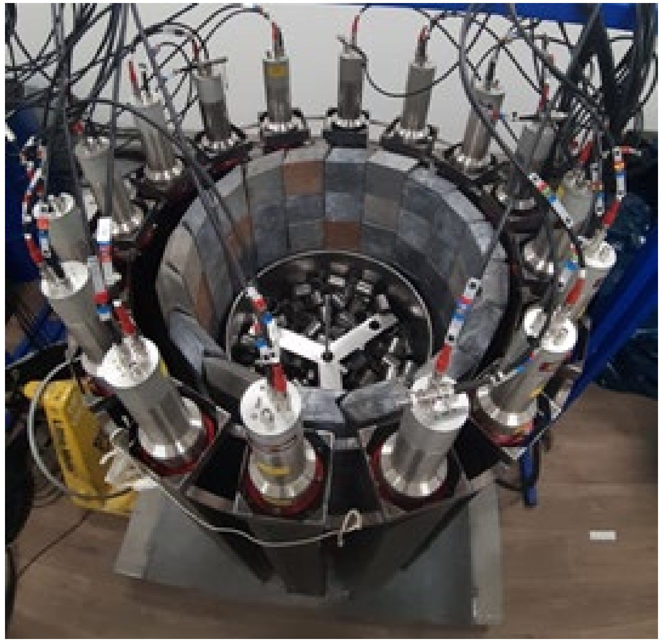
suppression of the 2nd pulse
in double detections
in adjacent detectors within Δt

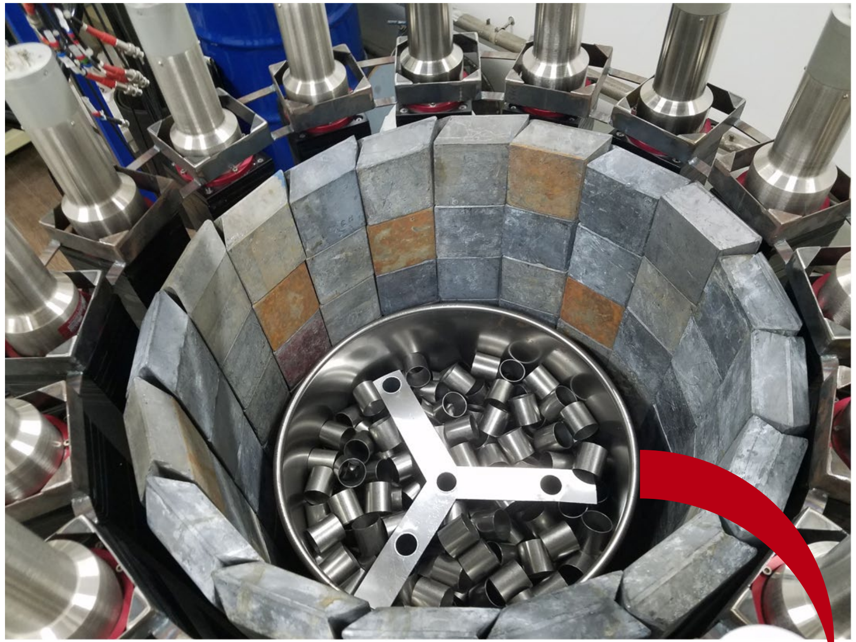




B. Simony, C. Deyglun, B. Pérot, C. Carasco, N. Saurel, S. Colas, J. Collot, Cross-talk characterization in passive neutron coincidence counting of radioactive waste drums with plastic scintillators, IEEE Transactions on Nuclear Science, Vol. 63, No. 3, June 2016, pp. 1513-1519

Validation in the lab with 118 L mock-up drums





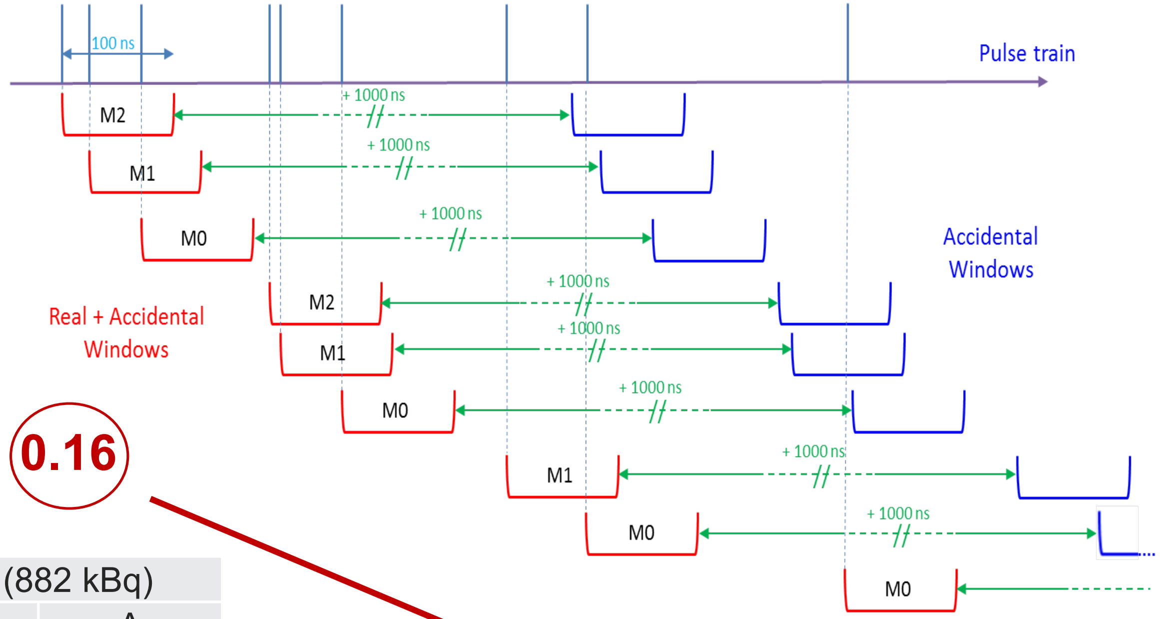
- 16 PVT scintillators 10 cm ×10 cm ×100 cm
- ^{137}Cs, ^{60}Co, ^{252}Cf, AmBe sources, Pu samples
- 5 cm lead shield
- FASTER electronics (CNRS)

Mock-up drums filled with iron or wood matrixes

V. Bottau, C. Carasco, B. Perot, C. Eleon, R. De Stefano, L. Isnel, I. Tsekhanovich, Detection of Fission Coincidences With Plastic Scintillators for the Characterization of Radioactive Waste Drums, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 69, NO. 4, APRIL 2022, pp. 818-824, DOI 10.1109/TNS.2022.3144346

Coincidence Multiplicity analysis

- **Shift register method** to unfold real from accidental coincidences
- **At least 3 pulses in coincidence** to separate spontaneous fissions (Pu or ^{252}Cf) from parasitic coincidences of (α,n) reactions, gamma cascades…



$$\frac{\text{Spontaneous fission neutrons of 252Cf}}{(\alpha,\text{n}) \text{ neutrons of AmBe}} \approx 0.16$$

