Pulsed Neutron Interrogation Test Assembly - PUNITA

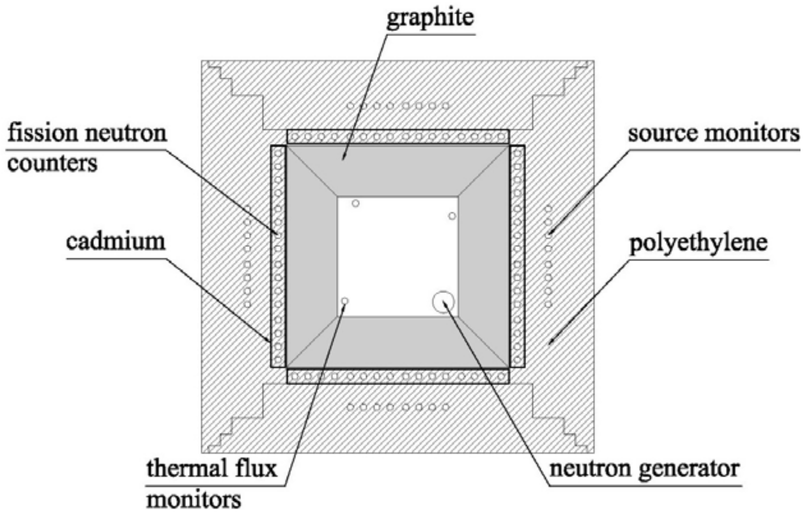
Bent Pedersen
Nuclear Security Unit
Institute for Transuranium Elements - ITU
Joint Research Centre

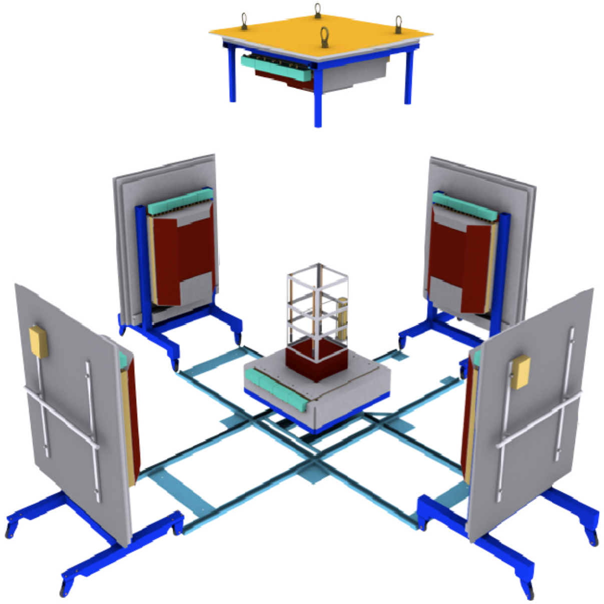
presented at

IPNDV WG3 meeting,
12-13 May 2016
JRC, Ispra site

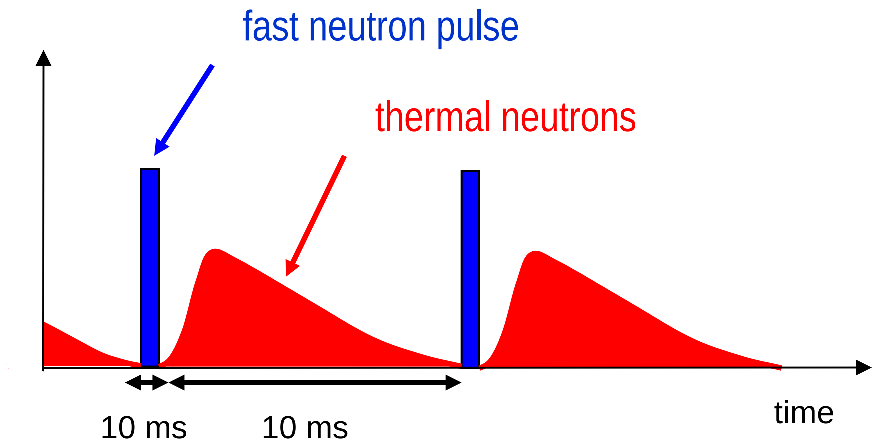
Outline

- characteristics of the Pulsed Neutron Interrogation Test Assembly
- some examples of research applications at PUNITA
  - fissile mass – differential die-away technique
  - design of a compact pulsed neutron device
  - explosives detection
  - detection of SNM
- useful signatures for nuclear disarmament verification





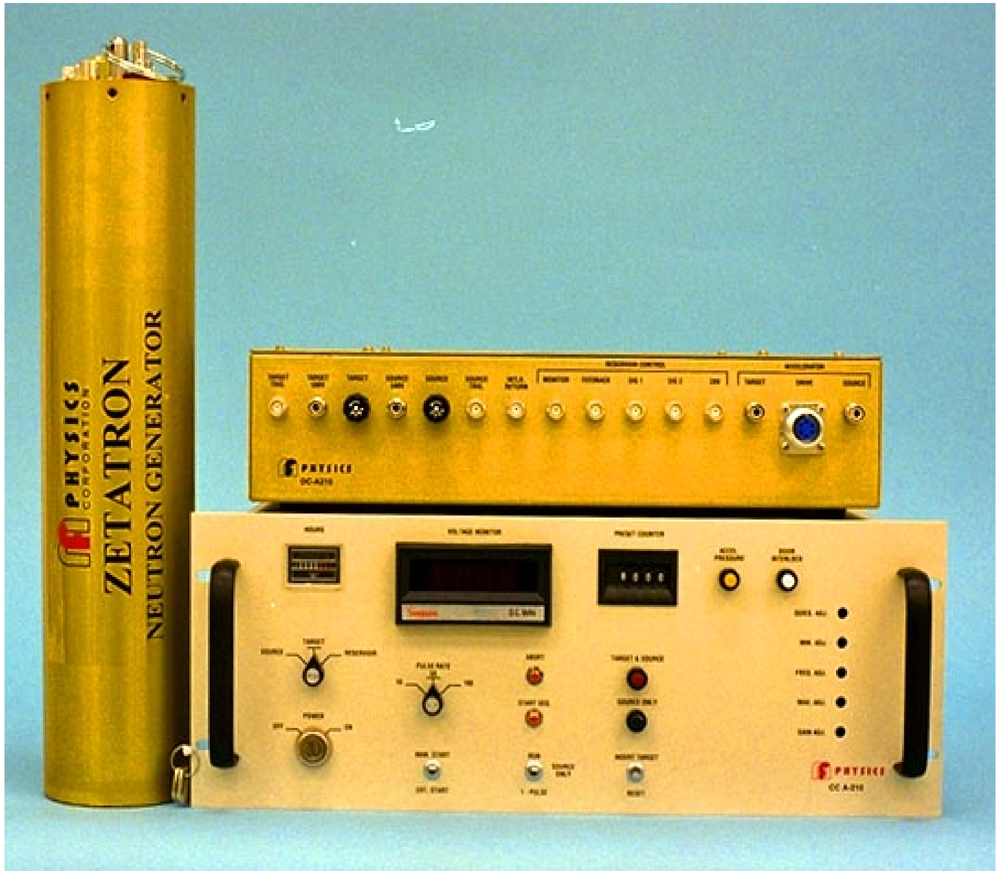
- 205 mm thick graphite linear
- 96 fission neutron counters: He-3 in HDPE
- 32 monitors for neutron generator output



- 14-MeV neutron generator (MF Physics Model A-211)
- sealed, D-T mixed beam
- pulsing: 100 s^{-1}

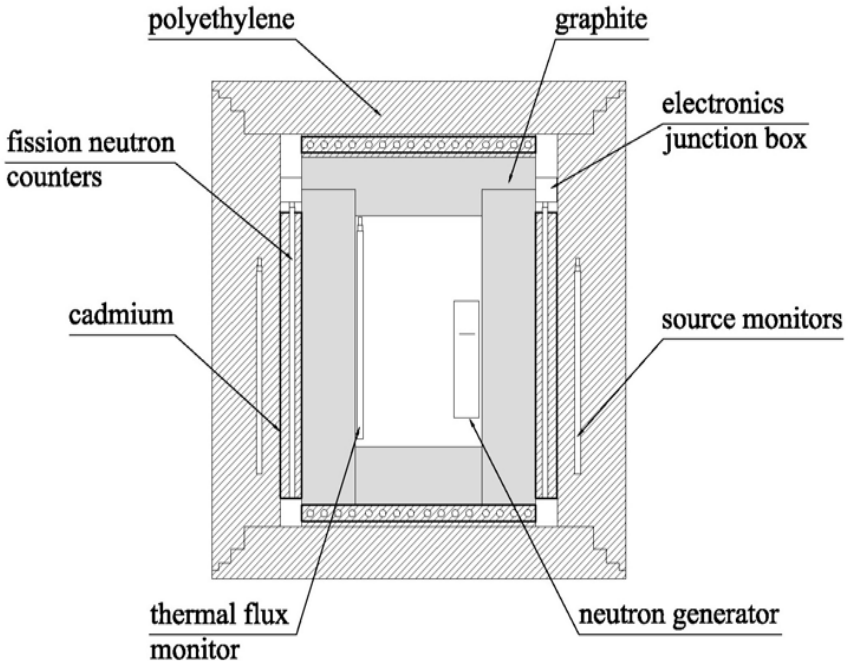
MF Physics Model A-211, 14-MeV neutron generator

