Neutron-Gamma Emission Tomography for radioactive waste characterization

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My great grandmother Draga Hultkvist née Simić (1875 – 1953).
with her husband Arthur Hultkvist (1873 – 1926)

How love came to play an important role in Serbian-Swedish relations in the beginning of the 20th century

Following the break up with Norway in early June, 1905, Sweden entered the reorganization of its diplomatic services. The Swedish government sent a proposal to the Serbian government in early March 1907 to start negotiations where the main goal would be concluding a trade agreement with Serbia. Serbia was at that time in a trade war with the Austro – Hungarian Empire and readily accepted the proposal by signing a trade agreement between the two countries on April 11th in Belgrade. This agreement also represented the backbone of their bilateral relations up until the creation of Yugoslavia.

In order to increase its exports to Sweden, the Kingdom of Serbia opened another Honorary Consulate in Norrköping in October 1907. The duty of the consul was entrusted to engineer Arthur Hultkvist, director of municipal services in this industrial city. Hultkvist was married to Draga Simić (originating from Negotin, Serbia), a cousin of the Radical Party politician and statesman **Pera Velimirović**.
Draga and Arthur met in Zürich in the 1890s where Draga was granted a scholarship by the Serbian government. She studied literature, pedagogy and ethics at the Faculty of Philosophy, from 1893 up to her marriage in 1897.

Thanks to Dusko Topalović

KTH Nuclear Physics Divison

Experiment

Prof. Bo Cederwall (Head of Division)
Prof. Ayse Ataç Nyberg
Dr Torbjörn Bäck, senior lecturer
Prof. em. Arne Johnson
Dr Igor Tawrovskyi, researcher
Dr Sarabjot Kaur, researcher
Dr Arshiya Sood, postdoc
Ebba Ahlgren Cederlöf, PhD stud.
Linda Eliasson, PhD stud.
Vivian Peters, PhD stud.
Jana Vasiljević, PhD stud.

Kåre Axell, SSM (affil.)

Master students

Theory

Assoc. Prof. Chong Qi
Prof. em. Roberto Liotta
Prof. em. Ramon Wyss
Daniel Karlsson, PhD stud.

Mission – Nuclear Science and Technology

“Fundamental” research funded by VR, KAW, GGS

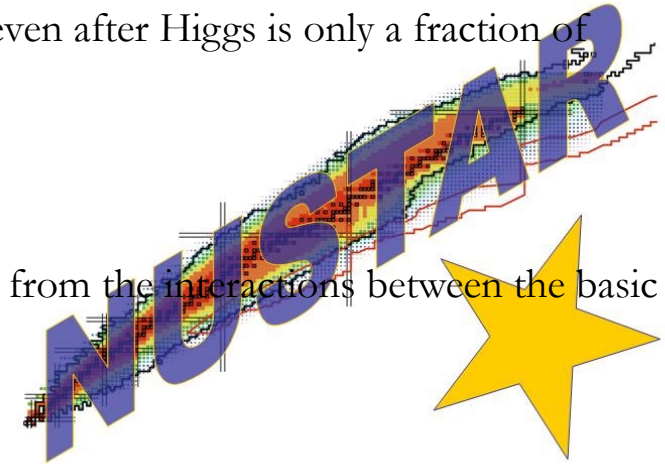
Understanding the strong force as a manifestation in nuclear properties (even after Higgs is only a fraction of hadron and nuclear masses explained)

•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?

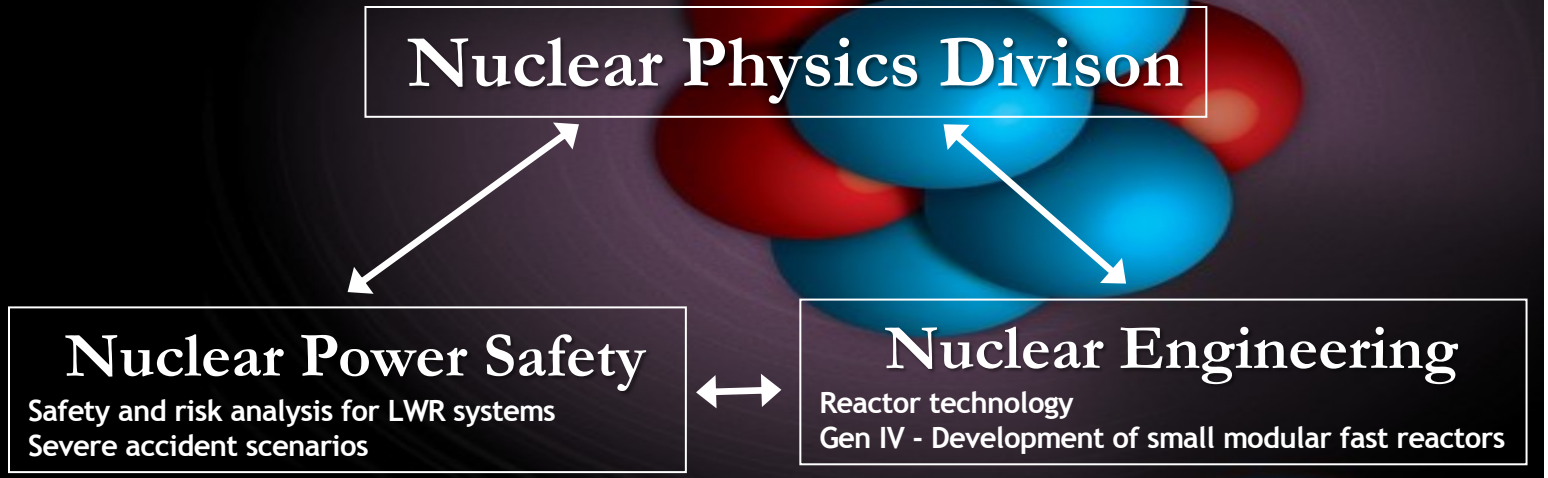


“Applied” research
funded by SSM, VR, KTH Innovation, Vinnova, Swedish Foundation for Strategic Research

Radiation sensing applications in

- **Nuclear Safeguards and Security**
- **Environmental**
- Nanodosimetry
- Medical Imaging

KTH Department of Physics
Strong applied nuclear research environment



The Physics Department includes also Particle and Astroparticle Physics, Condensed Matter Physics, Physics of Medical Imaging)

