KTH Nuclear Physics Group

Experiment
Prof. Bo Cederwall (Head of Division)
Prof. Ayse Ataç Nyberg
Dr Torbjörn Bäck, univ.lektor
Prof. em. Arne Johnson
Dr Débora Trombetta, researcher (VR starting grant)
Dr Biswarup Das, postdoc (from 20-01)
Dr Alf Göök, researcher (from 20-02)
Özge Aktas, PhD stud.
Linda Eliasson, PhD stud.
Aysegul Ertoprak, PhD stud.
Xiaoyu Liu, PhD stud.
Jana Petrović, PhD stud. (from 20-01)
Wei Zhang, PhD stud.
Cibi Sundaram, M.Sc. Stud.
Victor Bussy, M.Sc. Stud.

Maryam Saleem IVA-jobbsprånget intern
Mohannad Nayef IVA-jobbsprånget intern

Theory
Doc. Chong Qi, univ. lektor
Prof. em. Ramon Wyss
Prof. em. Roberto Liotta
Daniel Karlsson, PhD stud.
Karl Sallmén, M.Sc. stud.

KTH Nuclear Physics Group

Mission

Science and Technology

"Applied" research funded by SSM, VR, KTH Innovation, Vinnova

- **Develop radiation sensor applications in Medicine and Industry**
  - **Nuclear Safeguards and Security**
  - **Nanodosimetry**
  - **Medical Imaging**

"Fundamental" research funded by VR, KAW, GGS

Understanding the strong force as a manifestation in nuclear properties (even after Higgs is only a fraction of hadron and nuclear masses explained)

- What are the limits for the existence of nuclei?
- How do weak binding and extreme proton-neutron asymmetry affect nuclear properties?
- How do collective phenomea and symmetries emerge in complex nuclei from the interactions between the basic constituents?
- What are the origins of the elements?

Teaching

Courses on Cand., Master & PhD levels on Gen. Physics, Subatomic physics, Experimental techniques in Nuclear and Particle Physics and Radiation protection

Master's programme in Nuclear Energy Technology

Outreach

Radioactive Orchestra http://www.nuclear.kth.se/radioactiveorchestra/

Berkeley Radwatch project https://radwatch.berkeley.edu/dosenet/map

KTH Nuclear Safeguards and Security

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

Development of radiation detection and imaging systems for applications in nuclear safeguards and non-proliferation, nuclear security, environment and related areas

- Research focus area based on our expertise in **radiation detection and imaging** for enhanced sensitivity in detecting and characterizing nuclear materials in different environments.
- Fast <u>neutron-gamma correlations</u>, high-resolution gamma-ray spectroscopy, Compton imaging, <u>Monte Carlo techniques</u>

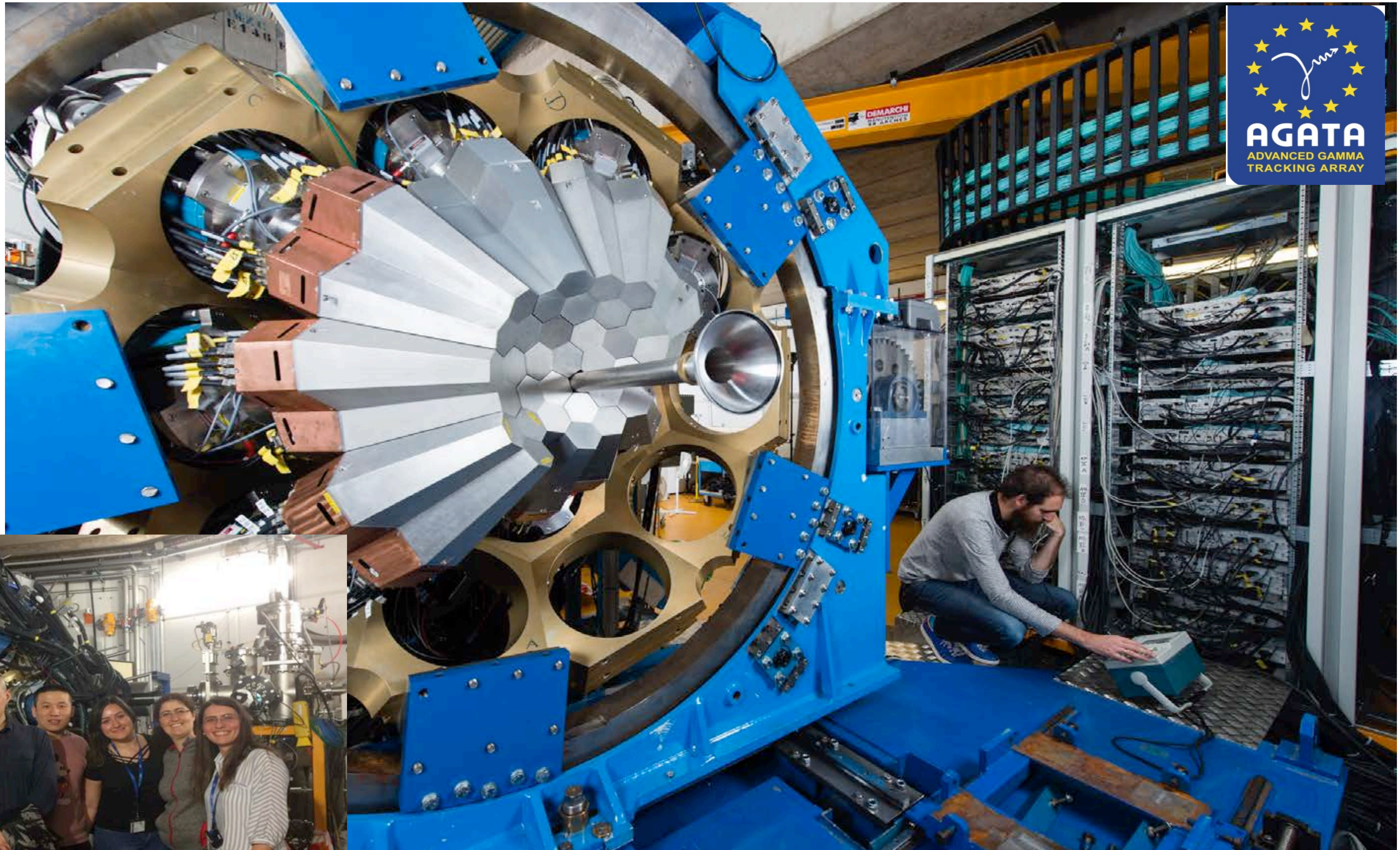
Local team

Bo Cederwall
Débora Trombetta (VR Starting grant 2020-2023)
Alf Göök, (from Feb 2020, funded by SSM)
Jana Petrović, PhD stud. (from Jan 2020, funded by SSM)
Cibi Sundaram, M.Sc. Stud.
Victor Bussy, M.Sc. Stud.
Maryam Saleem IVA-jobbsprånget intern
Mohannad Nayef IVA-jobbsprånget intern

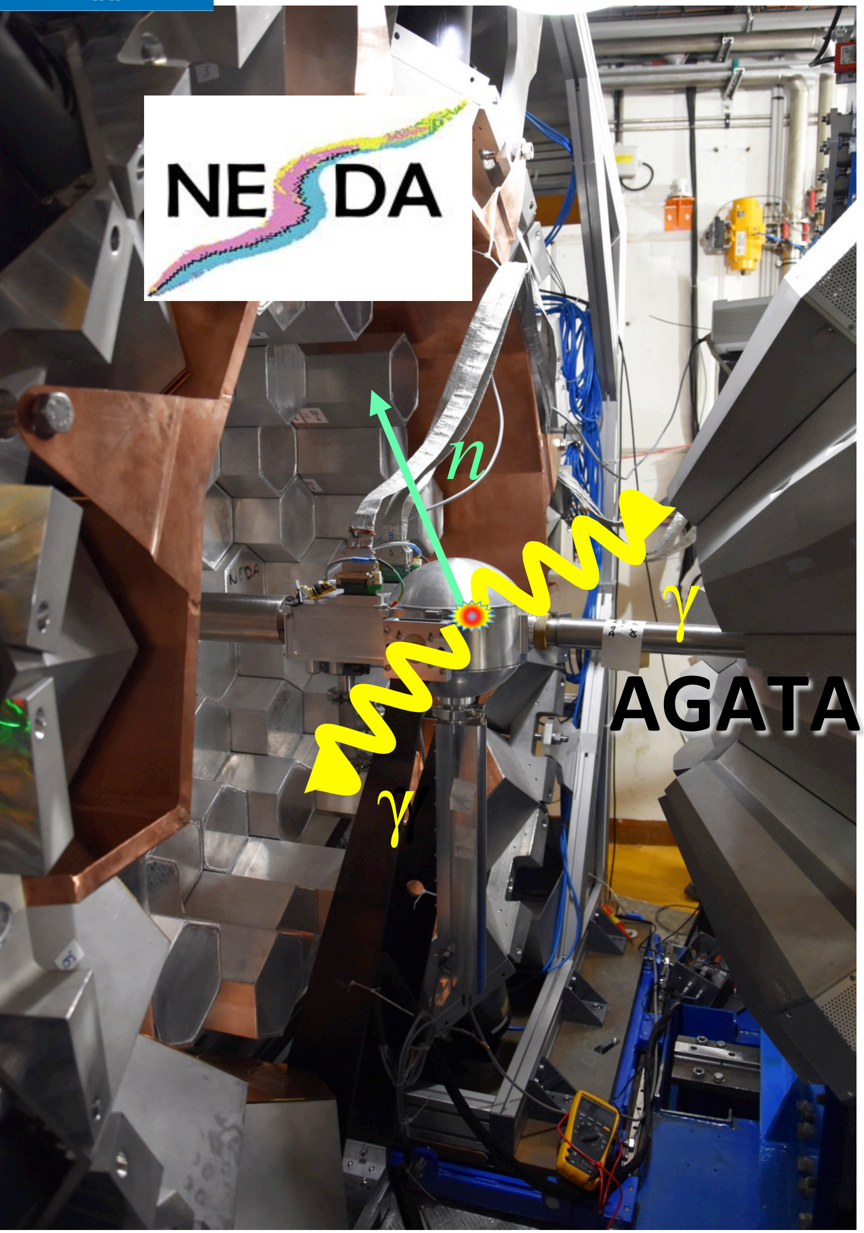
External

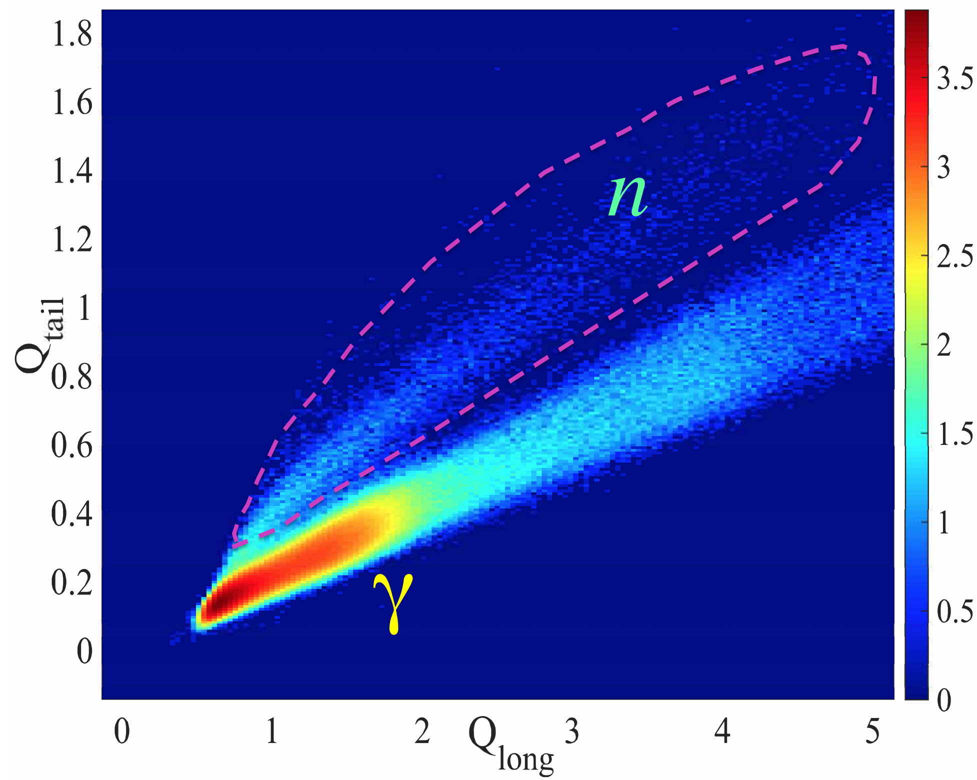
Kåre Axell, SSM
Dina Chernikova, IAEA

Fast γ-neutron coincidence detection adapted from fundamental nuclear physics experiments