- neutron emission:
  $2{\cdot}10^8$ /s, 10^6/burst in 4π angle
- sealed, D-T mixed beam
  300-500 hours life
- pulsing of ion source <u>and</u> acceleration voltage
  no emission between bursts
- neutron burst width:
  5-10 μs
- burst repetition rate:
  10 – 150 s^{-1}

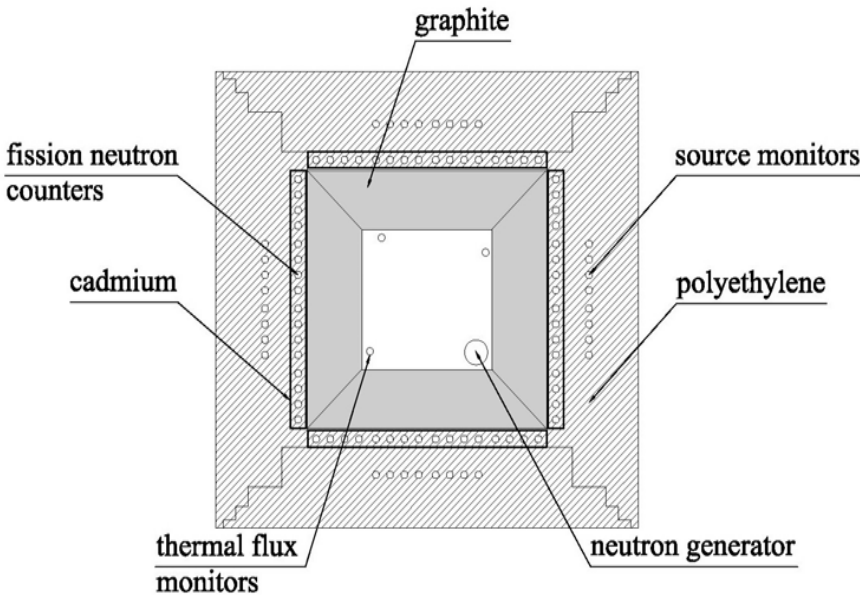


Features

- sample cavity: 50 cm x 50 cm x 80 cm
- thick graphite linear on all six side
- fission neutron counters: He-3 in polyethylene
- low pressure, thermal flux monitors
- monitor for n-generator output



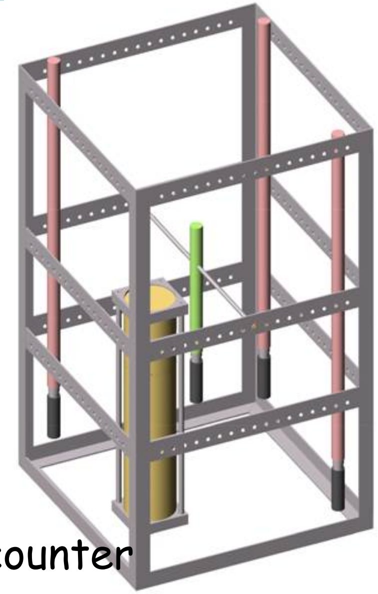
side view



top view

Pulsed Neutron Interrogation Test Assembly - PUNITA

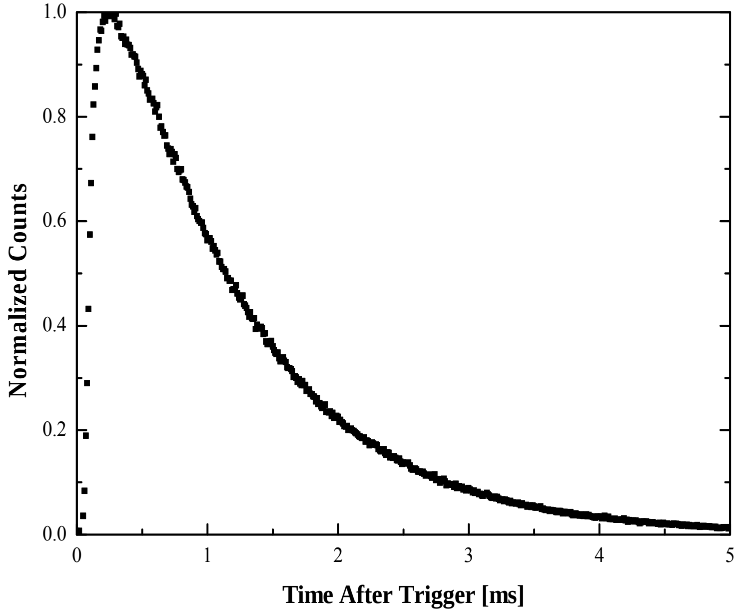
European Commission



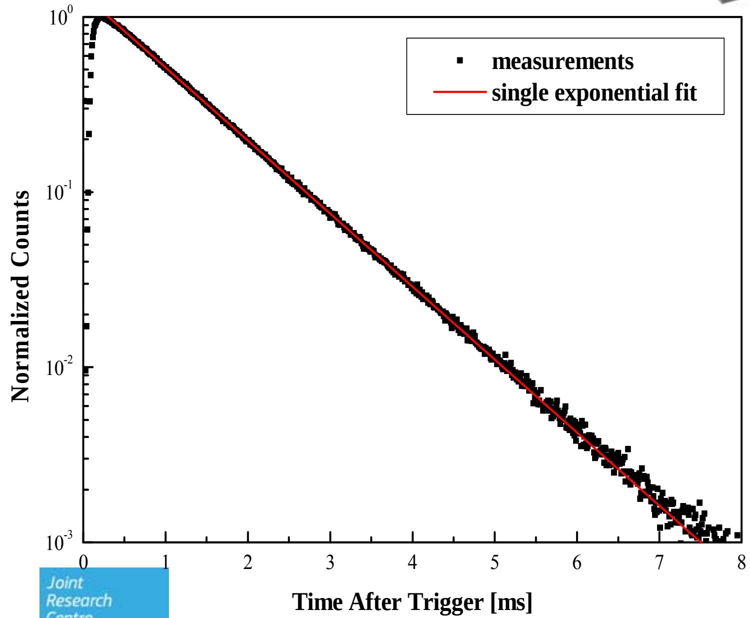
Exponential time response function of thermal neutrons

- maximum thermal flux at 280 μs after 14-MeV burst
- thermal neutron lifetime of 1.05±0.02 milliseconds

