stuk

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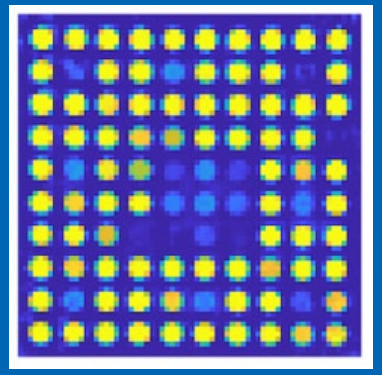

Non-destructive assay of spent nuclear fuel with Passive Gamma Emission Tomography (PGET)

Riina Virta

Work in collaboration with the Radiation and Nuclear Safety Authority of Finland and the Helsinki Institute of Physics

Contributors

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Nuclear fuel

Areva

Ruslan Krivobok/RIA Novosti

Nuclear safeguards

- Deter the spread of nuclear weapons
- Nuclear material only used for peaceful purposes: the base for nuclear energy

IAEA

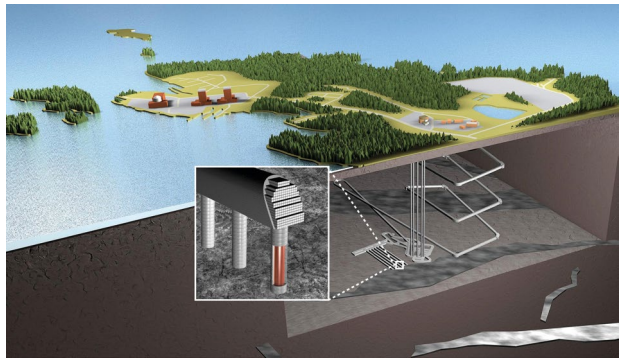
IAEA

Nuclear power in Finland

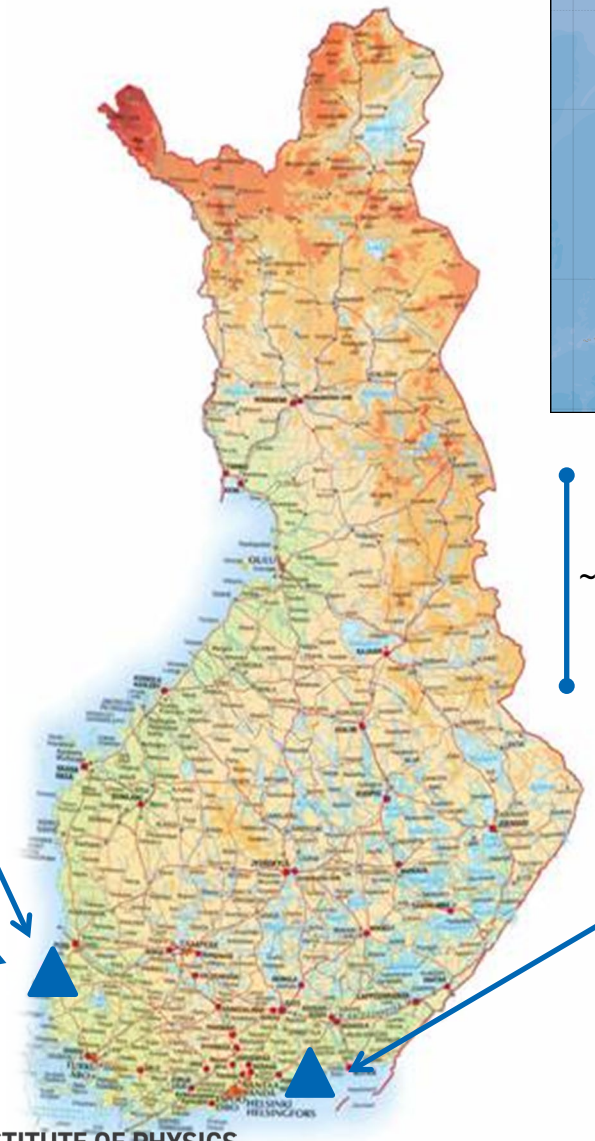
tvo

Olkiluoto NPP
(OL1, OL2, OL3)

POSIVA



Posiva (owned by TVO & Fortum): Encapsulation plant and geological repository for spent nuclear fuel