Fast correlation measurements using pulse shape analysis for neutron-gamma discrimination with organic scintillators





Fast neutron and gamma correlations for sensitive detection of SNM

Nuclear Inst. and Methods in Physics Research, A 927 (2019) 119–124

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Fast neutron- and γ-ray coincidence detection for nuclear security and safeguards applications

Débora M. Trombetta [a], Malin Klintefjord [a], Kåre Axell [b], Bo Cederwall [a,*]

[a] *Department of Physics, KTH Royal Institute of Technology, S-10691 Stockholm, Sweden*
[b] *Swedish Radiation Safety Authority, S-171 16 Stockholm, Sweden*

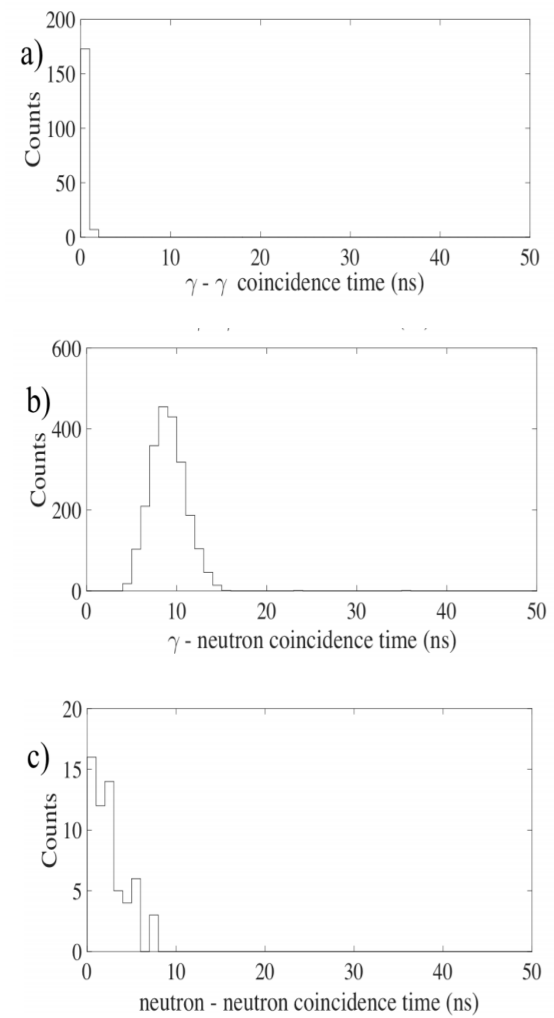
A R T I C L E I N F O

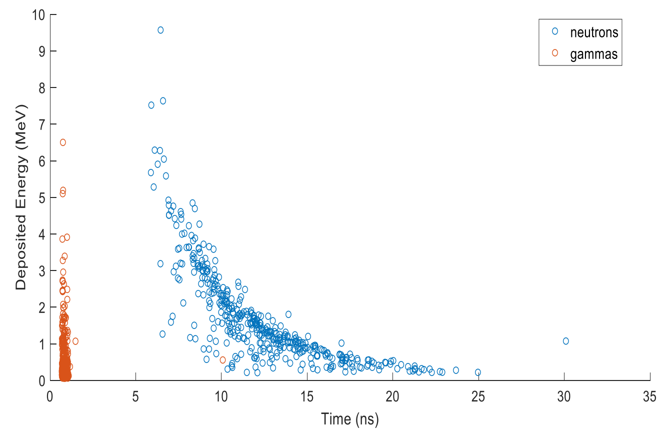
Keywords:
Fast neutron and gamma detection
Organic liquid scintillator detector
Monte Carlo simulations
Non-destructive analysis (NDA)
Nuclear security
Nuclear safeguards

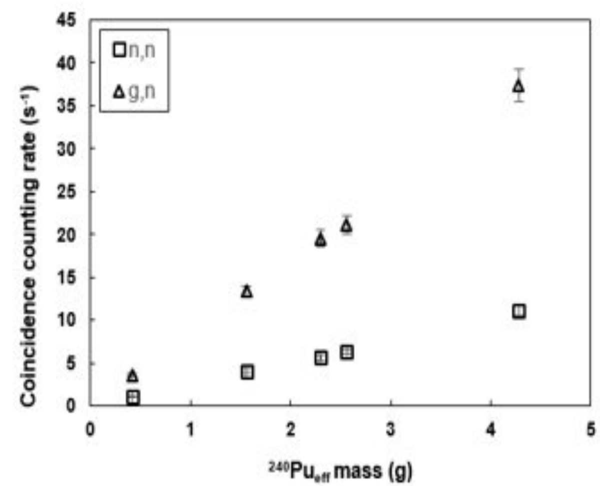
A B S T R A C T

The use of passive and active interrogation techniques to evaluate materials concerning their content of special nuclear materials (SNM) is fundamental in fields such as nuclear safeguards and security. Detection of fast neutrons and γ rays, which are a characteristic signature of SNM, has several potential advantages compared with the commonly used systems based on thermal and epithermal neutron counters, the most important being the much shorter required coincidence times and the correspondingly reduced rate of background events due to accidental coincidences. Organic scintillators are well suited for this purpose due to their fast timing properties and composition being based on carbon and hydrogen with large elastic scattering cross-sections for fast neutrons. Organic scintillators also have suitable detection efficiency for γ rays and exhibit pulse shape properties which are favorable for distinguishing between neutrons and γ rays. This paper presents experimental results and Monte Carlo simulations for a neutron–neutron and γ-neutron coincidence detection setup for identification and characterization of SNM based on such detectors. The measurements were carried out on different samples of PuO_2 material with varying content of ^{240}Pu at the Joint Research Center (JRC) of the European Commission, Ispra, Italy. The results demonstrate significant advantages of fast neutron-γ coincidence detection over fast neutron–neutron coincidence counting for certain applications, e.g. for nuclear security systems, even in the presence of moderate amounts of shielding.

- Coincidence time spectra



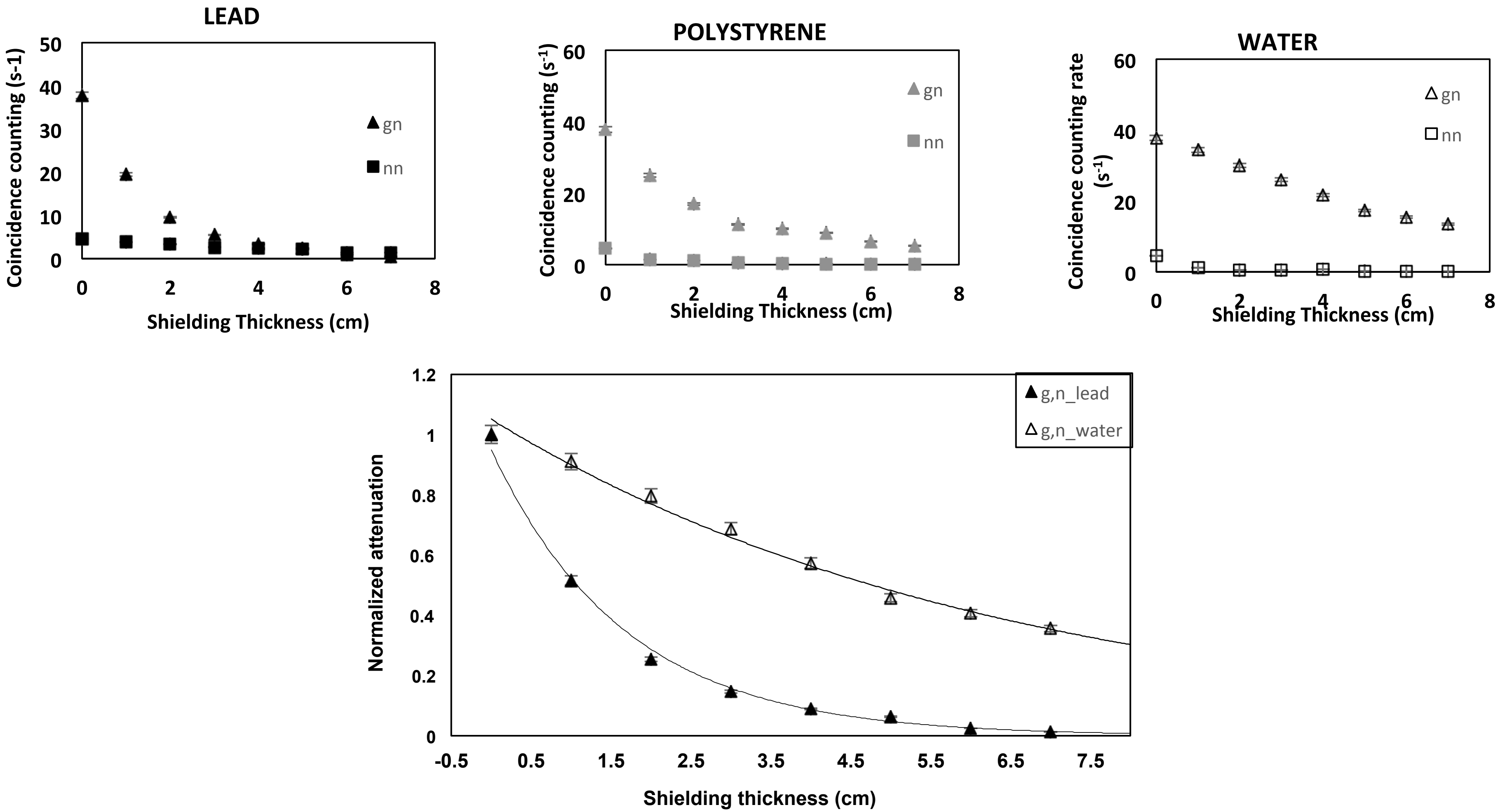




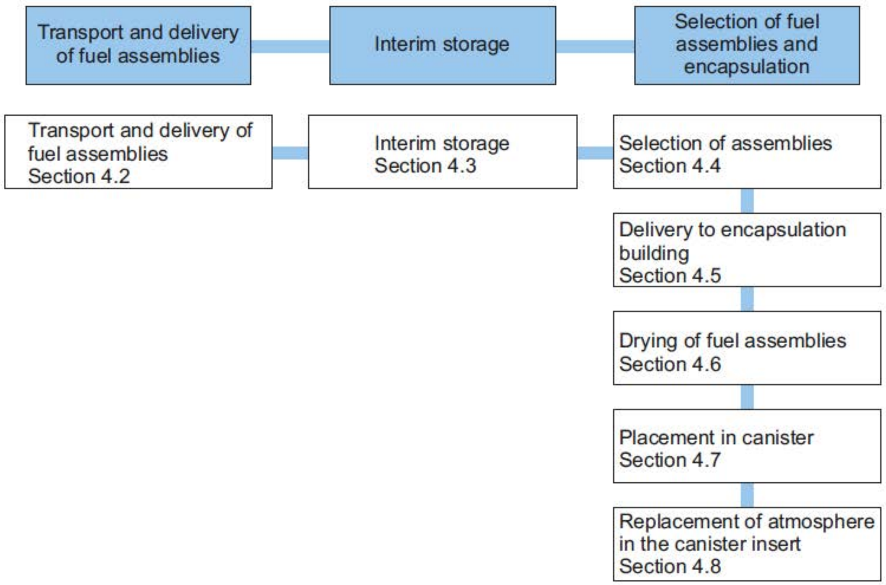
coincidence counting rates as function of $^{240}Pu_{eff}$ mass