KTH Nuclear Safeguards and Security

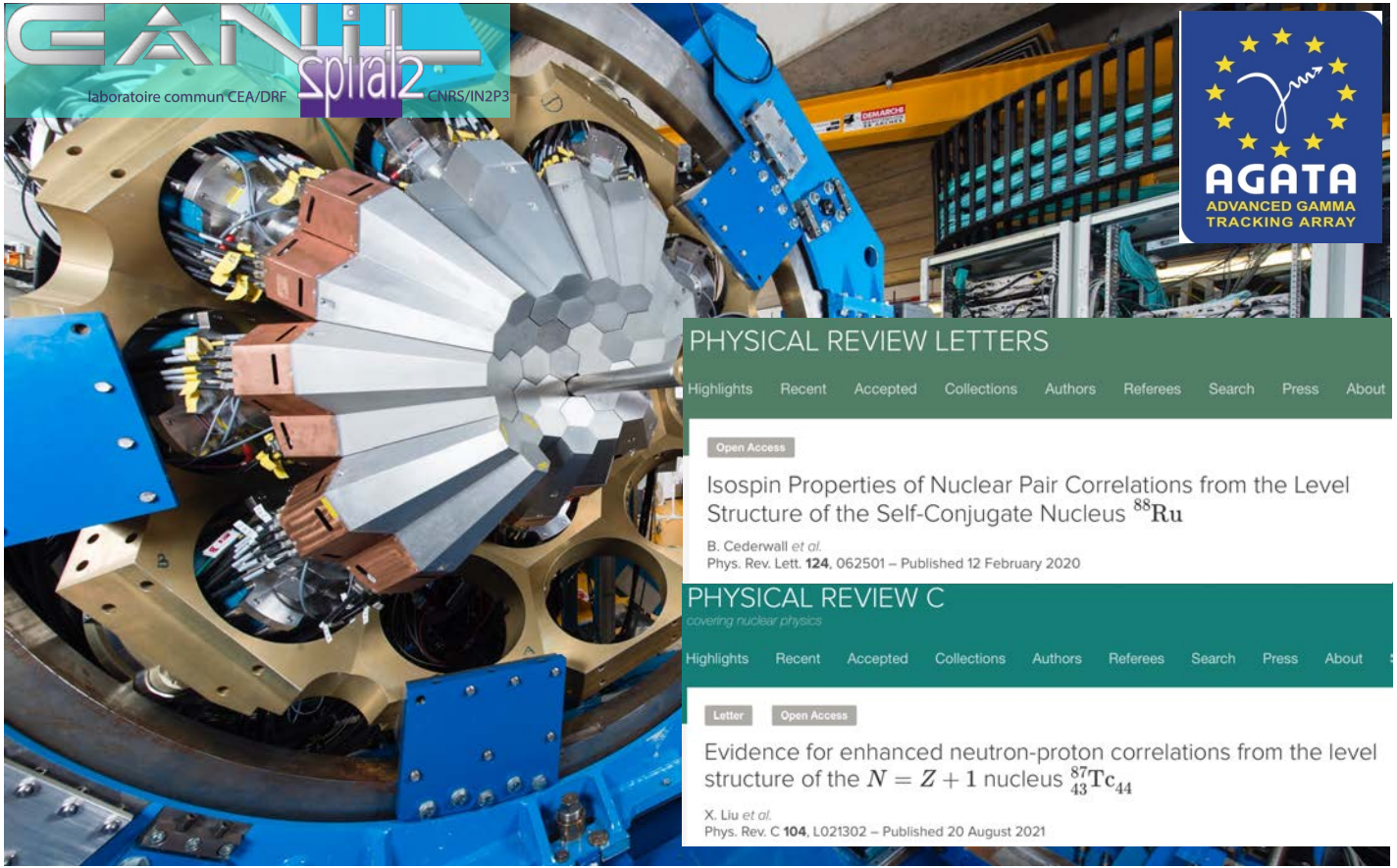
Approach
Passive and active NDA techniques for safeguards and security
Development of instrumentation and methods
MC simulations based on MCNP6, GEANT4 and Serpent2

This project:
Focus on **particle correlations (energy, time, space) as characteristic signatures of SNM**

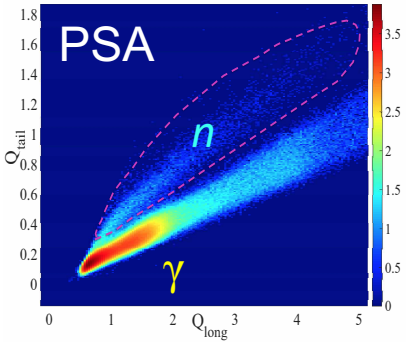
- Enhanced sensitivity for SNM
- Rapid and precise Imaging
- Target: **legacy waste** (there are ~ 10 000 legacy waste drums in Sweden
  mixed composition, poorly documented contents and origin (nuclear research, medical …)

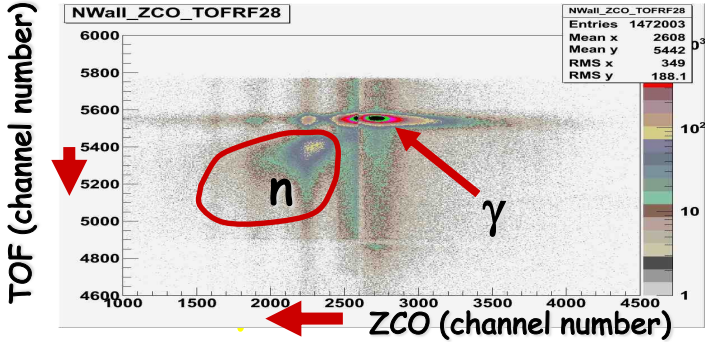
MC modeling Prototype development
- Security – RPM systems
- Safeguards - Verification of radioactive waste (legacy waste, spent fuel …)

Fast neutron - γ correlation technique adapted from fundamental nuclear physics experiments



Fast neutron - γ correlation technique adapted from fundamental nuclear physics experiments





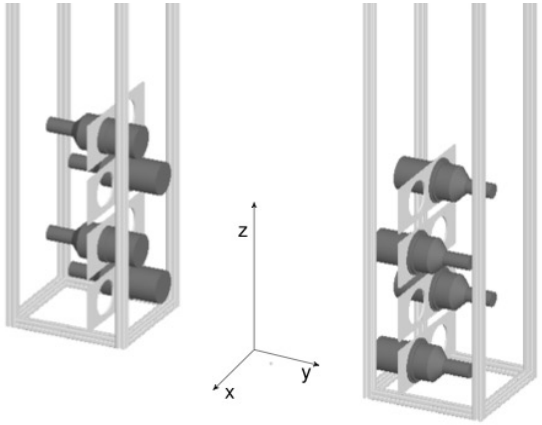
Prototype system for Nuclear Security and Safeguards

Swedish Foundation for Strategic Research

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

VINNOVA

Radiation Portal Monitor for general purpose and special nuclear materials detection