~200km

fortum

Fortum: Loviisa NPP

stuk
SÄTEILYTURVAKESKUS
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

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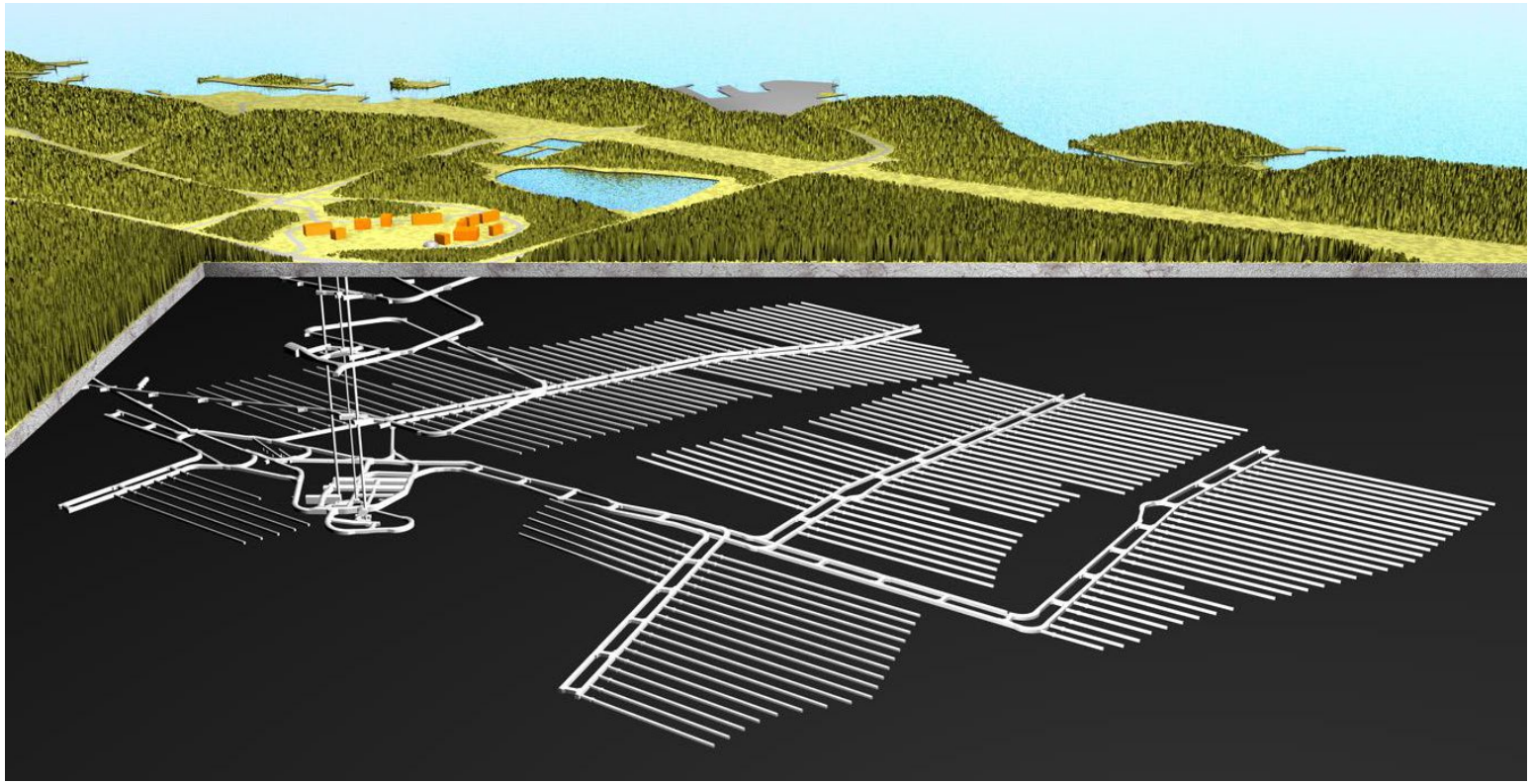
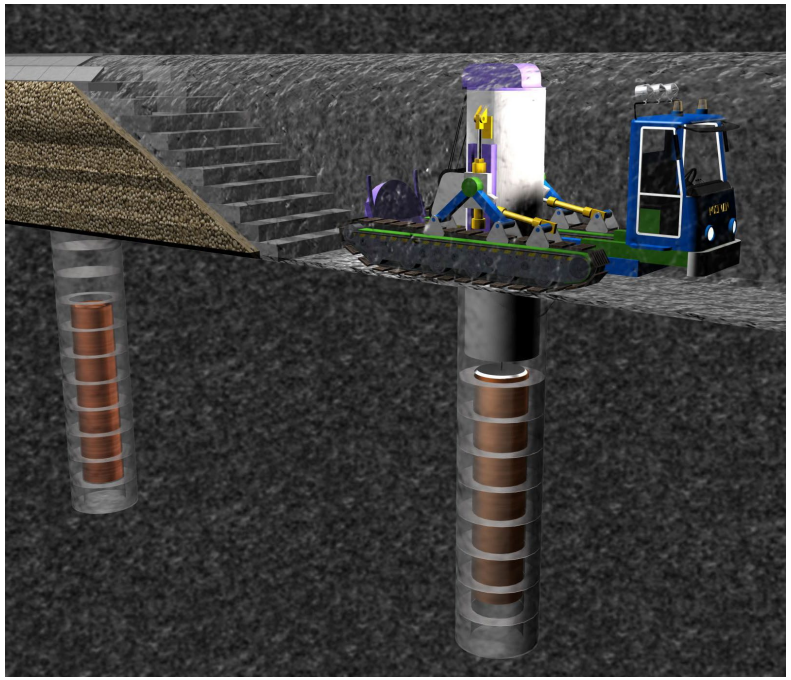
Photos: TVO, Posiva, Fortum