	^{252}CF (3.6x10^4 n/s)		AmBe (2.3x10^5 n/s)		^{60}Co (882 kBq)	
	R+A	A	R+A	A	R+A	A
M0	3379137	4479459	15577017	16671802	53638186	57771864
M1	857974	8310	1141198	102194	4947762	989025
M2	209237	1296	59474	5790	251249	81991
M3	38098	257	2312	253	9079	3516
M4	4806	42	67	14	239	97
M5	401	5	-9	0	-11	2
M6	18	1	-3	0	-7	0
M7	-1	0	-2	1	-2	0
S	14 965.6 s^{-1}		55 933.5 s^{-1}		196 155.0 s^{-1}	
D	4 667.6 s^{-1}		3 842.5 s^{-1}		14 381.3 s^{-1}	
T	1 174.8 s^{-1}		174.9 s^{-1}		342.2 s^{-1}	

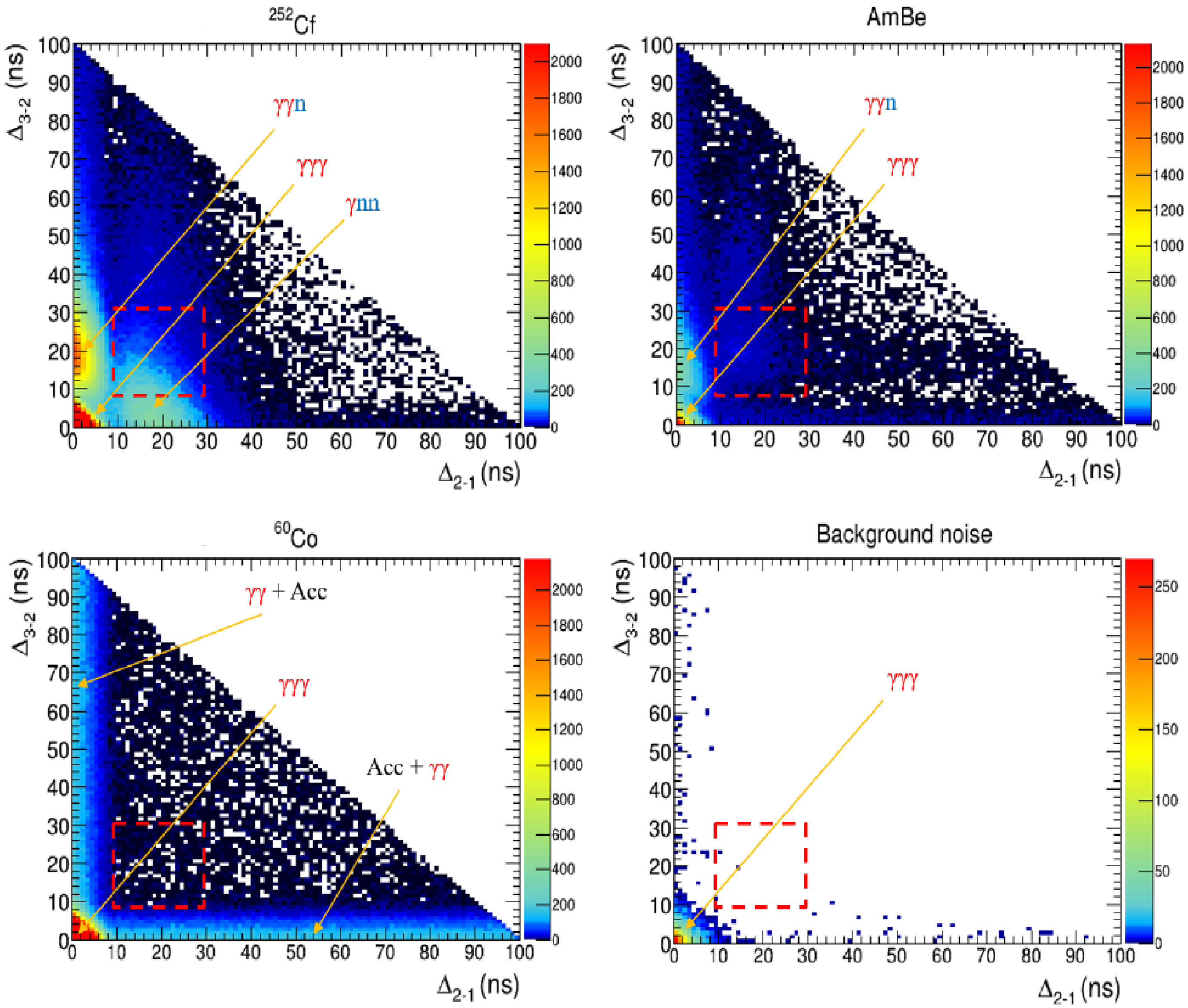
$$\text{Triples } \frac{T(252Cf)}{T(AmBe)} \approx 6.7$$

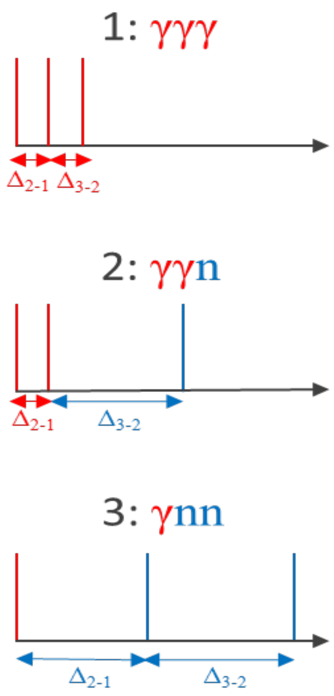
S, D, T = singles, doubles, triples after real vs. accidental coincidence unfolding

V. Bottau, et al, Sorting fission from parasitic coincidences of neutron and gamma rays in plastic scintillators using particle times of flight, ANIMMA 2021 International Conference, Prague, Czech Republic, EPJ Web of Conferences 253, 07014 (2021)

SNR improvement using 2D TOF maps (patented)

(γnn) region of interest





Radioactive source	Counts in ROI
^{252}Cf (3.6×10^{4} n.s^{-1})	10894
AmBe (2.3×10^{5} n.s^{-1})	761
^{60}Co (882 kBq)	522
SNR (^{252}Cf/AmBe)	**14.3***

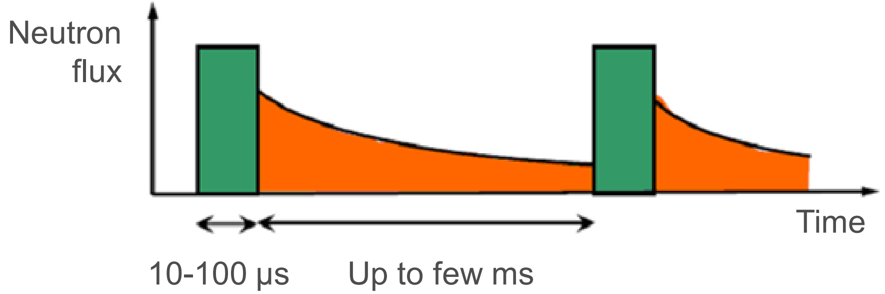
** After neutron and gamma scattering cross talk rejection*

- *V. Bottau, et al, Sorting fission from parasitic coincidences of neutron and gamma rays in plastic scintillators using particle times of flight,, EPJ Web of Conferences 253, 07014 (2021)*
- *V. Bottau, et al., Detection of Fission Coincidences With Plastic Scintillators for the Characterization of Radioactive Waste Drums, IEEE TNS VOL. 69, NO. 4, APRIL 2022*

5. Scintillators for neutron & photon activation analysis

Traditional HPGe neutron activation analysis)