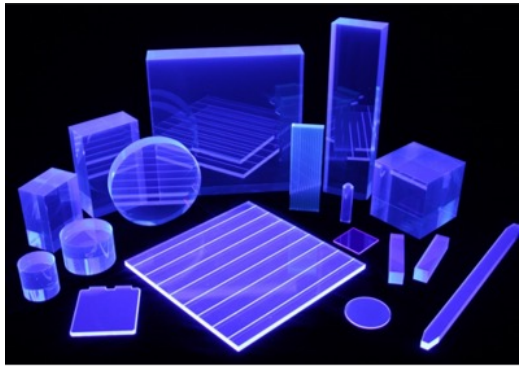
RPM Prototype Development

8x EJ-309 127 mm diameter x 127 mm length liquid scintillation detector

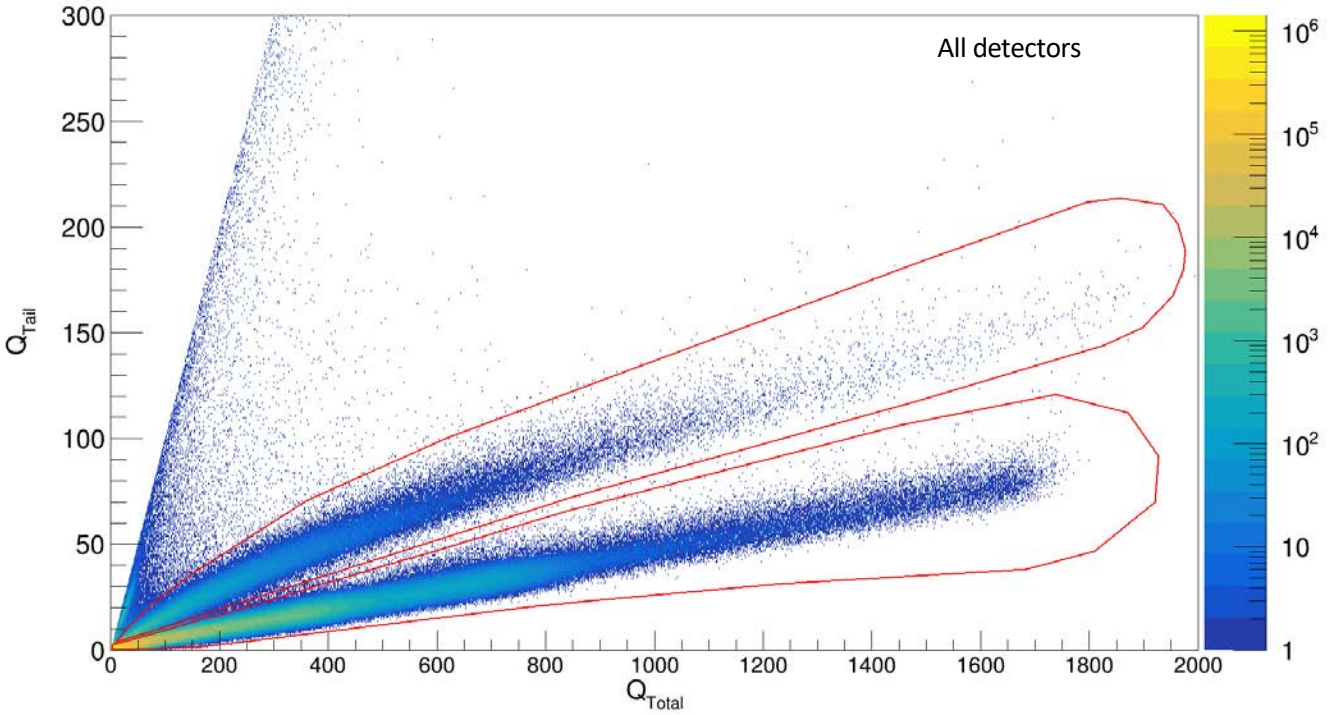
DACQ based on high-speed digitizers

- 8x 14 bit, 500 MHz
- Online n/γ PSD

Future development: EJ-276 plastic scintillators



RPM prototype data - PSD



Neutron-Gamma Emission Tomography (NGET)

Schematic illustration of NGET*

Probability density function (PDF) following the detection of a single correlated gamma-neutron pair from one fission event.

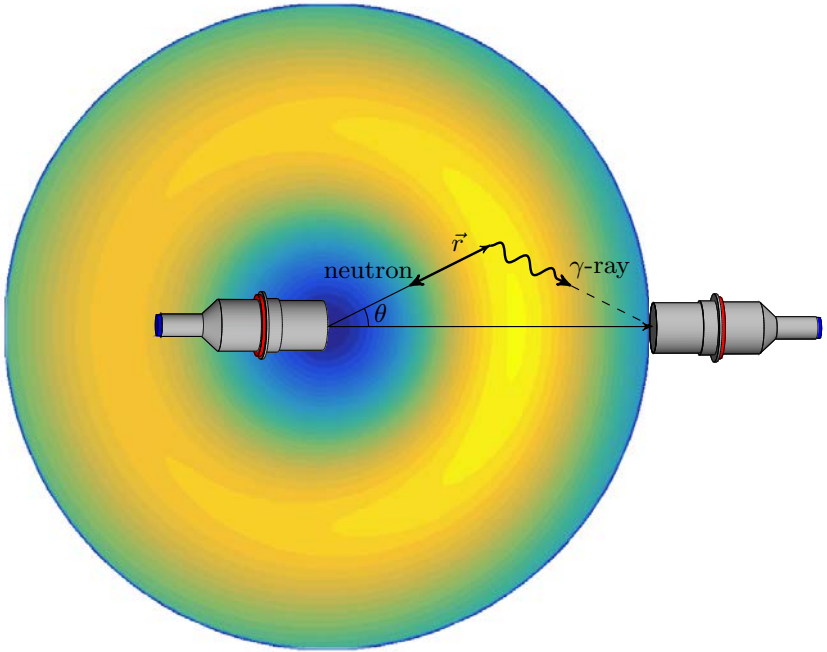
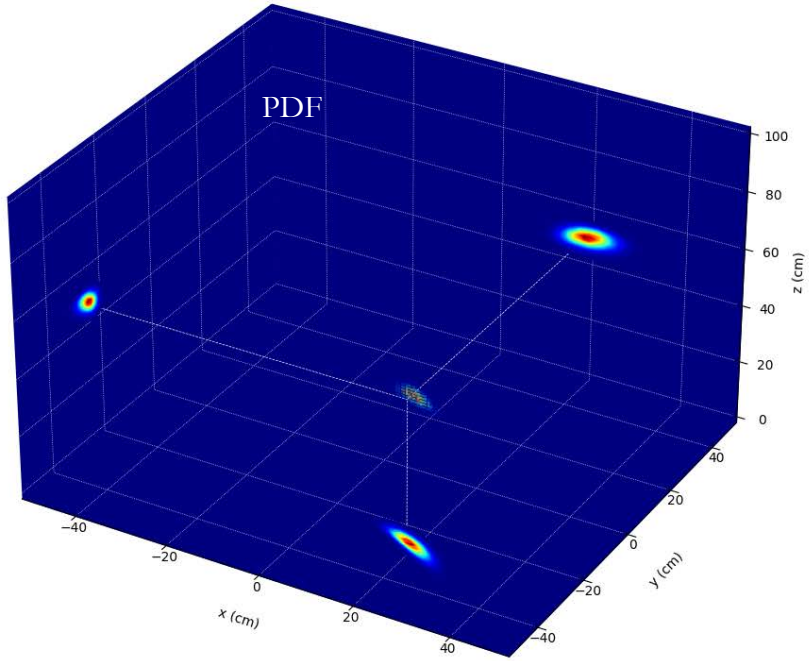
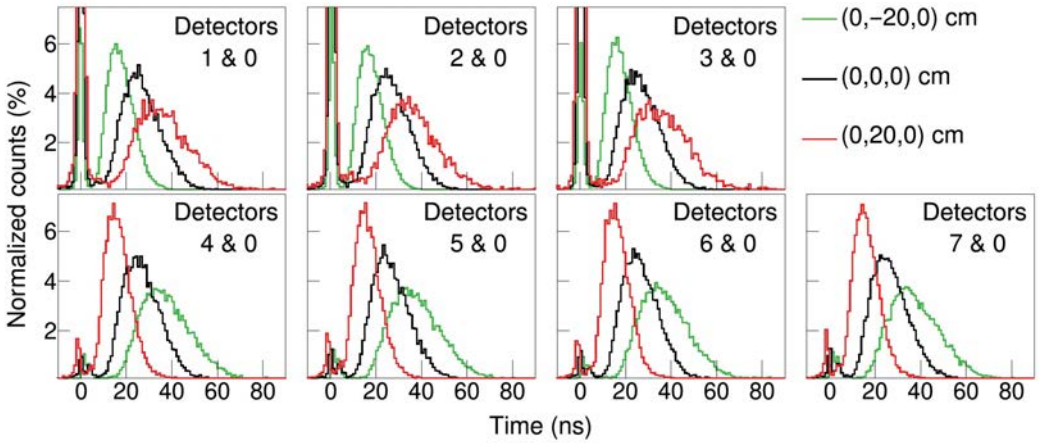


Image representing the combined PDF for approximately 60 events from a 10 s measurement of a 1.3 μCi ^{252}Cf source shielded by 4cm PE1000.