The Finnish geological repository

- Olkiluoto, Eurajoki, Finland



Posiva



Posiva

Geological repository safeguards

- Operations planned to start in 2025
- Fuel inaccessible to measurements after disposal: NDA verification crucial
  - PNAR (Passive Neutron Albedo Reactivity) to detect fissile material presence [1]
  - PGET (Passive Gamma Emission Tomography) to detect rod-level presence of fuel [2,3]

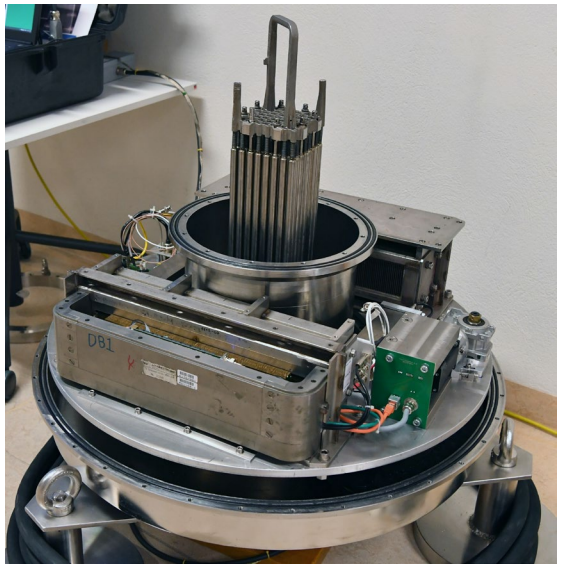
Posiva

Posiva

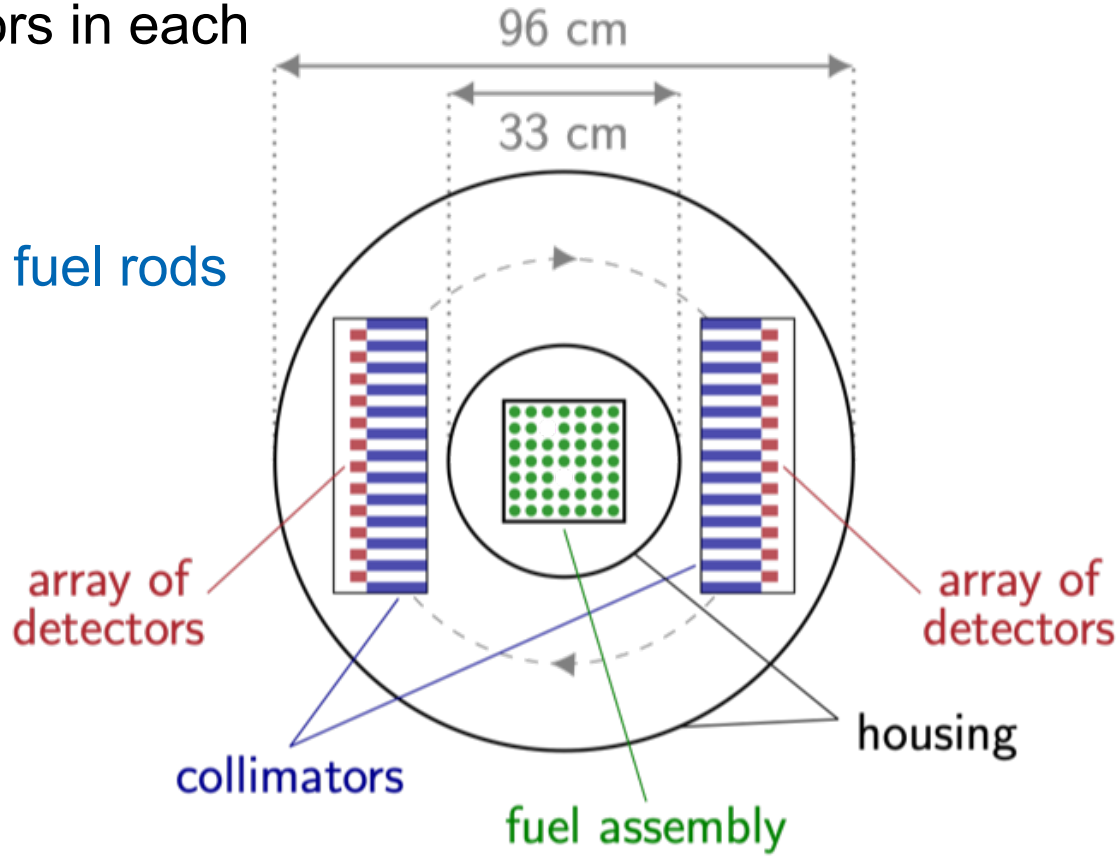
[1] Tupasela et al. 2021
[2] Honkamaa et al. 2014
[3] White et al. 2018