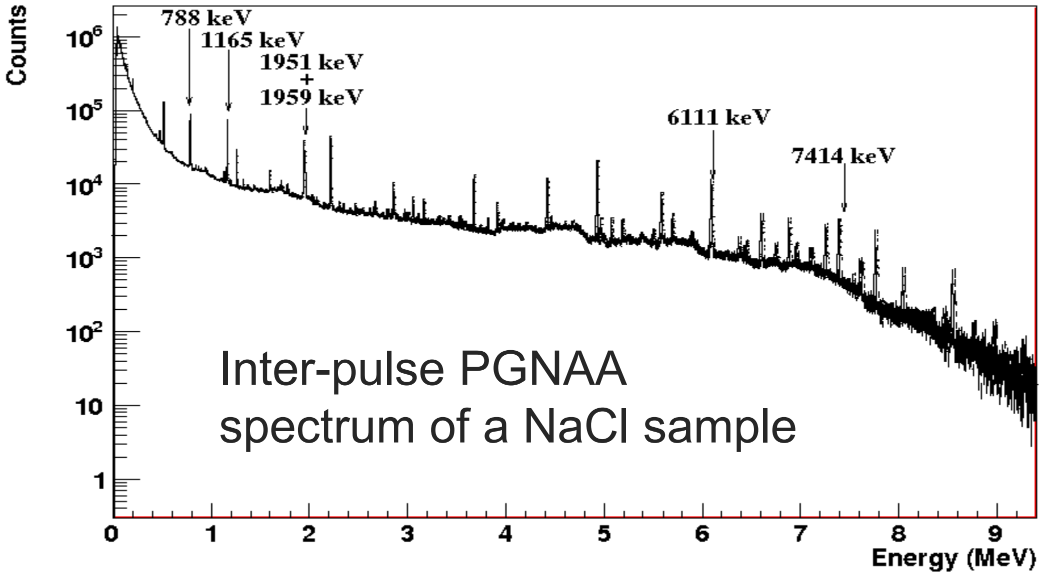
- **Pulsed neutron generator** + **HPGe** ⇨ Prompt Gamma Neutron Activation Analysis (PGNAA)
- **Toxic chemicals** (water, soils, rad-waste…), **recycling** (batteries, permanent coils, e-waste…)

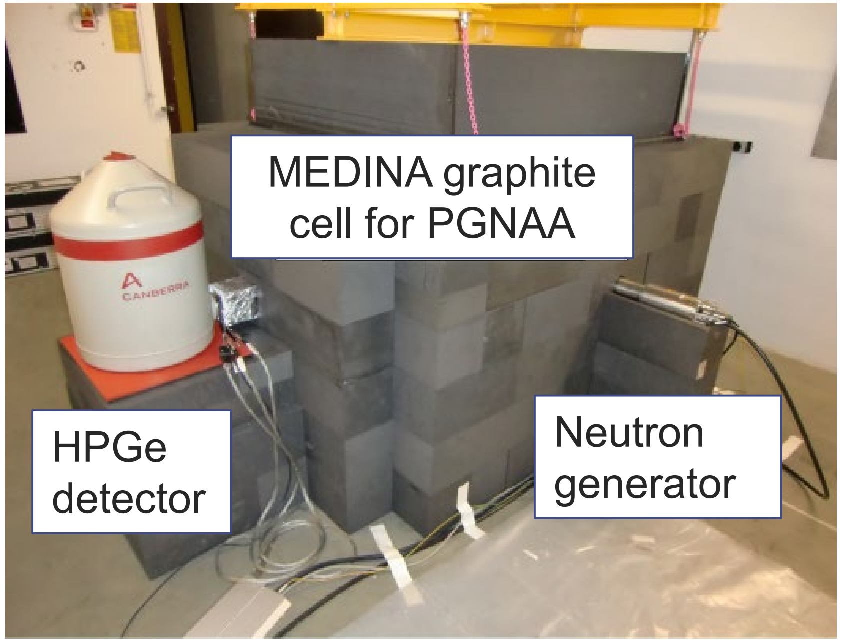


Fast neutrons during the pulses ⇨ (n,n'γ)

Thermal neutrons between pulses ⇨ (n,γ)

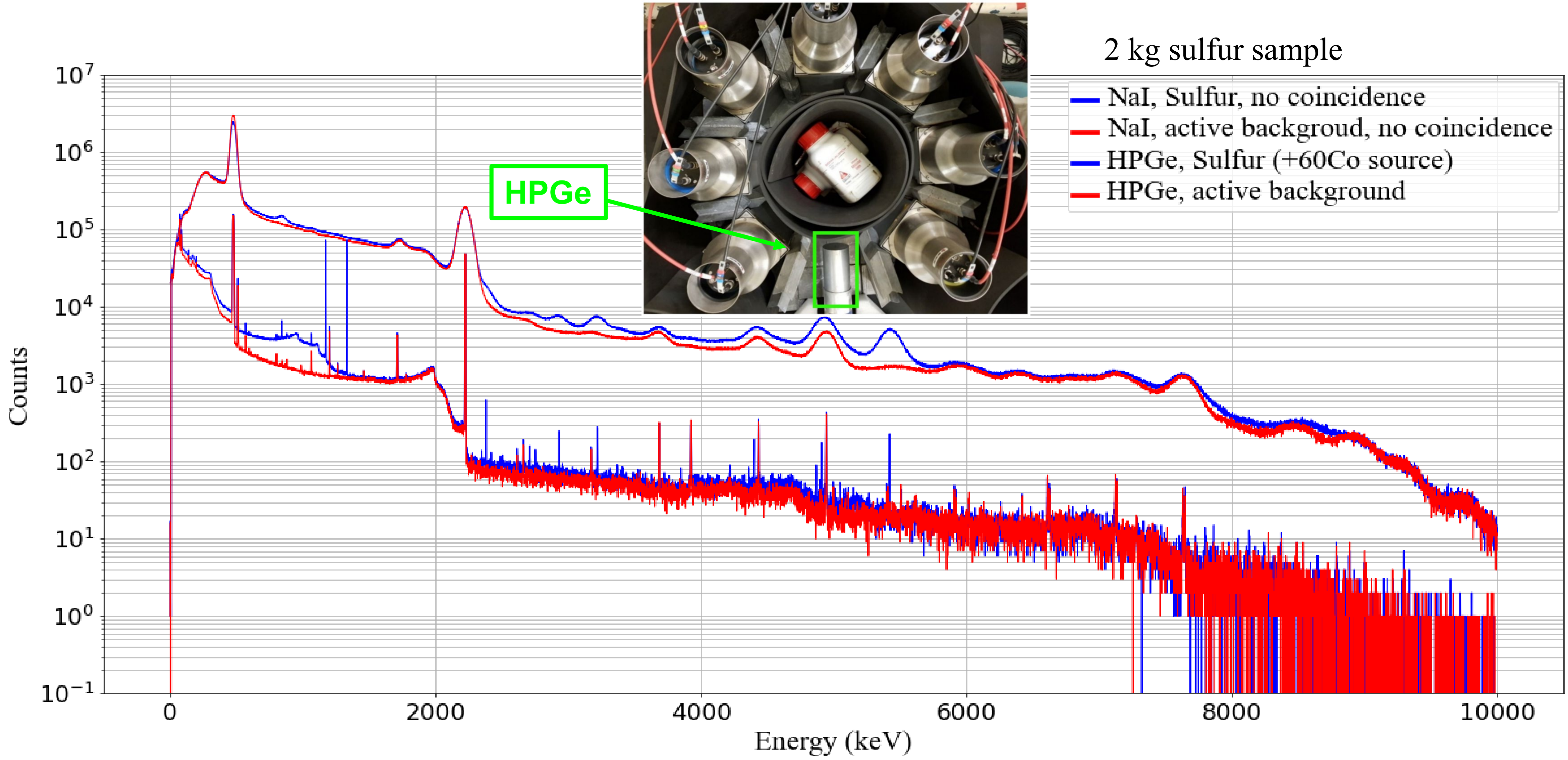
(+ delayed gamma rays of activation or fission products after irradiation)