*Jana Petrović, Alf Göök, and Bo Cederwall, “Rapid imaging of special nuclear materials for nuclear non-proliferation and terrorism prevention”, Science Advances 7, eabg3032 (2021)

Cumulative NGET approach based on Machine Learning



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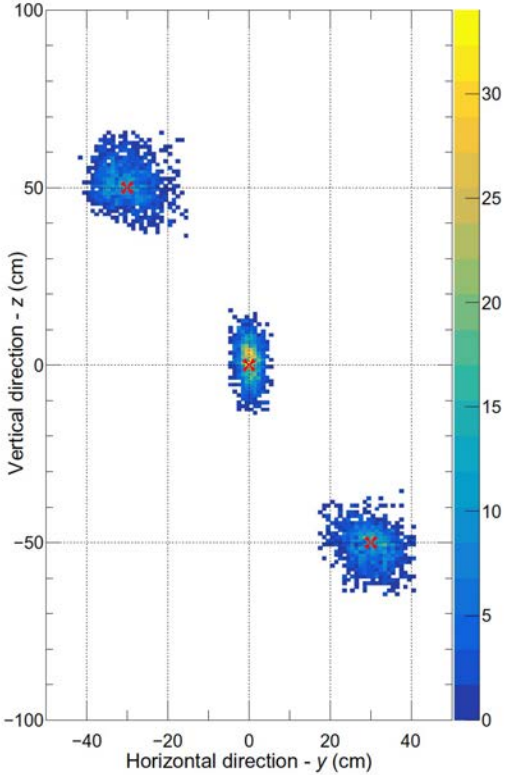
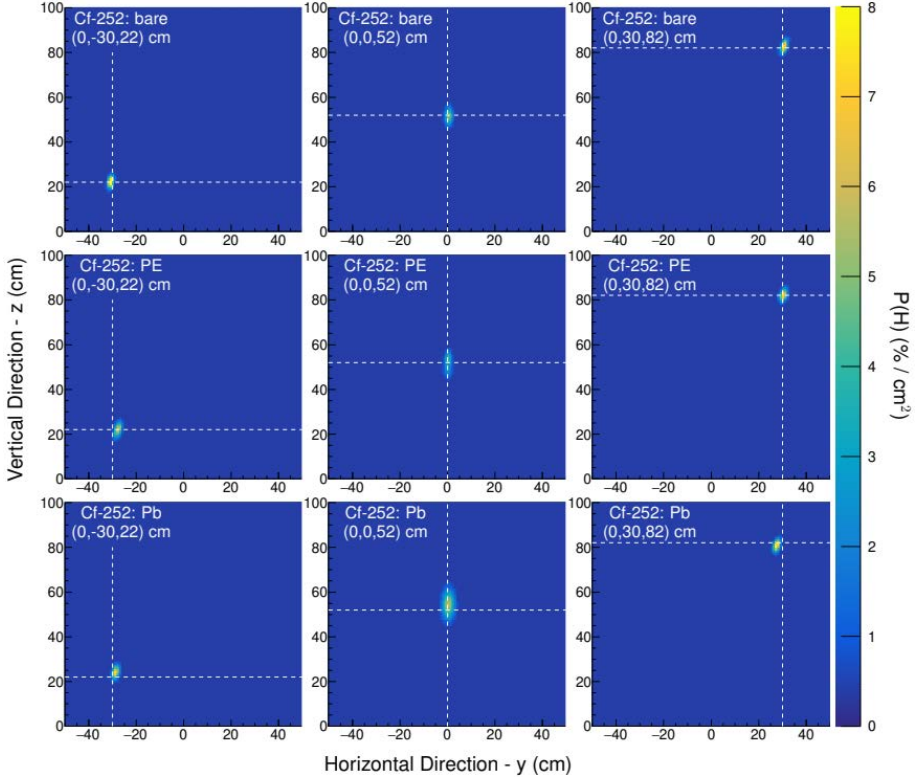
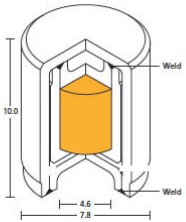


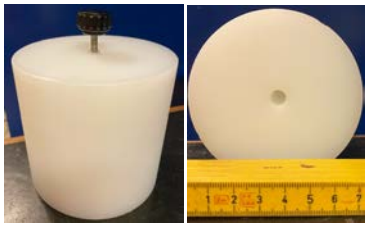
SNM localization using gamma-neutron correlations

★ Typical PDF after 10 s measurement of stationary object using Bayessian inference algorithm*





252Cf material is inside ceramic cylinder with dimensions 4.6 mm by 6 mm (yellow) and encapsulated in stainless-steel cylinder 7.8 mm by 10 mm



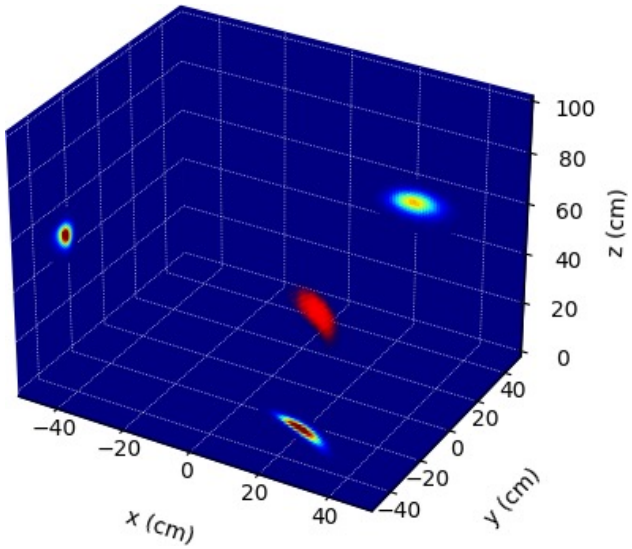
PE1000:
4 cm radial thickness,
8.3 cm height

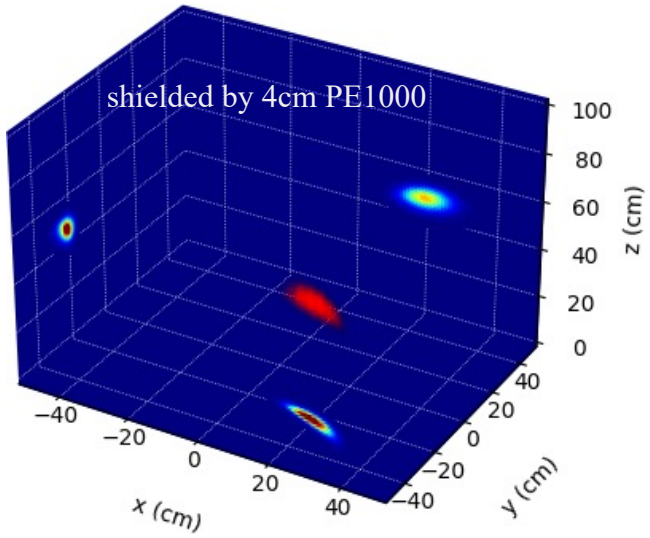
Lead: 1.6 cm radial thickness,
10.5 cm height

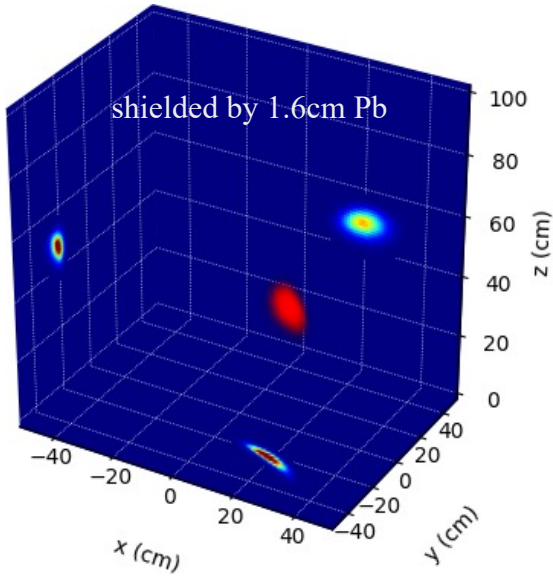
*Jana Petrović, Alf Göök, Bo Cederwall, "Rapid imaging of special nuclear materials for nuclear non-proliferation and terrorism prevention",Science Advances 7, eabg3032 (2021)