Passive Gamma Emission Tomography device

- 2 collimated banks with 91 CdZnTe gamma detectors in each
- 360 degree rotation around the fuel assembly
- Spatial image pixel size of 2mm x 2mm
- 2D transaxial images reconstructed [4,5], individual fuel rods visible



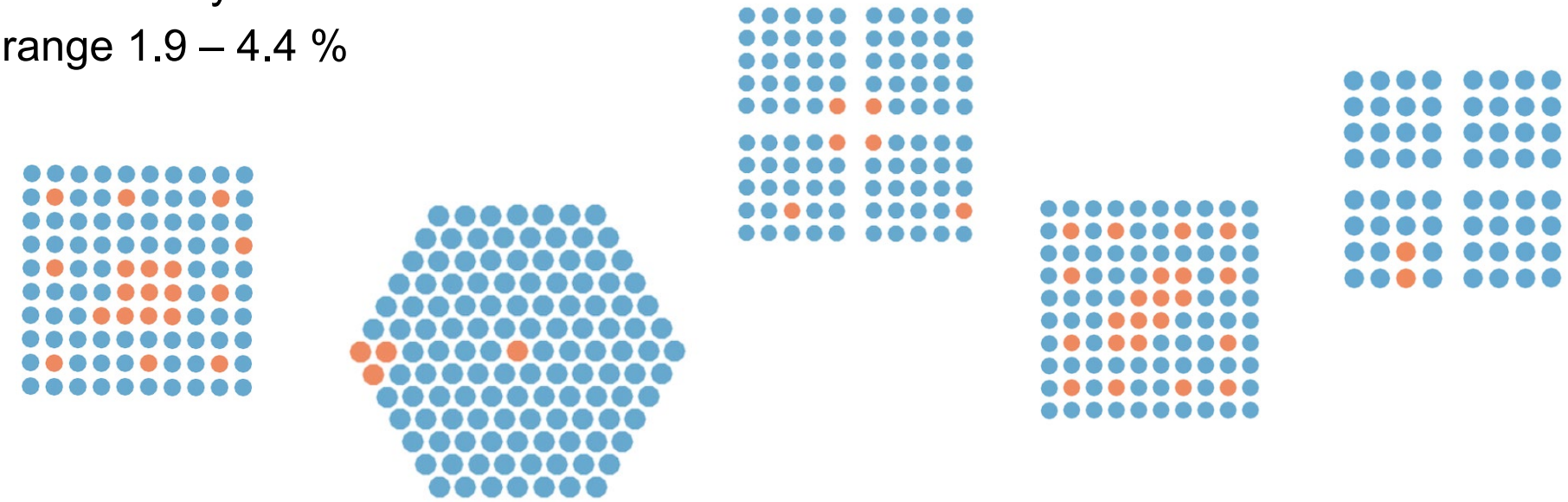
Dean Calma/IAEA



[4] Backholm et al. 2020
[5] Virta et al. 2020