Fast neutron and gamma correlations for sensitive detection of SNM - shielding

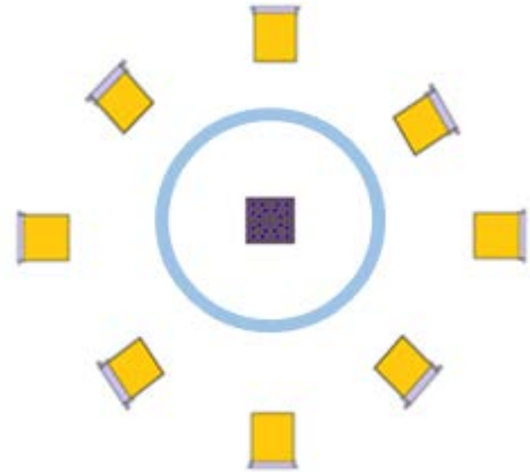
Resistance to shielding

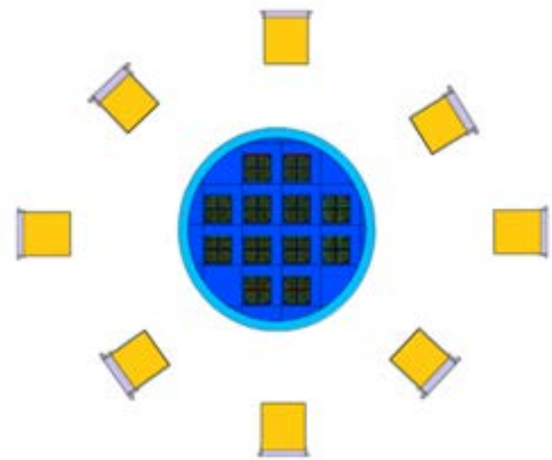


Spent fuel verification



Flow chart for the spent fuel line and its stages. A flow chart for the hand lated spent fuel is provided in the Canister production report,





TR-10-13, Spent nuclear fuel for disposal in the KBS-3 repository, Svensk Kärnbränslehantering AB, December 2010

Spent fuel verification
inside copper canister (+ transport cask)

- **MCNP6.2 COMPUTATIONAL SIMULATION**

Fuel compositon
Cooling Time
Burnup Cycles
3D geometry

SERPENT 2

Burnup calculations

Spent fuel nuclides library

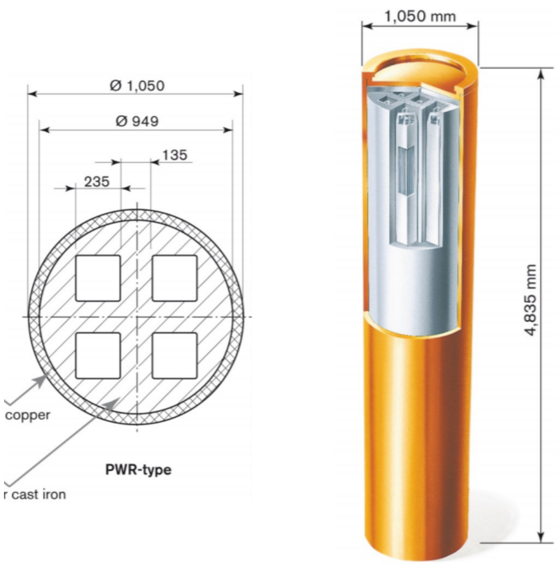
+

Setup geometry
Detector size
Structural Material

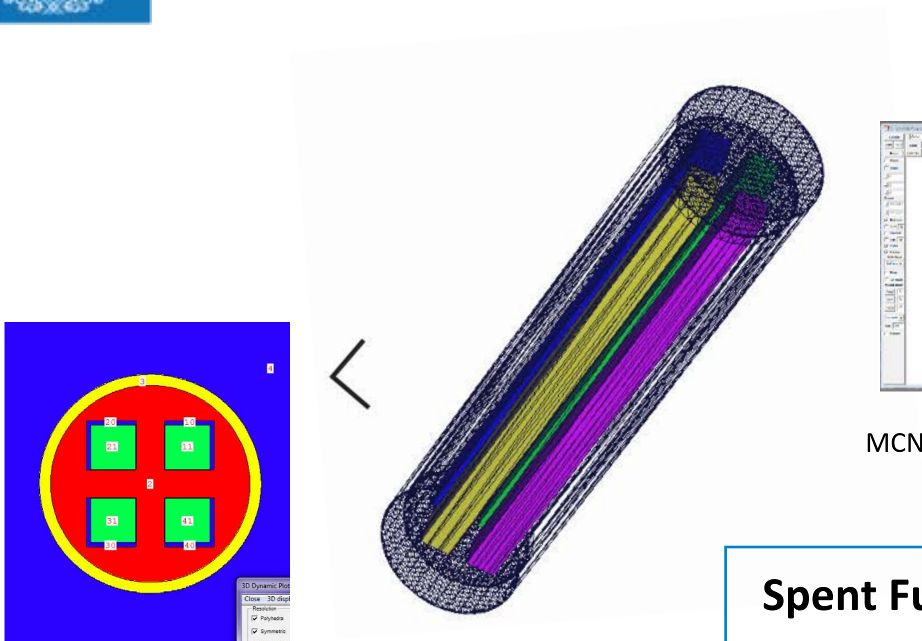
MCNP6.2

Particle transport simulation

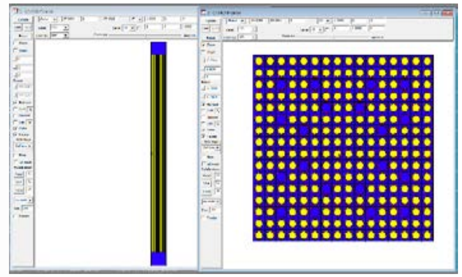
Gamma-ray flux;
Shielding specif.;
Coincidence rates;
Measument time required;
Attenuation of structural materials;
...



Spent fuel verification



MCNP input visualization: PWR assemblies inside copper canister



MCNP input visualization: PWR assembly

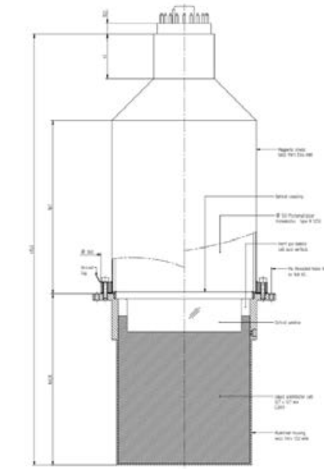
DETECTORS

Nº: 8

Type: EJ-309

Diameter: 12.7cm

Lenght: 12.7cm



Eljen Technology, Neutron/gamma PSD liquid Scintillator EJ-301, EJ-309, (n.d.)

Equivalent to:
44.8MWd/kgHM burnup
38y of cooling time

Spent Fuel design basis

PWR:
4 assemblies

Content:

~8kg of $^{240}Pu_{eff}$
~1.7x10³kg of ^{238}U
~2kg of ^{241}Am

Emission profile:
homogeneous

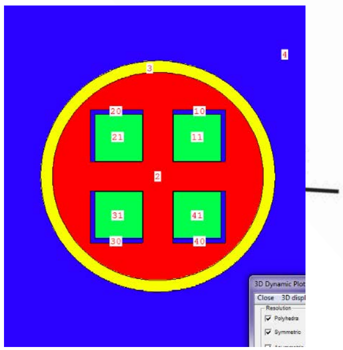
Neutron emission from SF
~10^8n/s

Neutron emission (α,n) reactions
~10^6n/s

Total gamma flux
~10^{16}p/s

$$m(^{240}Pu)_{eff} = m(^{240}Pu) + 2.51m(^{238}Pu) + 1.67m(^{242}Pu)$$

Spent fuel verification



MCNP input visualization: PWR assemblies inside copper canister

Distance from the cask: 15cm
Without shielding

Total neutron count rate at the detectors

45×10^{3} n/s

Total gamma count rate at the detectors

12×10^{7} g/s

Total gamma-neutron coincidences count rate at the detectors

770 gn/s

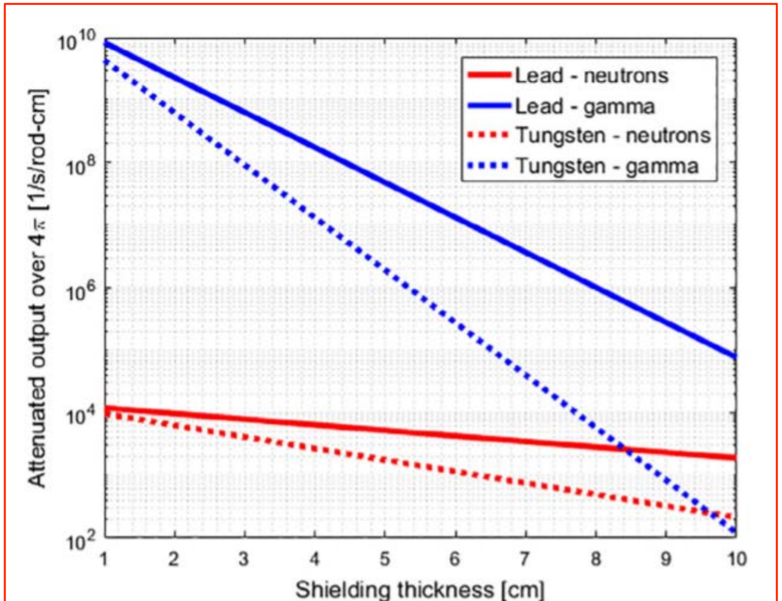
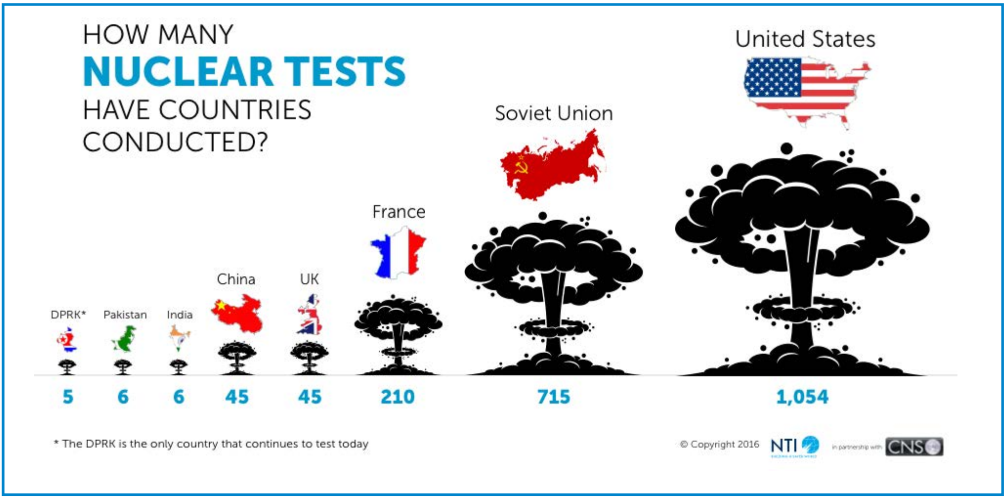


Fig. 8. Attenuation of the photon and neutron source of spent fuel with ~70 MWd/kg of burn-up and more than 10 years of cooling time in lead and tungsten.