Neutron-Gamma Emission Tomography – shielded sources

10 s measurement of a 1.3 μCi ^{252}Cf source





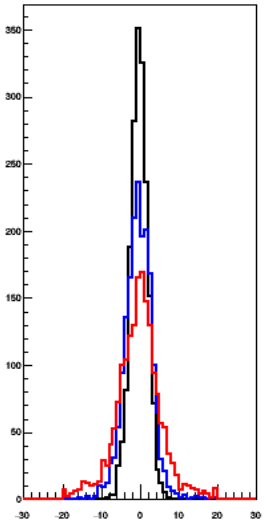


source position: (x,y,z) = (20,-30,52) cm

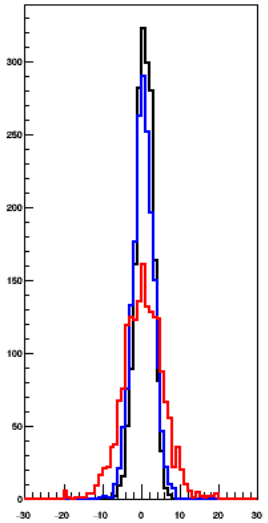
*Jana Petrović, Alf Göök, and Bo Cederwall, “Rapid imaging of special nuclear materials for nuclear non-proliferation and terrorism prevention”, Science Advances 7, eabg3032 (2021)

Spatial resolution

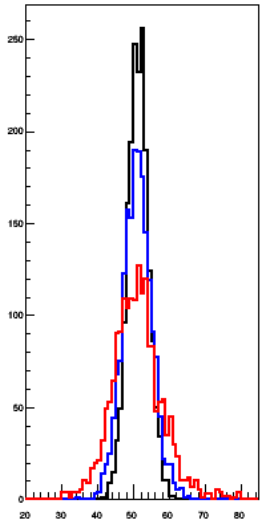
X projection



Y projection



Z projection



The total of 1800 10 s measurements;
central position (x,y,z) = (0,0,52) cm;
X, Y and Z projections;

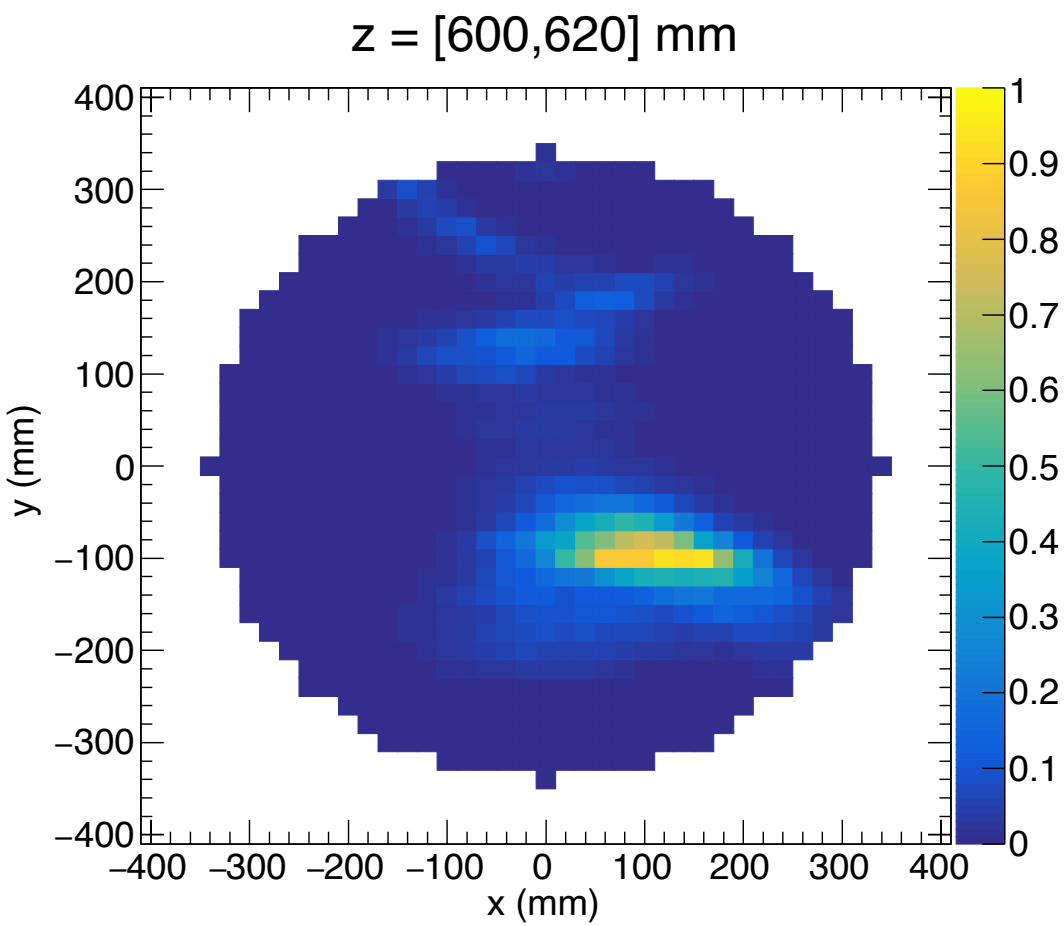
Black line – bare ^{252}Cf source
Blue line - ^{252}Cf +PE(4 cm)
Red line - ^{252}Cf +Pb(1.6 cm)

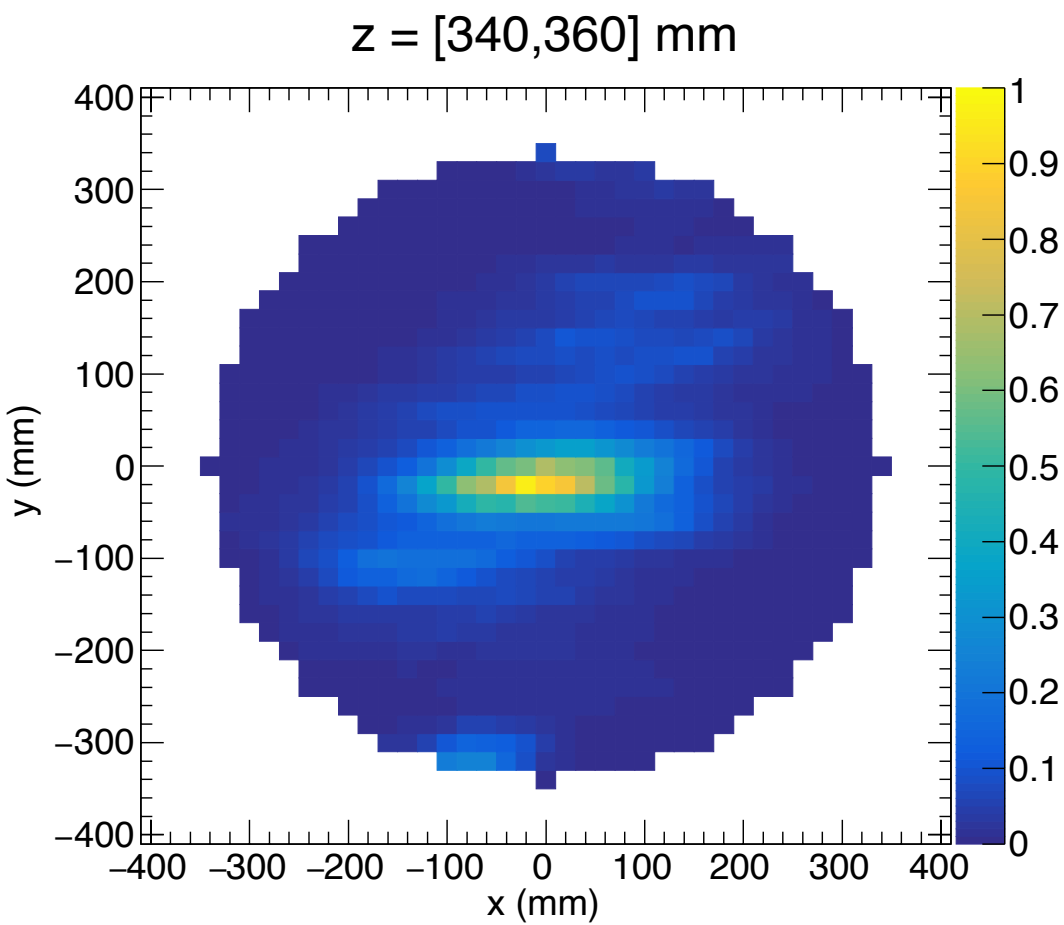
	stddev(x)	stddev(y)	stddev(z)
Bare ^{252}Cf	2.15 ± 0.04	2.17 ± 0.04	3.00 ± 0.05
^{252}Cf +PE	3.53 ± 0.06	2.70 ± 0.05	4.07 ± 0.07
^{252}Cf +Pb	5.8 ± 0.1	5.19 ± 0.09	6.9 ± 0.2

