DE LA RECHERCHE À L'INDUSTRIE

MESURES NUCLEAIRES NON DESTRUCTIVES ET APPLICATIONS AU LMN

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Laboratoire de Mesures Nucléaires

CEA, DEN, Cadarache

www.cea.fr

SÉMINAIRE LPC | CLERMONT FERRAND | 30 MARS 2018

LE CEA (CHIFFRES 2016)

- **4,1 milliards** d'euros de budget
- **9** centres de recherche
- **16 010** collaborateurs
- **51** unités de recherche sous cotutelle du CEA et de partenaires académiques
- **55** accords-cadres en vigueur avec les universités et écoles
- **743** dépôts de brevets prioritaires en 2016
- **27** Equipex (équipements d'excellence)
- **33** Labex (laboratoires d'excellence)
- **3** Idex (initiative d'excellence)
- **195** Start-up technologiques depuis 1972 , dont **132** depuis 2000
- Plus de **600** partenaires industriels
- **422** projets européens en cours en 2016
- **30** pôles de compétitivité auxquels participe le CEA dont **17** dont le CEA est administrateur

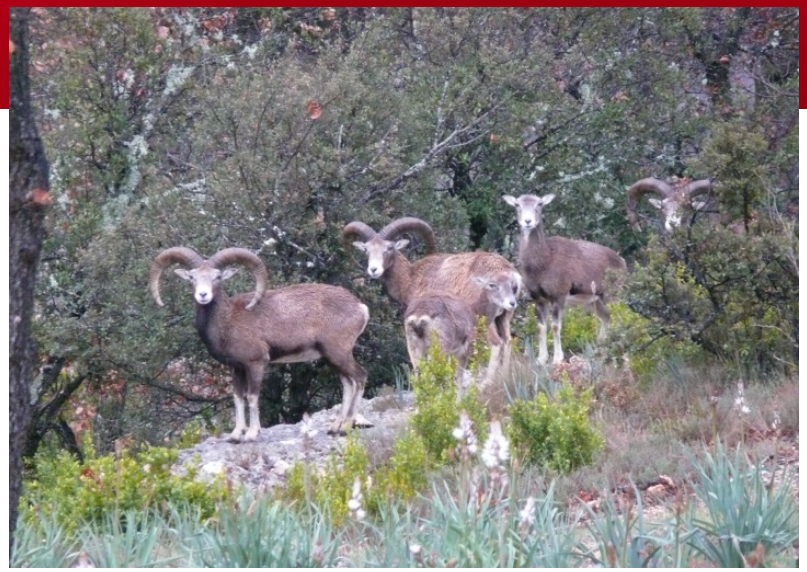
1 SIÈGE SOCIAL

CENTRES D'ÉTUDE CIVILS
2 PARIS-SACLAY établissements de Fontenay aux Roses et Saclay
3 GRENOBLE
4 MARCOULE
5 CADARACHE

CENTRES D'ÉTUDE POUR LES APPLICATIONS MILITAIRES
6 DAM Île-de-France
7 LE RIPAULT
8 VALDUC
9 CESTA
10 GRAMAT

PLATEFORMES RÉGIONALES DE TRANSFERT TECHNOLOGIQUE
11 TOULOUSE
12 BORDEAUX
13 NANTES
14 METZ
15 LILLE

LE CEA CADARACHE



- 1600 hectares dont 900 clôturés
- 2 400 salariés CEA sur un site de 5 500 personnes (700 TechnicAtome, 330 IRSN, 80 Intercontrôle…)
- 480 bâtiments et laboratoires dont 20 Installations Nucléaires de Base (INB) et 1 Installation Nucléaire de Base Défense (INBS)
- Grands projets ITER, RJH, RES
- Un pôle de formation (160 chercheurs-enseignants, 130 thésards et post-doctorants)
- Des partenariats et collaborations internationaux
- Une UMR (Biotechnologies), un laboratoire commun avec AMU (Instrumentation en milieu extrême)
- Environ 300 publications scientifiques par an
- 200 brevets actifs (20 par an)

LE LABORATOIRE DE MESURES NUCLÉAIRES

❑ Quelques chiffres

- ✓ **28 salariés CEA** : ingénieurs-chercheurs, techniciens, experts
- ✓ **~ 3 à 7 collaborateurs** : intérim, CDD, doctorants (3 à 4), stagiaires (2 à 3)
- ✓ **~ 50 projets ou collaborations :** unités CEA, industriels, universités, UE

❑ Missions principales

- ✓ **Mesures en labo et in situ** de caractérisation, expertise, contrôle
- ✓ **Simulation numérique et analyse des données** : utilisation et développement d'outils ⇨ études, interprétation des mesures
- ✓ **Conception, mise en œuvre, qualification** de systèmes de mesure
- ✓ **R&D** ⇨ optimisation et étude de nouvelles méthodes de mesure
- ✓ **Veille technologique** sources, détecteurs, électronique
- ✓ **Enseignement** : formation académique et continue

MÉTHODES DE MESURE

- **La caractérisation radiologique**
  - ✓ Spectrométrie gamma
  - ✓ Mesures neutroniques passives et actives
  - ✓ Interrogation photonique
- **La caractérisation physique par imagerie**
  - ✓ Radiographie / tomographie X haute énergie
  - ✓ Neutronographie
- **La caractérisation élémentaire par activation neutronique**
  - ✓ Interrogation pulsée (neutrons thermiques)
  - ✓ Technique de la particule associée (neutrons rapides)

DOMAINES D'APPLICATION

- **Le cycle du combustible**
  - ✓ Prospection de l'uranium
  - ✓ Retraitement des combustibles usés
  - ✓ Caractérisation des déchets radioactifs
  - ✓ Assainissement & démantèlement
- **Les mesures pour les réacteurs**
  - ✓ Transferts de contamination dans le circuit primaire
  - ✓ Examens non destructifs du futur réacteur RJH
  - ✓ Interaction corium-eau, mesures post-accidentelles
- **La sécurité**
  - ✓ Contrôle des matières nucléaires
  - ✓ Détection des menaces NRBCE

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

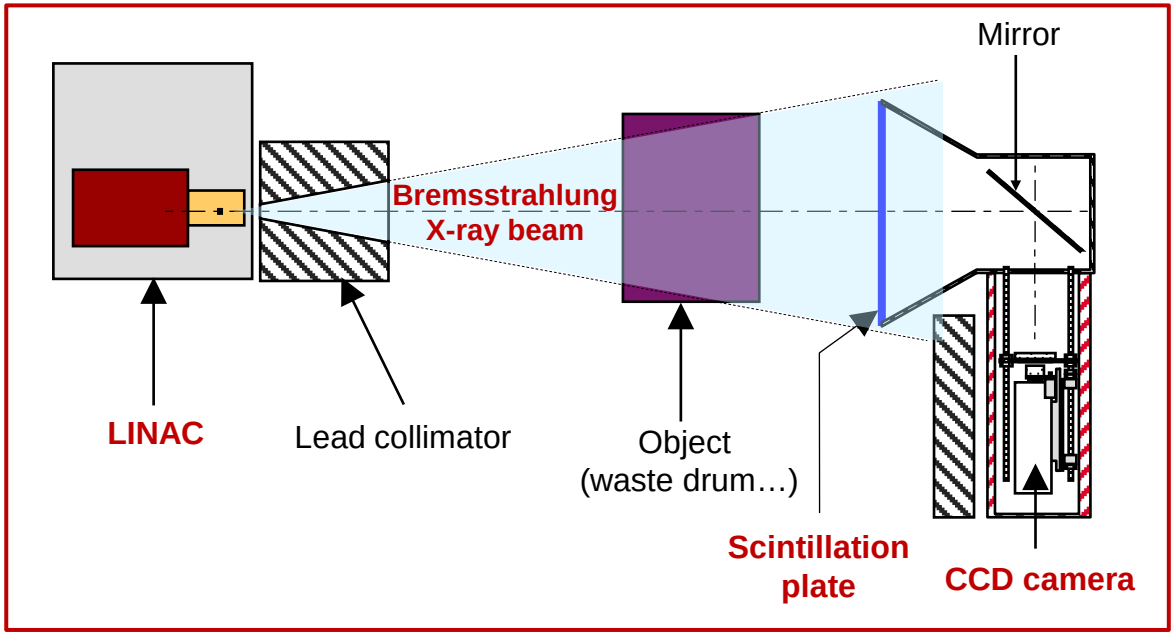
MESURES NEUTRONIQUES PASSIVES ET ACTIVES

MESURES COMBINÉES

ACTIVATION NEUTRONIQUE PULSÉE

TECHNIQUE DE LA PARTICULE ASSOCIÉE

HIGH ENERGY X-RAY IMAGING



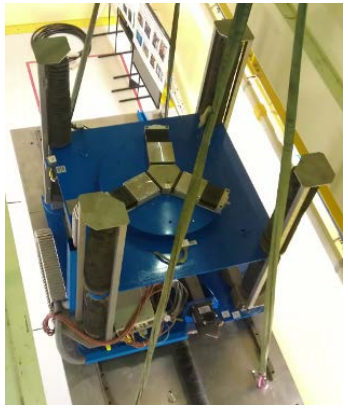
CINPHONIE high energy X-ray imaging

X-ray Vs. ^{60}Co imaging

- ***Radiography: 240 × faster***
  (40 h → 10 min)
- ***Tomography: 36 × faster***
  (15 h → 25 min)

LINAC 9 MeV, 15 Gy/min

Up to 2 tons platform



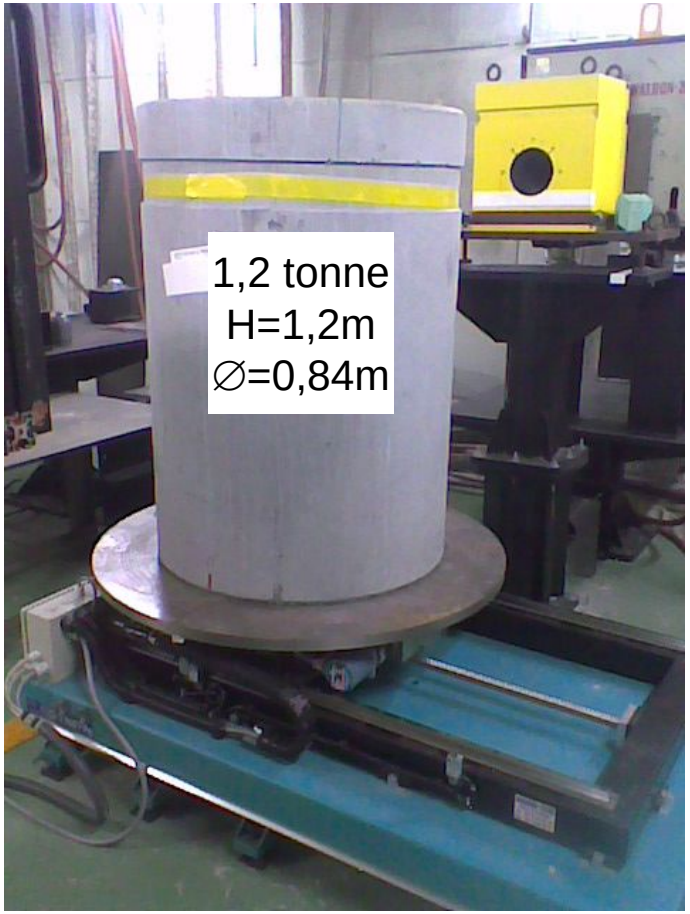
Scintillation plate 800x600 mm²

Gadox Gd_2O_2S ; 1.5 mm

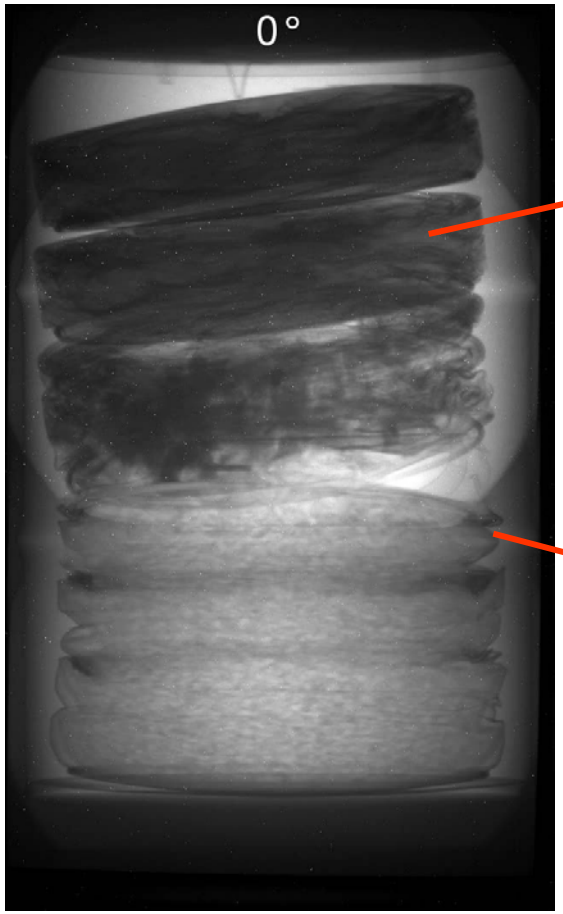
N. Estre, D. Eck, J-L. Pettier, E. Payan, C. Roure, E. Simon, High-Energy X-Ray Imaging Applied to Non Destructive Characterization of Large Nuclear Waste Drums, ANIMMA 2013, 23-27 June 2013, Marseille, France. DOI:10.1109/ANIMMA.2013.6727987

HIGH ENERGY IMAGING OF LARGE CONCRETE DRUMS

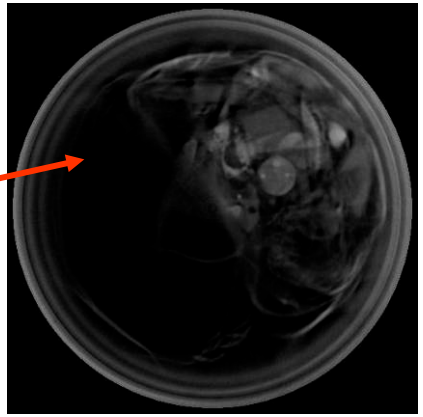
Concrete waste (density > 2)
Less than 1 s per single radiography

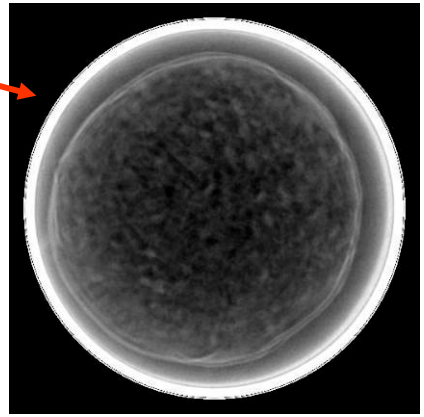


Radiography



Tomography





HIGH ENERGY X-RAY RADIOSCOPY

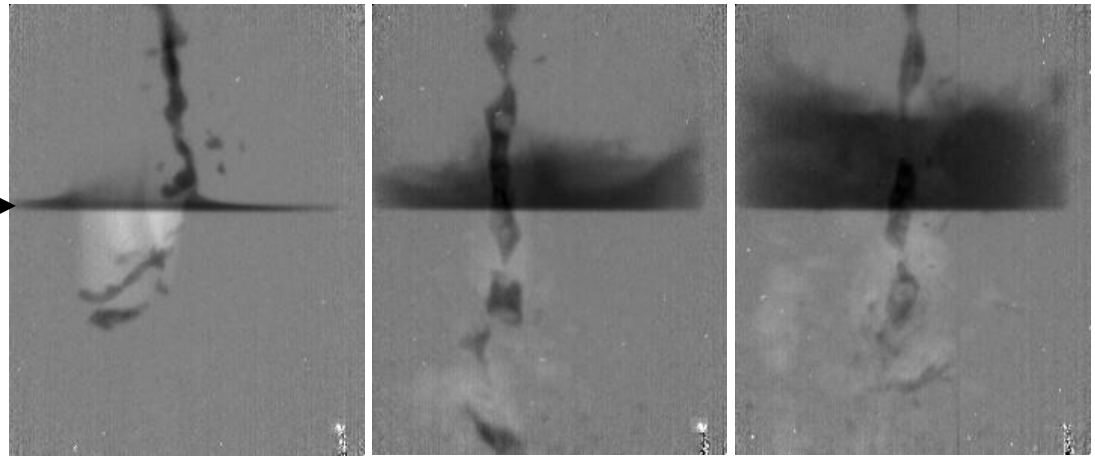
Dynamic radiography

- Originally one camera with 50 pictures / sec and 230 × 240 pixels
- Now 4 cameras ⇨ up to 200 pictures / sec and 2560 × 2160 pixels

Application to corium / water interaction

⇨ MC3D code validation (nucl. accident studies)

Water surface



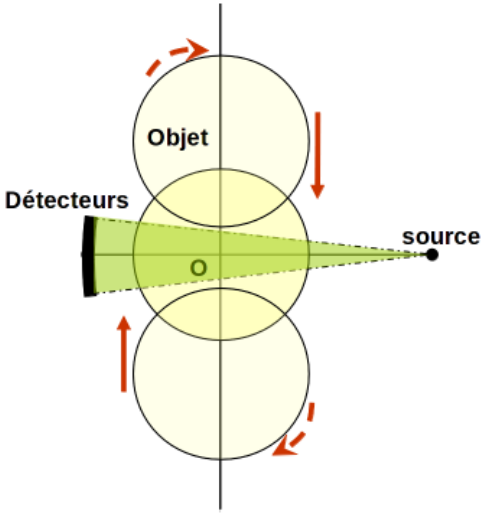
In yellow: 9 MeV LINAC
In black : imaging plate

N. Estre, E. Payan, L. Berge, Fast Megavoltage X-Rays Radioscopy ,Nuclear Science Symposium, 29 Oct. – 4 Nov. 2016, Strasbourg, France.