Environmental and emergency response

Detection, Characterization and Imaging in the field



NUCLEAR FUEL CYCLE ACCIDENTS

The cleanup of the area surrounding the Chernobyl nuclear disaster is expected to continue for decades, while parts may remain uninhabitable for thousands of years. - NAT GEO IMAGE COLLECTION

A member of Greenpeace Germany's anti-nuclear program takes a radiation reading on the banks of the Techa river in the village of Muslyumovo on Nov. 17, 2010. The village is located 30 kilometres from the Mayak nuclear complex

REGULAR OPERATION

OF REACTORS OR/AND REPROSSECING PLANTS

"According to the 2000 UNSCEAR Report (United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Report 2000: Sources and Effects of Ionizing Radiation, New York, UNSCEAR (2000).), Pu nuclides produced and globally dispersed in atmospheric nuclear testing sum up to around 156PBq. The document also presents estimated values of Pu nuclides (238Pu, 239Pu, 240Pu) distributed on the earth's surface as 3500 kg by atmospheric nuclear weapons test and 100 kg by underground tests. The TECDOC-1663 (Radioactive particles in the Environment: Sources, Particle Characterization and Analytical Techniques, IAEA-TECDOC-1663, 2011) presents quantities of radionuclides released into the environment from the Chernobyl accident, around 0.5 PBq of Pu nuclides was estimated. The same document points out, "At Sellafield, discharges into the Irish Sea amounted to about 1.3PBq between 1950 and 1992, including significant amounts of transuranium nuclides, i.e. 0.72 PBq."

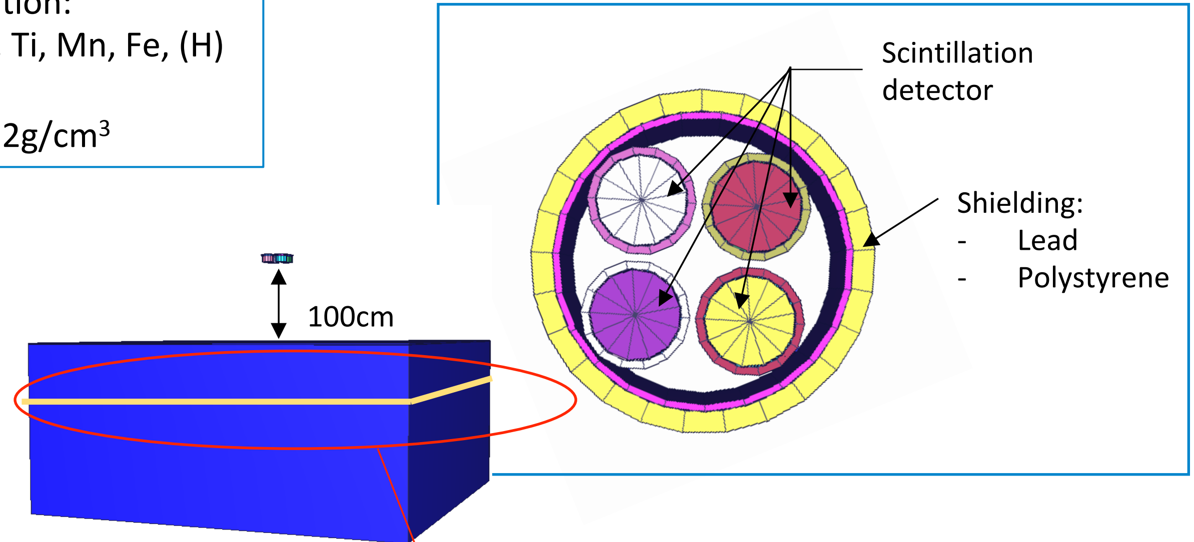
Environmental and emergency response

SOIL

- Composition:
  O, Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, (H)
- Density: 1.52g/cm^3

Pu^{240}/Pu^{239}
- Weapon testing fallout =0.165
- FNPP reactor core = 0.356

DETECTORS ASSEMBLY



SOURCE

SMALL: 18cm^3

LAYER: 900cm^2

DEPTHS: 10, 20, 30, 40, 50, 100cm

Pu^{240}/Pu^{239} = 0.2

Pu_{eff} mass= 2.3g

Nuclides distribution;
Soil constitution;

+

Setup geometry
Detector size
Structural Material

MCNP6.2

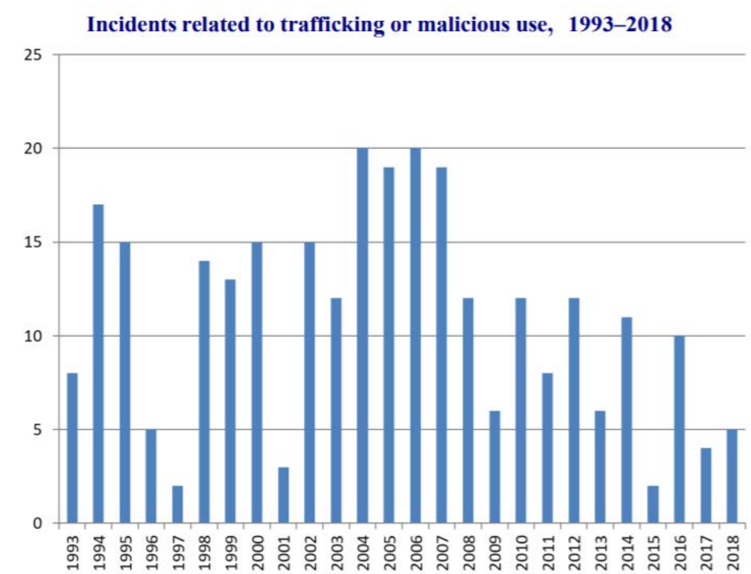
Particle transport simulation

Shielding specif.;
Coincidence rates;
Measument time required;
...

Radiation Portal Monitors
"Multi-messenger" signatures of SNM using time and energy correlations

- **MOTIVATION**

  - **Unauthorized activities and events involving nuclear and other radioactive material** – still happens!



Incidents reported to the ITDB that are confirmed, or likely, to be connected with trafficking or malicious use, 1993–2018.

IAEA Incident Trafficking Database (ITDB) 2019 Fact Sheet

Criminal organizations, some with ties to the Russian KGB's successor agency, are driving a thriving black market in nuclear materials in the tiny and impoverished Eastern European country of Moldova - BBC News – Oct., 7, 2015.

Radiation Portal Monitors
“Multi-messenger” signatures of SNM using time and energy correlations

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

- **MOTIVATION**

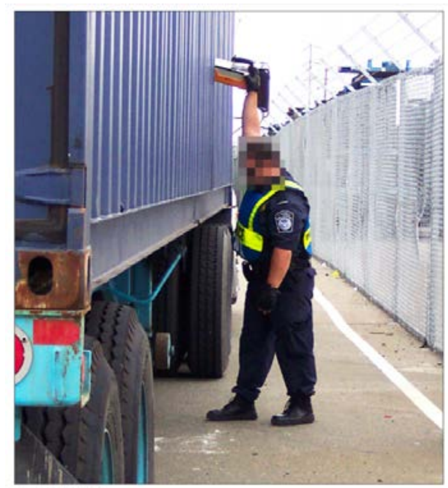
  - **Unauthorized activities and events involving nuclear and other radioactive materials** – still happens!

  - **Necessity of improvements on threat discrimination** - minimizing “nuisance” alarms created by NORM;

- NORM (uranium, thorium, ^{40}K)
- Medical Isotopes

↓

Secondary Inspection



Radiation Portal Monitors
"Multi-messenger" signatures of SNM using time and energy correlations

- **MOTIVATION**

  - **Unauthorized activities and events involving nuclear and other radioactive material** – still happens!

  - **Necessity of improvements on threat discrimination** - minimizing "nuisance" alarms created by NORM and false positive;

  - **The future shortage of He-3** – investigation of technology substitution;

Helium-3 Shortage Could Mean Nuke Detection 'Disaster'

2010/04/helium-3-shortage-could-mean-nuke-detection-disaster/

Radiation Portal Monitors
"Multi-messenger" signatures of SNM using time and energy correlations

- **MOTIVATION**

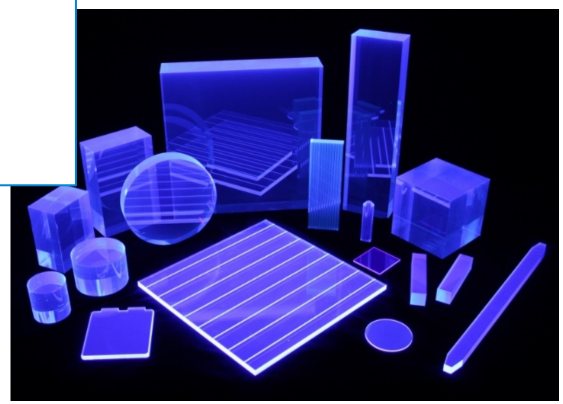
  - **Unauthorized activities and events involving nuclear and other radioactive material** – still happens!

  - **Necessity of improvements on threat discrimination** - minimizing "nuisance" alarms created by NORM and false positive;

  - **The future shortage of He-3** – investigation of technology substitution;

  - **High potential of organic scintillator detectors**

- H and C based composition
- Fast neutrons and gamma-rays
↓ measurement time
↑ sensitivity



Radiation Portal Monitors
"Multi-messenger" signatures of SNM using time and energy correlations

- **MOTIVATION**

  - **Unauthorized activities and events involving nuclear and other radioactive material** – still happens!