235-U fission chamber



Small He-3 proportional counter

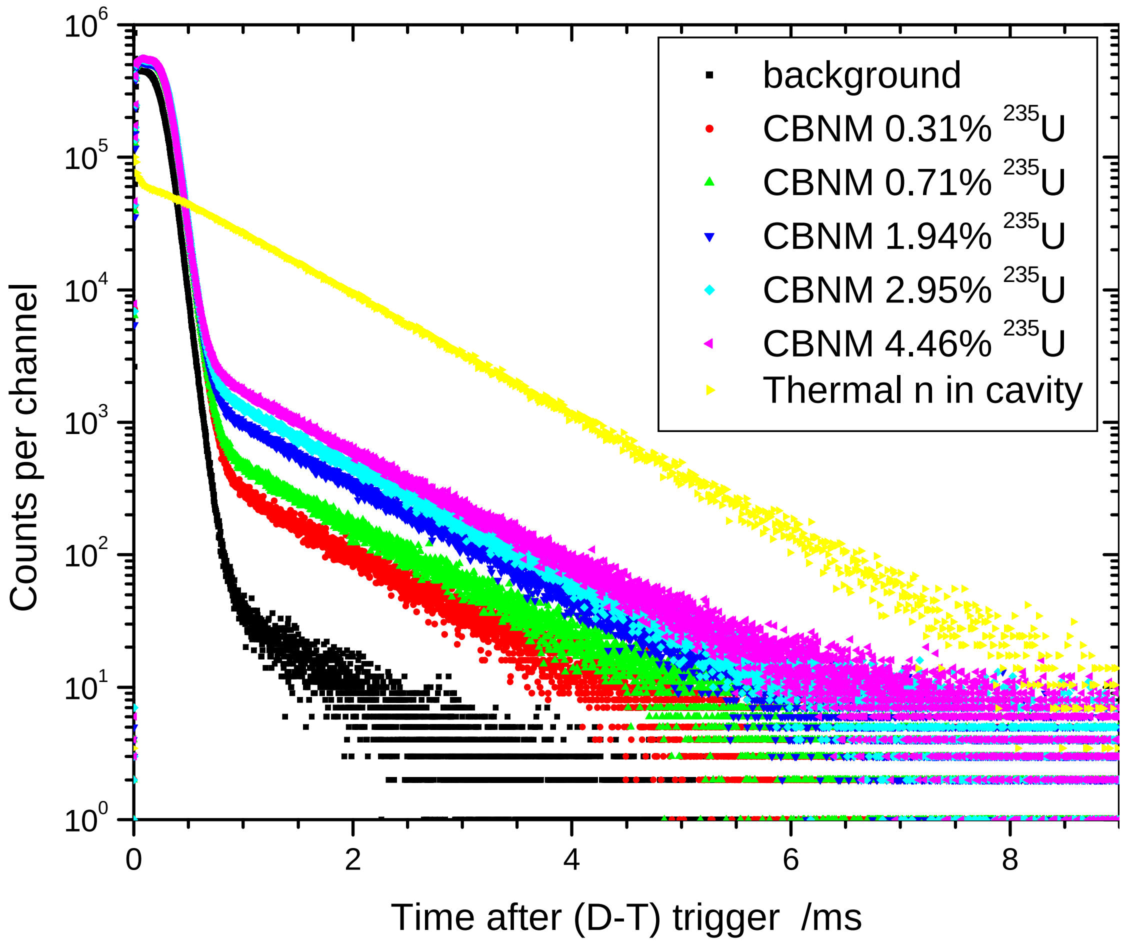


Joint Research Centre

European Commission

Detection of prompt fission neutrons - Differential Die-Away technique (DDA)

CBNM U_3O_8 standards



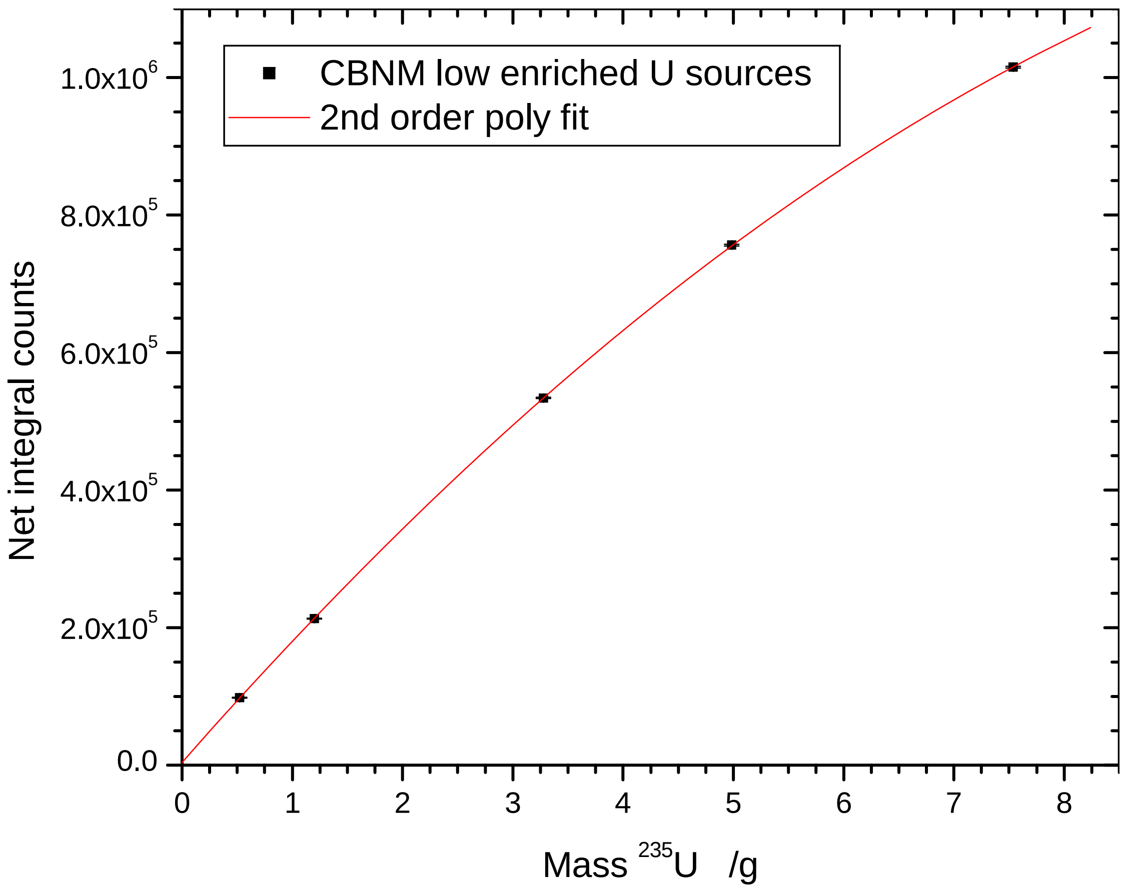
^{235}U mass range: 0.5 – 7.5 g
Meas. time: 10 min
14-MeV rate: 10^7 /s
Pulse rate: 100 Hz
Detectors: 3-He

European Commission

Detection of prompt fission neutrons - Differential Die-Away technique (DDA)

CBNM U_3O_8 standards

Integral range: 700 – 4700 µs



^{235}U mass range: 0.5 – 7.5 g
Meas. time: 10 min
14-MeV rate: 10^7 /s
Pulse rate: 100 Hz
Detectors: 96 ^{3}He

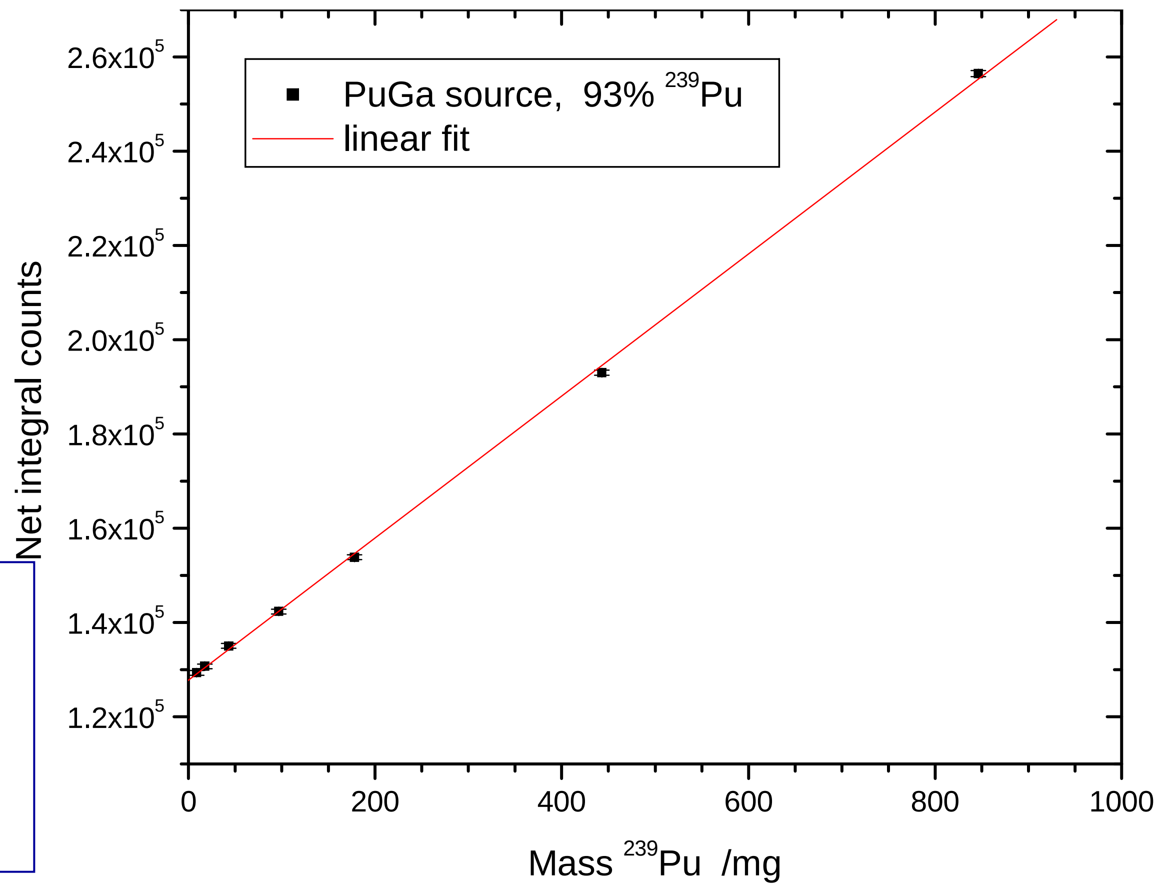
Joint Research Centre

European Commission

Detection of prompt fission neutrons - Differential Die-Away technique (DDA)

PuGa standards

Integral range: 700 – 4700 μs



^{239}Pu mass range:	8.6 – 846 mg
Meas. time:	10 min
14-MeV rate:	10^7 /s
Pulse rate:	100 Hz
Detectors:	3-He

European Commission

Can we design a compact device for mass assay of small fissile samples by active neutron interrogation?