E. Mauerhofer et al. Quantitative comparison between PGNAA measurements and MCNP calculations in view of the characterization of radioactive wastes in Germany and France, CAARI 2012, 22nd International Conference on the Application of Accelerators in Research and Industry, August 5 – 10, 2012, Fort Worth, Texas, USA. AIP Conf. Proc. 1525, 432 (2013)

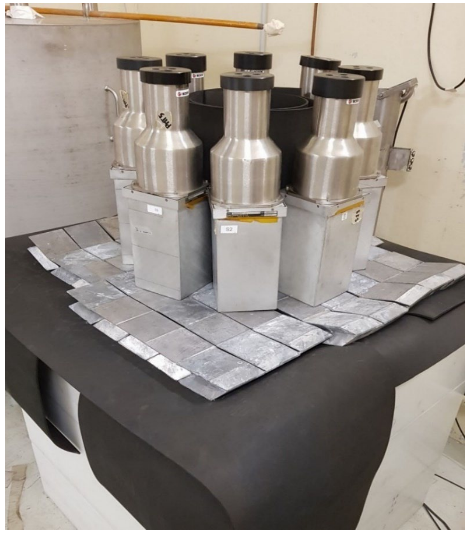
Large NaI scintillators (5”x5”x10”) vs. HPGe (30 %)

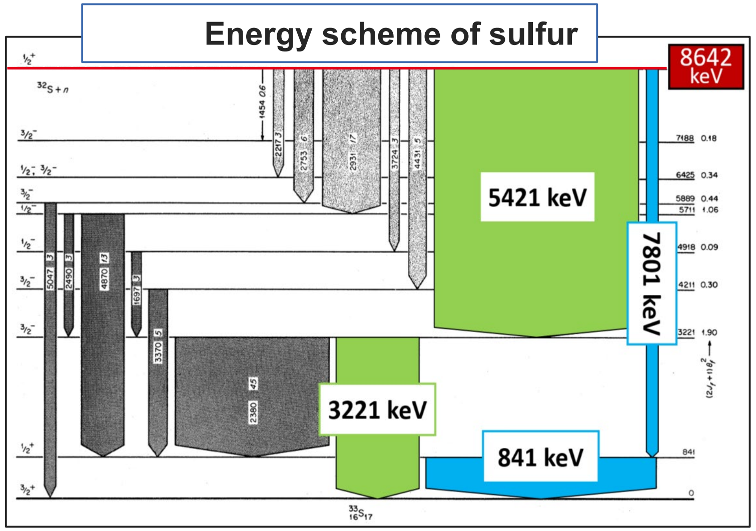


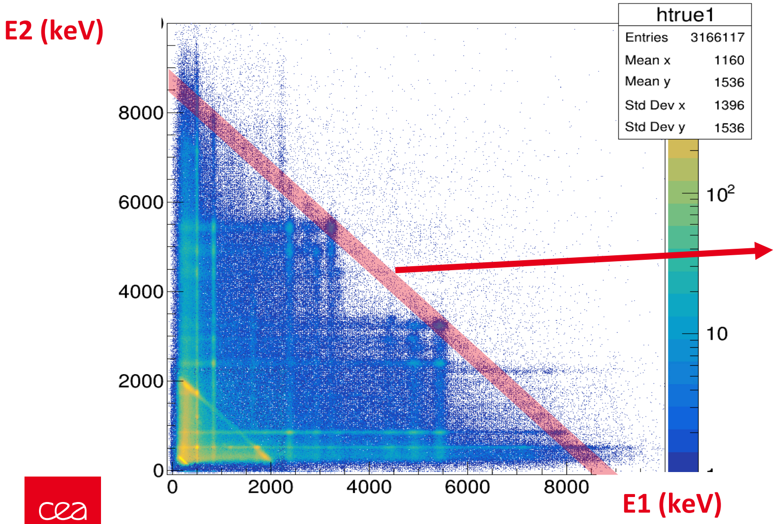
J. Roult et al, Experimental Gamma Coincidence spectra recorded in Prompt Gamma Neutron Activation Analysis, submitted to JRNC, JRNC-D-24-00414

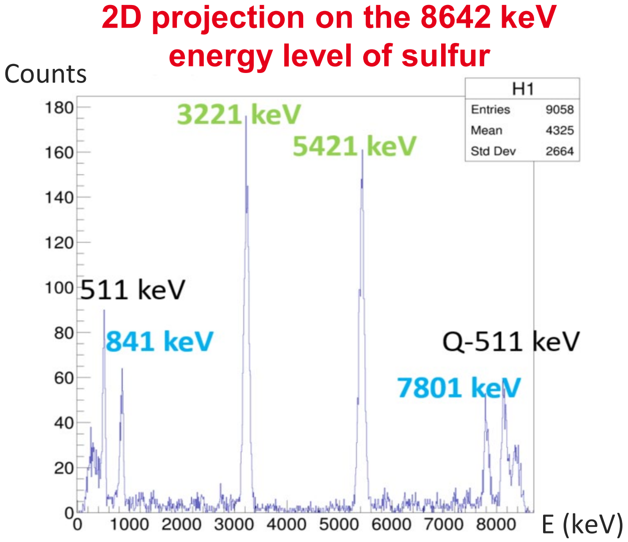
Pulsed NAA with scintillators

Gamma coincidences with large **NaI(Tl) scintillators**



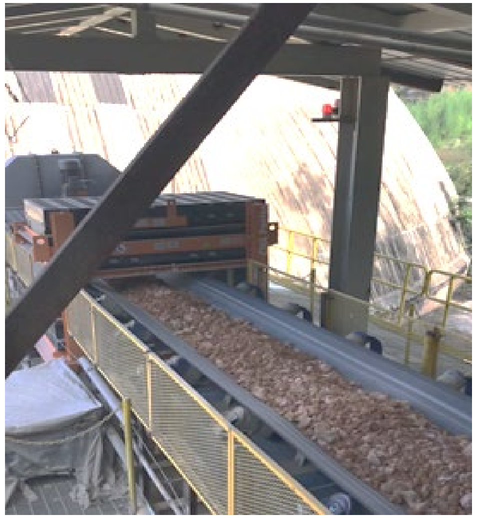


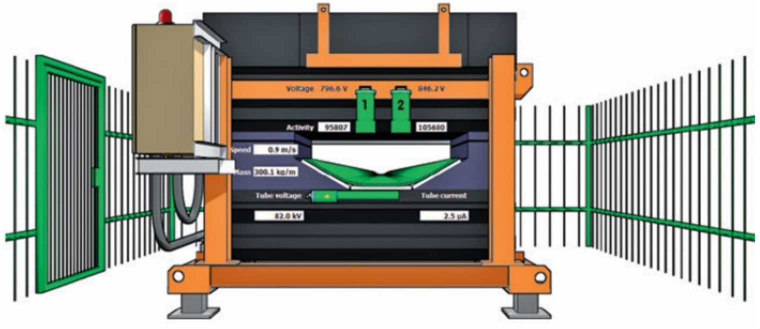




J. Roult et al, Experimental γ Coincidence spectra recorded in PGNAA, submitted to JRNC-D-24-00414

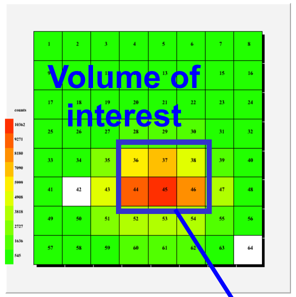
SODERN's online elemental analyzer for cement, coal and mining industries **with BGO scintillators** (spectrum unfolding ⇨ see next slide)