HIGH ENERGY X-RAY TOMODENSITOMETRY

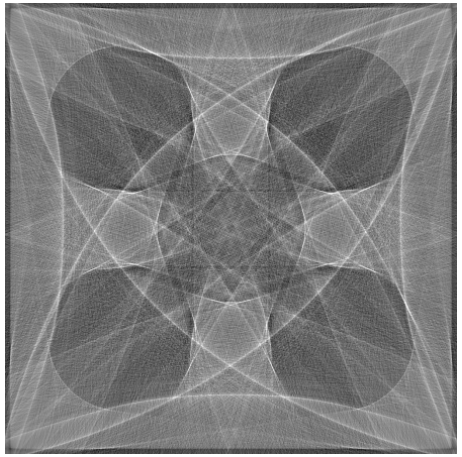
- **Attenuation up to 5 decades (40 cm steel)**
- Radiography and 2D plane tomography
- 3D helicoidally tomography
- **0.5 to 2 mm spatial resolution**
- 1 h (2D) to several days (3D) acquisitions

Collimated CdTe detectors

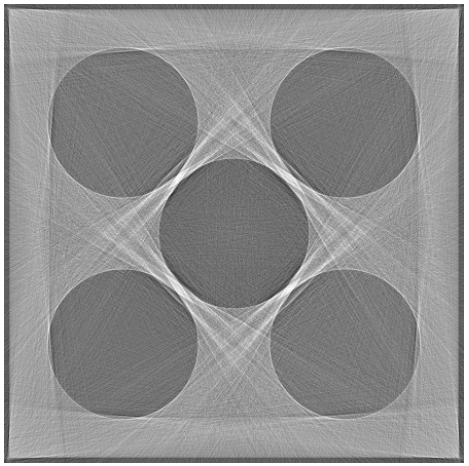


Simulations of a 5 m³ concrete waste package

9 MeV LINAC



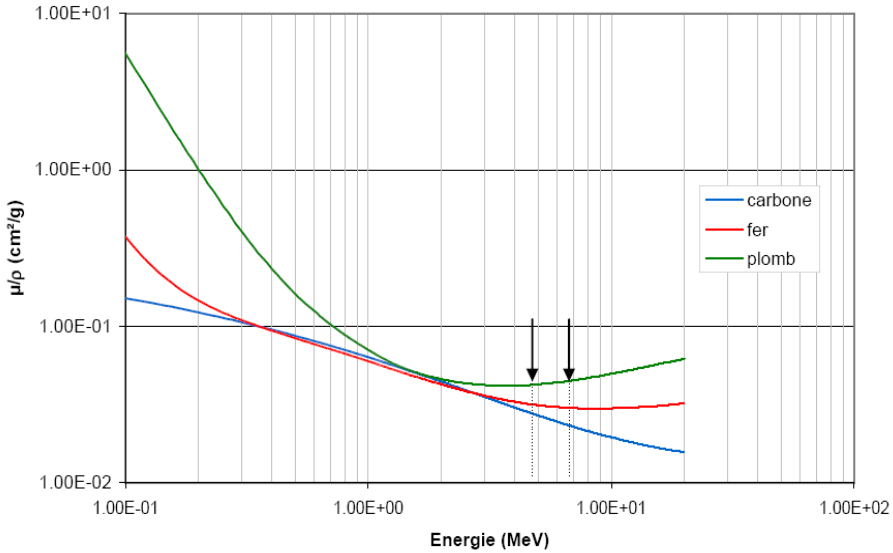
15 MeV LINAC



CEA DEN CAD, LMN

DUAL ENERGY IMAGING WITH A SATURNE LINAC

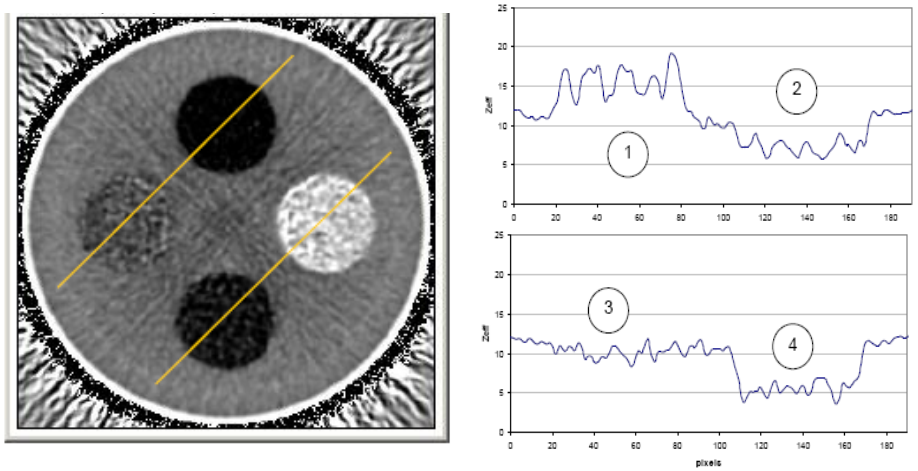
Mass attenuation coefficient μ/ρ



LINAC acquisitions at 15 MeV and 9 MeV

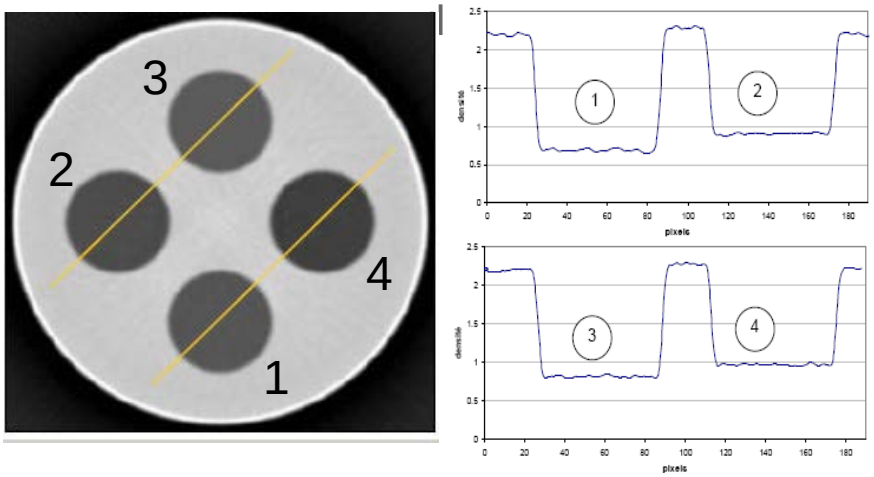
μ_{15MeV} ($\bar{E}$~ 6 MeV) / μ_{6MeV} ($\bar{E}$~4 MeV)

Atomic number Z (simulation of a 870 L drum)



N° insert	matériau	Z_{eff} théorique	Z_{eff} calculé
1	PVC	12	15.90 ± 11.3%
2	Cellulose	6.68	7.05 ± 15%
3	plastique	9.3	9.96 ± 11.1%
4	CH_2	5.28	5.46 ± 15.5%

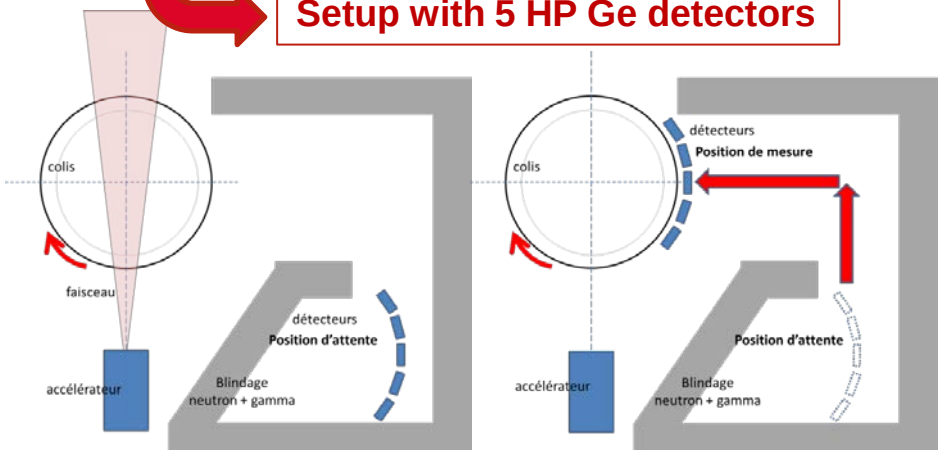
Density (simulation of a 870 L

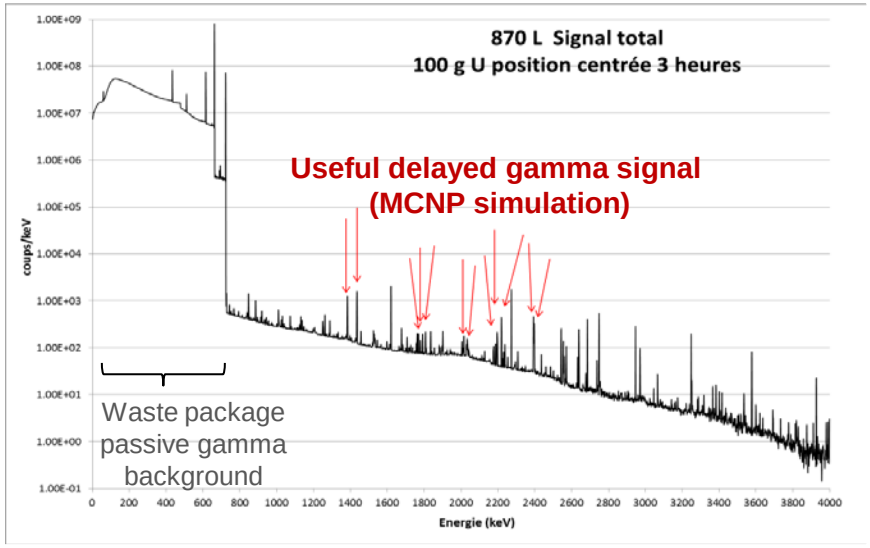


OTHER USE OF HIGH ENERGY X-RAYS: PHOTOFISSION

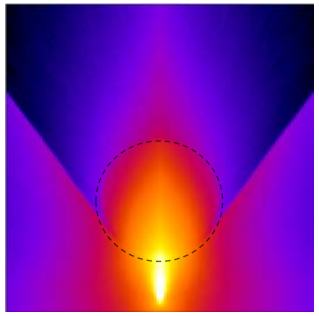
- **U and Pu** measurement in **large concrete waste packages**
- **High energy X rays** produced by an electron LINAC (photofission threshold ~ 6 MeV)
- **Delayed neutron counting** between the pulses
- **Delayed gamma-ray spectroscopy** after stopping irradiation

Setup with 5 HP Ge detectors





15 MV Linac beam
(870 L drum)



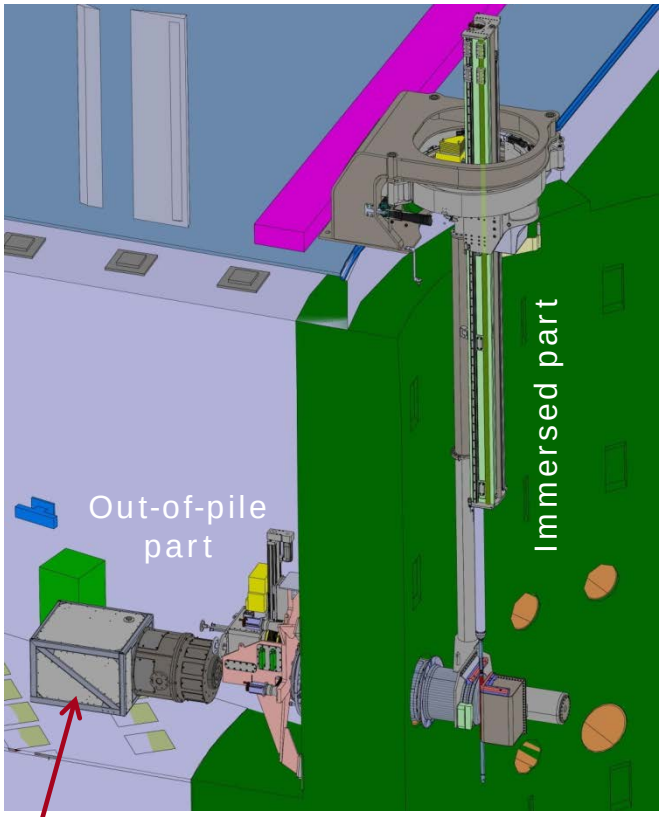
U in the center	Background & detection limit - 1 detector			Backgr. & detection limit - 5 detector cluster		
γ ray (keV)	B (counts)	L_D (counts)	L_D (g ^{235}U)	B (counts)	L_D (counts)	L_D (g ^{235}U)
1384	80	44	0,92	240	75	0,312
1436	116	53	0,84	580	115	0,36
1768	64	40	7,98	320	86	3,43
1791	64	40	7,98	320	86	3,43
1807	60	39	6,45	300	83	2,78
2016	96	48	9,66	480	105	4,18
2032	100	49	8,21	500	107	3,56
2176	34	30	9,94	170	63	4,22
2196	32	29	2,89	158	61	1,22
2218	34	30	1,74	168	63	0,74
2392	36	31	1,70	180	65	0,72
2398	36	31	2,35	180	65	1,00

E. Simon, F. Jallu, B. Pérot, S. Plumeri, Feasibility study of fissile mass quantification by photofission delayed gamma rays in radioactive waste packages using MCNPX, Nuclear Instruments and Methods in Physics Research A 840 (2016) 28–35

UNDERWATER X-RAY IMAGING FOR JHR REACTOR

❑ High resolution mechanics

to move the JHR test devices in 3D



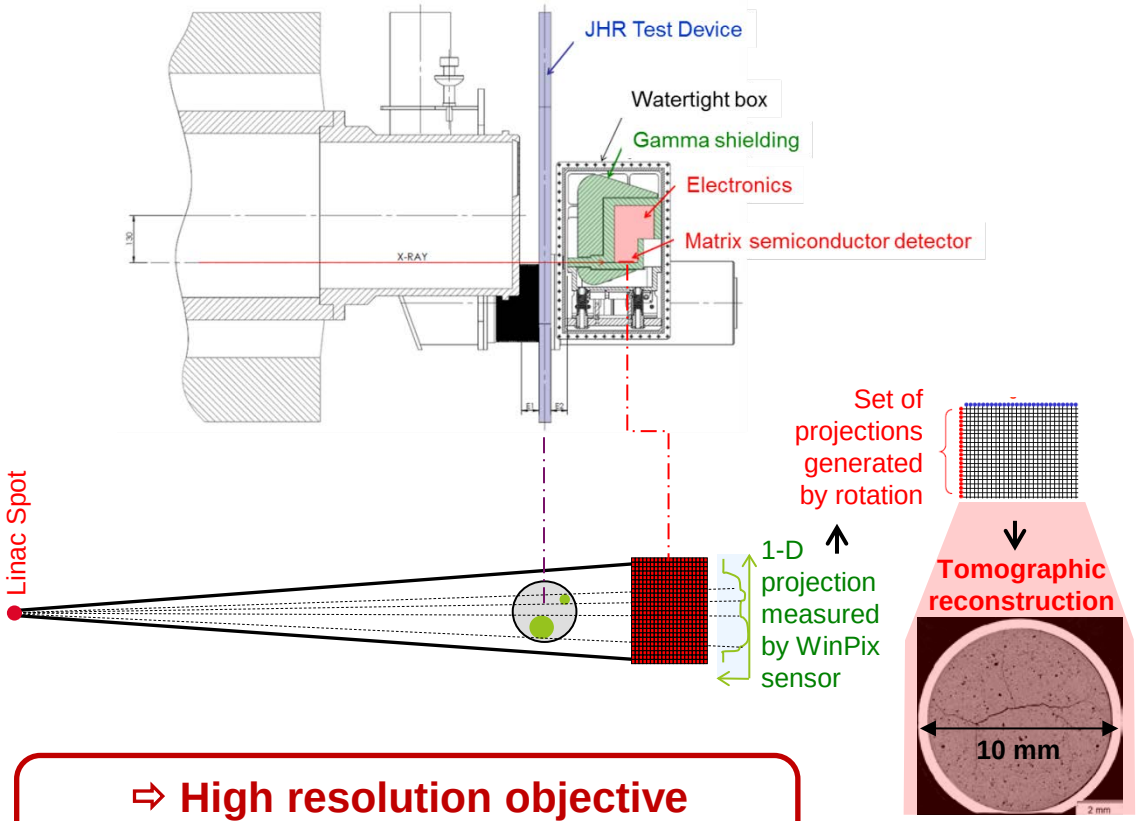
❑ 6 MeV LINAC

~ 500 µm focal spot

❑ Highly collimated X-ray camera

WinPix semi-conductor sensor

(~ 50 µm x 50 µm pixels)

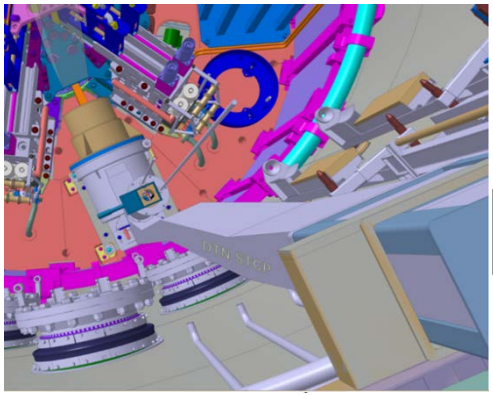


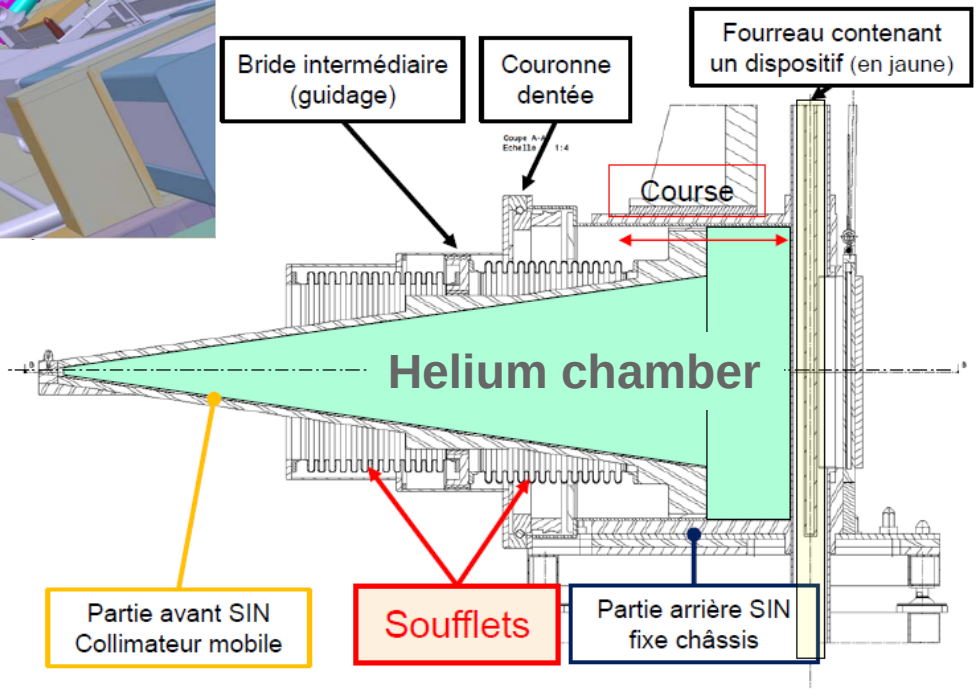
⇨ High resolution objective

~ 100 µm to observe cracks, corrosion…

C. Roure, B. Cornu, E. Simon, N. Estre, et al., Non-Destructive Examination Development for the JHR Material Testing Reactor, ANIMMA 2013, doi:10.1109/ANIMMA.2013.6727882, 23-27 June 2013, Marseille, France.