  - **Necessity of improvements on threat discrimination** - minimizing "nuisance" alarms and false positives created by NORM;

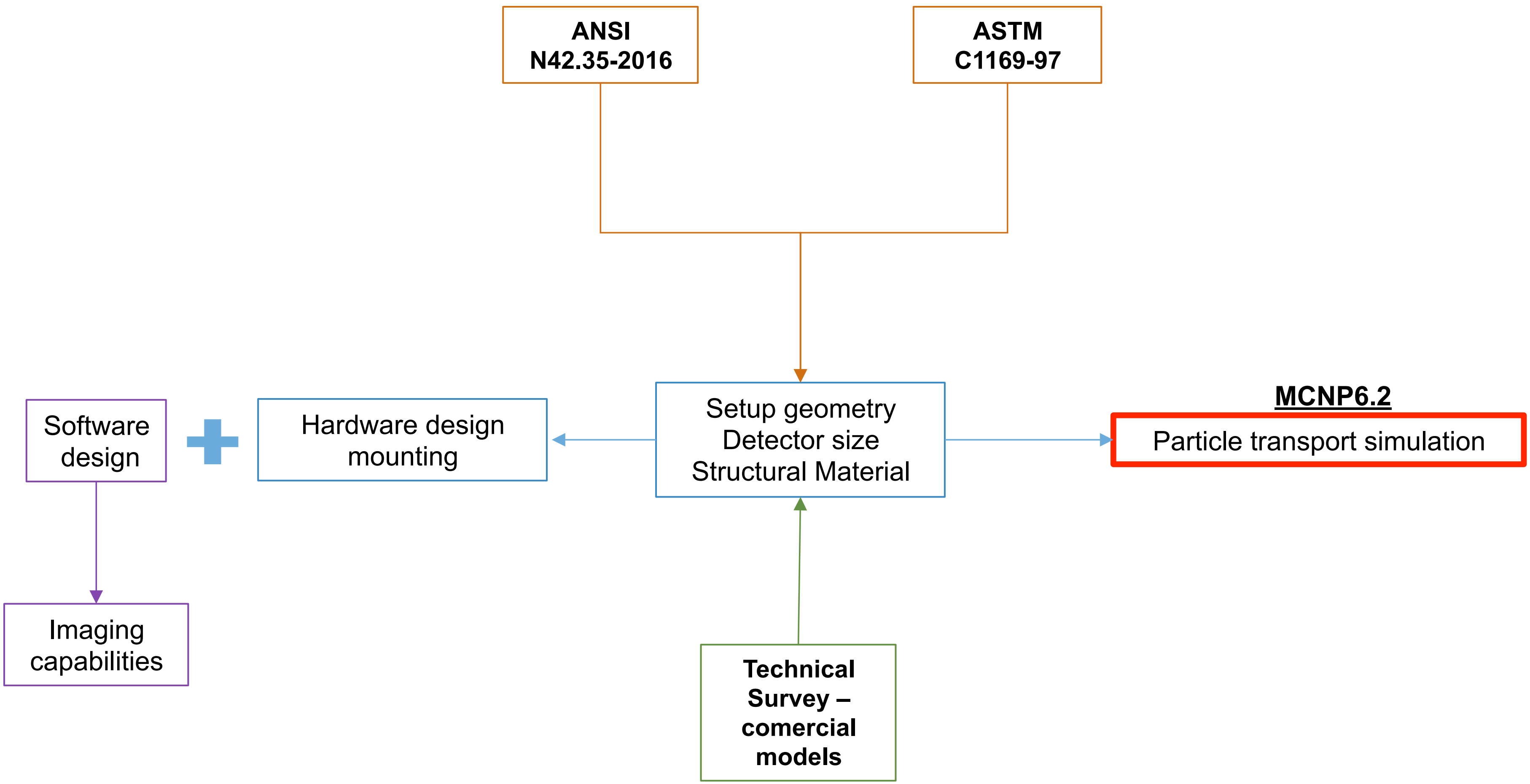
  - **The future shortage of He-3** – technology substitution;

  - **High potential of organic scintillator detectors**

<u>OBJECTIVE</u>

Detection, Characterization and Imaging

Radiation Portal Monitors
"Multi-messenger" signatures of SNM using time and energy correlations



- **MCNP6.2 – COMPUTATIONAL SIMULATIONS**

SOURCES

- **Cf-252 20,000ns^{-1} emission (ANSI N.42-35)**
  - Bare: encapsulated by 1cm of steel and 0.5cm lead
  - Moderated: spherical container of 4cm thick high-density polyethylene (HDPE)

- **Cf-252 1,000ns^{-1} emission (CVN.6)**
  - Nominal mass=10E-6g
  - Encapsulation: 0.78cm of stainless steel canister

- **PuO_2**
  - less than 6% of ^{240}Pu and around 93% of ^{239}Pu - **(ASTM C1169)**

Sample ID	**1**	**4**
Isotope	Unit (g)	
^{238}Pu	0.001	0.064
^{239}Pu	6.184	4.140
^{240}Pu	0.417	1.679
^{241}Pu	0.004	0.099
^{242}Pu	0.003	0.278
^{240}Pu$_{eff}$	0.42	2.30
Total mass	6.716	6.719

- **MCNP6.2 – COMPUTATIONAL SIMULATIONS**

SOURCE MODEL VALIDATION - **Cf-252 (ANSI N.42)**

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 929, 11 June 2019, Pages 107-112

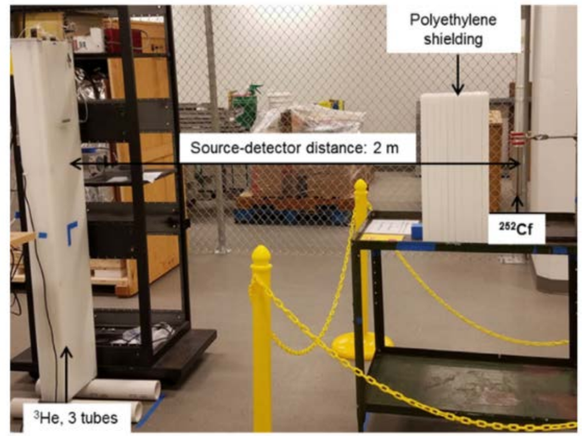
Comparative neutron detection efficiency in He-3 proportional counters and liquid scintillators

S.A. Pozzi [a], S.D. Clarke [a], M. Paff [a], A. Di Fulvio [a], R.T. Kouzes [b]

⊞ Show more

https://doi.org/10.1016/j.nima.2019.03.027

Get rights and content



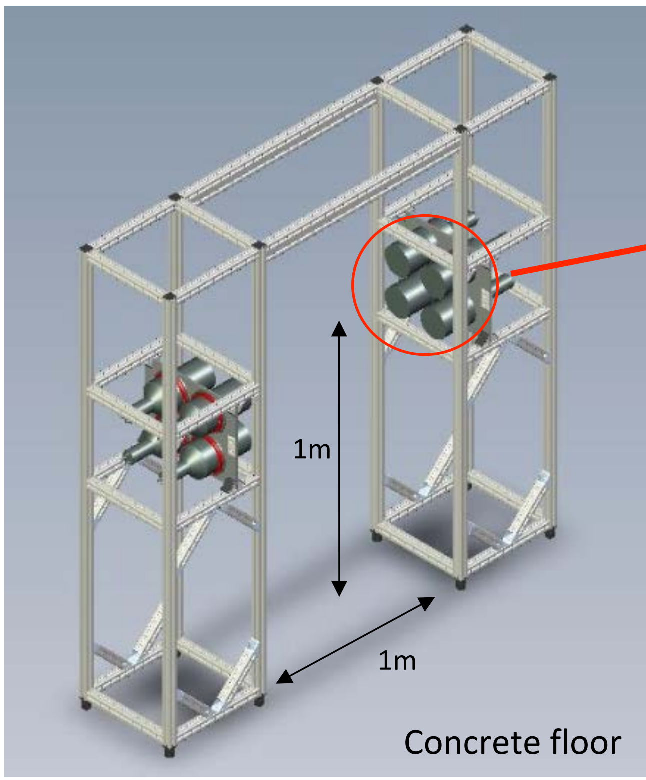
Cf-252 source		Neutron flux	
		bare	moderated
This work	MCNP6.2	17.0 ±0.1 $s^{-1}cm^{-2}$	11.0 ±0.1 $s^{-1}cm^{-2}$
Pozzi et al.	Measurement	18.0 $s^{-1}cm^{-2}$	13.0 $s^{-1}cm^{-2}$
	MCNPX –PoliMi	24.5 $s^{-1}cm^{-2}$	17.0 $s^{-1}cm^{-2}$

RPM Prototype development

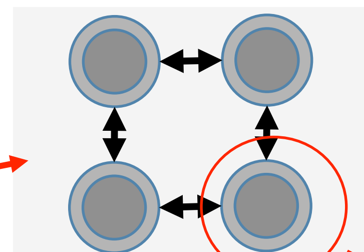
- **MCNP6.2 – COMPUTATIONAL SIMULATIONS**

RPM DESIGN – LIQUID SCINTILLATORS

DOUBLE SIDED RPM



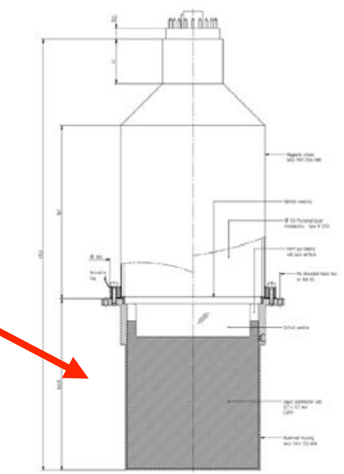
DETECTION ASSEMBLY



DETECTOR EJ-309

Diameter: 12.7cm

Lenght: 12.7cm



Eljen Technology, Neutron/gamma PSD liquid Scintillator EJ-301, EJ-309, (n.d.)