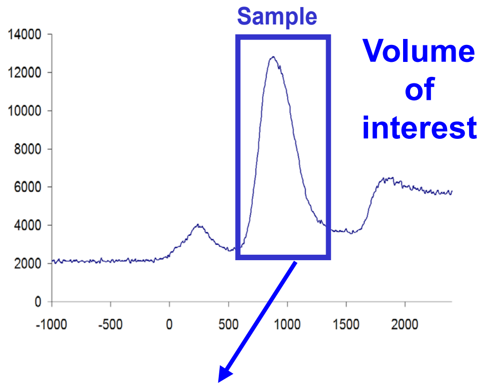


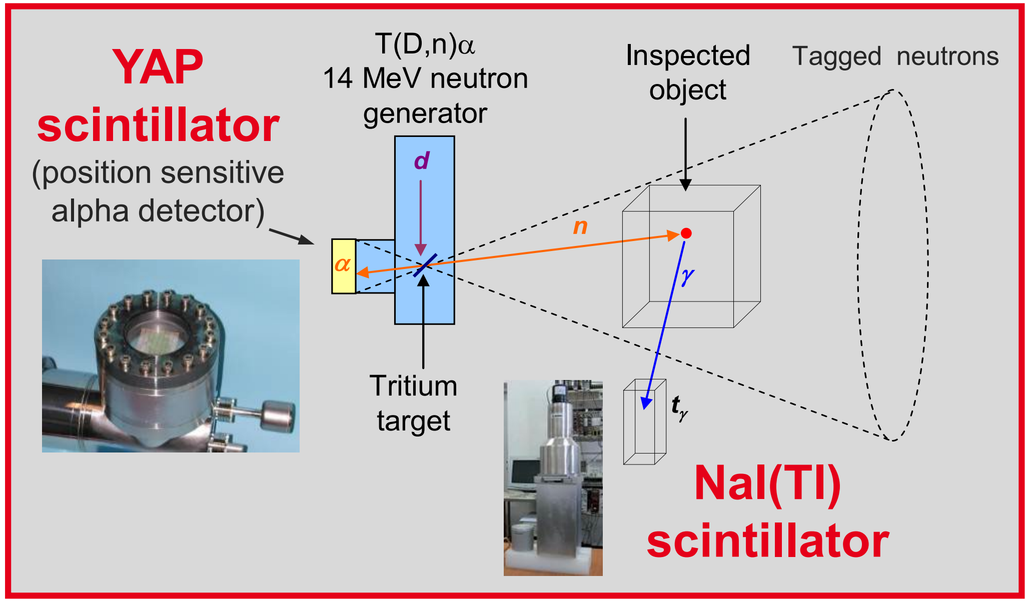
NAA with the Associated Particle Technique (APT)

YAP position sensitive alpha detector

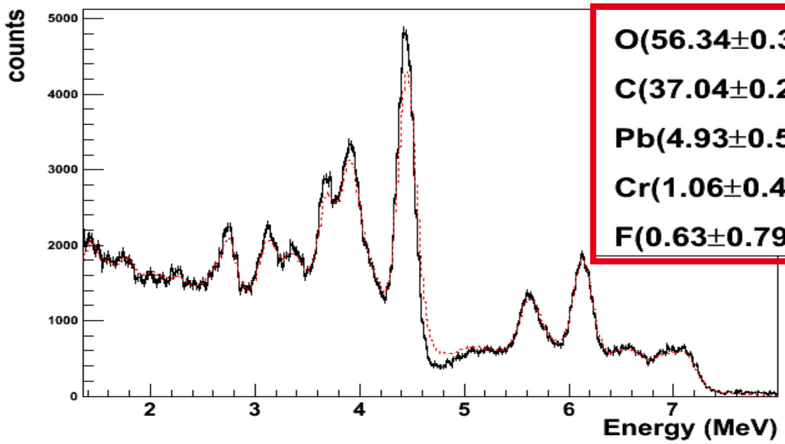


Neutron TOF (alpha-gamma coincidence)



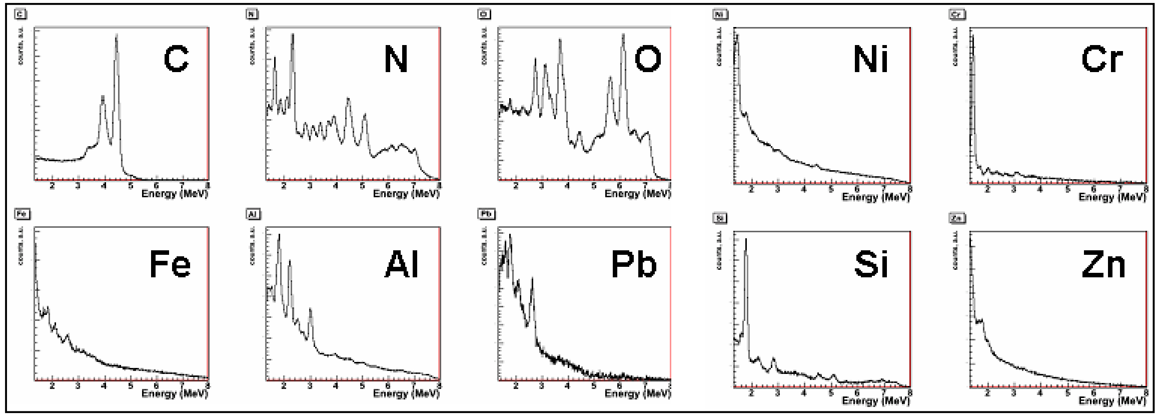


NaI(Tl) gamma spectrum (selected voxel)