Purpose:

mass assay of U and Pu samples of small volume

- e.g. smear samples, process samples, liquid solutions
- for accountancy, transport declarations, inventory

Advantages in "compact" design:

- less shielding
- less ^{3}He detector volume
- integrate with existing equipment
- lower price

Requirements:

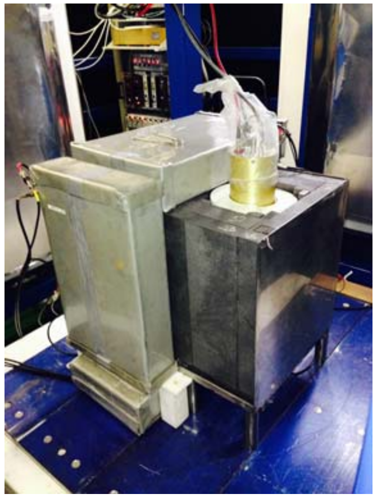
- high neutron flux at sample position
- long life time in moderator, short life time in detector
- high detection efficiency for fission neutrons

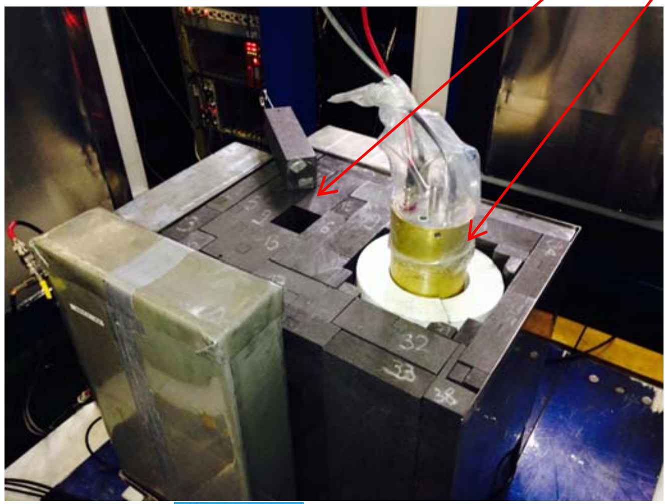
European
Commission

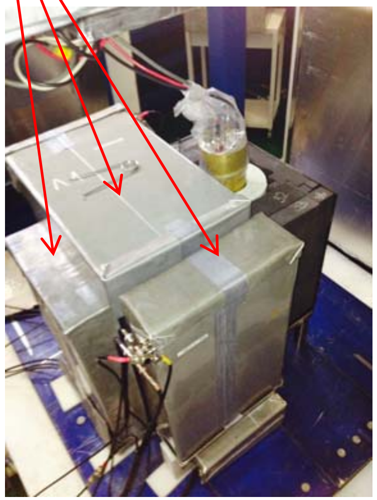
Experimental setup

- 5 detector banks, each composed of:
  - 5 ^{3}He detectors, polyethylene moderator, complete Cd cover
  - fission neutron detection efficiency: 11.6%
- graphite moderator block:
  - reactor grade purity, density 1.67 g/cm^3
  - dimensions: length: 509mm, height: 420mm, width: 402mm
  - distance generator target – sample: 240 mm

sample cavity
neutron generator
detector banks







Joint
Research
Centre

European Commission

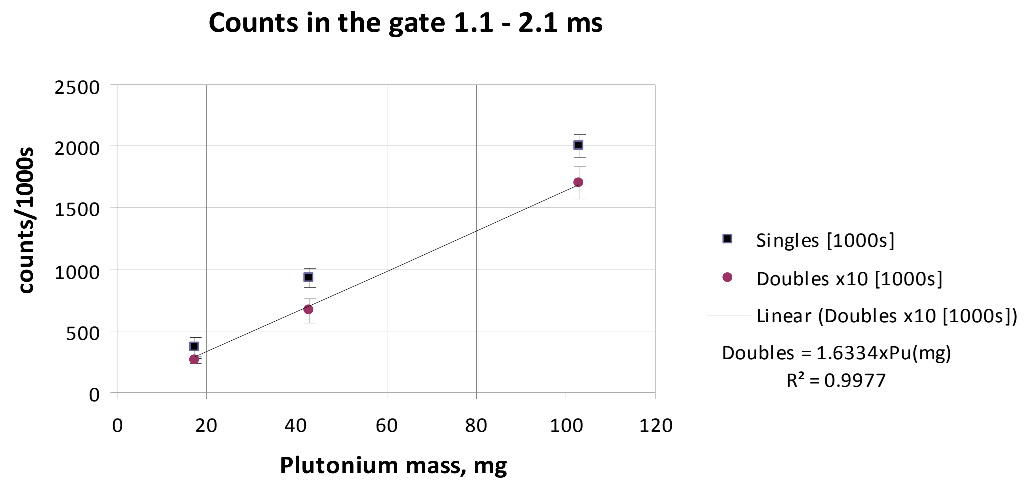
Experimental results

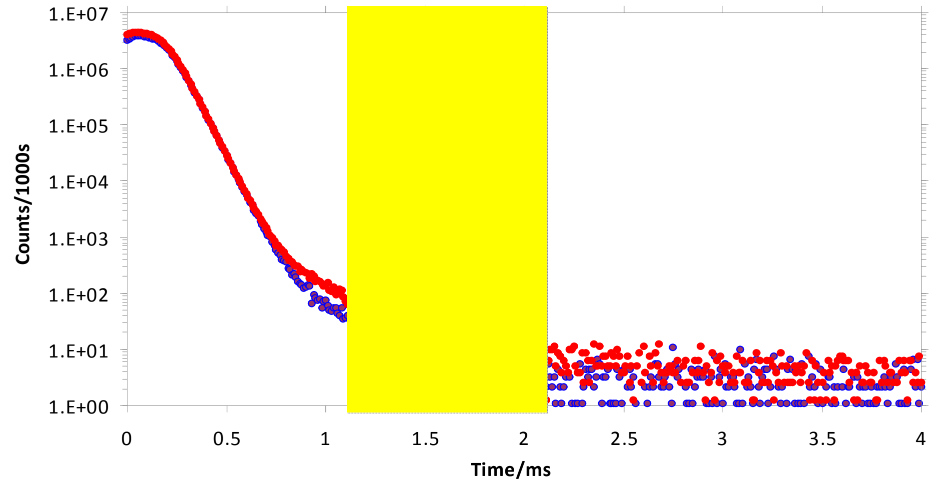
^{239}Pu Limit of Detection,
3 sigma of background,
meas time 1000s:

- Singles: LOD_S = 0.786 mg
- Doubles: LOD_D = 5.170 mg

using: $$LOD = \frac{3\sqrt{background}}{regression\ slope}$$

@ neutron emission rate:
$0.9*10^7\ s^{-1}$,
(max rate $2.0*10^8\ s^{-1}$)

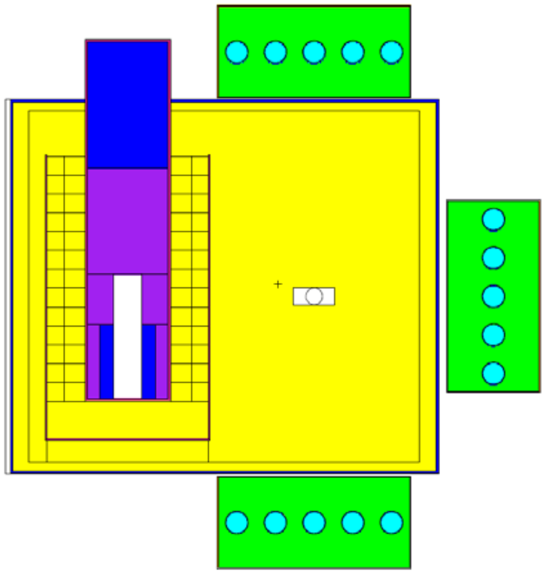




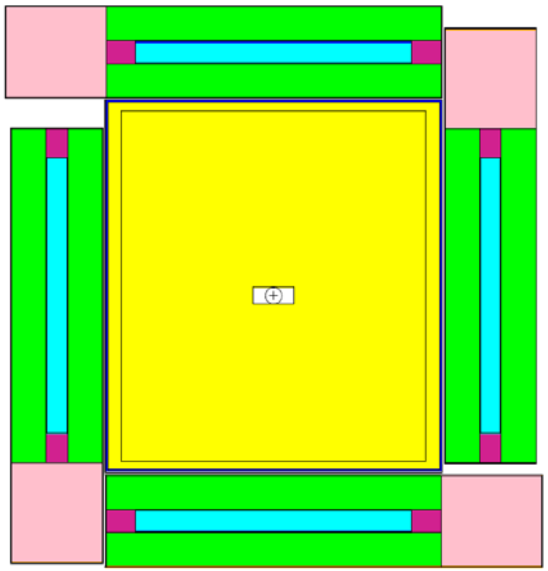
Joint Research Centre

MCNP simulations, experimental configuration

- 5 detector banks (standard "neutron collar"), each composed of:
  5 3He detectors, polyethylene moderator, complete Cd cover
  fission neutron detection efficiency: 11.6%
- graphite moderator block: reactor grade purity, density 1.67 g/cm3
  dimensions:length: 509mm, height: 420mm, width: 402mm
  distance target–sample: 240 mm