KTH VETENSKAP OCH KONST

RPM Prototype development

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

8x EJ-309 127 cm2 x 13 cm liquid scintillation detectors

DACQ based on high-speed digitizers

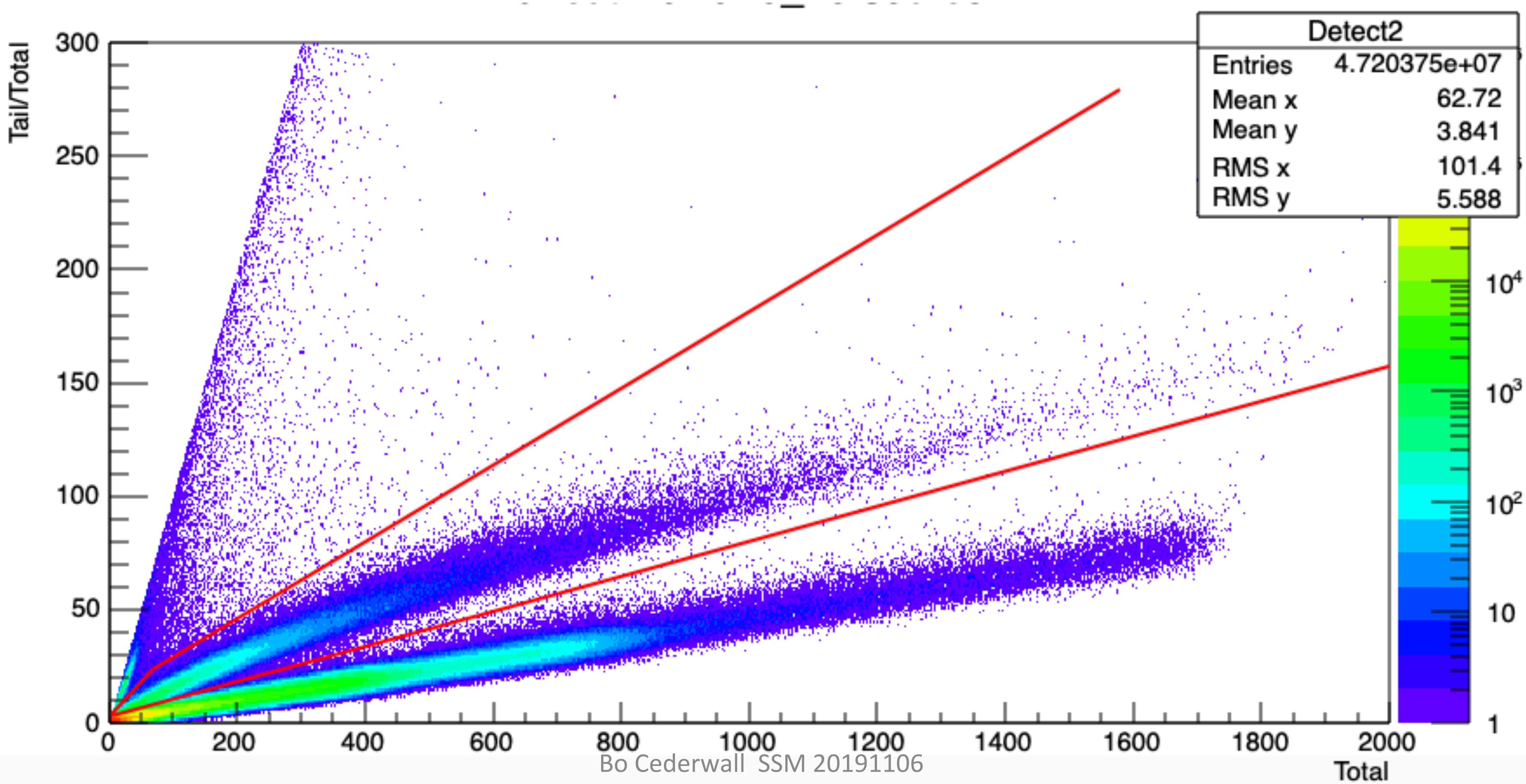
- 8x 14 bit, 500 MHz
- Online n/γ PSD

RPM Prototype development

RPM prototype development

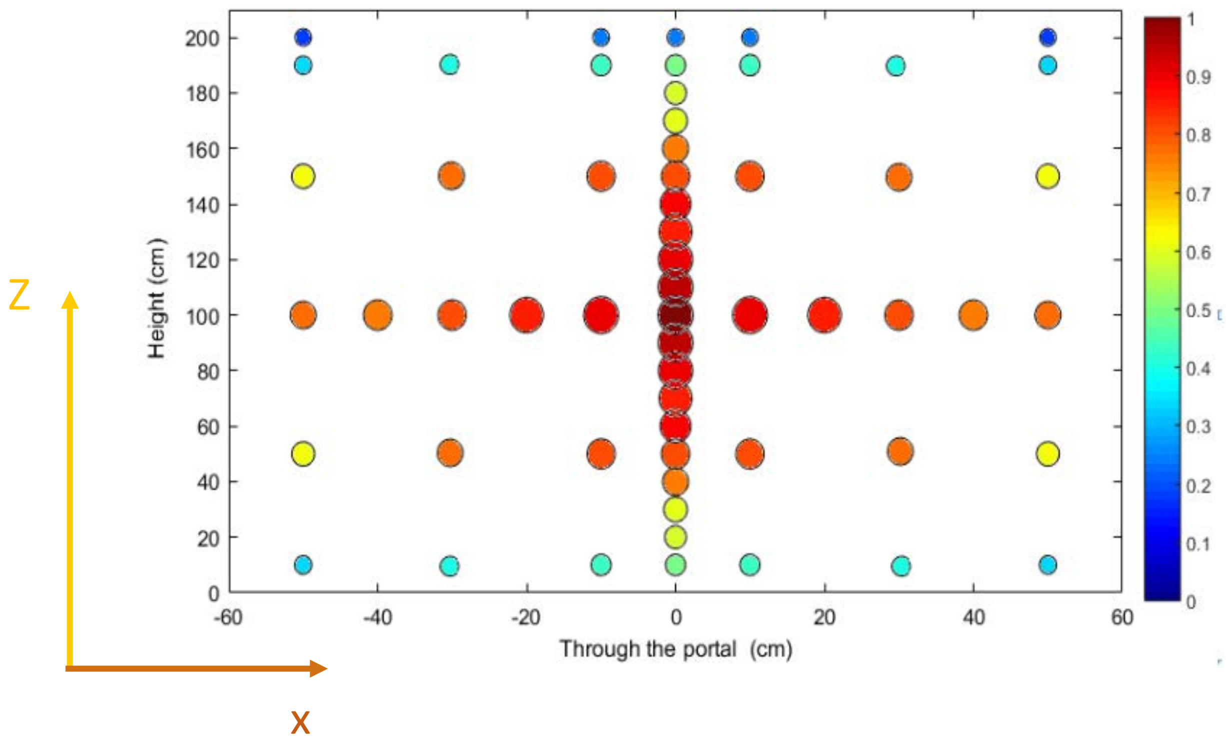
Strål säkerhets myndigheten
Swedish Radiation Safety Authority