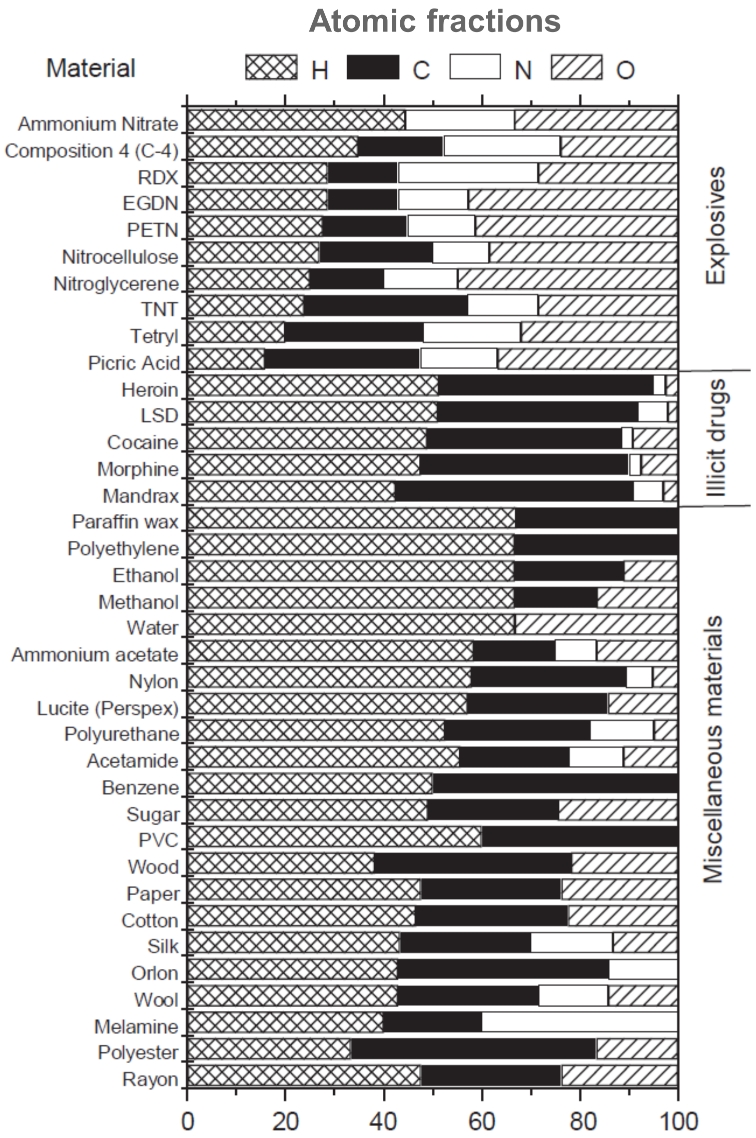


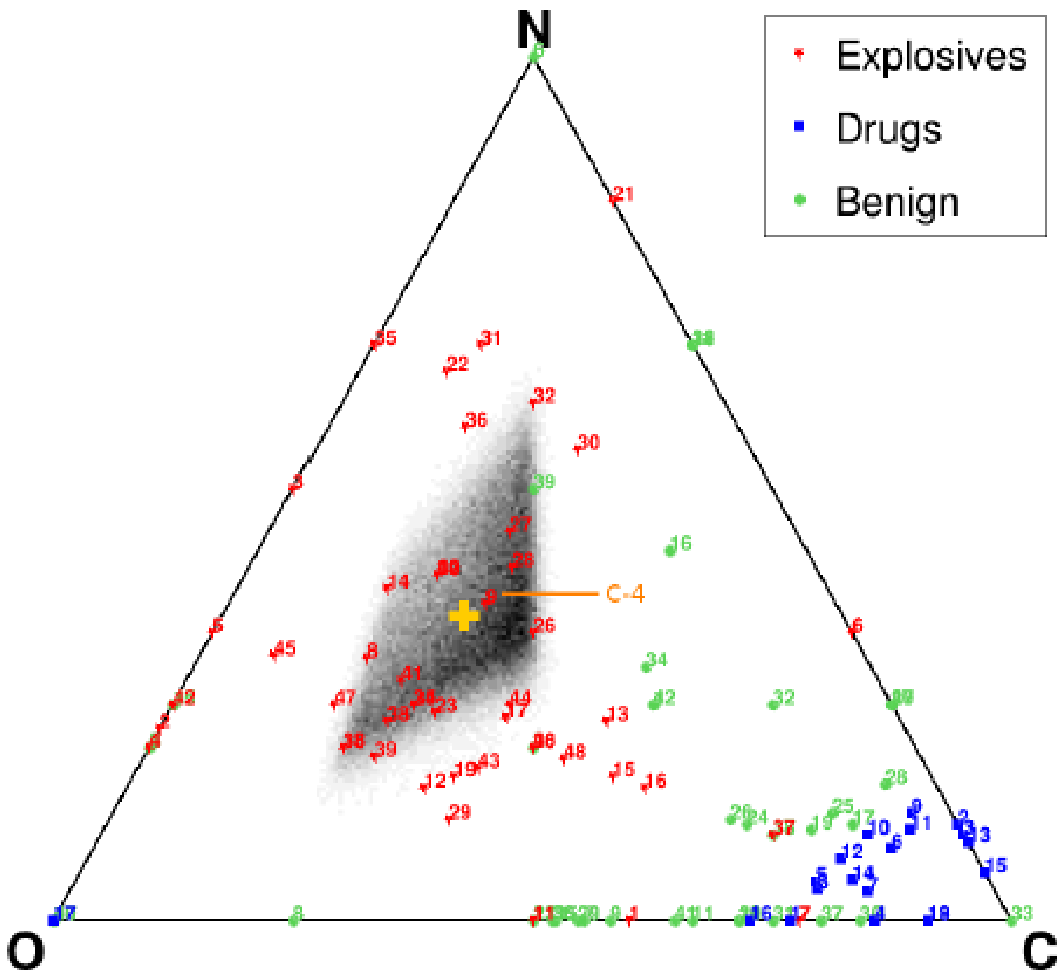
O(56.34±0.31)%
C(37.04±0.22)%
Pb(4.93±0.54)%
Cr(1.06±0.46)%
F(0.63±0.79)%

Unfolding (with a calibration database)



Organic Materials identification with APT



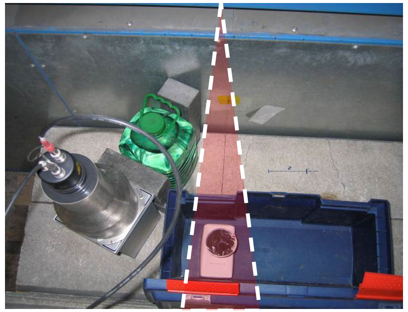


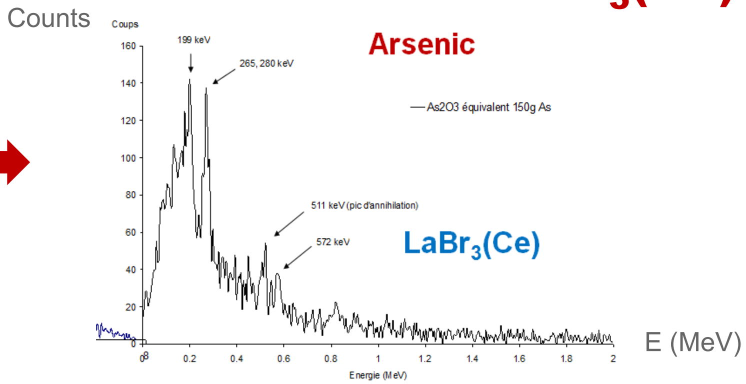
A. Buffler, http://dx.doi:10.1016/j.radphyschem.2004.04.110

Different scintillators used with APT

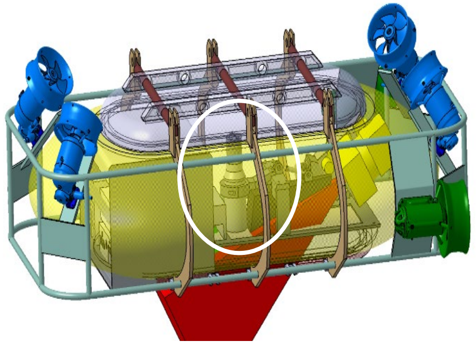
Cargo containers ⇨ large 5”x5”x10” NaI(Tl)