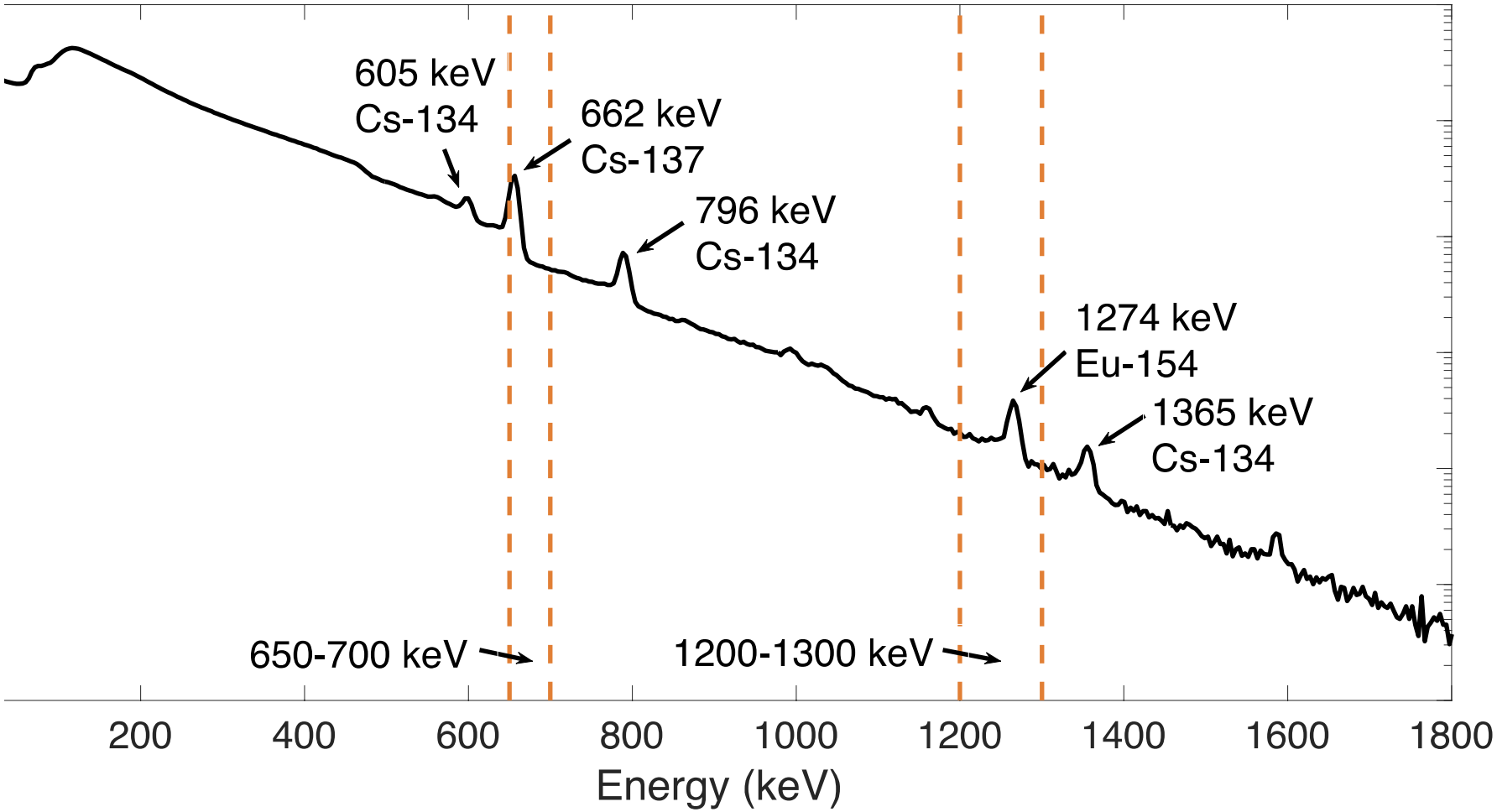
Measurements of spent nuclear fuel

- Underwater, in spent nuclear fuel ponds
- 4 different gamma energy windows, capturing Cs-137 at 662 keV or Eu-154 at 1274 keV
- Over 100 assemblies measured 2017-2022 [5,6]
  - Burnup range 5.7 – 55 GWd/tU
  - Cooling time range 1.9 – 38 years
  - Initial enrichment range 1.9 – 4.4 %