vertical cross section



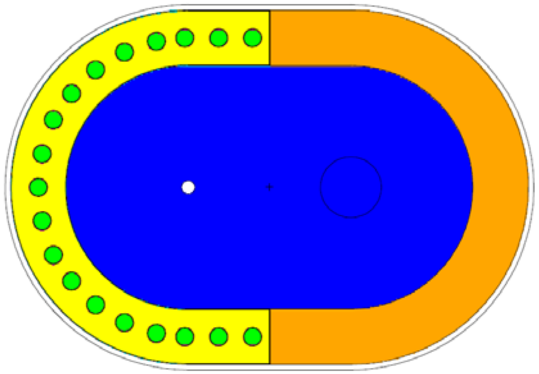
vertical cross section

European Commission

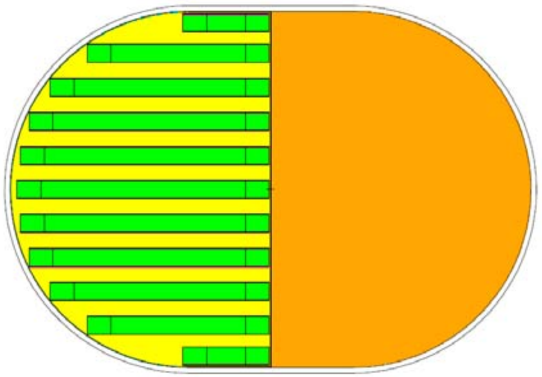
MCNP simulations, improved geometry

- better detector position, 3He in HDPE, Cd cover, 80 mm width
- only 20% more ^{3}He volume

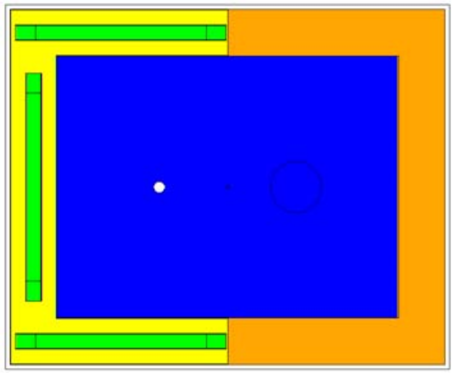
Moderator zone: max length 600 mm, max width 360 mm, height 360 mm
Reflector zone: width 80 mm
14-MeV source: 45 mm radius for W filter
Sample cavity: void, radius 10 mm, distance to source 240 mm



horizontal cross section



horizontal cross section

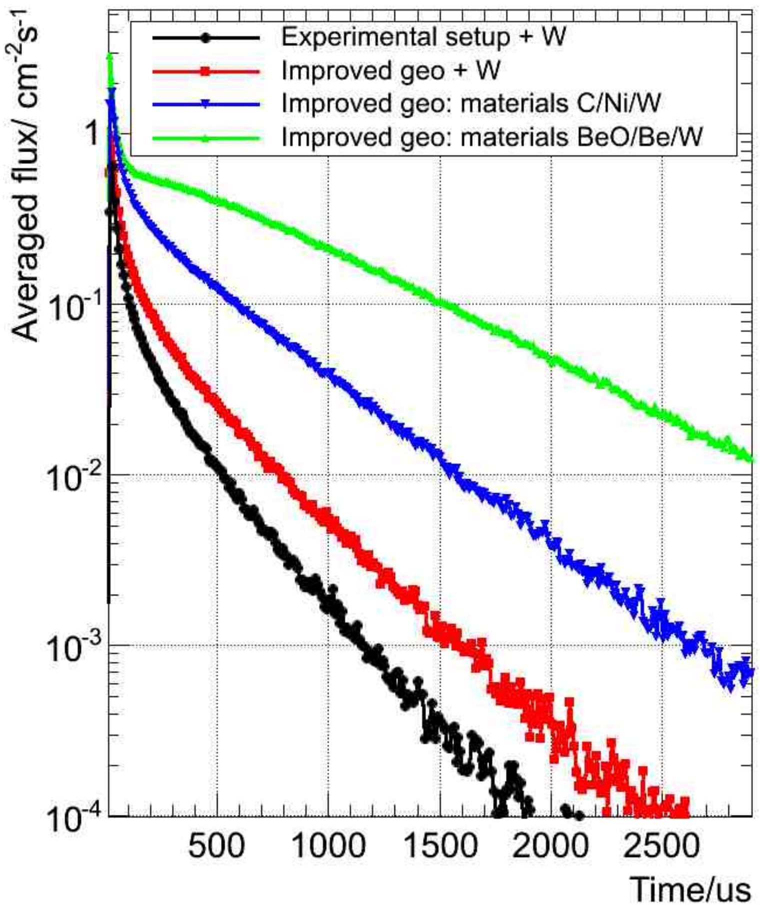


vertical cross section

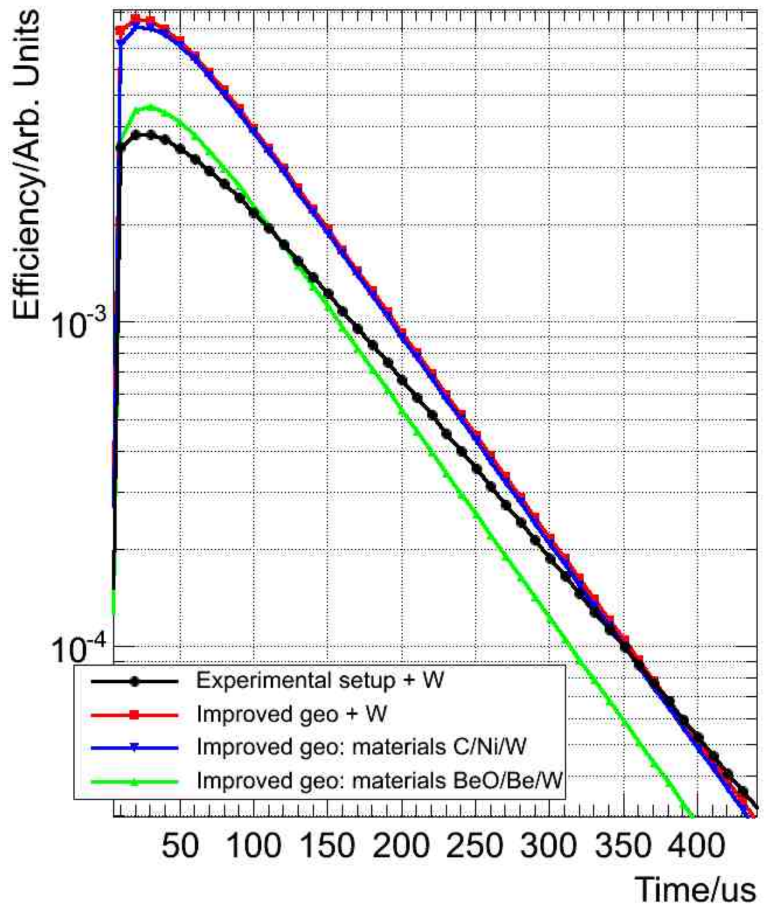
European Commission

MCNP simulations

Flux at sample position



Detection of fission neutrons



MCNP simulations,

Integral configurations

Model	$\varepsilon/\varepsilon_{ref}$	Φ/Φ_{ref}	FOM
Experimental configuration	0.529	1.14	0.603
Experimental configuration, W around 14-MeV source	0.526	1.77	0.931
Improved geometry	1	1	1
Improved geometry with W around 14-MeV source	1.00	3.20	3.20
Improved geometry, BeO moderator, Be reflector, W	0.555	17.48	9.70
Improved geometry, C ρ = 2.07 g/cm^3, Ni reflector, W	0.960	9.22	8.85

What “limit of detection” can we achieve in the compact design?

$$LOD_{improved} = LOD_{experimental} \frac{FOM_{experimental}}{FOM_{improved}} = 785\mu g \frac{0.603}{8.85} = 53.6\mu g$$

Assuming:

conservative design:

- graphite moderator of $\rho = 2.07$ g/cm^3
- Ni reflector
- W on 14-MeV source

conservative generator operation: neutron emission rate: $0.9 \cdot 10^7$ s^{-1} (max rate $2.0 \cdot 10^8$ s^{-1})

European Commission

Prompt Gamma Neutron Activation Analysis – PGNAA

Method

- Interrogation first by fast neutrons later by thermal neutrons
- Detection of characteristic gamma rays from inelastic scattering and capture
- Known detector efficiency, nuclear data, and net peak areas yields element ratios
- Interesting elements for explosives detection are:
  nitrogen, carbon, hydrogen, oxygen, chlorine, fluorine, a.o.