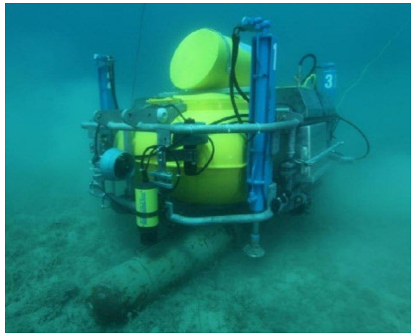
Chemical warfare detection ⇨ 3”x3” $LaBr_3(Ce)$





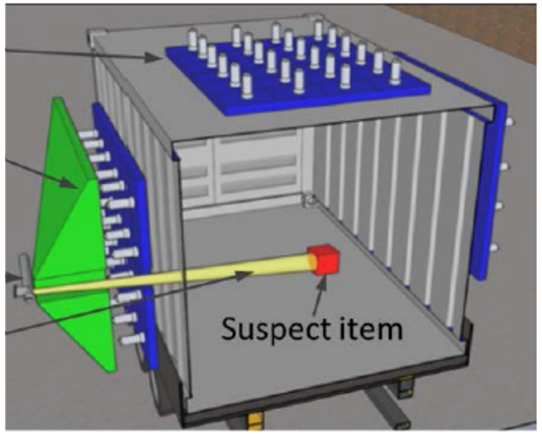
Submarine explosive detection ⇨ 3”x3” $LaBr_3(Ce)$

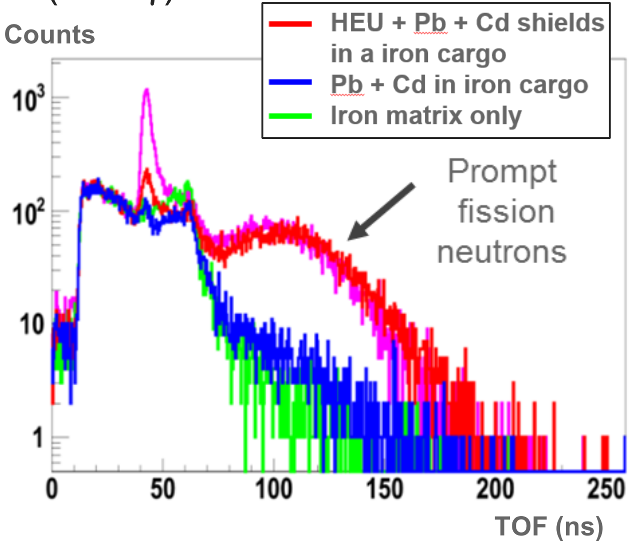




Nuclear material detection ⇨ large PVT panels

Coincidences between 1 α + 3 (n or γ)





B. Pérot, G. Sannié, Détection neutronique de matières illicites : technique de la particule associée, Editions Techniques de l’Ingénieur, RE 177, février 2015
B. Pérot, C. Carasco, et al., Sea Container Inspection with Tagged Neutrons, EPJ Nuclear Sci. Technol. 7, 6 (2021), https://doi.org/10.1051/epjn/2021004