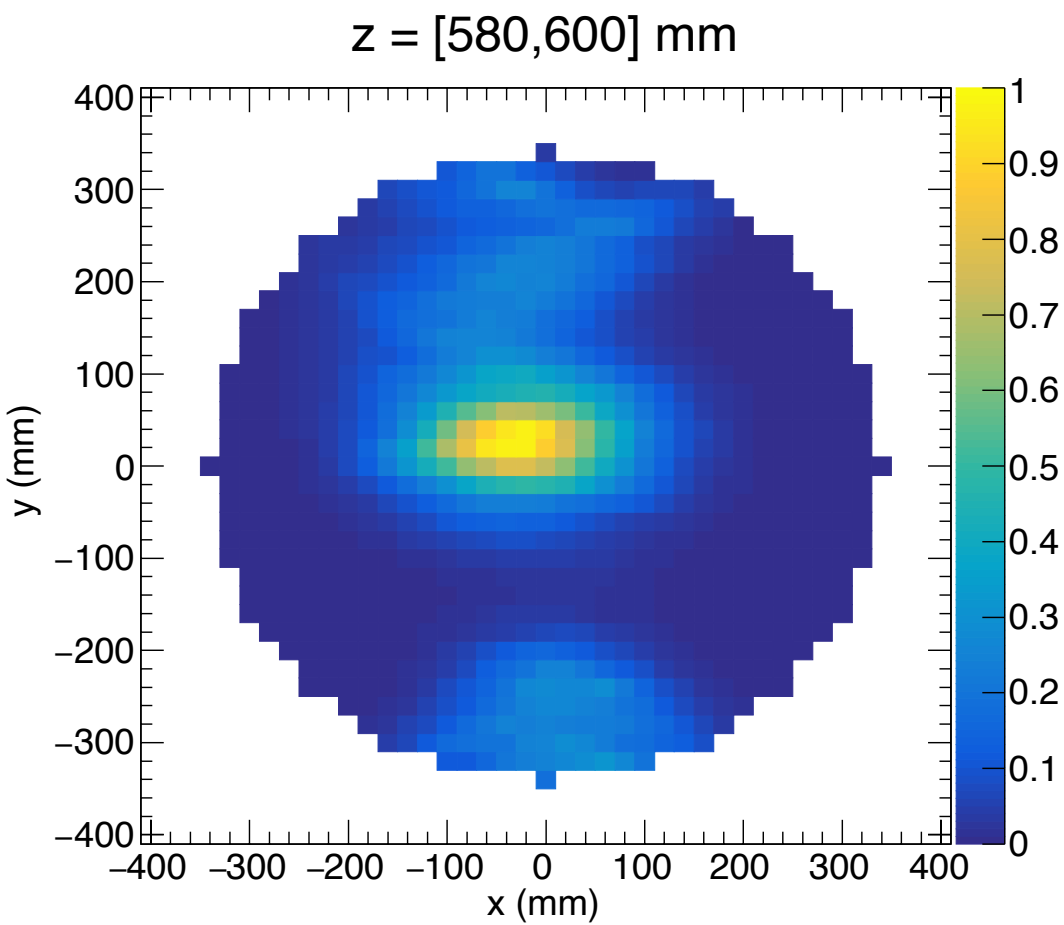
Note: detector dimensions in this setup 127 mm (h) x 127 mm (diam)

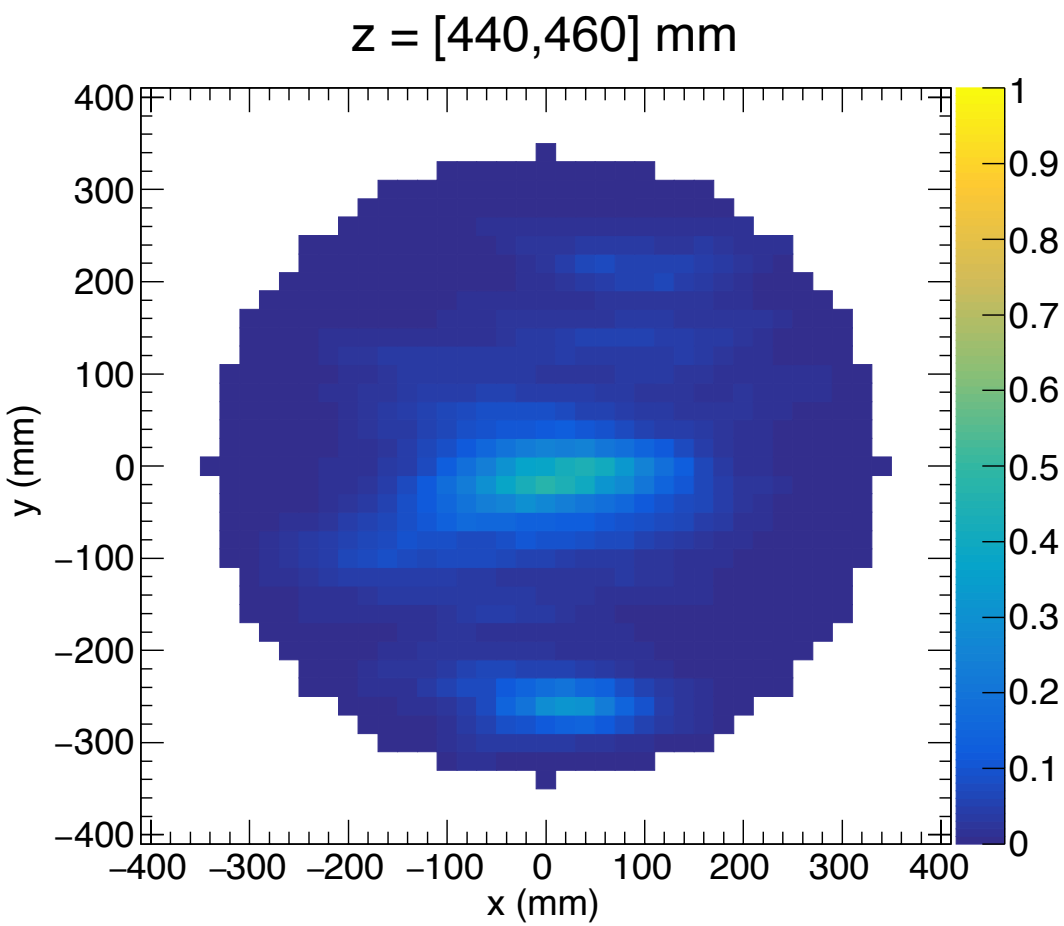
3D-scanning of legacy waste drums, AB SVAFO, Studsvik nuclear decommissioning site