Equipment

- Detector shielding against thermal neutrons and gamma background
- Lanthanum bromide scintillation detectors (1½" x 1½" and 2" x 3")
- Digital spectrometers: Ortec DigiBase and Xia Polaris

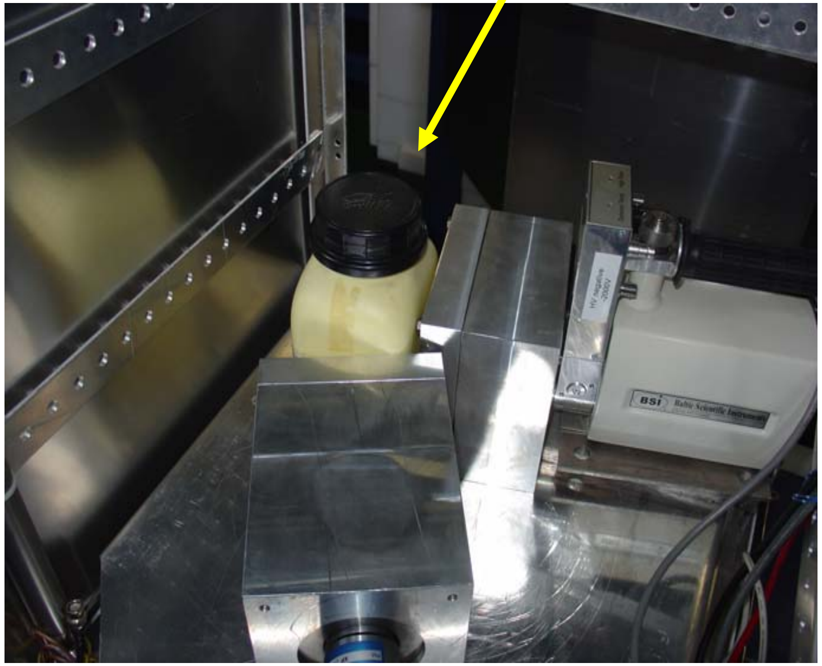
European
Commission

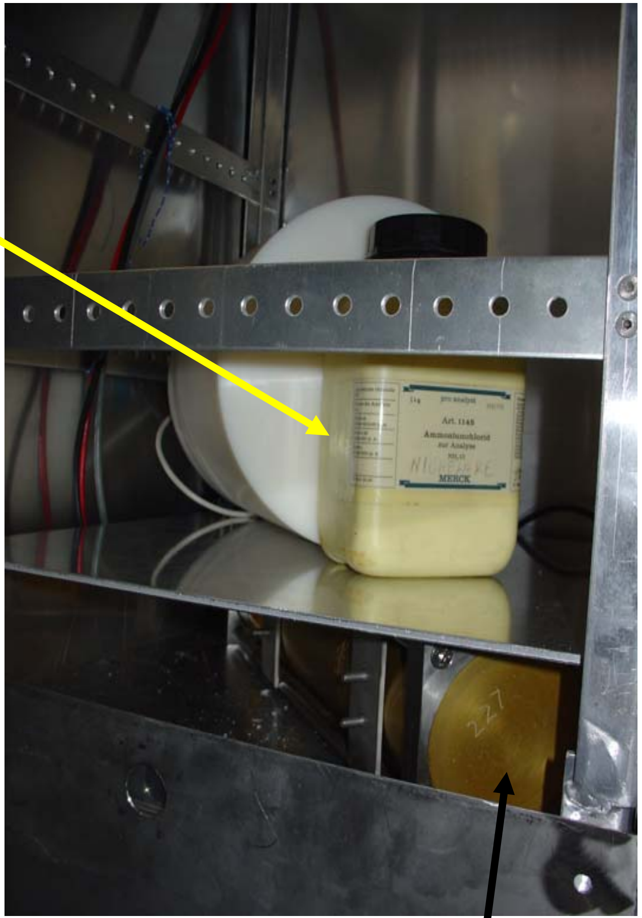
Shielding arrangements for $LaBr_3$ scintillation detectors

European Commission

Experimental setup

Test sample (NH_4Cl)