Photofission delayed gamma rays ⇨ U, Pu characterization

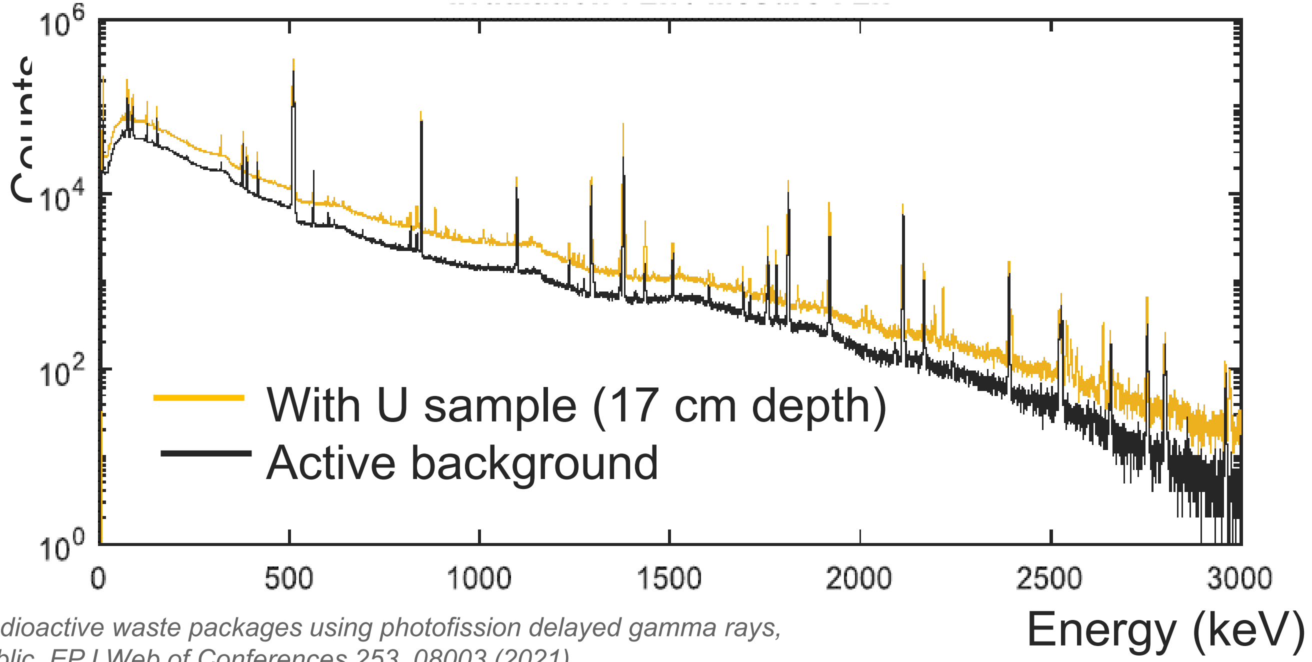
15-20 MeV LINAC with its shielded head

Irradiation 2h

Transfer time to HPGe + cooling delay of a few min

HPGe acquisition 2h

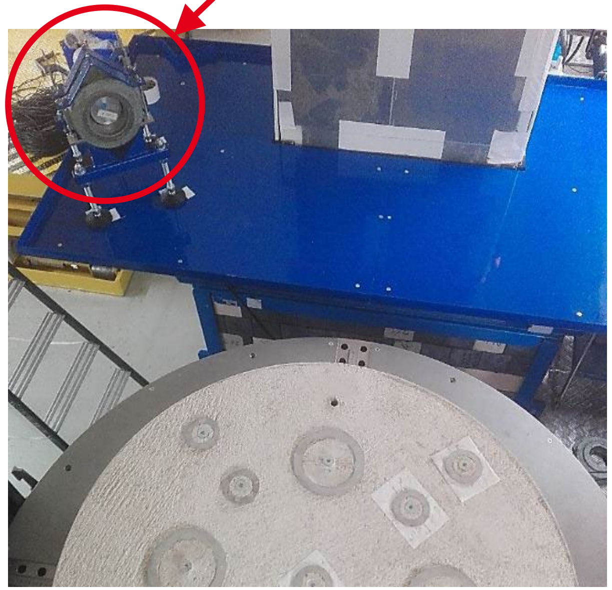
Highly shielded HPGe

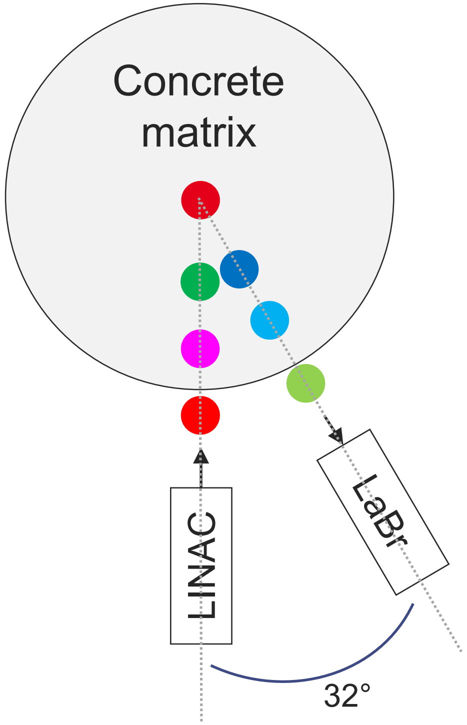


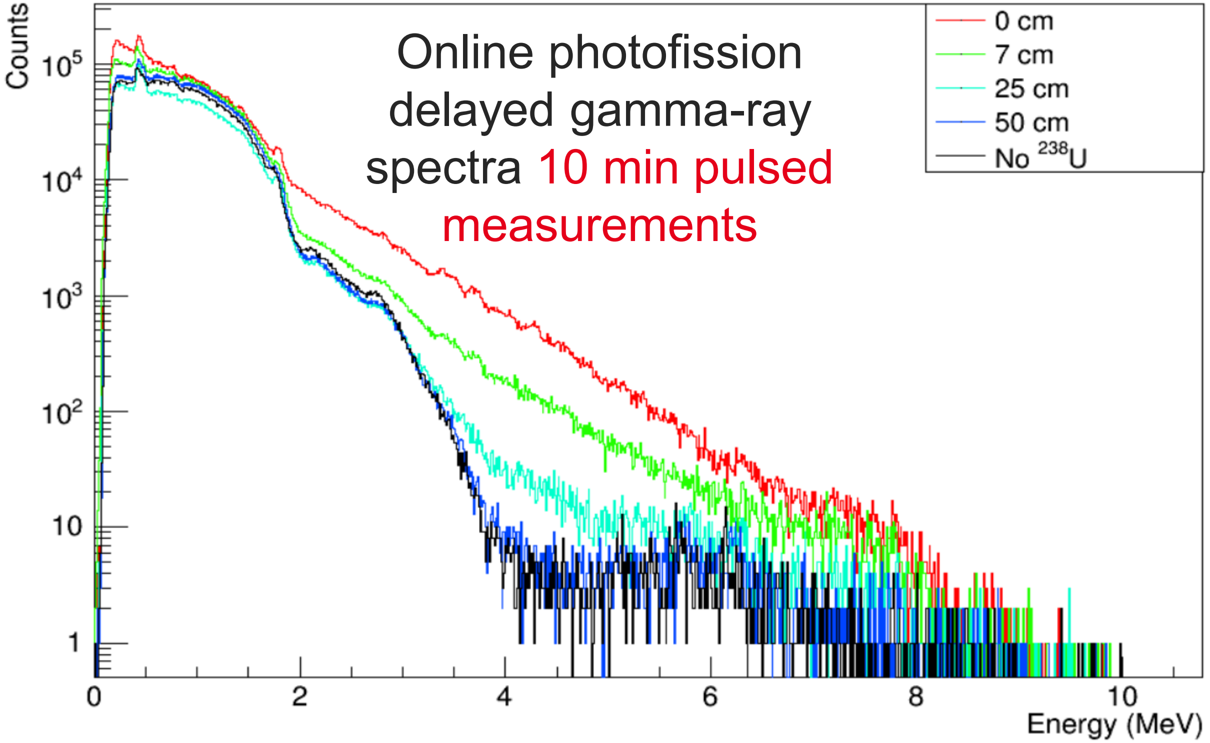
Manon Delarue et al., Localization of nuclear materials in large concrete radioactive waste packages using photofission delayed gamma rays, ANIMMA 2021 International Conference, June 2021, Prague, Czech Republic, EPJ Web of Conferences 253, 08003 (2021)

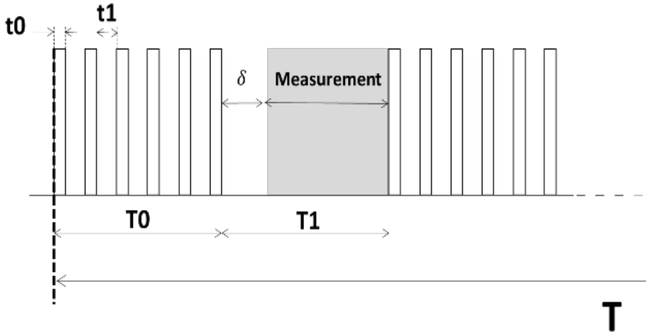
Using a $LaBr_3(Ce)$ scintillator in pulsed irradiation

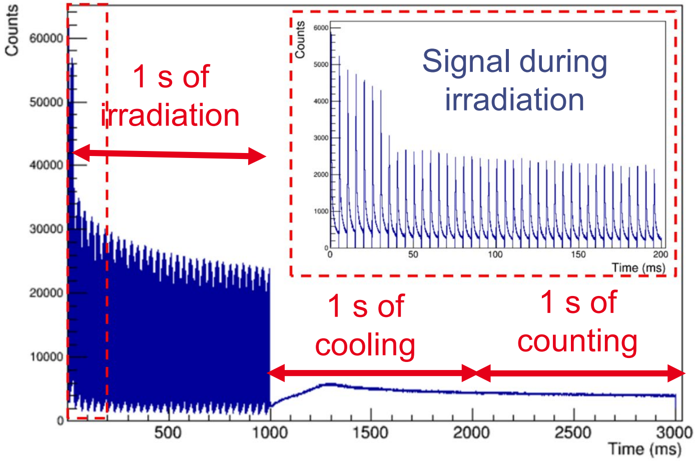
$LaBr_3(Ce)$ scintillator











Energy threshold	Net counts from ^{238}U	Background counts	Net counts / background
2	544017± 826	69371	8
2.5	308041±599	25434	12
3	171349±429	6496	26
3.5	92585±310	1824	51
4	48954 ±226	1184	41
4.5	24960±164	1004	25
5	12357±118	866	14

C. Carasco et al. Photofission delayed gamma-ray measurements in a large cemented radioactive waste drum during LINAC irradiation, NIM A 1053 (2023) 168360

6. Conclusion and prospects

Conclusion and prospects

❑ Many advantages for scintillators

- ➢ Fast timing, high count rates, high efficiency, low cost, rugged, no cooling, many shapes…
- ⇨ Appropriate for a wide range of in situ and online applications

❑ Constant innovations

- ➢ Developments of scintillation materials, setups (mixtures of scintillation materials, light guides, optical fibers, segmented detectors, multi-anodes PM, SiPM, …), fast numeric electronics, onboard signal processing (PSD, CFD, coincidences, ToF…), etc.
- ➢ Improvements in time and energy resolutions, detection efficiency, throughput (small count losses at high count rates), specificity (e.g. by loading organic scintillators with B or Li, or coating with Cd or Gd to detect thermal neutrons, n/γ discrimination using pulse shape or detection times, …), spatial selectivity with segmented light readout, segmented detectors, large scintillator arrays at reasonable cost…
- ➢ Machine learning, ANN and other mathematical approaches to counterbalance some drawbacks such as the poor spatial and energy resolutions, cross talk, γ sensitivity, etc.

⇨ More and more applications open up for scintillators

cea

THANK YOU

bertrand.perot@cea.fr