NEUTRON RADIOGRAPHY FOR JHR REACTOR





❑ Dysprosium activation

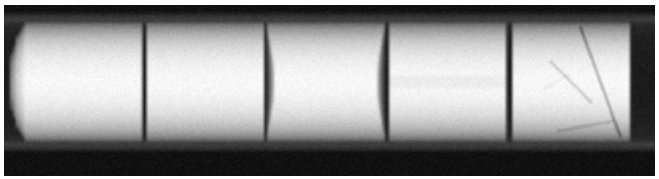
- Neutron convertor foil made of metallic Dy
- $^{164}Dy(n,\gamma)^{165}Dy$ activation
- β decay of ^{165}Dy ($T_{1/2}$ ~ 2 h)
  ⇨ delayed β imaging

Transfer

❑ Imaging detector

- Silver film (historic method)
- Imaging Plate: photo-stimulable phosphor screen
- Gadox scintillator (~ 10 µm) + CCD or CMOS camera

Simulation of UO_2 pellets radiography
(resolution objective ~ 200 µm)



C. Roure, B. Cornu, E. Simon, N. Estre, et al., Non-Destructive Examination Development for the JHR Material Testing Reactor, ANIMMA 2013, doi:10.1109/ANIMMA.2013.6727882, 23-27 June 2013, Marseille, France.

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

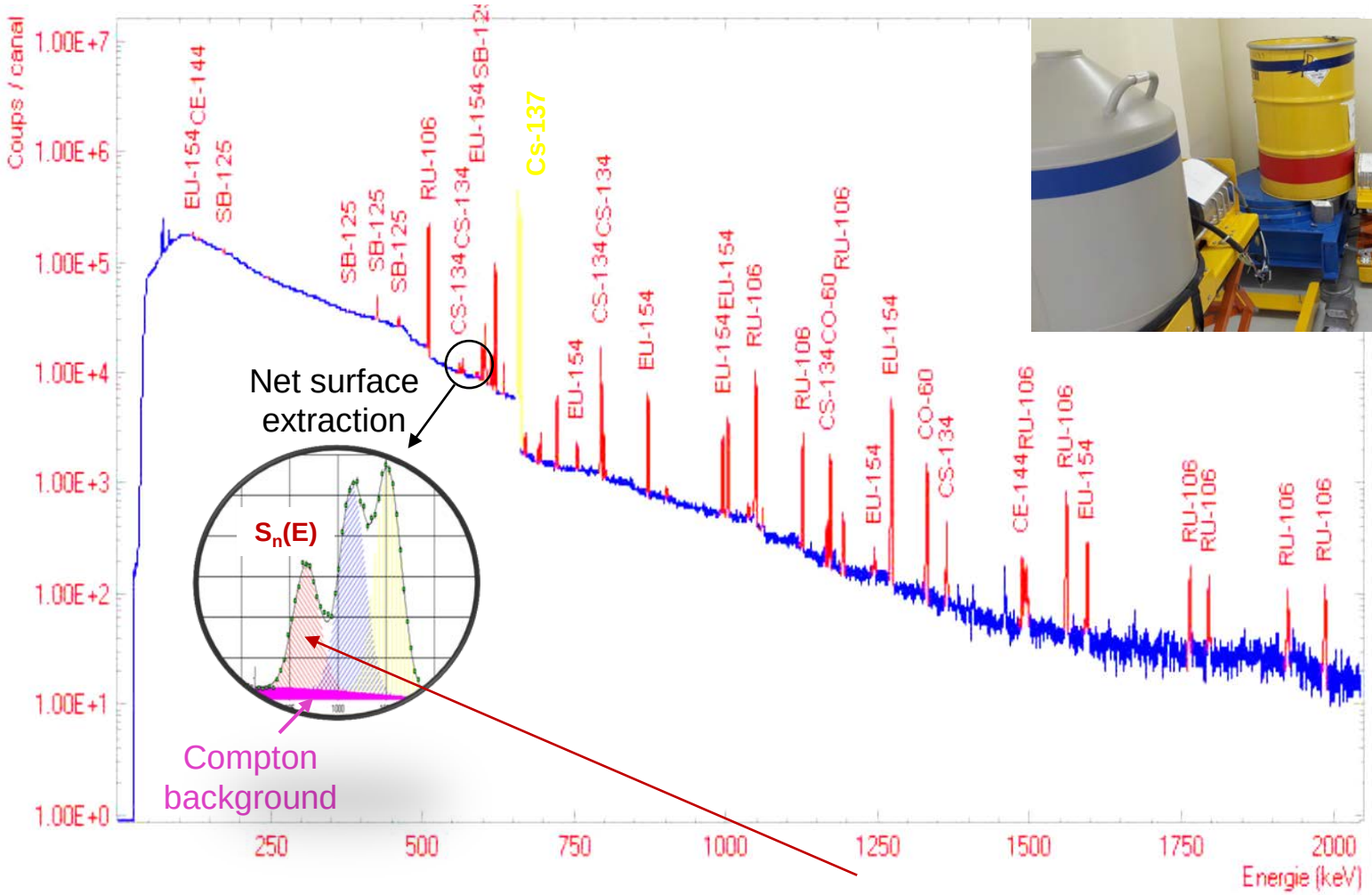
MESURES NEUTRONIQUES PASSIVES ET ACTIVES

MESURES COMBINÉES

ACTIVATION NEUTRONIQUE PULSÉE

TECHNIQUE DE LA PARTICULE ASSOCIÉE

GAMMA-RAY SPECTROSCOPY



Radionuclide activities:

$$A(E) = \frac{Sn(E)}{\varepsilon(E) \times \underbrace{I(E)}_{\text{Gamma-ray intensity}} \times T}$$

Detection efficiency

Measurement time

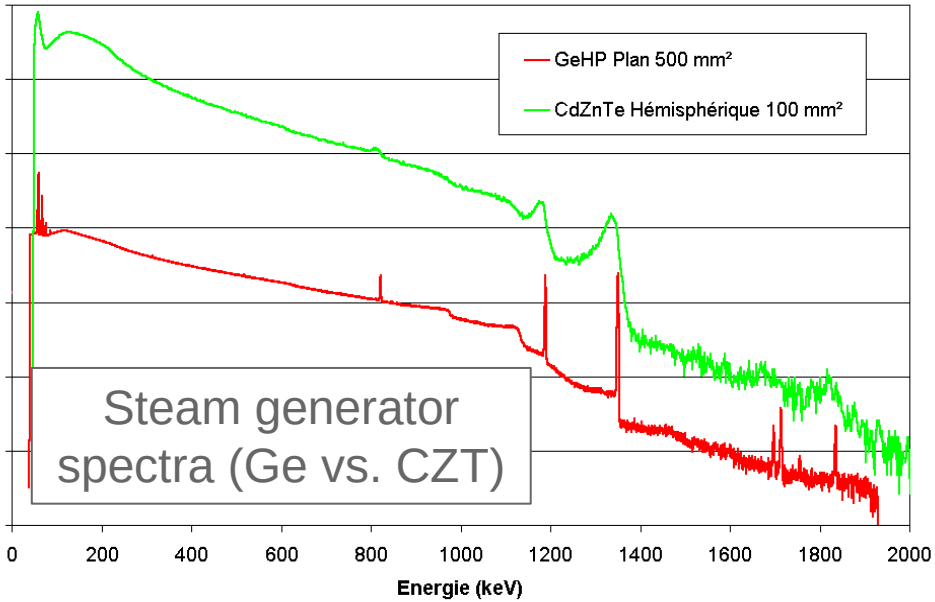
GAMMA SPECTROSCOPY IN THE LABORATORY

- **Radioactive waste characterization**
- **Part of combined measurements** e.g. for ANDRA

"Super-Controls" with X-ray imaging and neutron assay

GAMMA SPECTROSCOPY IN NUCLEAR REACTORS

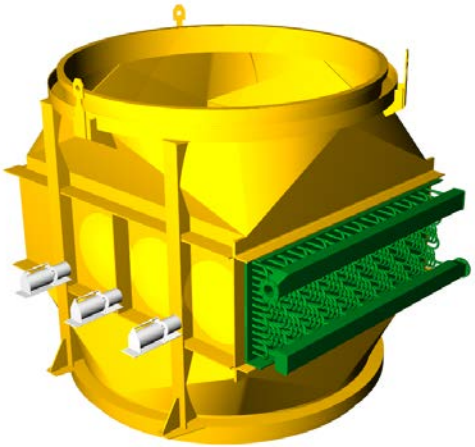
- **Historic activity** > 300 campaigns (end of 70's)
- **EDF** and foreign power plants
- **EMECC** device & software
  - Intermediate activities (1 MBq/m² → 100 GBq/m²)
  - Pipes, steam generators, heat exchangers, filters…
  - Characterization of a whole plant (all circuits)
  - Deposited or volumetric activities (GBq / m² or m³)
  - Experimental qualification by EDF
  - Support to **OSCAR** contamination transfer code



IN SITU GAMMA SPECTROSCOPY

Uranium hold-up measurement in a heat exchanger

Segmented gamma spectrometry

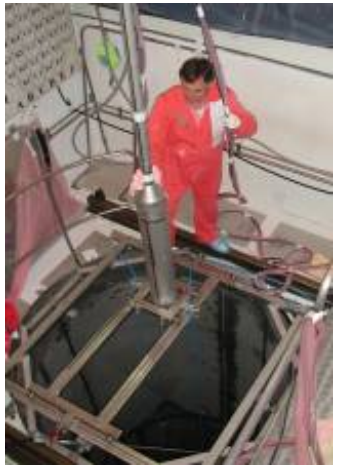


SFR cold trap characterization

HP Ge + CZT in inspection hall

Vessel contamination and activation

Underwater HP Ge gamma-ray spectroscopy



Characterization of activated components

TORE SUPRA wastes – HP Ge

GAMMA SPECTROSCOPY OF NUCLEAR MATERIALS

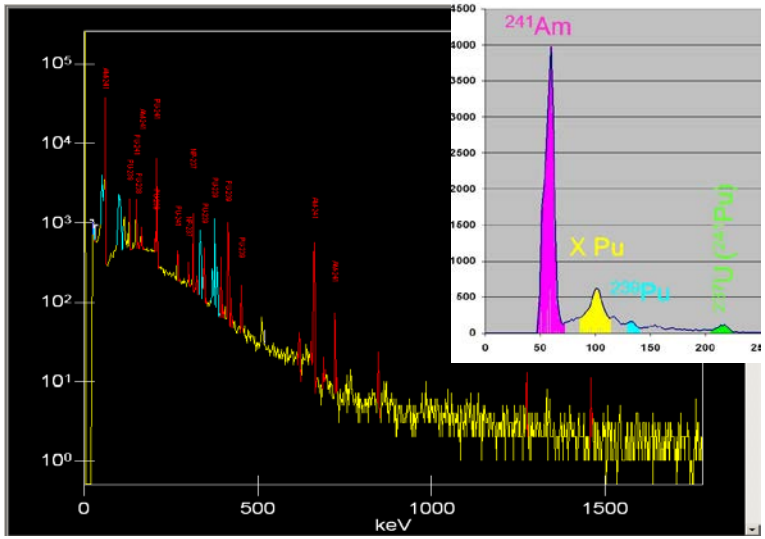
- **Dismantling operations**
  Fuel fabrication and reprocessing units

- **HP Ge detector**
  ⇨ isotopic composition, activity or mass

- **CZT** probe introduced in glove boxes
  ⇨ localization

Characterization of Pu in glove boxes of a Pu fuel fabrication facility

Fissile mass estimation in a reprocessing unit



HP Ge detector

CZT probe

GAMMA SPECTROSCOPY MAPPING

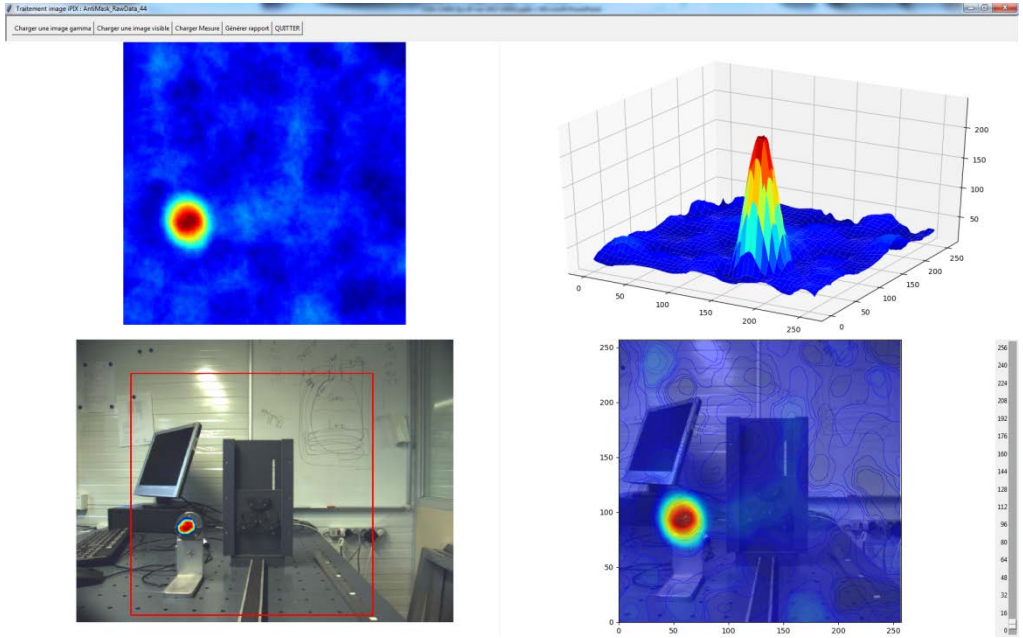
Inside
After removing all components

Outside
Walls control

High efficiency HP Ge with tungsten shield

GAMMA CAMERA

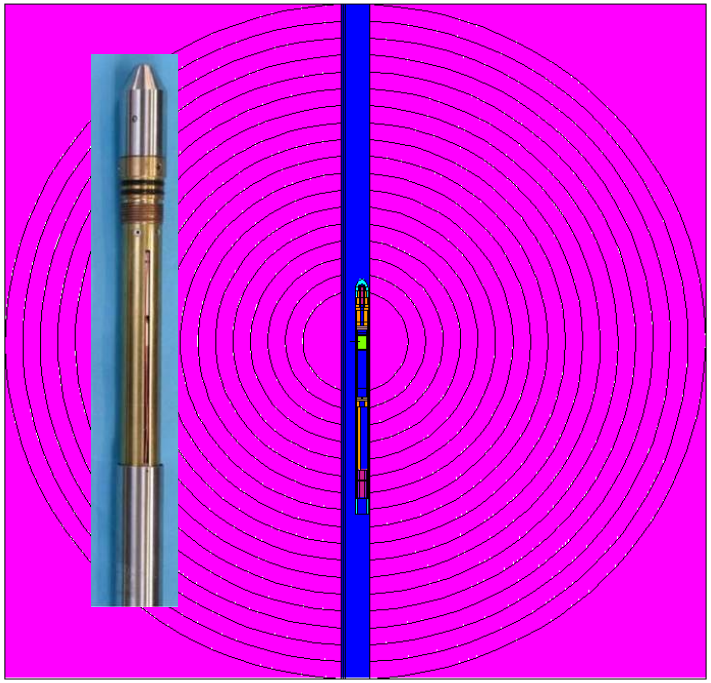
- **Real time Localization & Quantification** of radioactive sources
- **Spectral data** for radioisotopes identification
- **iPIX camera recently acquired by LMN**
  (a CANBERRA-MIRION product based on CEA GAMPIX camera)