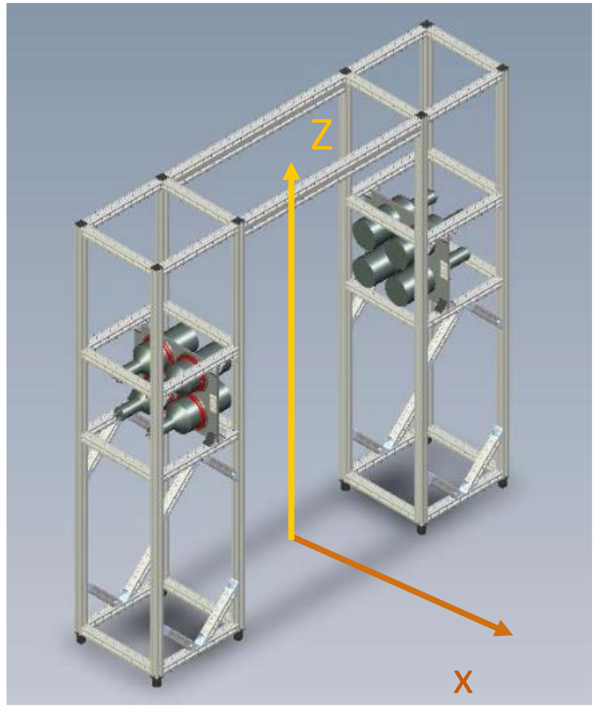
PROTOTYPE DATA - PULSE SHAPE DISCRIMINATION



RESULTS – SENSITIVITY MAP

Single-neutron

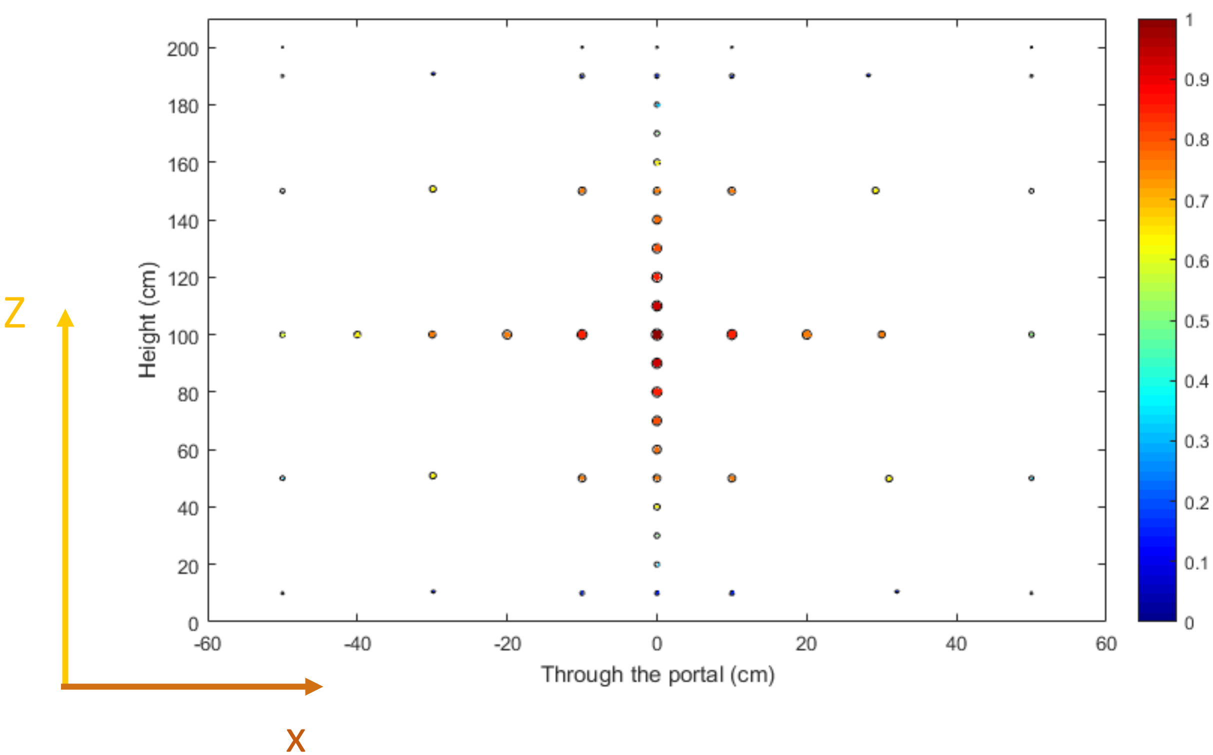


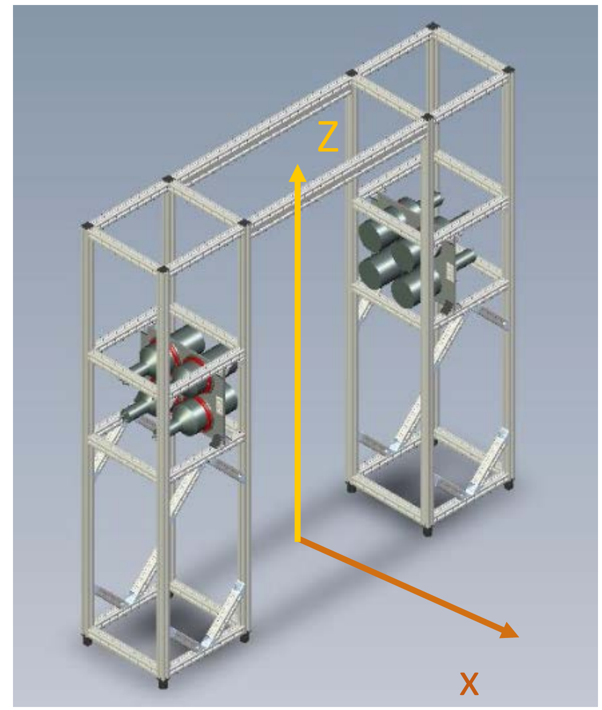


RPM Prototype development

RESULTS – SENSITIVITY MAP

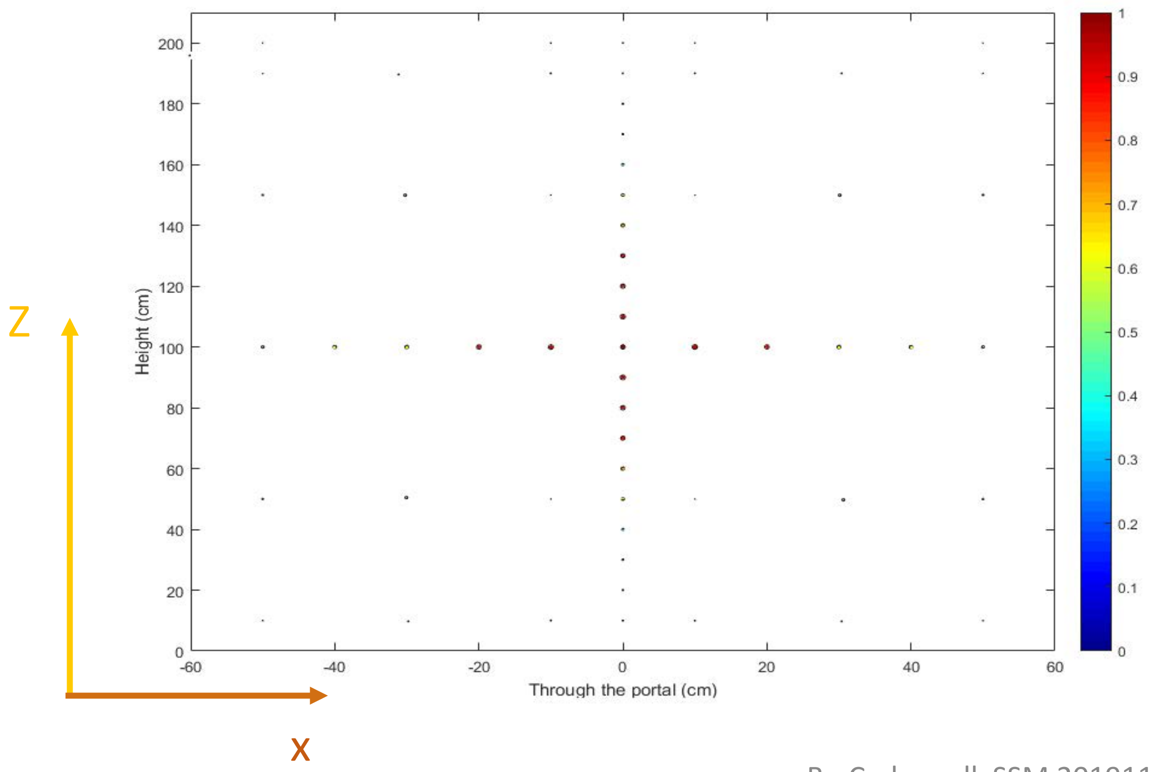
Gamma-neutron

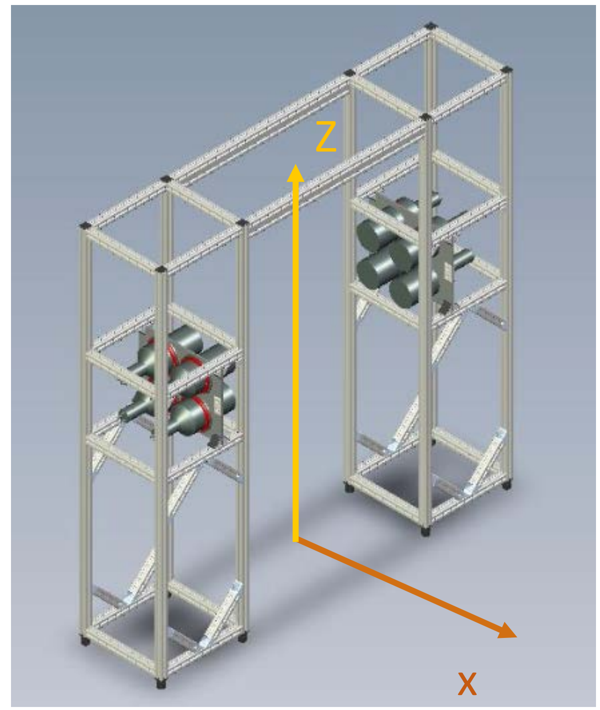




RESULTS – SENSITIVITY MAP

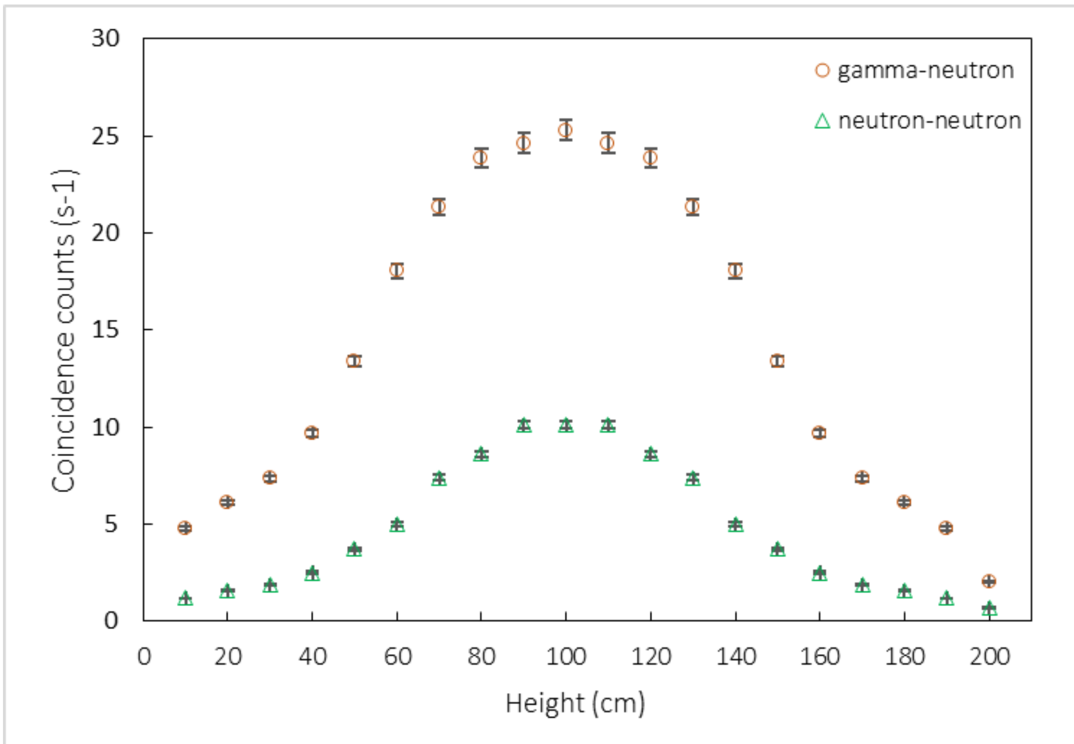
Neutron-neutron





RPM Prototype development

RESULTS – Coincidence Rates inside the detection zone

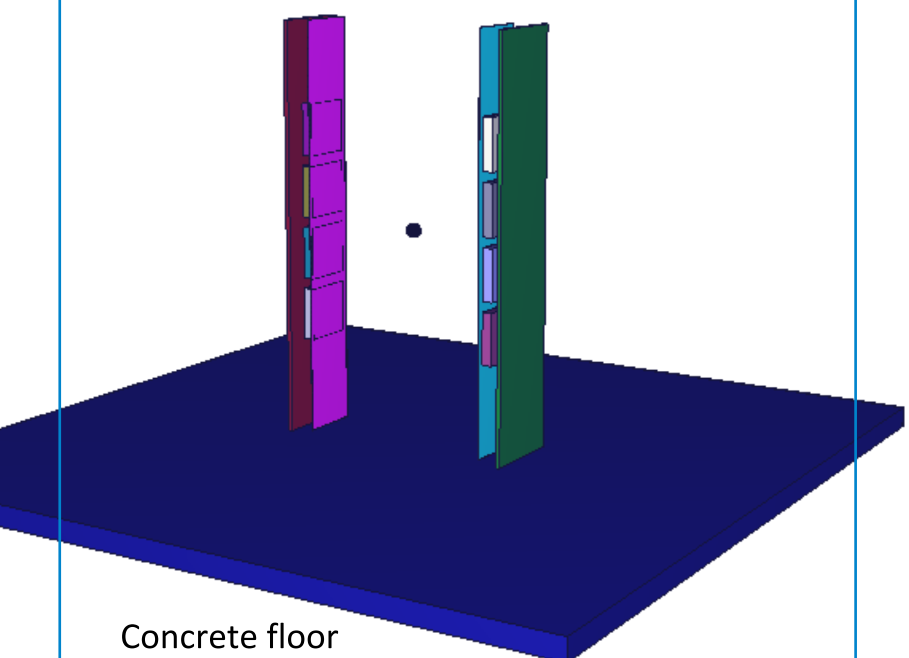


RPM Prototype development

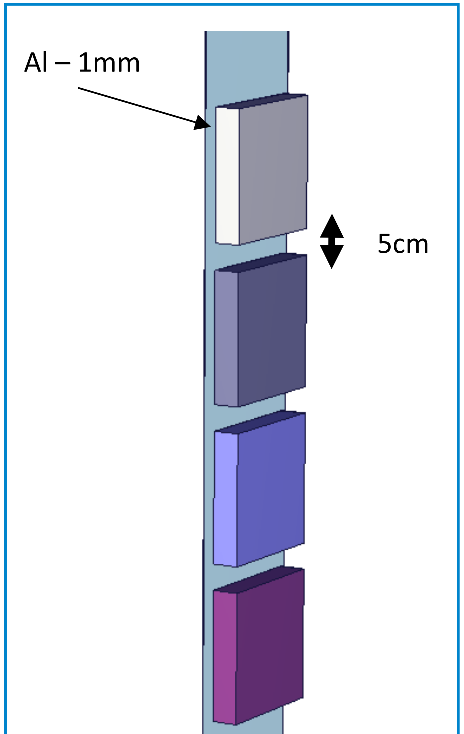
- **MCNP6.2 – COMPUTATIONAL SIMULATIONS**

ALTERNATIVE RPM DESIGNS – SOLID ORGANIC SCINTILLATORS (PLASTIC, STILBENE …)