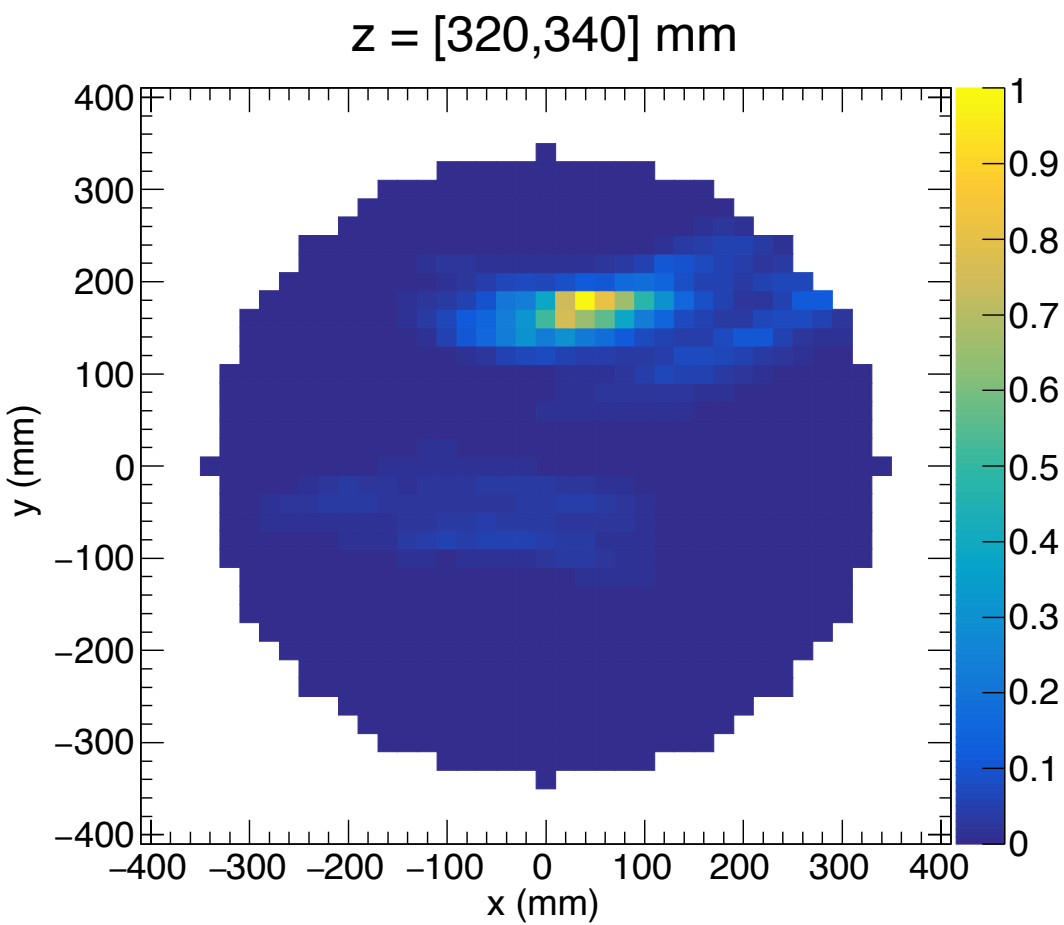
Tests with legacy waste (at SVAFO, Sweden, May 2021)


z = [600,620] mm
400
300
200
100
0
−100
−200
−300
−400
y (mm)
−400
−300
−200
−100
0
100
200
300
400
x (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

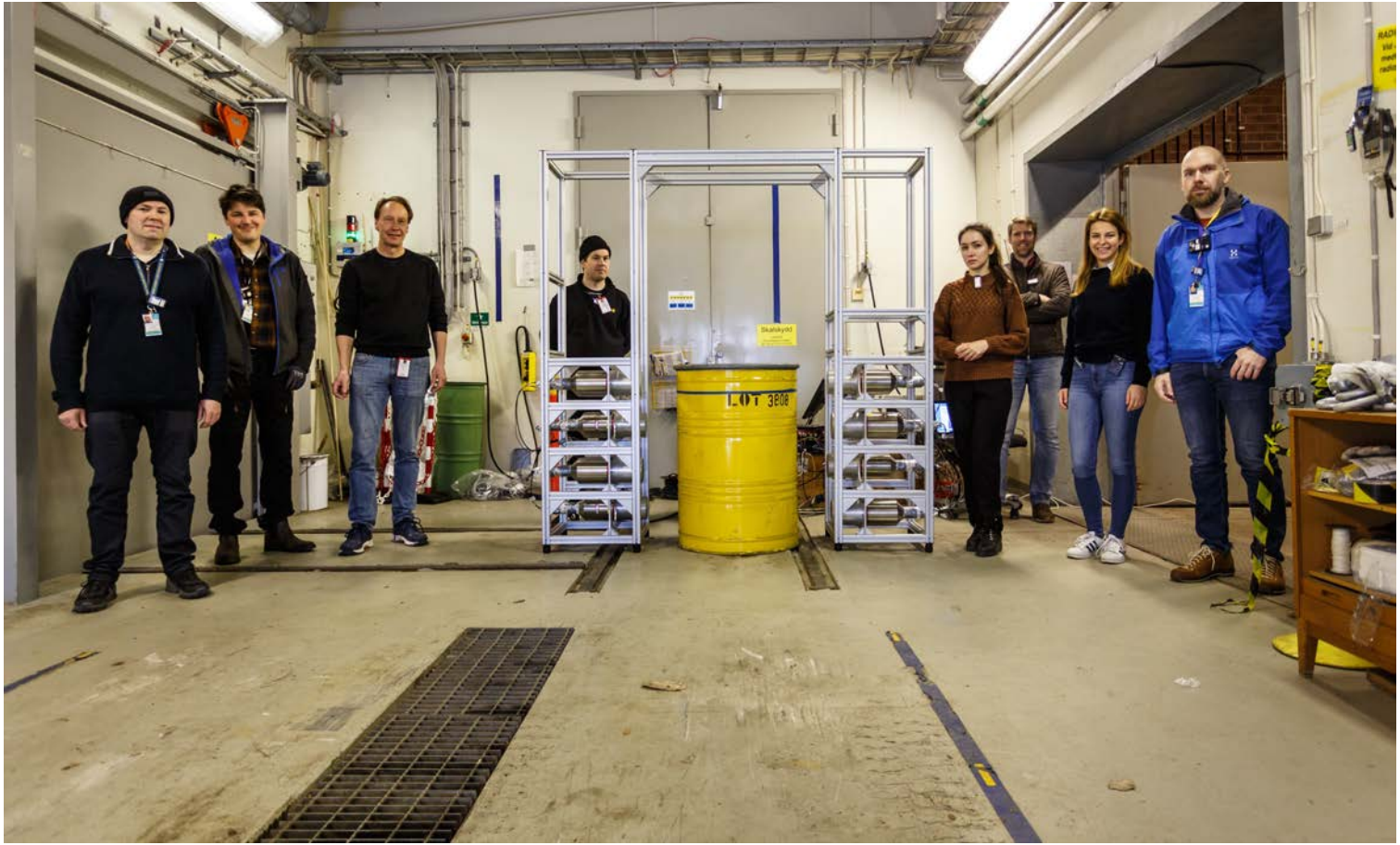

z = [340,360] mm
400
300
200
100
0
−100
−200
−300
−400
y (mm)
−400
−300
−200
−100
0
100
200
300
400
x (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


z = [580,600] mm
400
300
200
100
0
−100
−200
−300
−400
y (mm)
−400 −300 −200 −100 0 100 200 300 400
x (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