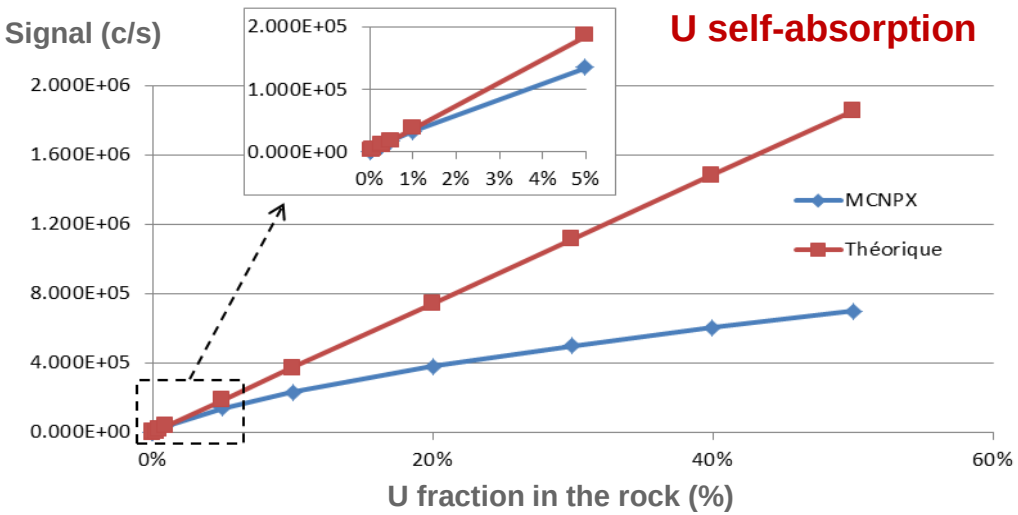


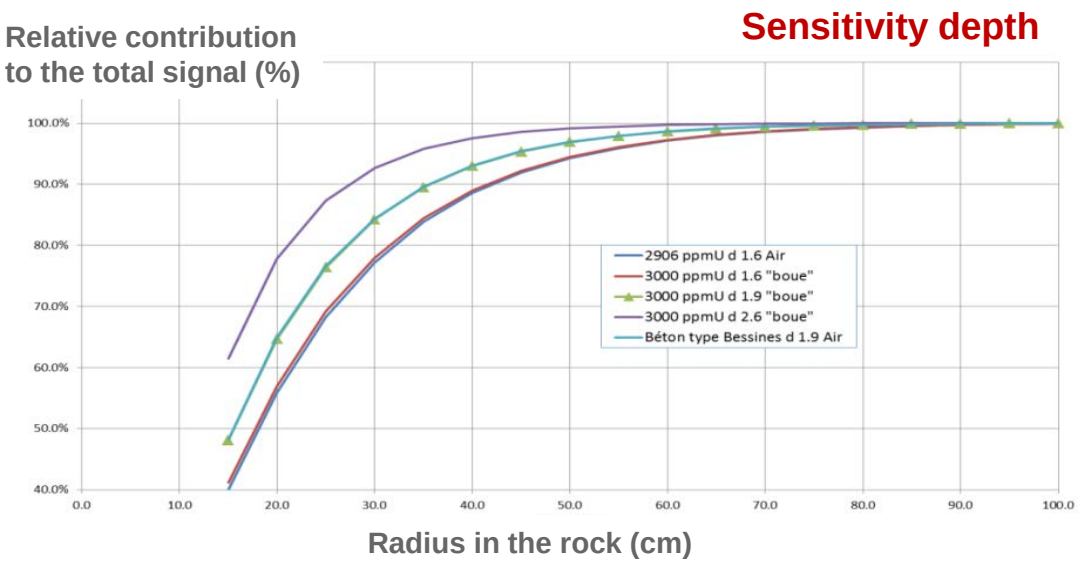
URANIUM BOREHOLE GAMMA LOGGING

- **CEA - AREVA Mines** collaboration
- **NaI(Tl)** total counting in borehole
- **MCNP parametric studies** on gamma corrections: U self-absorption, rock + tubing + filling fluids attenuations…

Carasco et al. Improving gross count gamma-ray logging in uranium mining with the NGRS probe, ANIMMA 2017, 19-23 June, Liège, Belgium

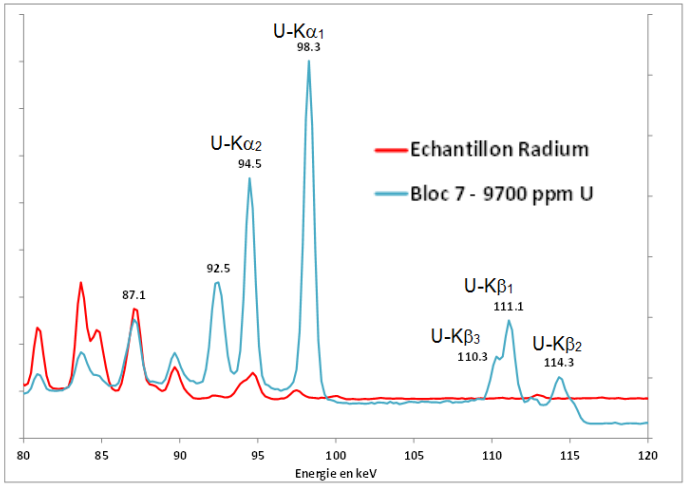




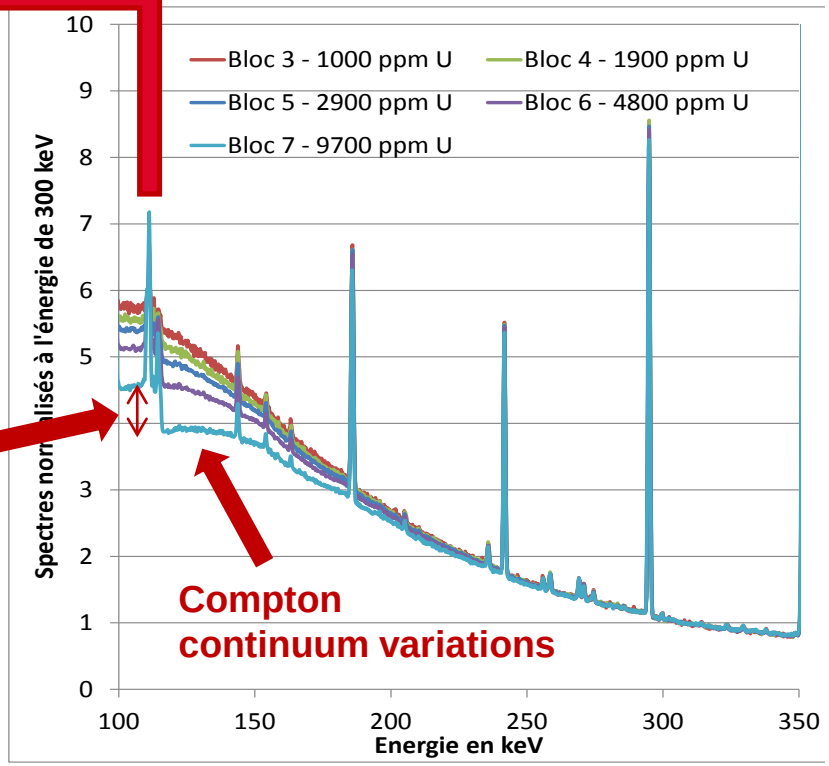


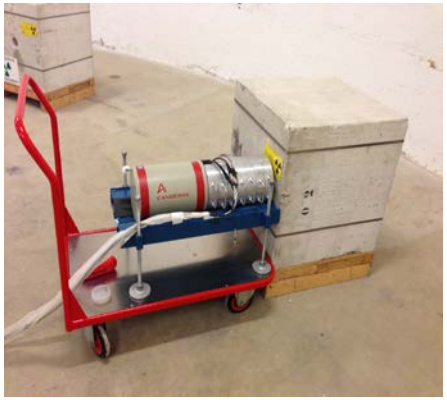
R&D : GAMMA SPECTROSCOPY ON URANIUM ORES

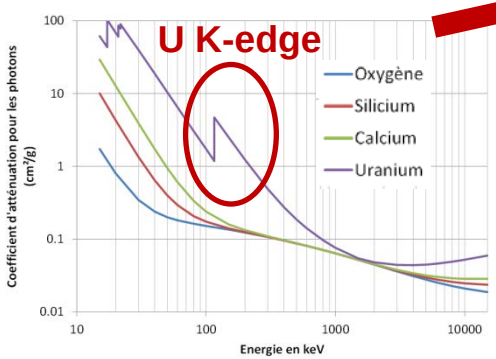
- **Disequilibrium in the U decay chain** due to differential leaching (roll fronts)
  ⇨ U concentration underestimated: gamma signal due to the end of the U chain: ^{214}Pb, ^{214}Bi
- **Disequilibrium detection by HP Ge γ spectroscopy** on samples : 1001 keV γ ray of ^{234m}Pa
- **R&D on new, faster techniques:** self-induced fluorescence X rays, K-edge, peak/Compton



U self-fluorescence X rays







T. Marchais et al, Optimization of gamma-ray spectroscopy for uranium mining, ANIMMA 2017, 19-23 June, Liège, Belgium

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

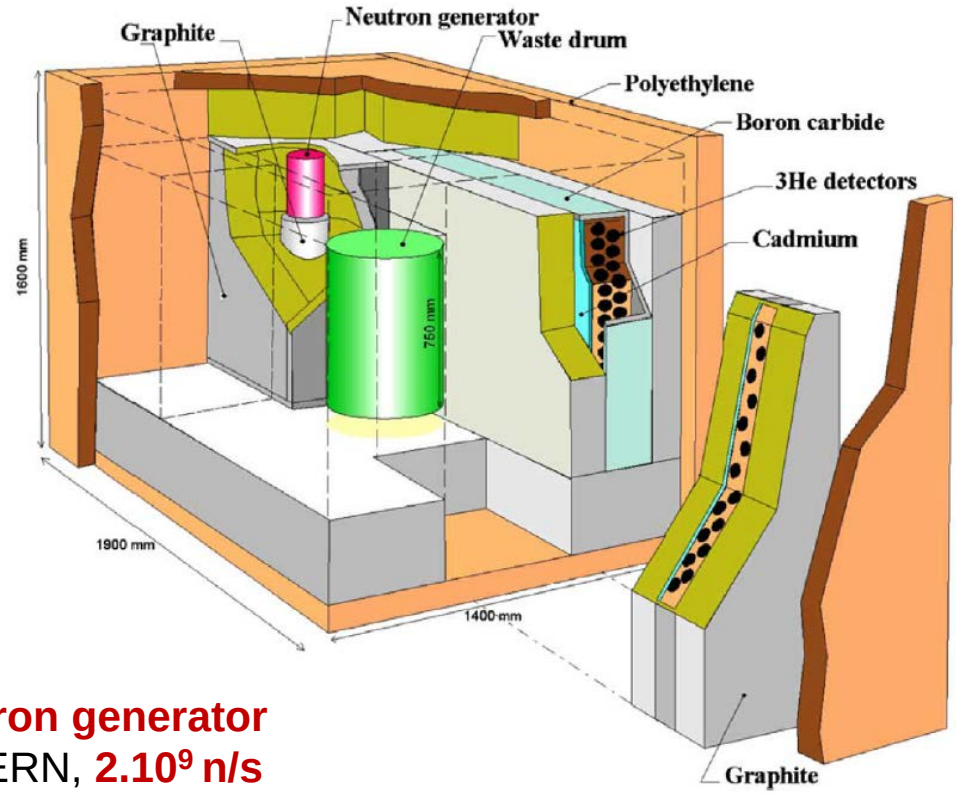
MESURES NEUTRONIQUES PASSIVES ET ACTIVES

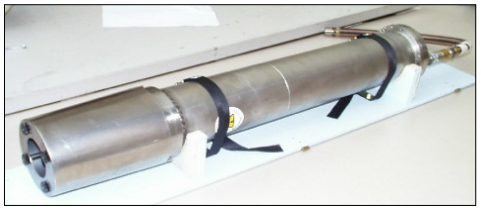
MESURES COMBINÉES

ACTIVATION NEUTRONIQUE PULSÉE

TECHNIQUE DE LA PARTICULE ASSOCIÉE

A TYPICAL NEUTRON MEASUREMENT CELL





Pulsed DT neutron generator
GENIE 36 SODERN, **2.10^9 n/s**

- *Christian Passard et al., PROMETHEE: An Alpha Low Level Waste Assay System Using Passive And Active Neutron Measurement Methods, NUCLEAR TECHNOLOGY VOL. 140 DEC. 2002.*
- *A. Mariani et al., The help of simulation codes in designing waste assay systems using neutron measurement methods: Application to the alpha low level waste assay system PROMETHEE 6, Nuclear Instruments and Methods in Physics Research B 211 (2003) 389–400.*
- *Fanny Jallu et al., Alpha-Particle Low-Level Waste Control: Improvement of the PROMETHEE 6 Assay System Performances, Nuclear Technology Vol. 153 Jan. 2006.*

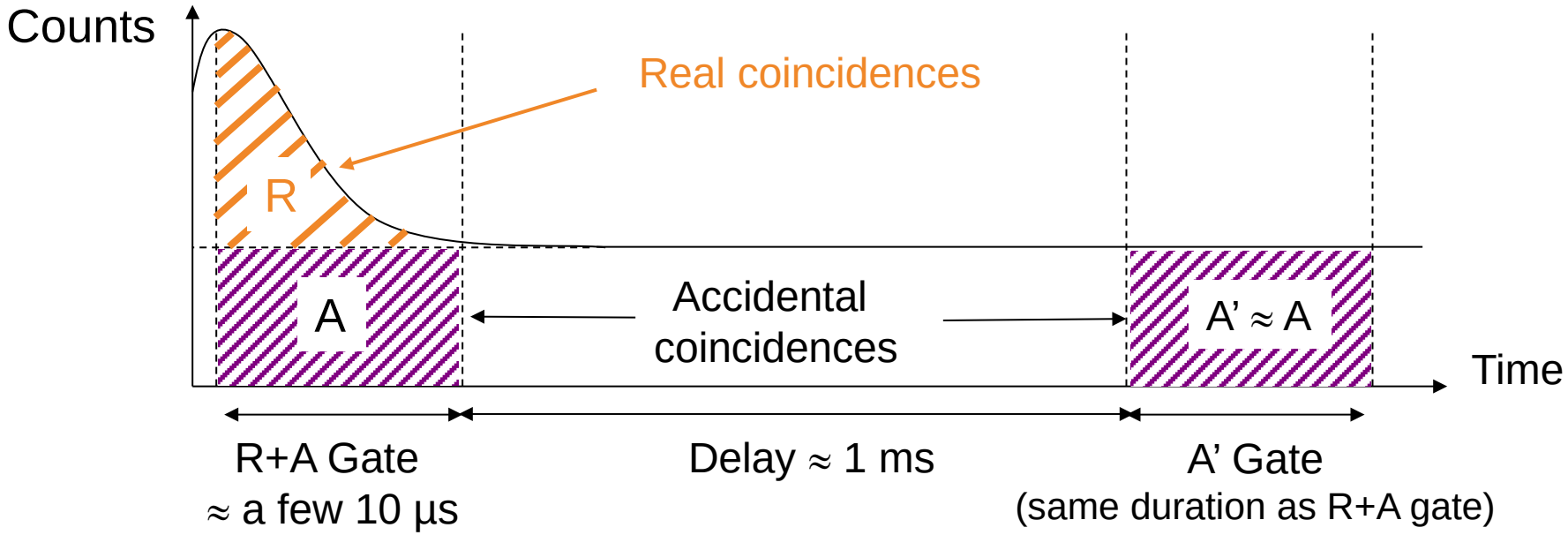
PASSIVE NEUTRON MEASUREMENT

❑ Total counting

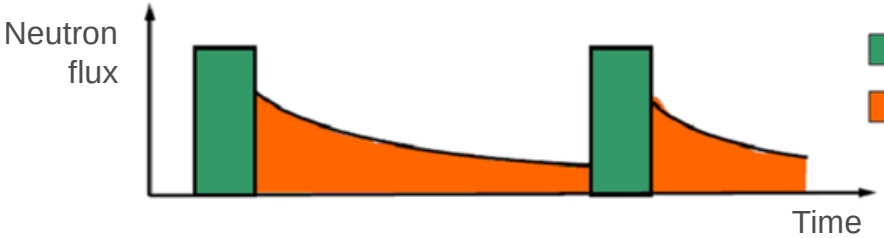
Spontaneous fission + (α,n) neutrons ⇨ $^{242 \text{ and } 244}$Cm, $^{238, 240 \text{ and } 242}$Pu, ^{241}Am (+ ^{238}U if mass > kg)