Gamma energy spectra

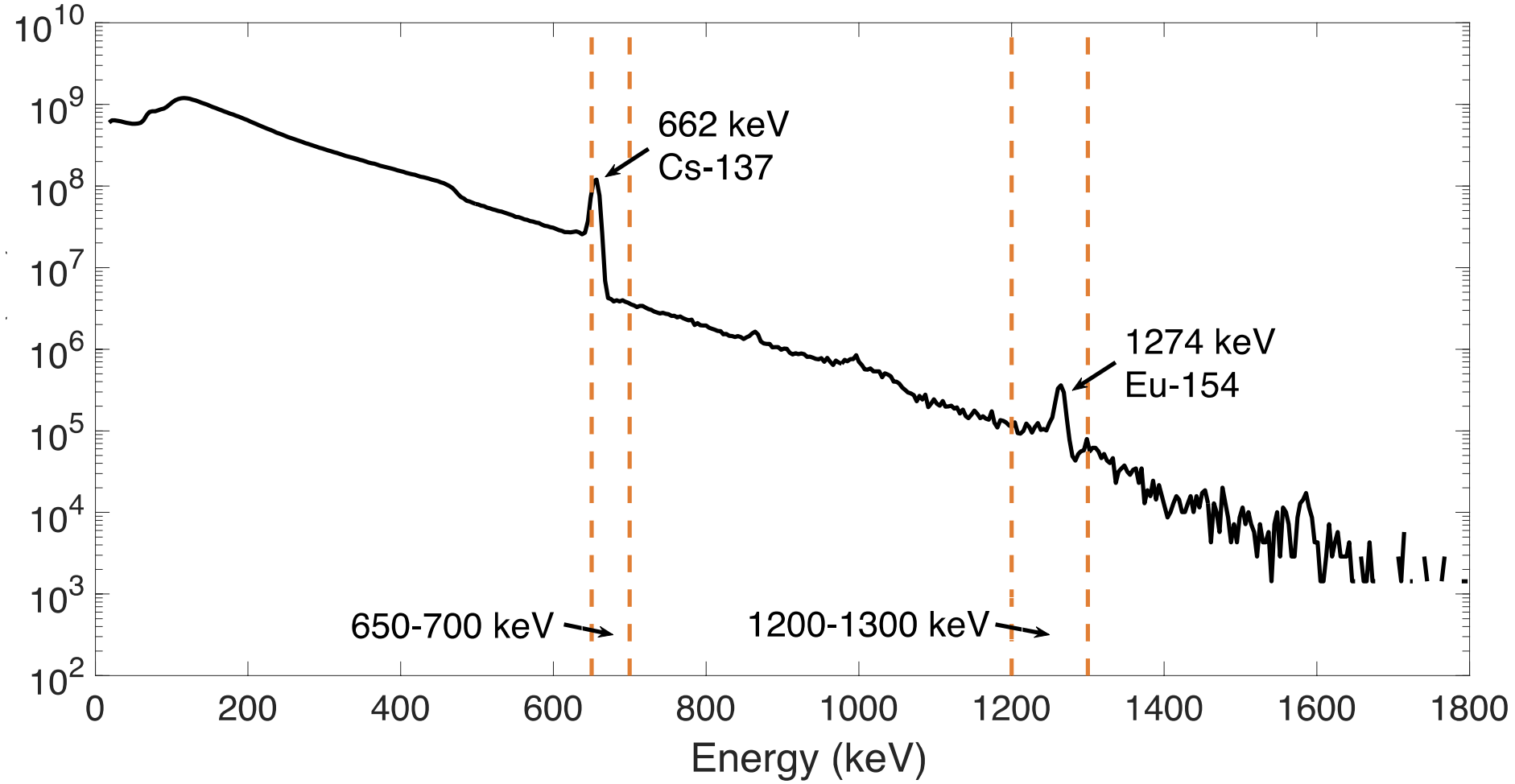
VVER-440
BU 44 GWd/tU
CT 7.2 a



[6] Virta et al. 2022