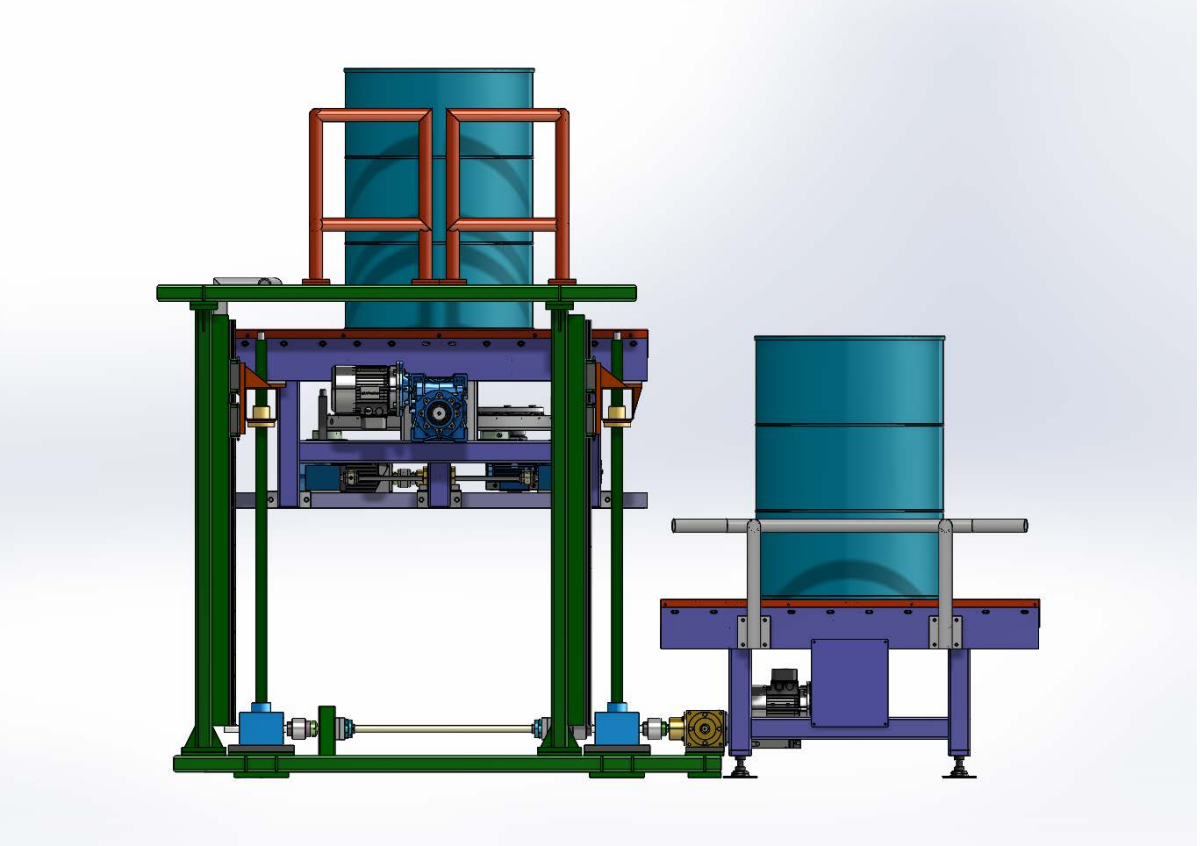

z = [440,460] mm
400
300
200
100
0
−100
−200
−300
−400
y (mm)
−400 −300 −200 −100 0 100 200 300 400
x (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


z = [320,340] mm
400
300
200
100
0
−100
−200
−300
−400
y (mm)
−400 −300 −200 −100 0 100 200 300 400
x (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Tests with legacy waste (at SVAFO, Sweden, May 2021)



Automatic 3D-scanning prototype system - in collaboration with ELSE NUCLEAR



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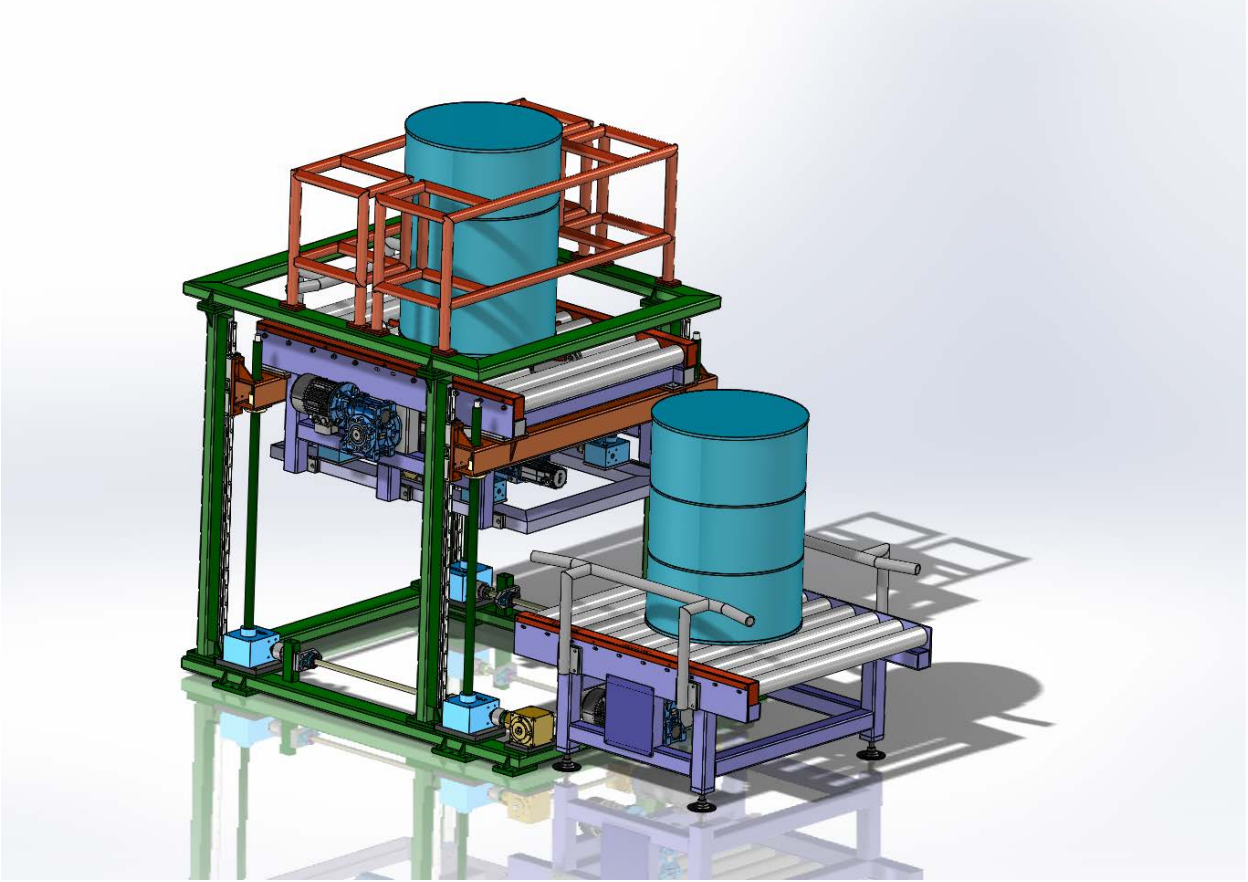

Hvala!
to the BPU11 organizers and for your attention

Technology Status

- Imaging of SNM in realistic conditions (legacy waste) achieved
- Quantitative Estimates $< 1g\ ^{240}Pu_{eff}$ (based on MC simulations)
- Enhanced QE in combination with HPGe measurements
- Prototype development in collaboration with AB SVAFO, Studsvik nuclear decommissioning center, Sweden and ELSE Nuclear, Milano, Italy.

IP

- Patent application on the core technology filed in EU, USA, China (B.C, IPR owned by KTH Holding).
- Awarded EURATOM Nuclear Innovation Prize (1st prize) 2022

VINNOVA

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

Swedish Foundation for Strategic Research

References

Jana Petrović, Alf Göök, and Bo Cederwall,

"*Rapid imaging of special nuclear materials for nuclear nonproliferation and terrorism prevention*", Science Advances, **Vol. 7**, No. 21, eabg3032 (2021). https://doi.org/10.1126/sciadv.abg3032

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Royal Swedish Academy of Engineering Sciences
https://www.iva.se/en/published/new-100-list-research-for-sustainable-emergency-preparedness-with-commercial-potential/