❑ Coincidence counting

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

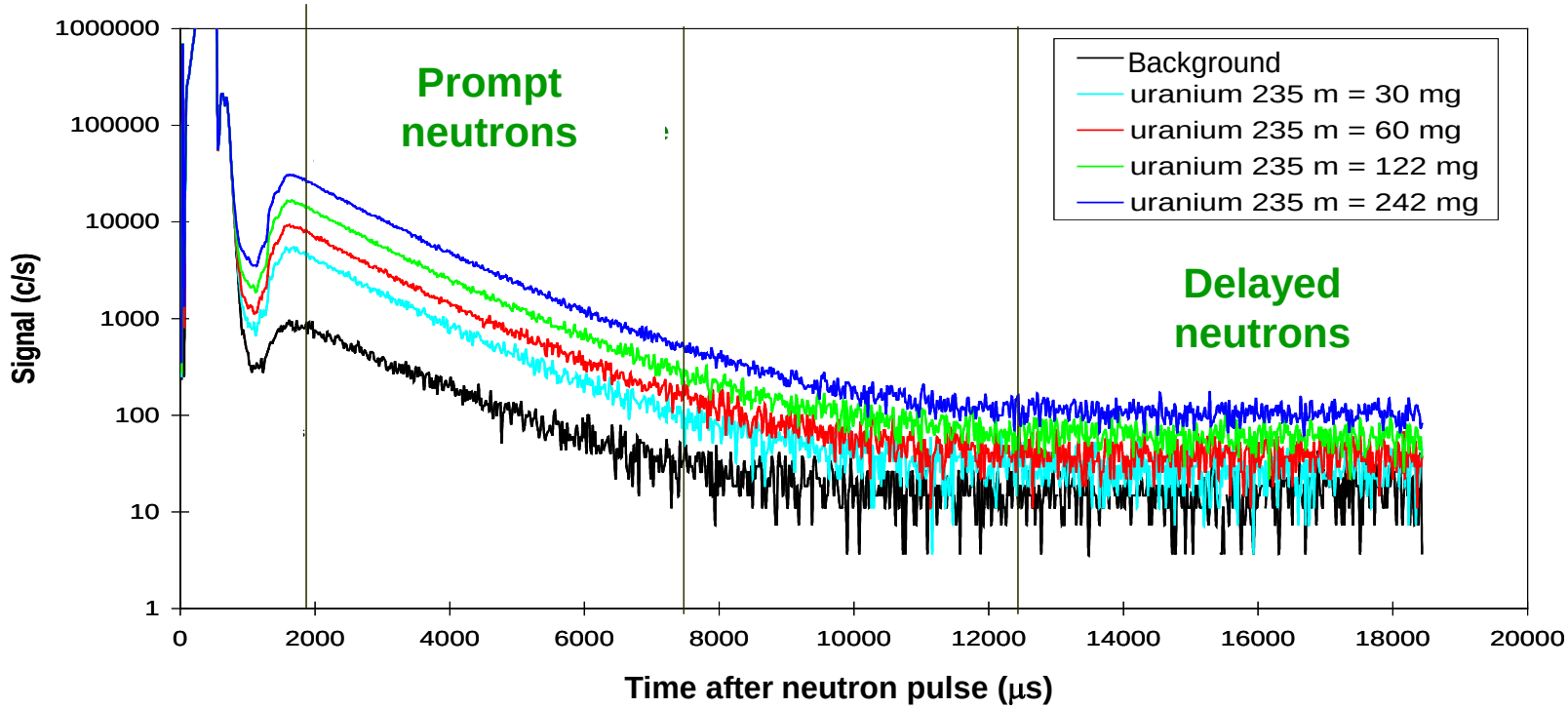


ACTIVE "DIFFERENTIAL DIE AWAY TECHNIQUE"



Fast neutrons during the pulses ⇨ fast fissions

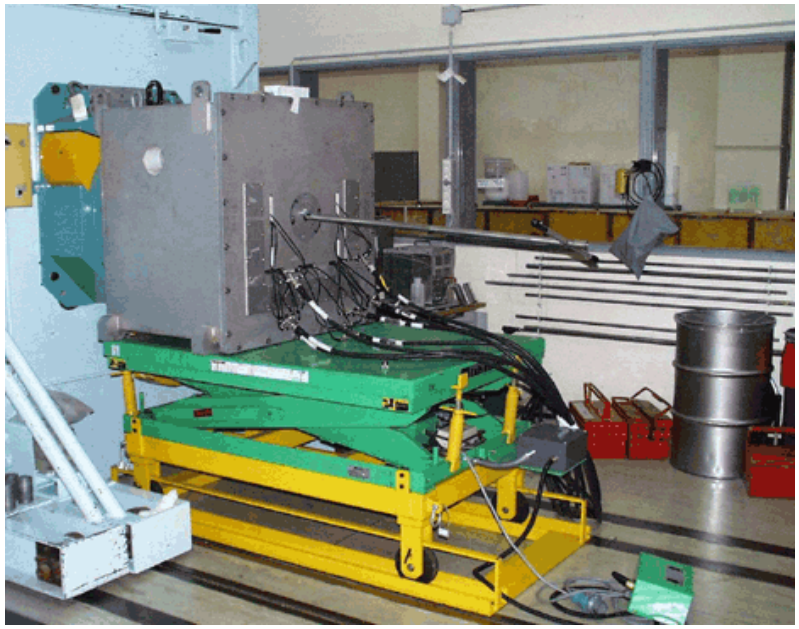
Thermal neutrons between pulses ⇨ thermal fissions



- **Prompts neutrons (from thermal fissions only)** ⇨ ^{235}U, $^{239 \text{ and } 241}Pu$
- **Delayed neutrons (from fast + thermal fissions)** ⇨ ^{235}U, $^{239 \text{ and } 241}Pu$ + ^{238}U and ^{232}Th

PLUG-IN NEUTRON SYSTEMS FOR HOT CELLS

PACCMAN, COQUINA: active neutron interrogation systems plugged to hot cells to assess Pu and U in high level wastes



LMN, CEA DEN CADARACHE

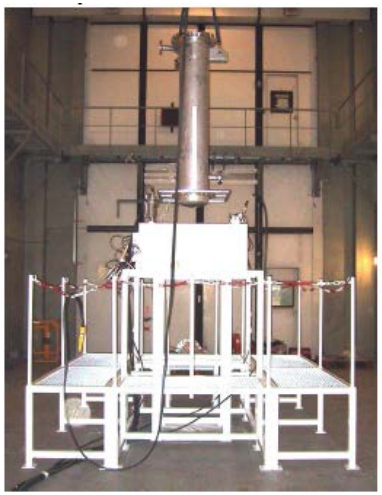
ATALANTE, CEA DEN MARCOULE

IN SITU NEUTRON MEASUREMENTS

Characterization of large components in uranium enrichment facilities

(UF_6 gas diffusion technology)

Passive neutron measurement of the uranium hold-up in UF_6 compressors



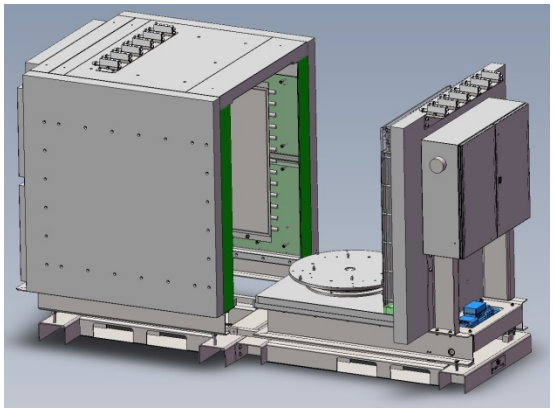
Passive (and active) neutron measurements of uranium hold-up in an UF_6 crystallizer

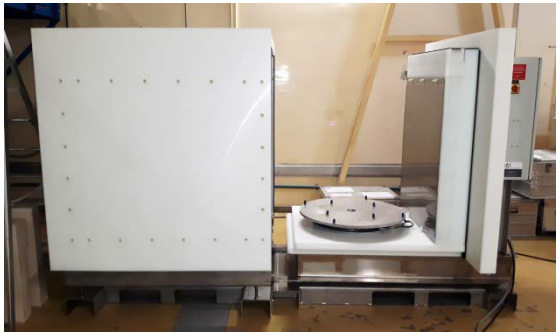
Measurement of the uranium enrichment in an UF_6 container by active neutron interrogation

F. Jallu et al., Dismantling and decommissioning: The interest of passive neutron measurement to control and characterise radioactive wastes containing uranium, Nuclear Instruments and Methods in Physics Research B 271 (2012) 48–54

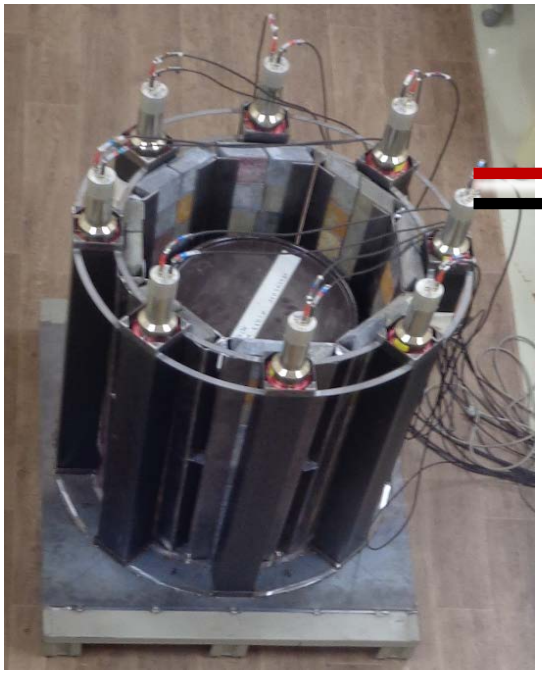
Mobile passive neutron measurement cell

(LMN, CEA Cadarache)



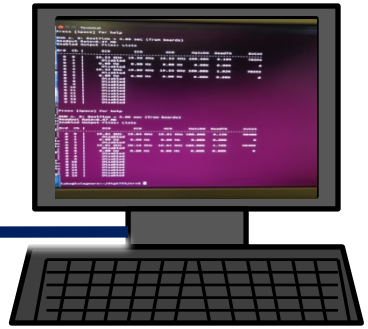


R&D : ALTERNATIVES TO ^{3}HE DETECTORS



HV supply
+
CAEN DT5730
digitizer

Data processing



- Plastic scintillators 10 cm ×10 cm ×100 cm
- ^{137}Cs, ^{60}Co, ^{252}Cf, AmBe sources
- Pu samples
- Test results confidential but feasibility confirmed

118 L waste drum mock-ups

Wood

Iron

SIMULATION OF SCINTILLATOR PERFORMANCES

^{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

Passive neutron coincidence counting of radioactive waste drums

MCNPX PoliMi simulation:

- 118 L waste drums
- Plastic detectors + Pb shield
- ~ 0.5 g of $^{240}Pu_{eq}$
- 1500 s acquisition time

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

Triples (multiplicity 2 coincidences)

- *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*
- *B. Simony, B. Pérot, C. Carasco, F. Jallu, N. Saurel, S. Colas, P. Girones, J. Collot, Passive neutron coincidence counting with plastic scintillators for the characterization of radioactive waste drums, IEEE Transactions on Nuclear Science, Vol. 64, No. 10 (2017) 2719-2724*

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

MESURES NEUTRONIQUES PASSIVES ET ACTIVES

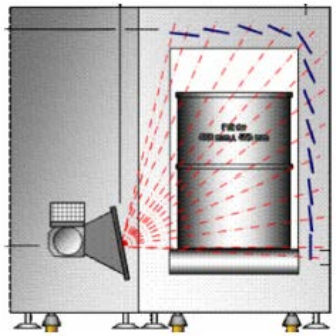
MESURES COMBINÉES

ACTIVATION NEUTRONIQUE PULSÉE

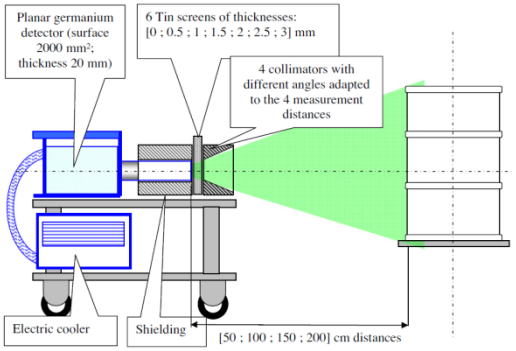
TECHNIQUE DE LA PARTICULE ASSOCIÉE

PASSIVE MEASUREMENT SYSTEM FOR LEGACY WASTE

X-ray radiography

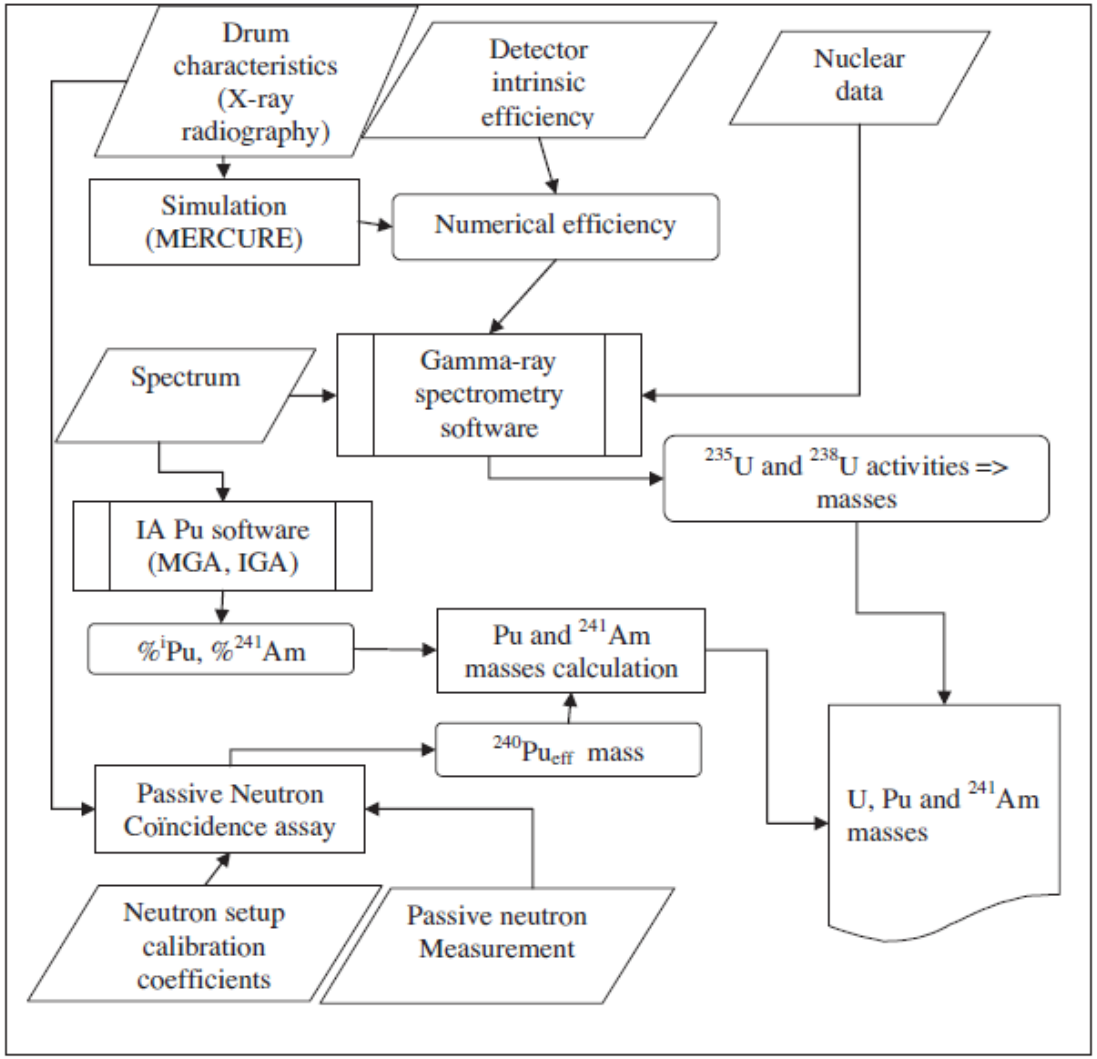


Gamma-ray spectroscopy



Neutron coincidence counting

Combined measurement interpretation diagram



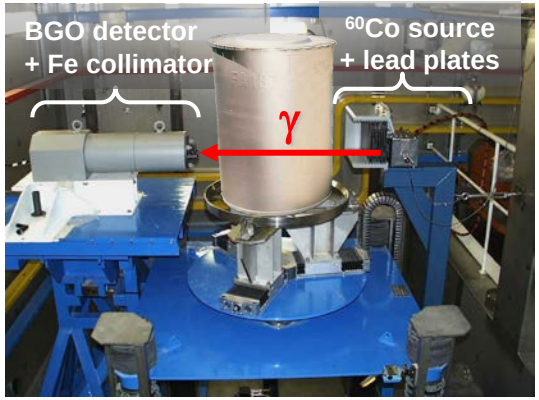
F. Jallu et al. / Nuclear Instruments and Methods in Physics Research B 271 (2012) 48–54

ACTIVE MEASUREMENT SYSTEM FOR LEGACY WASTE

> 60,000 historic 225 L bituminized waste drums (Marcoule, France)

Non Destructive Assay performance study

Low resolution gamma radiography (^{60}Co)

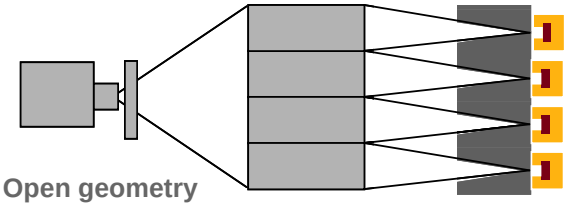


Gamma spectroscopy

⇨ β,γ radionuclides ⇨ ^{241}Am α activity

Coaxial HP Ge (100% rel. eff.)