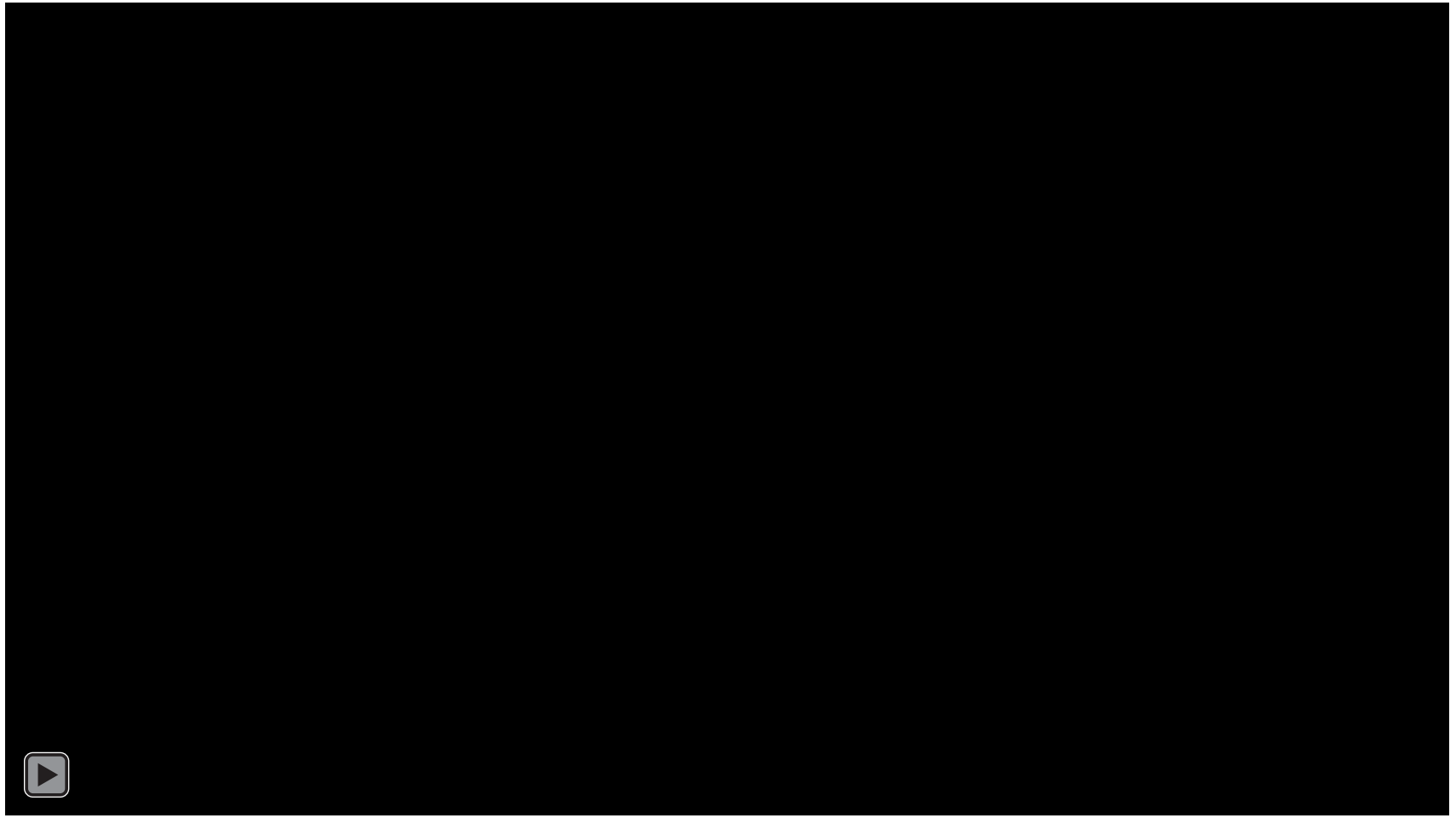
Gamma energy spectra

VVER-440
BU 34 GWd/tU
CT 29 a