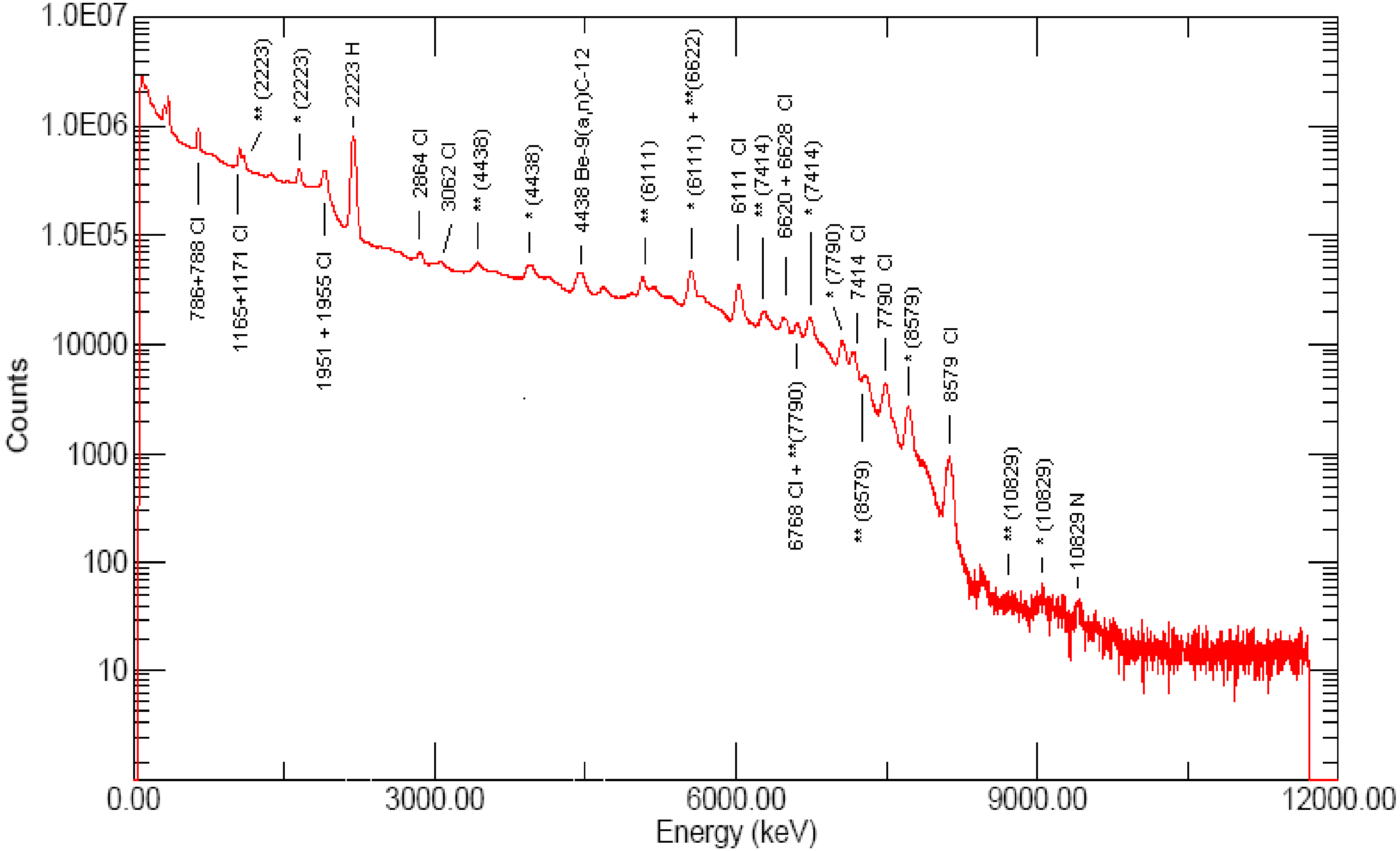




Neutron generator

European
Commission

Gamma spectrum, PGNAA neutron capture



NH_4Cl sample by small $LaBr_3$ scintillation detector

Joint
Research
Centre

European Commission

Result, example: element ratios

Test sample: NH_4Cl, and evaluation of the mass ratios H/Cl

Method: prompt thermal activation analysis

Measured mass ratio H/Cl	Theoretical mass ratio H/Cl
0.10±0.03	0.11

European Commission

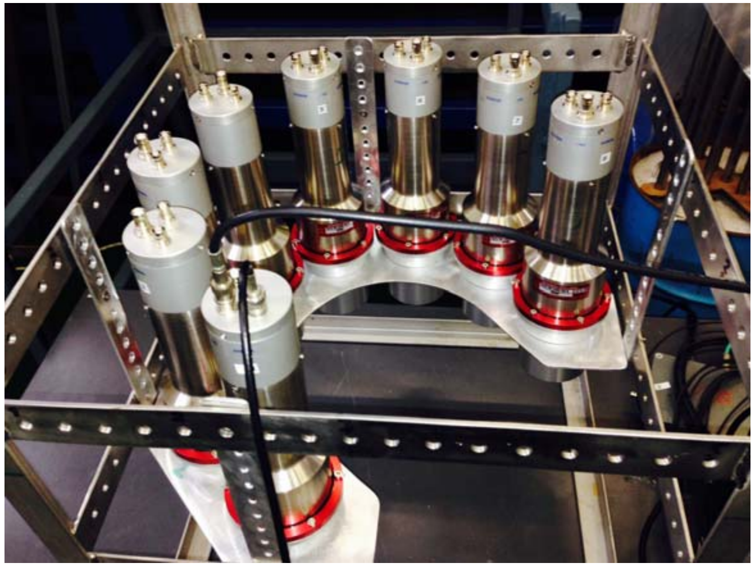
Objective: Detection of Special Nuclear Material for Nuclear Security applications

Application:
- detection of SNM in shielded containers

Physics principle:
- induce fission by epi-thermal/thermal neutrons (pulsed neutron source)
- fission signatures are the evidence for presence of SNM:
  - only fast prompt fission neutrons appear in PSD peak
  - neutron coincidences in short gates of 10-20 ns.

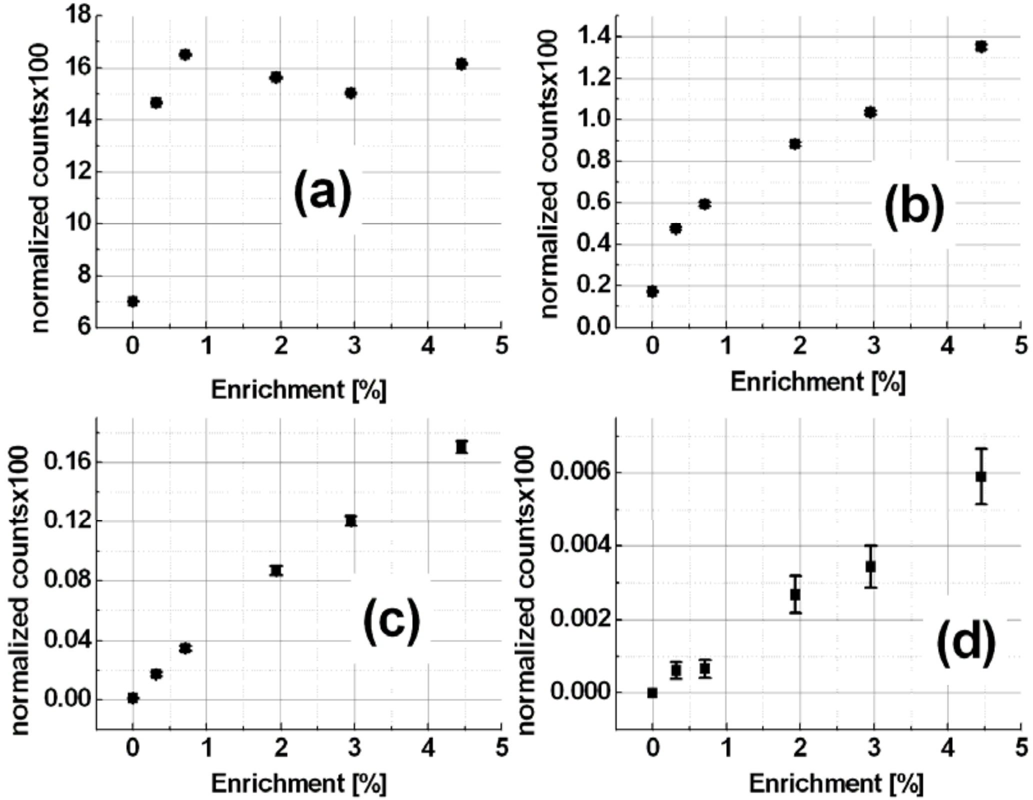
Technical implementation issues:
- high count rates in neutron/photon mixed fields
- fast neutron detection at high efficiency
- good neutron/photon separation necessary

Technical/scientific implementation:
- 8x 3”x3” EJ-309 liquid scintillation detectors
- signal analyzing hardware (fast digitizers)
- (online interpretation (PSD) in FPGA hardware)



European Commission

Detection of triple coincidences using CBNM U_3O_8 standards
thermal interrogation (250μs to 40000μs)



Kinds of three-fold coincidences:

(a) γγγ
(b) γγn
(c) γnn
(d) nnn

Detection of SNM

European Commission

Example I, nuclear security:

Scale-up of experimental results to industrial size (preliminary results)

PUNITA simulations:

- To compare experiments to MCNP model we apply the following figure of merit:
  FOM = [thermal n-flux] x [detector n-efficiency]
  in order to optimize both parameters individually.

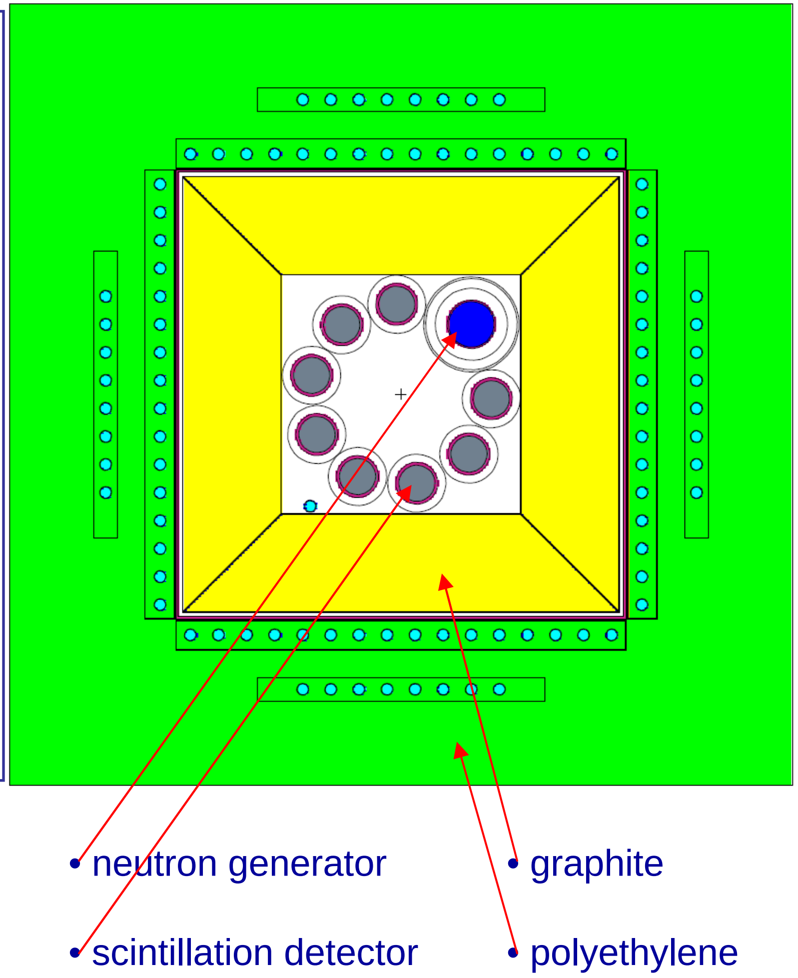
- Due to generator pulsing (100 Hz) we integrate n-flux over 10 ms period:

$$\varphi_{th} = 224891\ cm^{-2}$$

- As a measure of fission neutron detection efficiency we define recoil protons with E_{kin} > 700 keV as a neutron detection event:

$$\varepsilon_n = 6.07 \pm 0.30\ \%$$

MCNP model of PUNITA setup

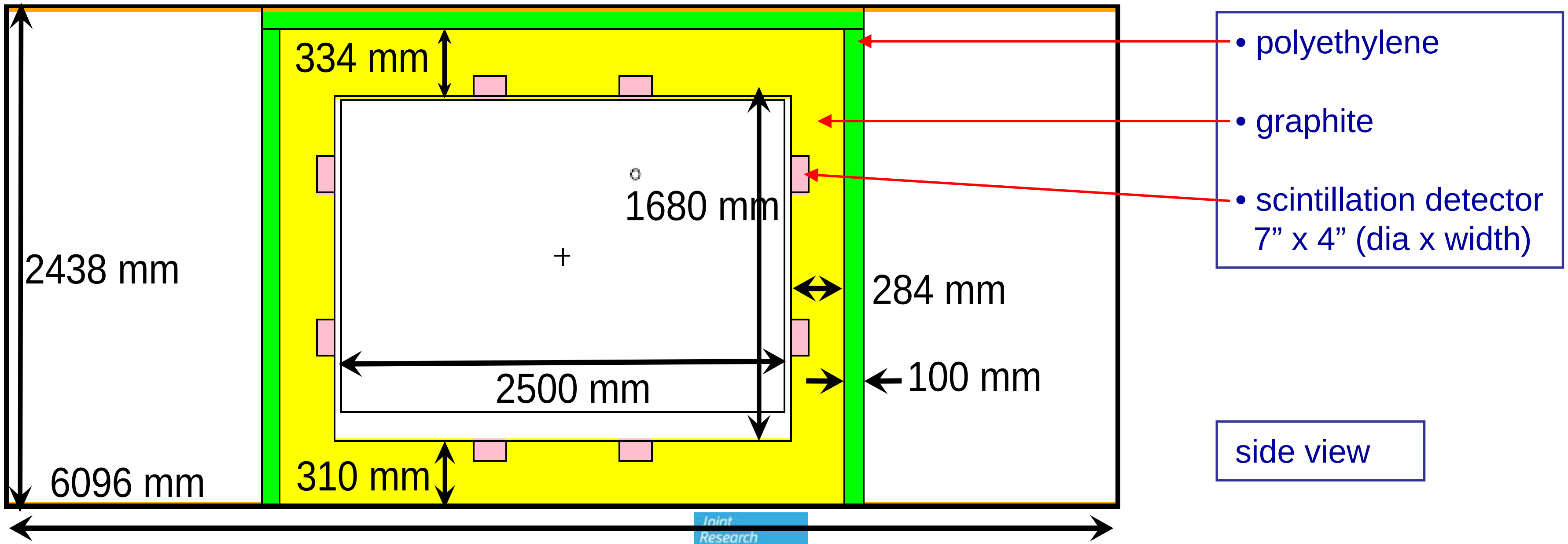


Joint Research Centre

European Commission

Scale-up of experimental results to industrial size (preliminary results)

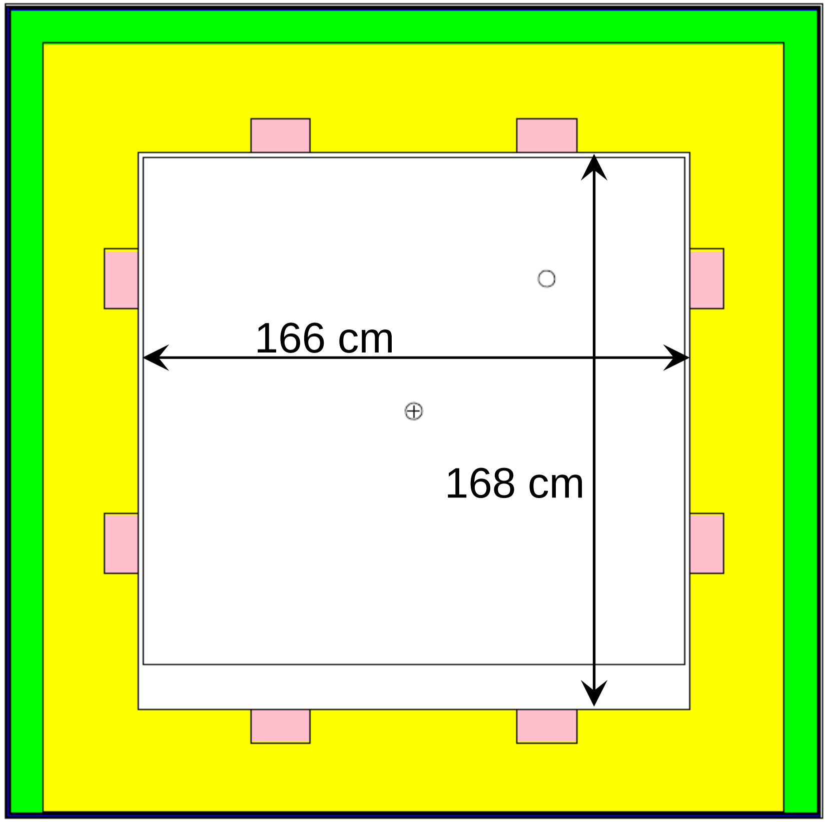
- Assay of Unit Load Devices (ULDs) for air cargo
- Accommodate largest standard ULD:
  LD1 for Boeing 747-400: 234 x 153 x 163 cm, 4.90 m^3
- Device implemented into standard 20-foot container
  not shown: - conveyer belt through entire container
  - n-generator centered below cavity



European Commission

Scale-up of experimental results to industrial size (preliminary results)

Assay device as implemented in 20-foot container (view from entrance) showing:
detector positions, n-generator position



Standard ULD as applied for air cargo

European Commission

Scale-up of experimental results to industrial size (preliminary results)

Geometry comparison "ULD device / PUNITA":

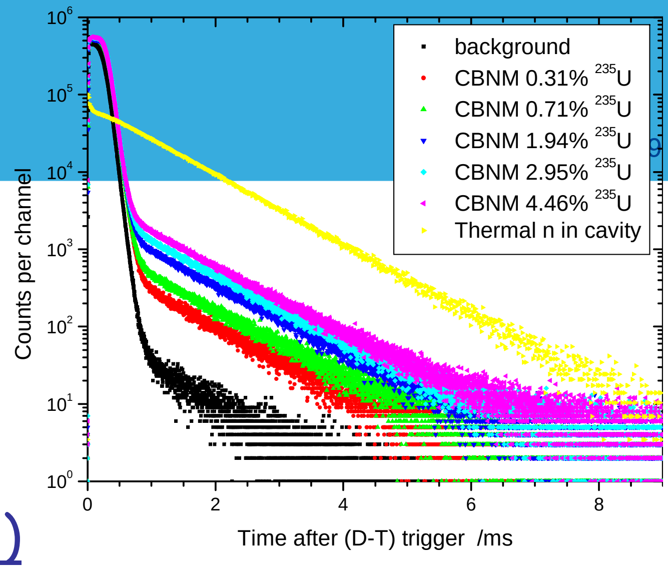
moderator volume ratio	11.9	
• sample cavity size ratio	31.7	
• detector volume ratio	21.8	
• neutron generator	same	(1x 10^8 /sec, 100 Hz pulsing)

Preliminary simulation results "ULD device / PUNITA":

thermal n-flux ratio, centre pos.	$\varphi_{th,ULD\ device} / \varphi_{th,PUNITA}$ =	0.0061 ± 0.0002
fission neutron det. efficiency	$\varepsilon_{n,\ ULD\ device} / \varepsilon_{n,\ PUNITA}$ =	$0.379 \pm 9.94 \cdot 10^{-4}$
FOM ratio		1/436 ± 1/11065

Based on the (conservative) estimate of a detection limit in the PUNITA configuration of 0.52 g ^{235}U in a 100 second measurement when using the 3-fold neutron coincidences as signature, the detection limit of the "ULD device" described above would be approximately a factor 436 higher, or LOD = 228 g ^{235}U.

Pulsed neutron interrogation for nuclear disarmament verification



Verification of nuclear materials (Pu and HEU)

Neutron generator (OK), moderator materials (probably not OK)

- Pulsed n-generator (14-MeV)
- Tailor n-spectrum with filters around target
- Induce fission with fast and epi-thermal spectrum
- Detect useful fission signatures, in particular prompt fission neutrons
- Use die-away curve (neutron self-multiplication) to confirm "presence of large fissile mass".

Verification of high explosives

- Need for moderator to acquire useful neutron capture gamma lines
- In-elastic scattering gamma lines are difficult

Thank you!

Bent Pedersen
Joint Research Centre
Institute for Transuranium Elements
Nuclear Security Unit
21027 Ispra (VA), Italy

bent.pedersen@jrc.ec.europa.eu