Planar HP Ge + BGO Compton suppression



Passive & active neutron cell ⇨ Pu, U

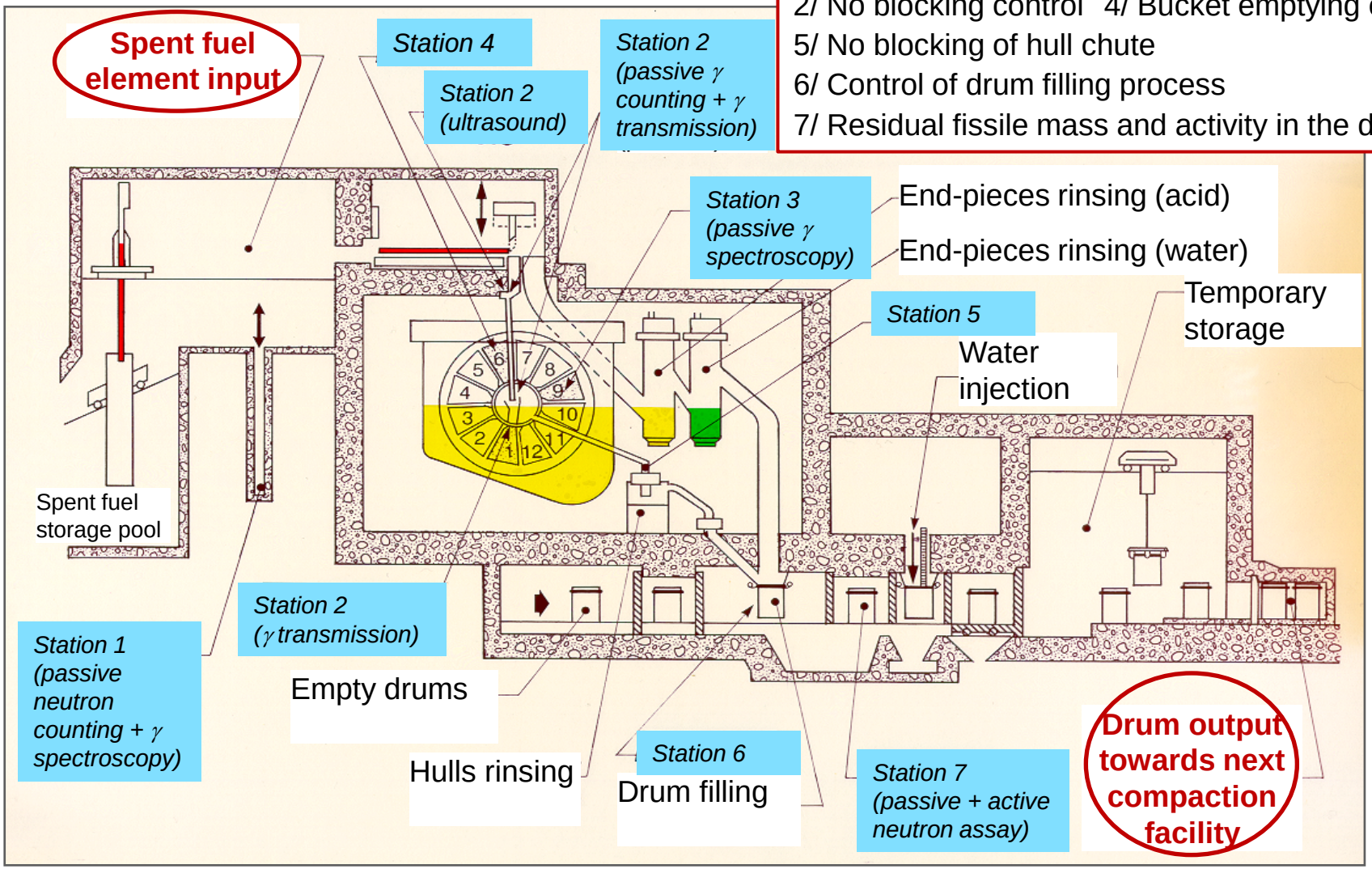
- Graphite and polyethylene cell
- 99 ^{3}He counters + Pb and Cd shields
- Pulsed 2.10^{9} n/s neutron generator

B. Pérot et al., http://dx.doi.org/10.1115/ICEM2003-4597

NUCLEAR PROCESS MONITORING AT AREVA LA HAGUE

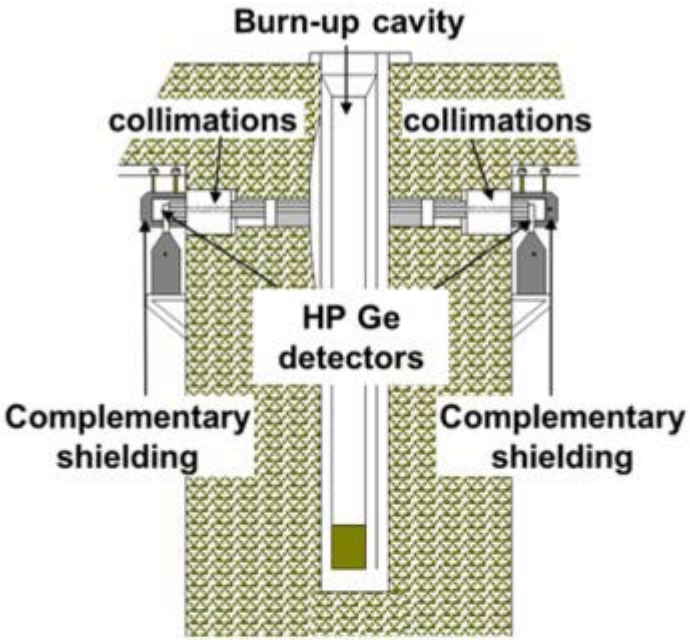
Spent fuel shearing and dissolution

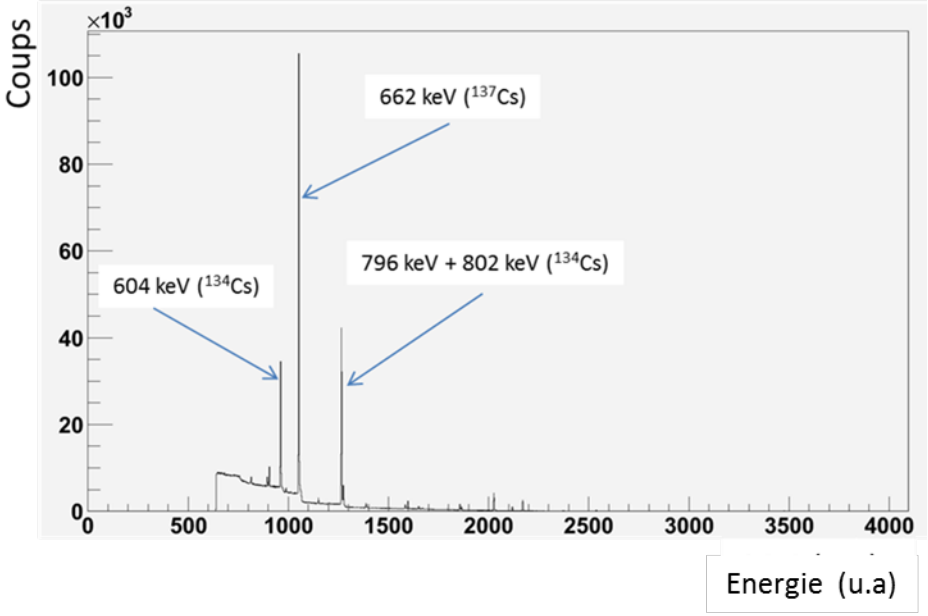
1/ Burn-up control
2/ No blocking control
3/ Dissolution control
4/ Bucket emptying control
5/ No blocking of hull chute
6/ Control of drum filling process
7/ Residual fissile mass and activity in the drums

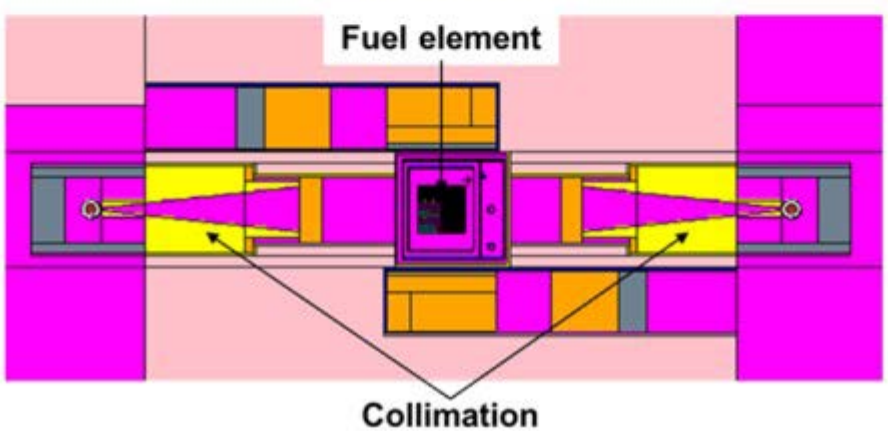


⇨ γ transmission, γ spectroscopy, passive and active neutron measurements

BURN-UP CONTROL BY GAMMA-RAY SPECTROSCOPY







- **Burn-up ⇨ criticality control**

  BU α Act (^{134}Cs) / Act (^{137}Cs)

  BU α Act (^{137}Cs)

  (also: passive neutron emission ~ BU^4)

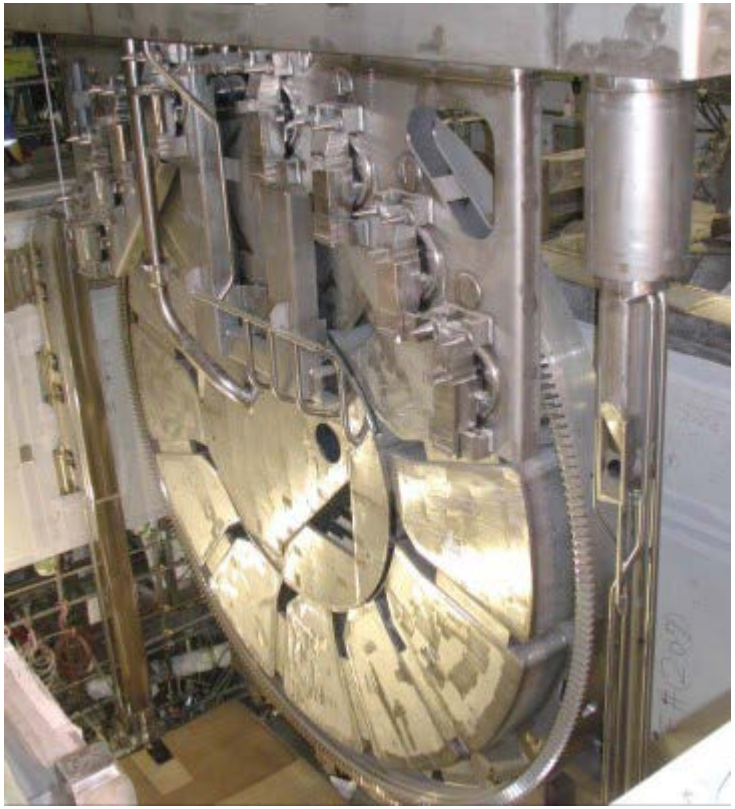
- **Cooling time**

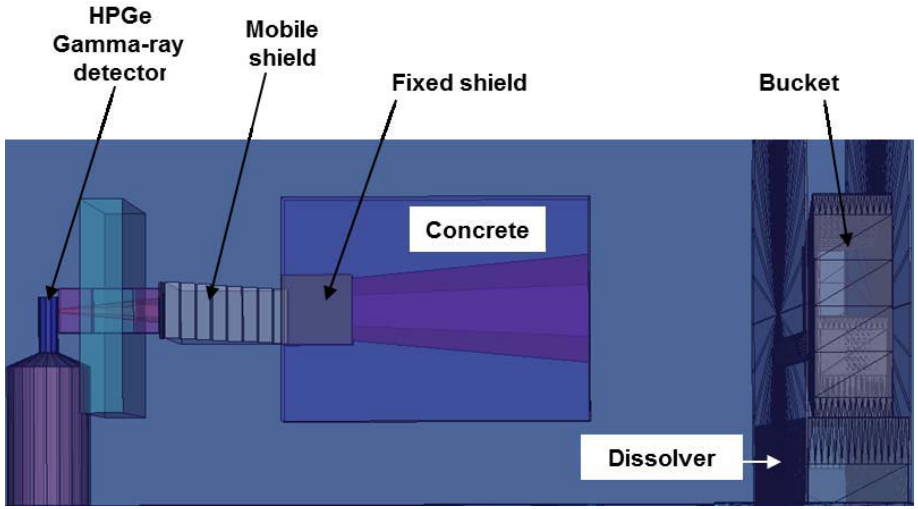
  CT α A(^{154}Eu) / A(^{134}Cs)

C. Eleon, C. Passard, N. Hupont, N. Estre, O. Gueton, F. Brunner, G. Grassi, M. Batifol, P. Doumerc, T. Dupuy, B. Battel, Status of the nuclear measurement stations for the process control of spent fuel reprocessing at AREVA NC/La Hague, ANIMMA 2015, Advancements in Nuclear Instrumentation Measurement Methods and their Applications, 20-24 April 2015, Lisbon, Portugal

DISSOLUTION CONTROL BY GAMMA-RAY SPECTROSCOPY

12-bucket dissolver wheel





- **Collimated HP Ge detector aiming the bucket**

  emerging from the dissolution vessel

- **Mobile shield adapted to BU and CT**

  to limit the count rate of the HP Ge detector

- **Criticality control**

  ⇨ residual ^{137}Cs activity < safety threshold

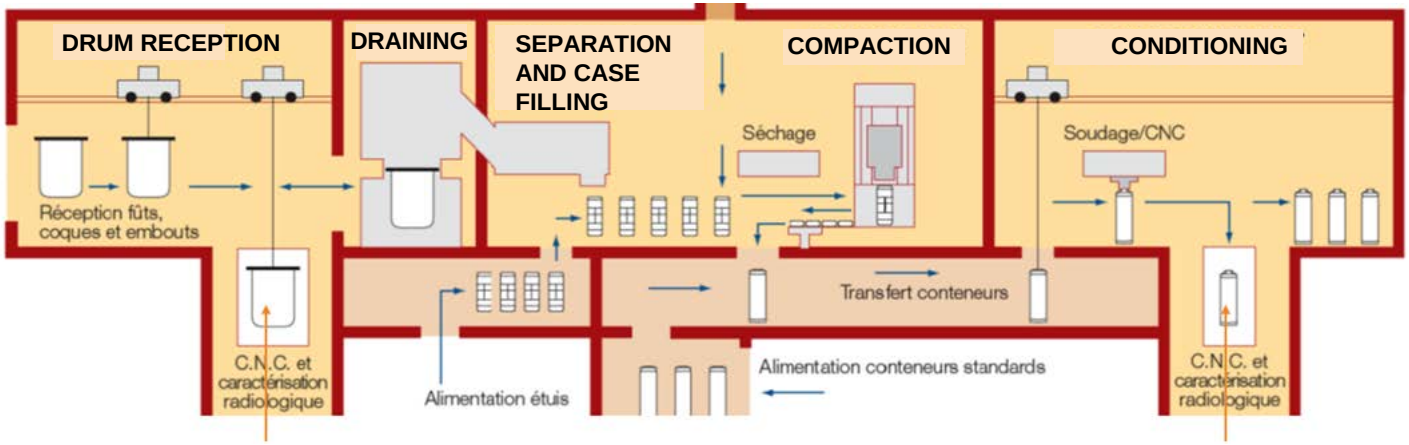
C. Eleon, C. Passard, N. Hupont, N. Estre, O. Gueton, F. Brunner, G. Grassi, M. Batifol, P. Doumerc, T. Dupuy, B. Battel, Status of the nuclear measurement stations for the process control of spent fuel reprocessing at AREVA NC/La Hague, ANIMMA 2015, Advancements in Nuclear Instrumentation Measurement Methods and their Applications, 20-24 April 2015, Lisbon, Portugal