DOUBLE SIDED RPM



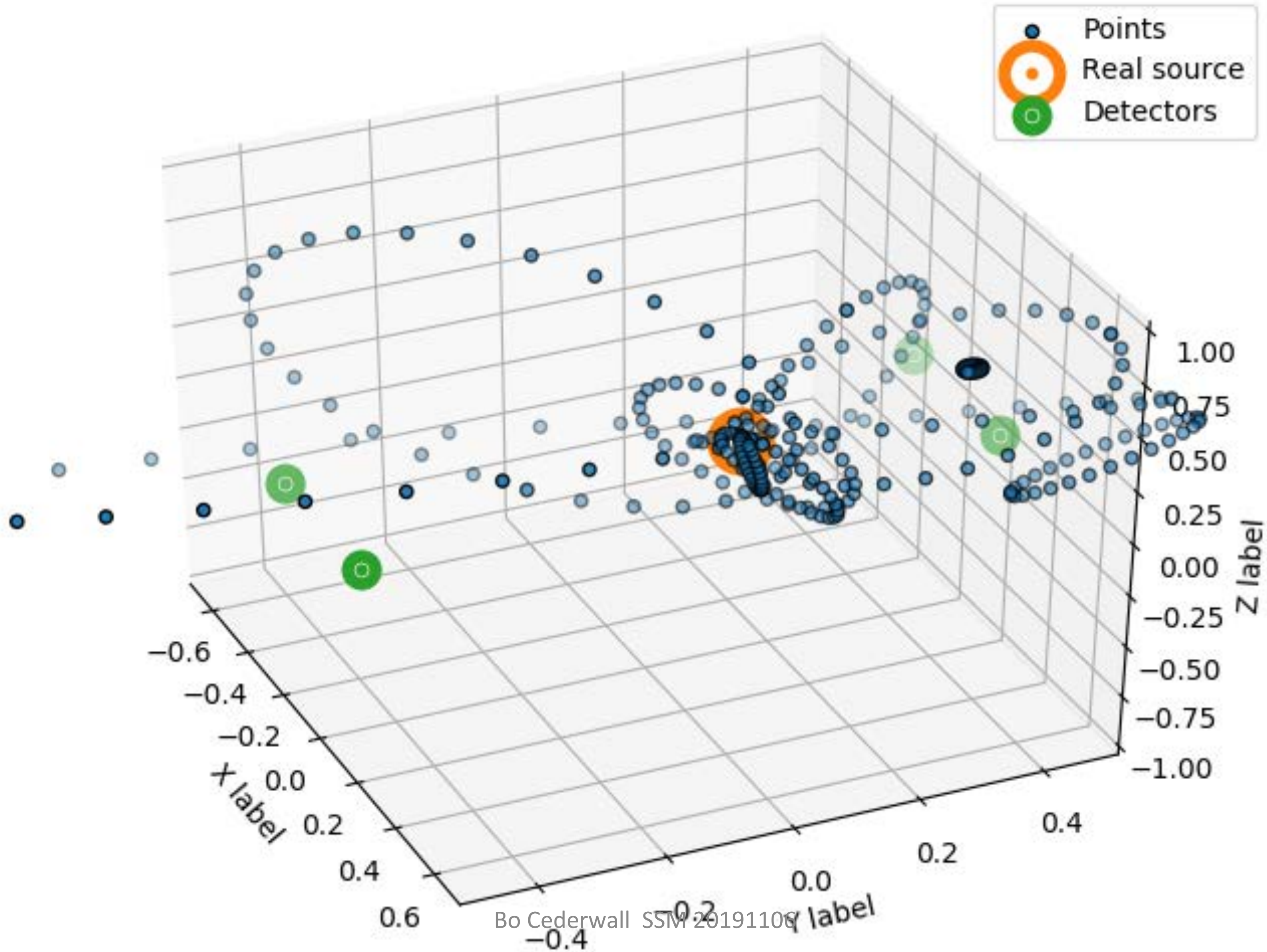
DETECTION ASSEMBLY



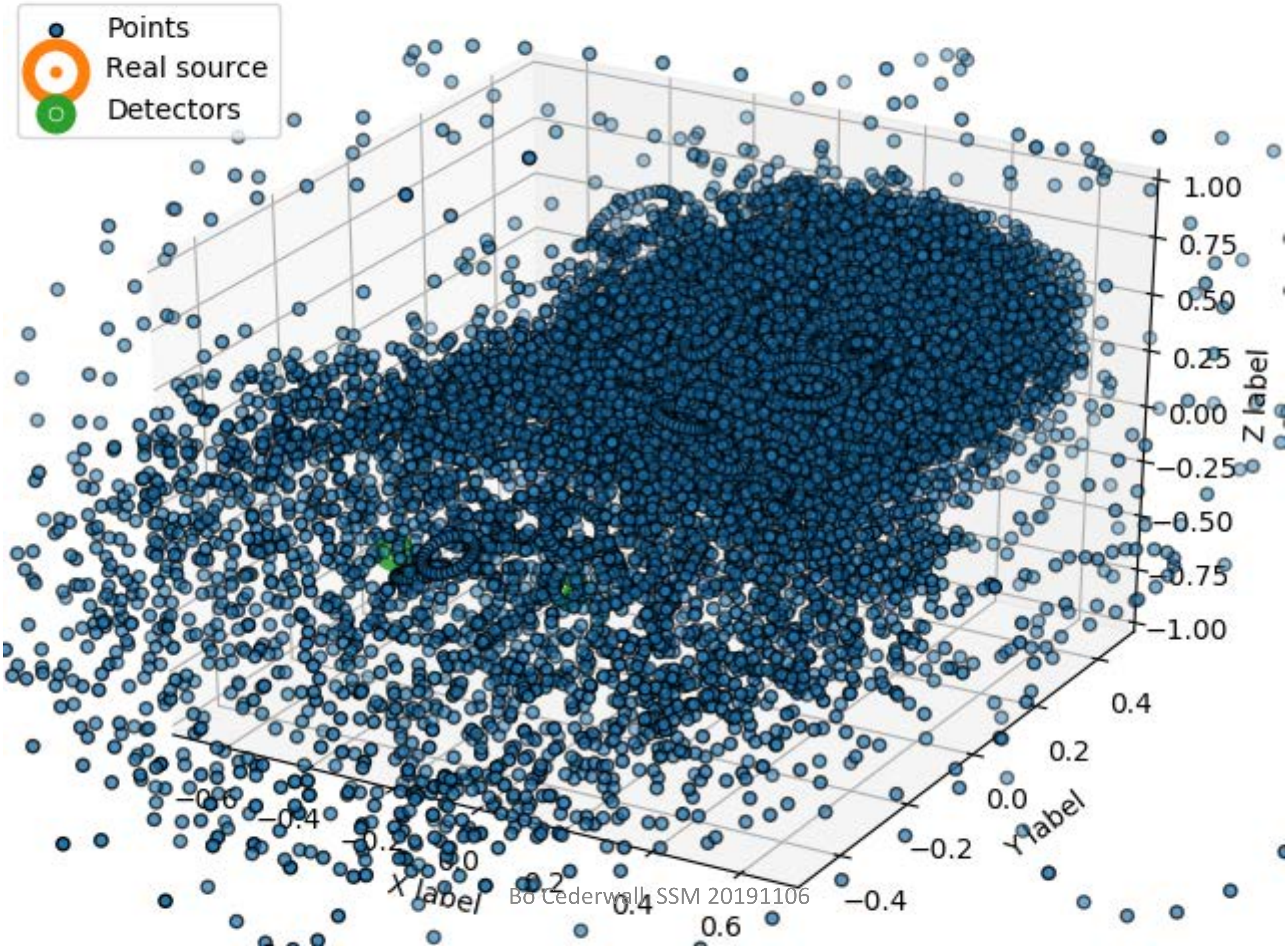
DETECTOR EJ-299

Area: 25cm x 25cm
Thickness: 25cm

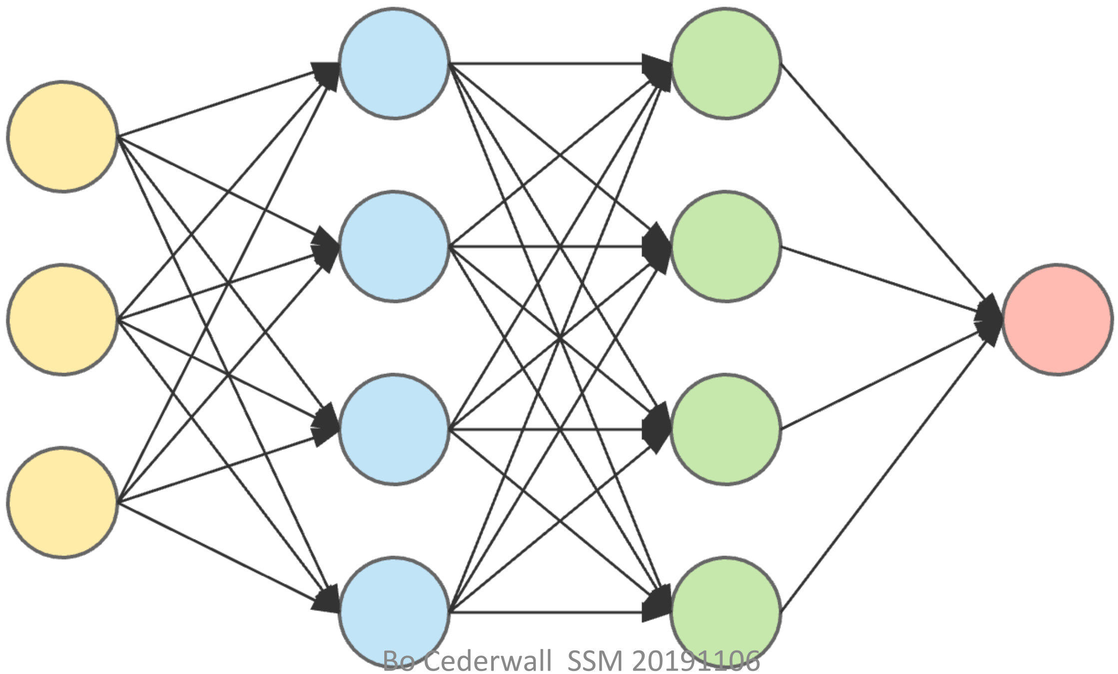
SNM Imaging algorithms



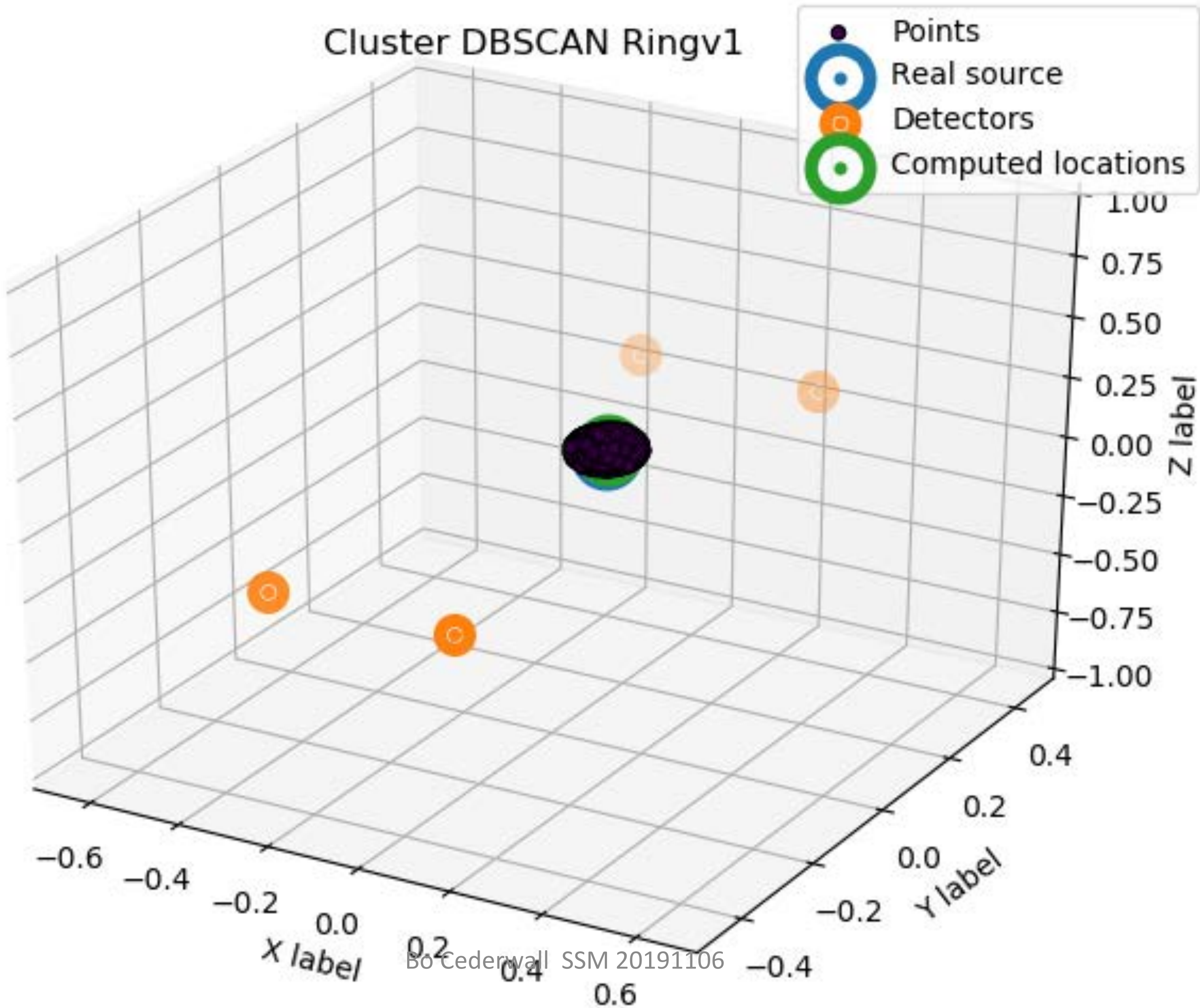
SNM Imaging


Points
Real source
Detectors
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
Z label
0.4
0.2
0.0
−0.2
−0.4
Y label
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
X label

Imaging and Deep Learning



SNM Imaging



Cluster DBSCAN Ringv1
Points
Real source
Detectors
Computed locations
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
Z label
0.4
0.2
0.0
−0.2
−0.4
Y label
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
X label

SUMMARY

- Fast γ-neutron correlations (in conjunction with other methods like high-resolution gamma-ray spectroscopy not discussed here) are being developed as a novel sensitive tool to detect SNM for NDA in passive and active interrogation scenarios.

- The method is inspired by techniques used in state-of-the-art nuclear physics experiments using arrays of liquid organic scintillation detectors, high-speed sampling ADCs ("digitizers") and pulse processing algorithms for discriminating between neutrons and γ-rays.

- Applied to Nuclear Safeguards, Nuclear Security, and Environmental applications.

    - RPM applications

    - "In-situ" spent fuel verification and imaging before final repository

    - Environmental surveying, emergency response