COMPACTION OF HULLS AND END-PIECES

T1/R1 facilities

ACC facility

CSD-C drums



Station #0 for 800 L drums

- ❑ **Gamma-ray spectroscopy**
- ❑ **Passive and DDT neutron measurements**

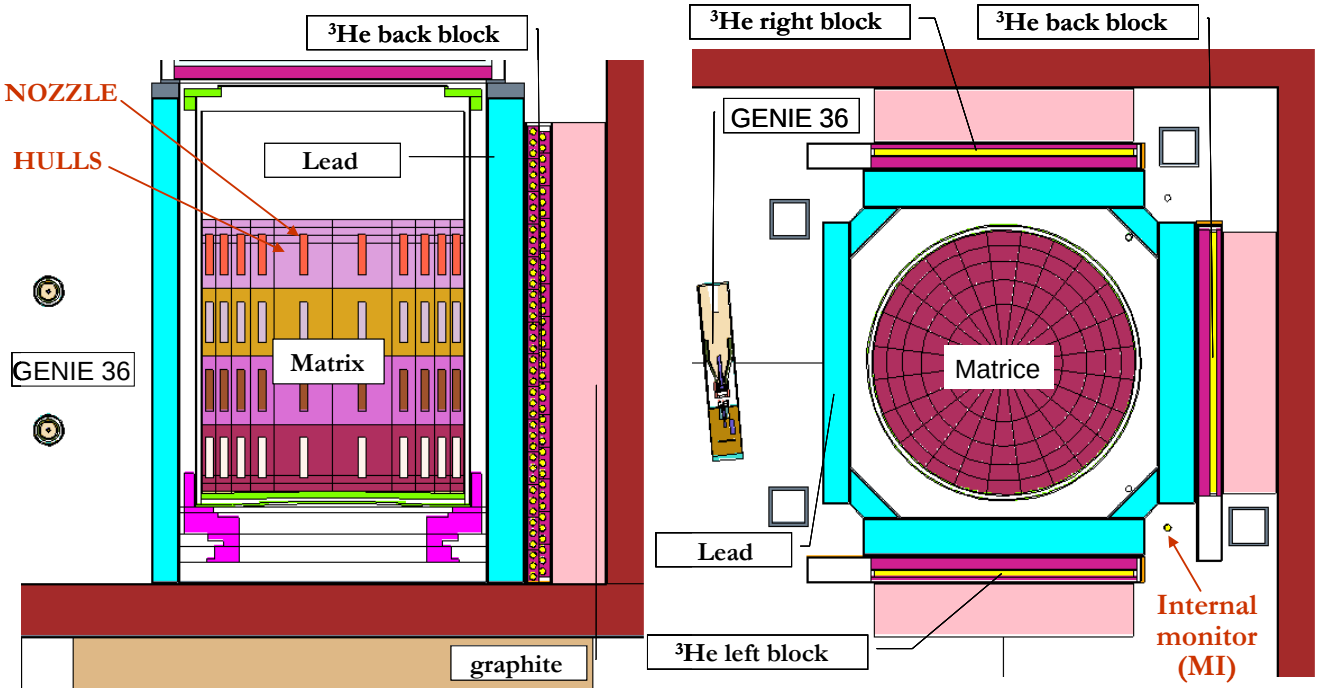
Station #2 for CSD-C

H. Toubon et al., Innovative nuclear measurement techniques used to characterize waste produced by COGEMA's new compaction facility Proc. of WM'01, Waste Management Conference (2001) 19 p., February 25-March 1, 2001, Tucson, AZ, USA

NEUTRON CELL FOR 800 L DRUMS AT ACC INPUT

- **Fissile mass in the 800 L drum**
  Active DDT with prompt neutrons
- **Masses of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
  Active DDT prompt and delayed neutrons
- **^{244}Cm activity**
  Passive neutron total counting

- **249 ^{3}He counters**
- **2 neutron generators**
  (GENIE 36 SODERN, 2.10^{9} n/s each)



R. Antoni, C. Passard, J. Loridon, B. Perot, et al., Matrix effect correction with internal flux monitor in radiation waste characterization with the Differential Die-away Technique, IEEE Transactions on Nuclear Science, Vol. 61, No. 4 (2014) 2155-2160

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

MESURES NEUTRONIQUES PASSIVES ET ACTIVES

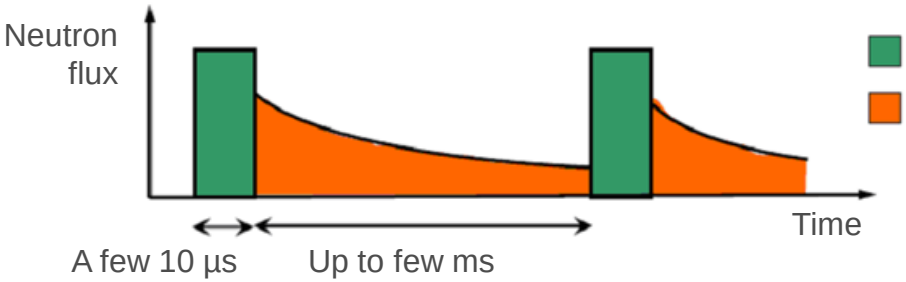
MESURES COMBINÉES

ACTIVATION NEUTRONIQUE PULSÉE

TECHNIQUE DE LA PARTICULE ASSOCIÉE

NEUTRON ACTIVATION ANALYSIS

- **Toxic chemical or matrix material** characterization in radioactive wastes
- **PGNAA** Prompt Gamma Neutron Activation Analysis
- **Pulsed neutron generator** + **HP Ge gamma-ray detector**

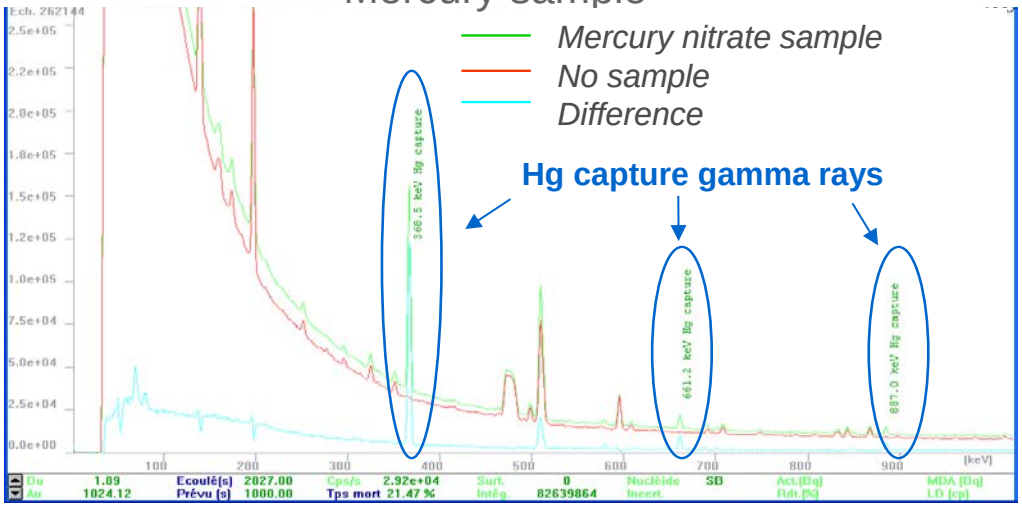


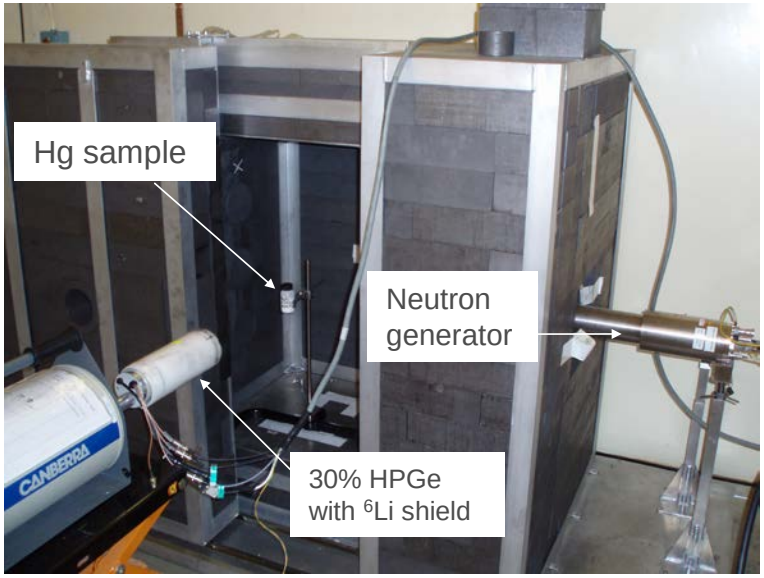
Fast neutrons during the pulses ⇨ (n,n'γ)

Thermal neutrons between pulses ⇨ (n,γ)

(+ deactivation gamma rays after irradiation)

Mercury sample





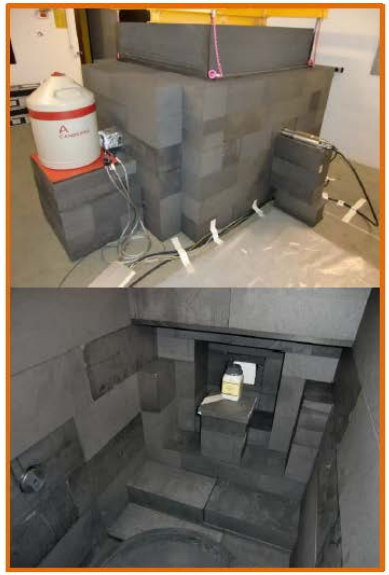
REGAIN cell, LMN, CEA Cadarache

J.-L. Ma et al., Prompt Gamma Neutron Activation Analysis of toxic elements in radioactive waste packages, Applied Radiation and Isotopes 70 (2012) 1261

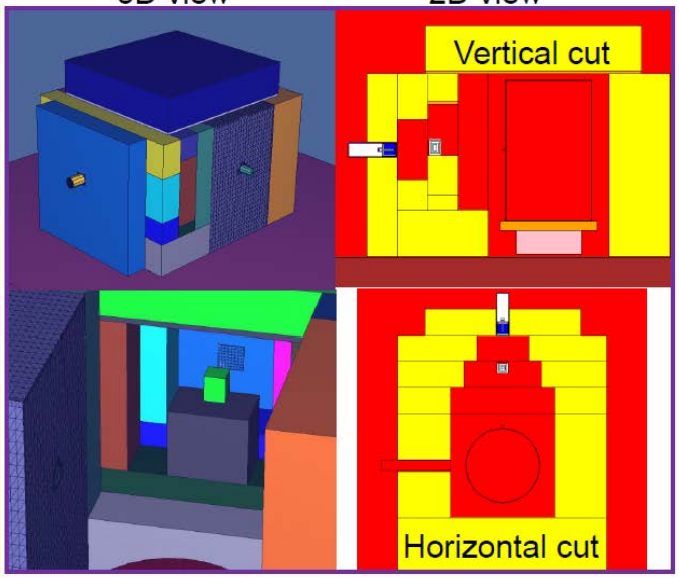
CEA- FZJ COLLABORATION ON PGNAA

- **MEDINA** PGNAA cell
  - ✓ FZJ, Germany
  - ✓ 10^8 n/s neutron generator
  - ✓ 104% relative efficiency HP Ge
- **EXP / MCNP** comparisons with (n,γ) data from different libraries
- **MCNP performance** optimization
- **Fission delayed γ** (see next slides)

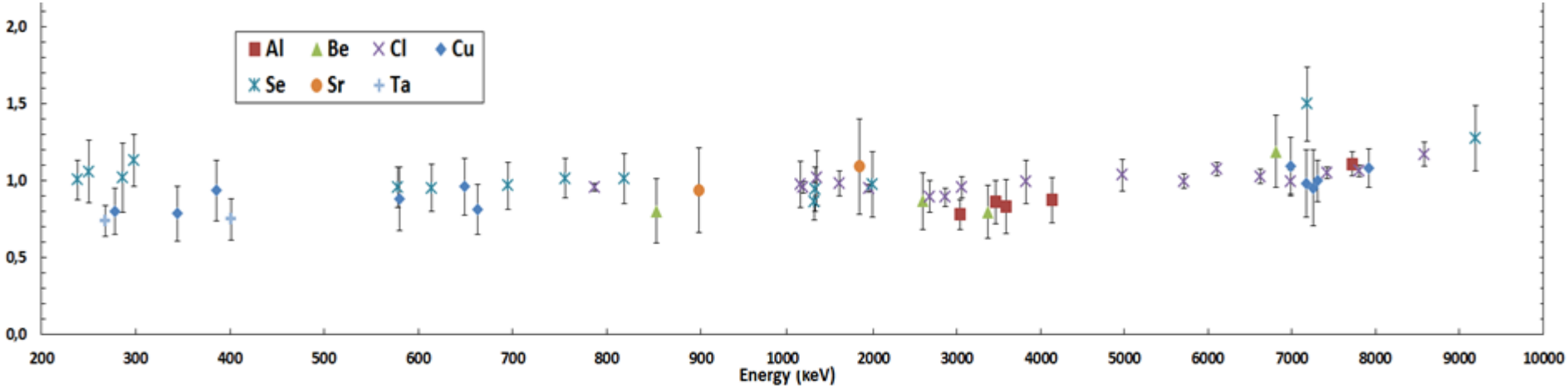
Exp. setup



MCNPX model



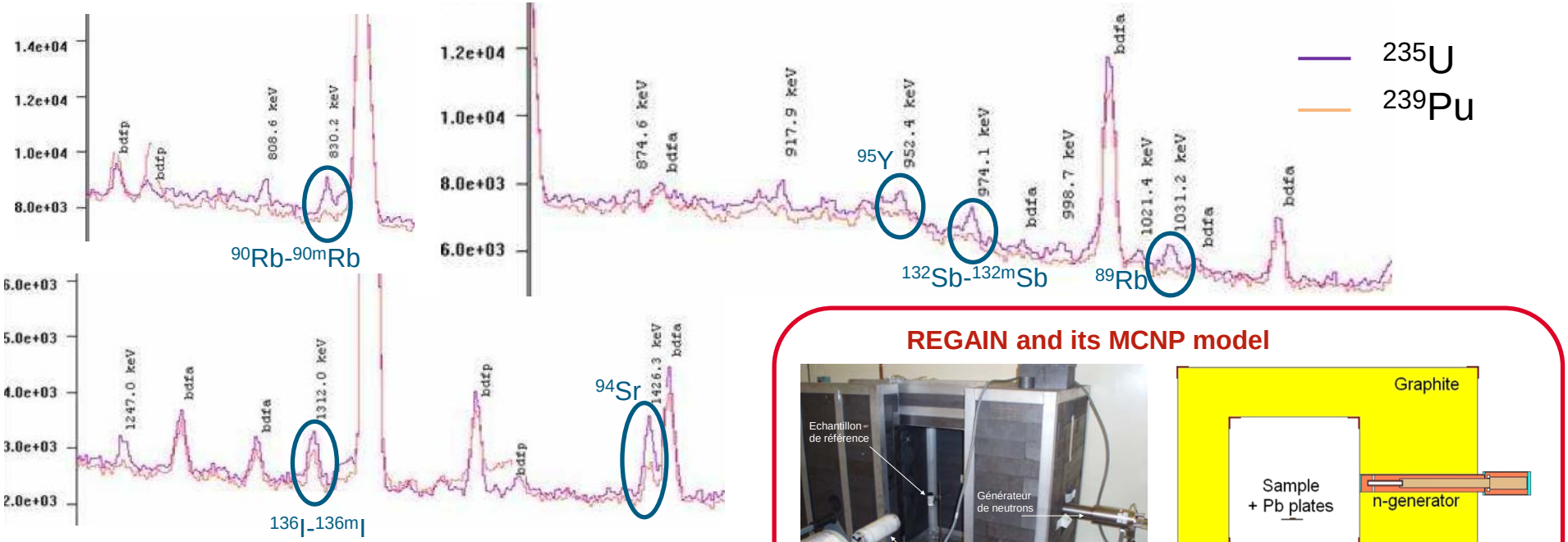
MCNP/ EXP with ENSDF



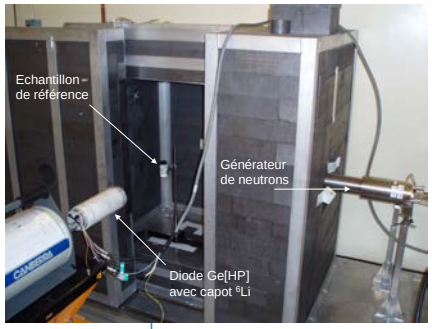
T.Nicol, C. Carasco, B. Perot, J.L. Ma, E. Payan et al., Quantitative comparison between PGNAA measurements and MCNPX simulations, Journal of Radioanalytical and Nuclear Chemistry, Vol. 306 N°1 (2015) pp 1-7

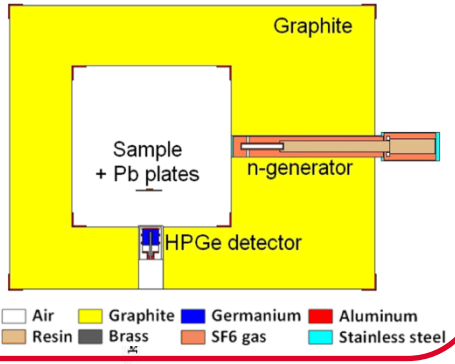
NEUTRON-INDUCED FISSION DELAYED γ RAYS YIELDS

❑ Gamma spectra of ^{235}U and ^{239}Pu samples measured in REGAIN between neutron pulses

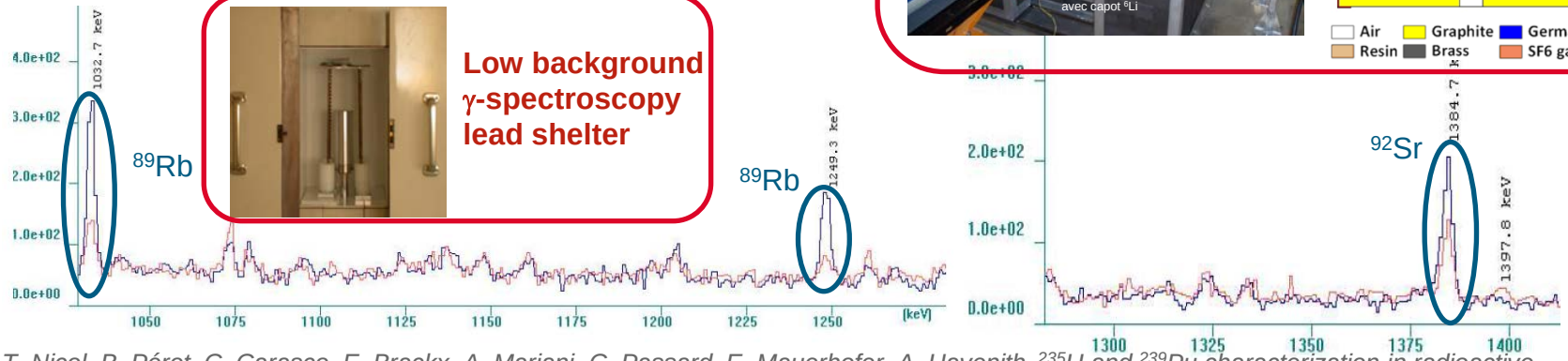


REGAIN and its MCNP model





❑ Gamma spectra after irradiation



Low background γ-spectroscopy lead shelter

T. Nicol, B. Pérot, C. Carasco, E. Brackx, A. Mariani, C. Passard, E. Mauerhofer, A. Havenith, ^{235}U and ^{239}Pu characterization in radioactive waste using neutron-induced fission delayed gamma rays, Nuclear Instruments and Methods in Physics Research A 832 (2016) 85-94

IMAGERIE X ET NEUTRONOGRAPHIE

SPECTROMÉTRIE GAMMA

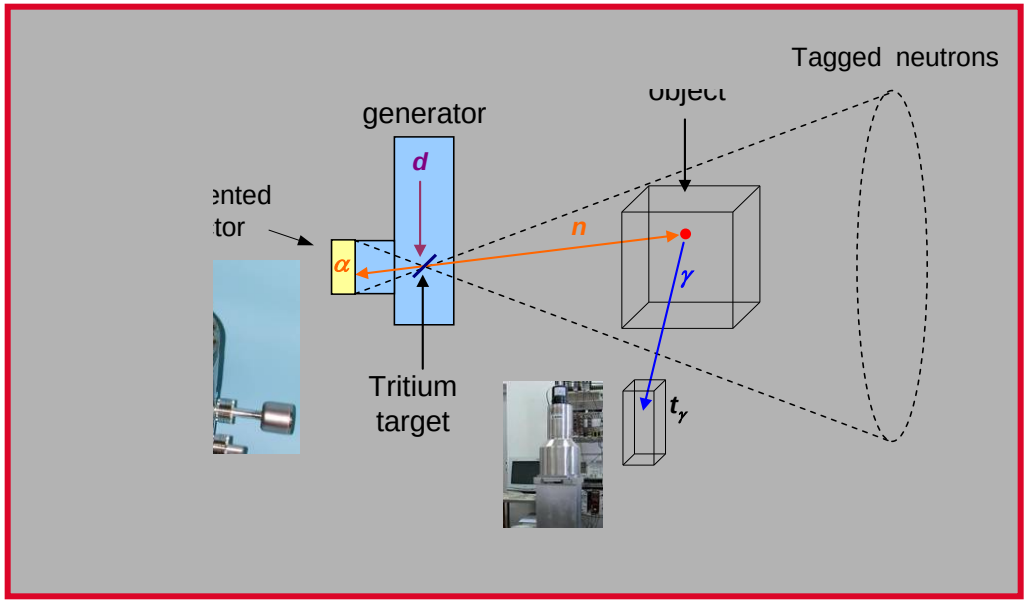
MESURES NEUTRONIQUES PASSIVES ET ACTIVES

MESURES COMBINÉES

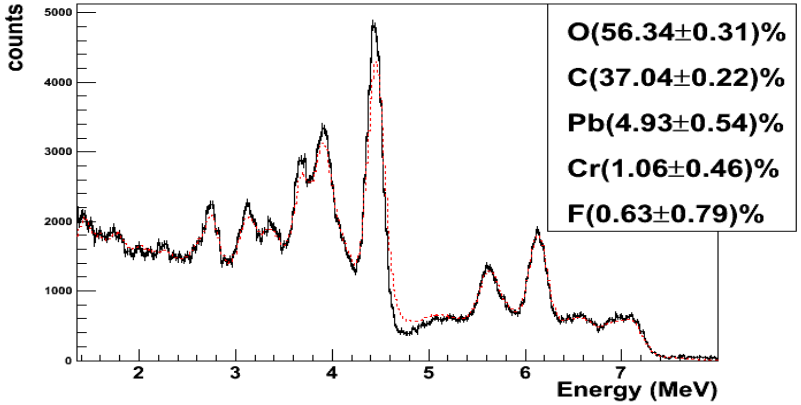
ACTIVATION NEUTRONIQUE PULSÉE

TECHNIQUE DE LA PARTICULE ASSOCIÉE

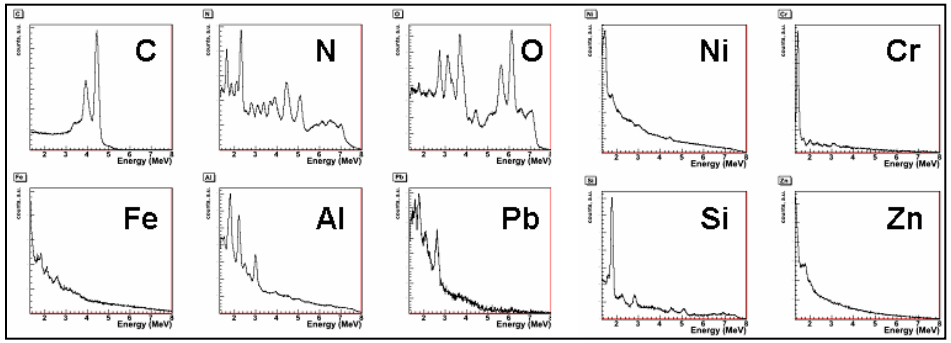
THE ASSOCIATED PARTICLE TECHNIQUE



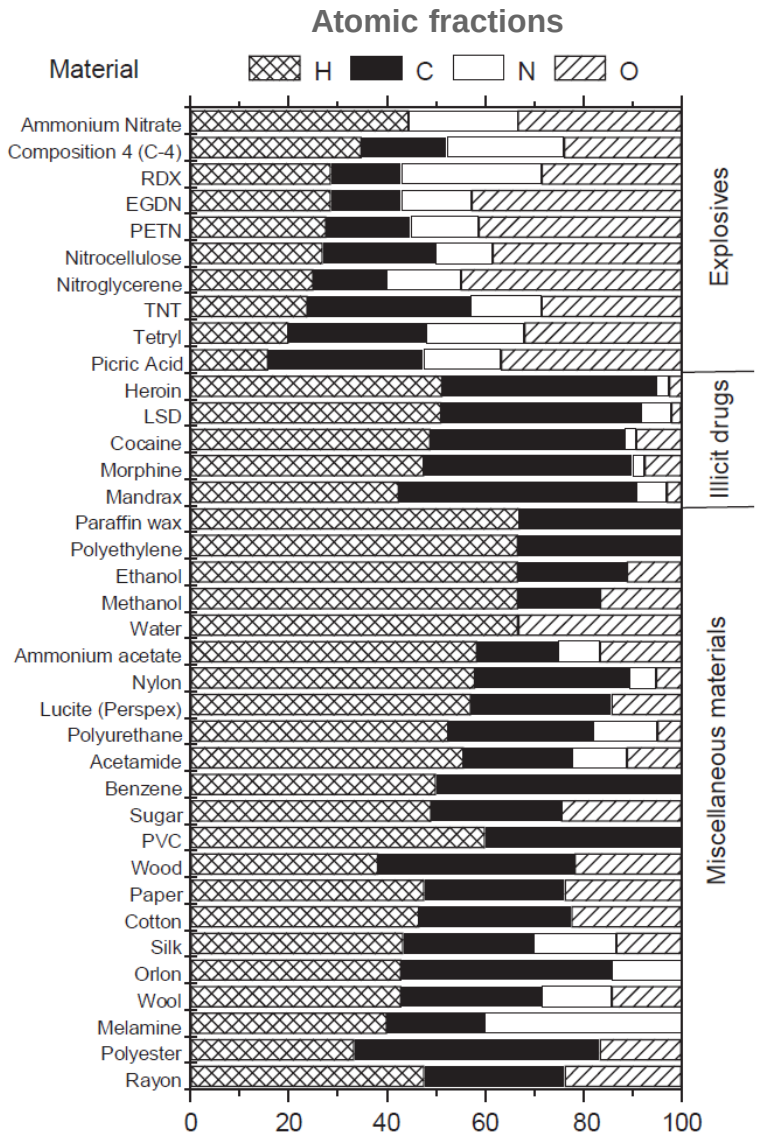
Gamma spectrum (selected volume)

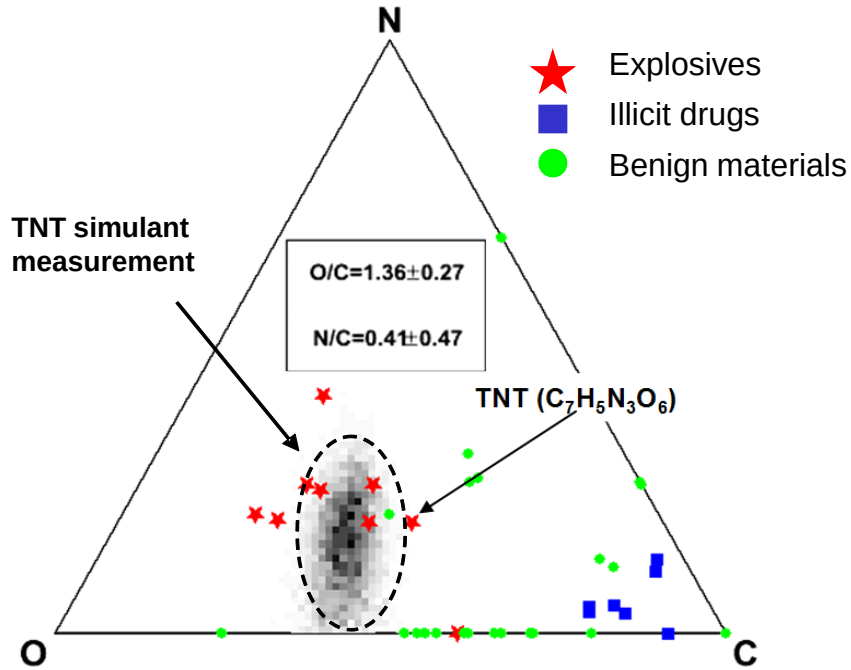


Unfolding (with a calibration database)



ORGANIC MATERIALS IDENTIFICATION

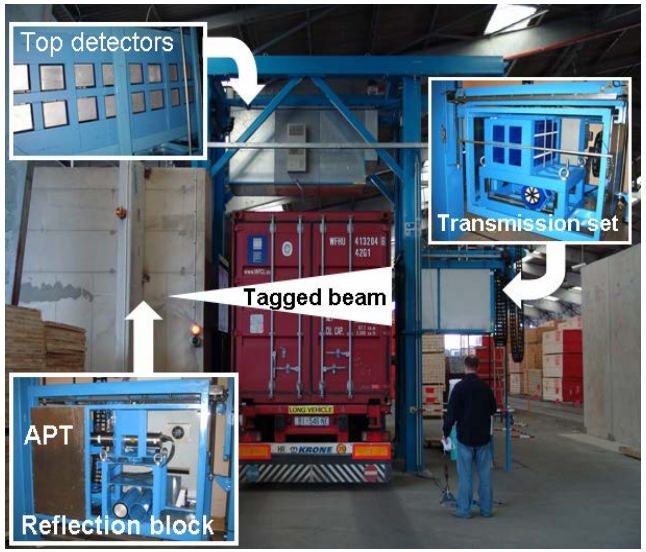


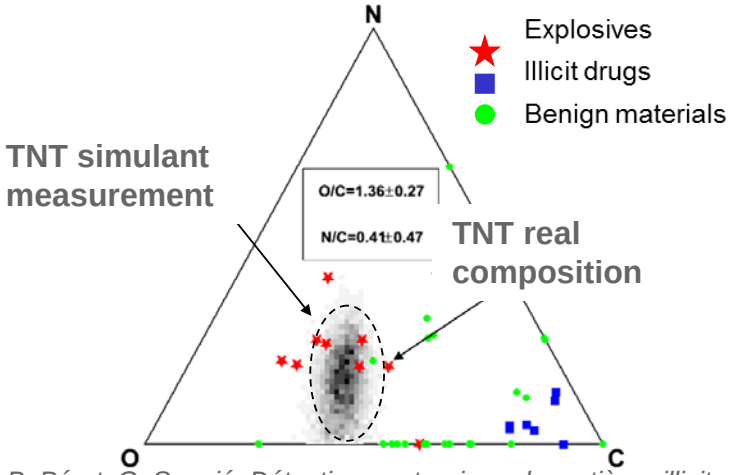


A. Buffler, http://dx.doi:10.1016/j.radphyschem.2004.04.110

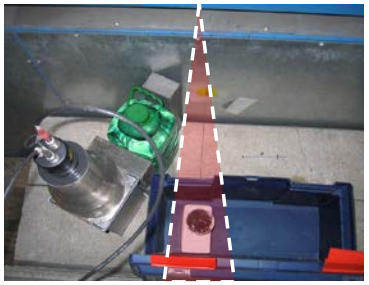
EUROPEAN AND FRENCH R&D PROJECTS

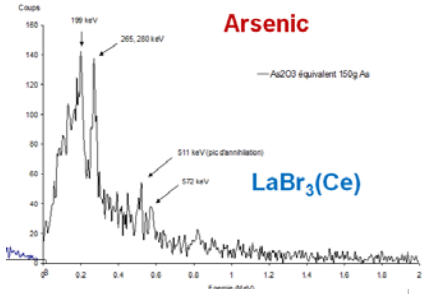
Cargo containers inspection
From EURITRACK (FP6) to C-BORD (H2020)

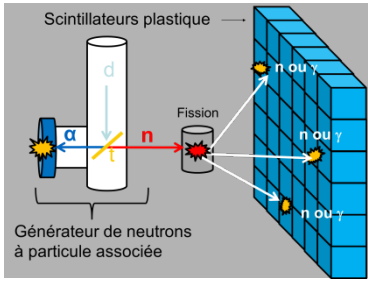


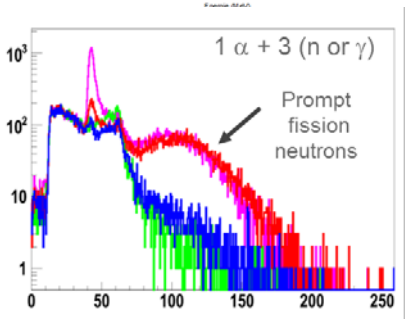


Chemical warfare and nuclear material detection
French CBRNE trans-governmental R&D program

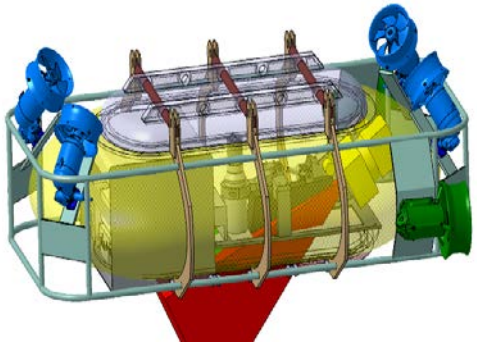


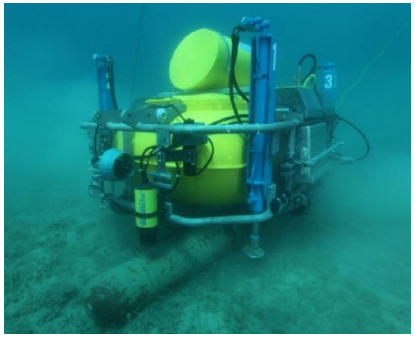






Submarine explosive detection UNCOSS (FP7)





- *B. Pérot, G. Sannié, Détection neutronique de matières illicites avec la technique de la particule associée, Techniques de l'Ingénieur, RE 177, 2015*
- *B. Pérot, Material characterisation with the Associated Particle Technique, Invited oral presentation, IEEE NSS 2012, Anaheim, California*

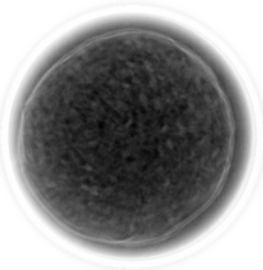
PERSPECTIVES

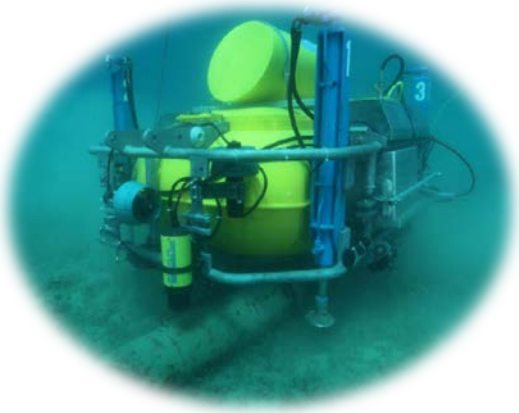
Grands défis scientifiques

- **Imagerie X** haute énergie / double-énergie / in situ **+ neutronographie** RJH
- **Spectrométrie gamma** in situ ⇨ CZT, LaBr… et caméras gamma
- **Mesures neutroniques** ⇨ contrôle nucléaire des nouveaux procédés (déchets, retraitement) et alternatives aux compteurs à ^{3}He
- **Photofission** ⇨ colis bétonnés de grand volume et couplage imagerie X
- **Activation neutronique** ⇨ sécurité NRBCE, déchets radioactifs ou non…

Comment faire sauter les verrous technologiques ?

- **Sources** intenses, bas bruit, haute résolution, auto-blindées, compactes…
- **Détecteurs** haute résolution (temps, énergie), + efficaces ou + compacts…
- **Electroniques** numériques, rapides, compactes, traitements embarqués…
- **Capacités de calcul** (TGCC) : simulations Monte Carlo réalistes, traitement de grandes quantités de données expérimentales ou simulées





MERCI

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Expert International CEA

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Service Mesures et Modélisation des
Transferts et des Accidents Graves