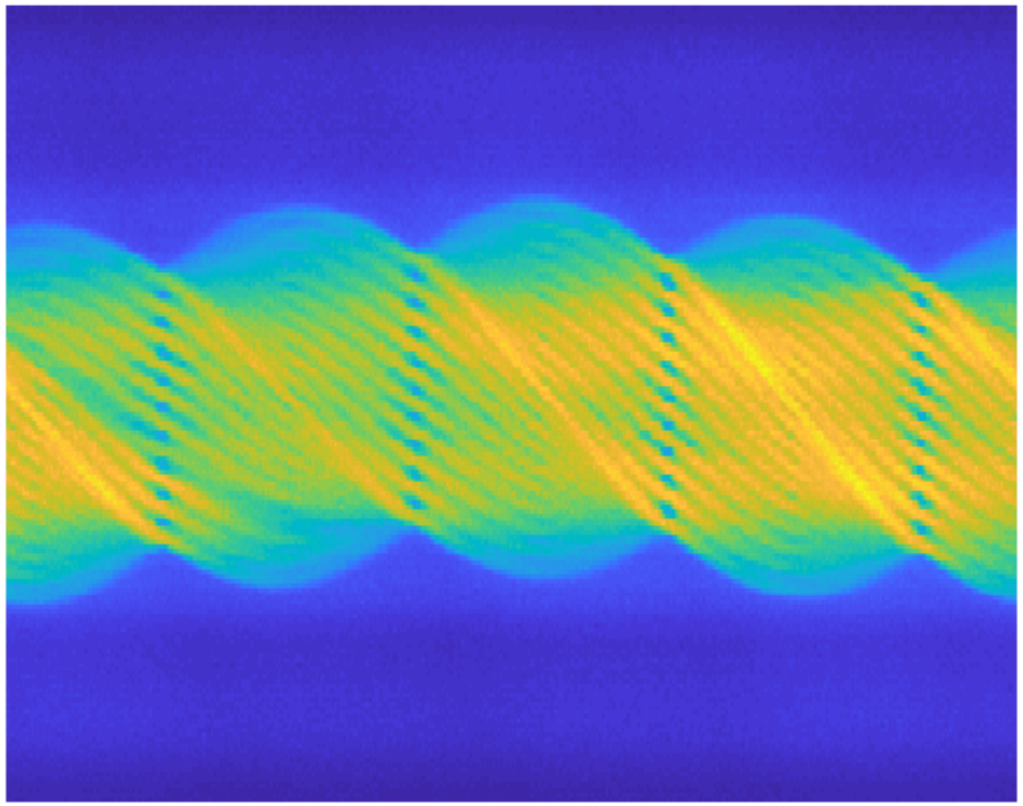
[6] Virta et al. 2022

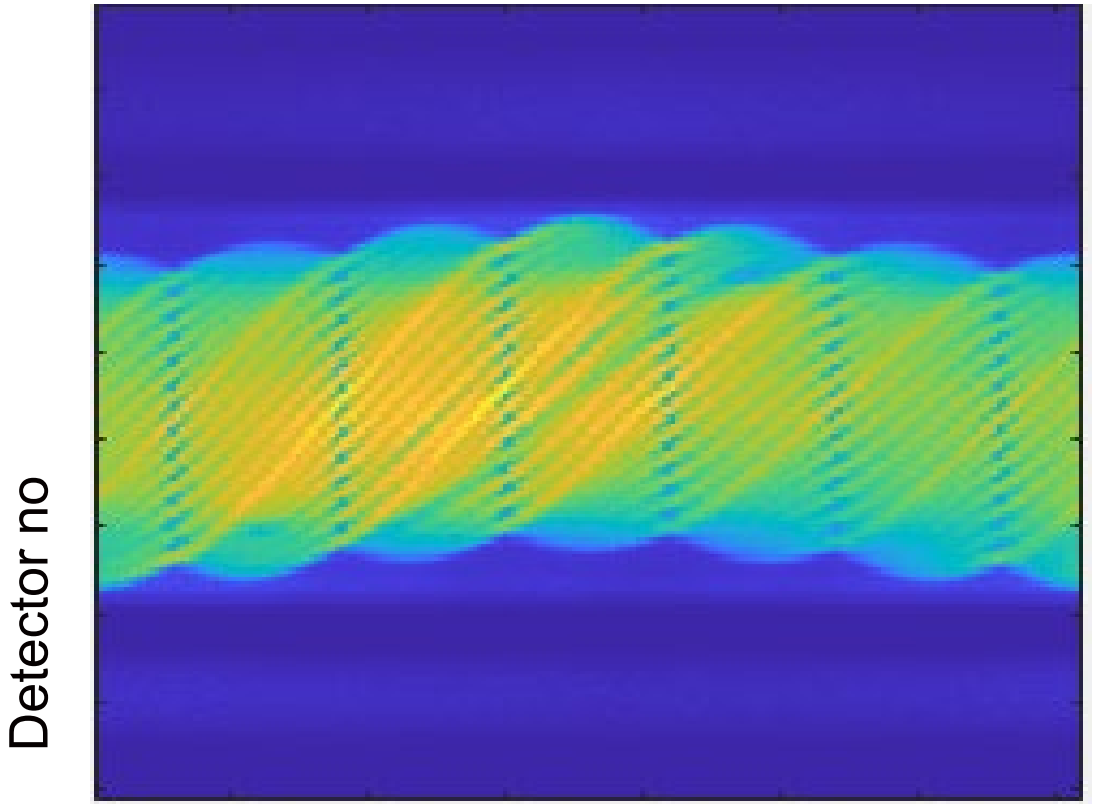
Gamma tomography



Samuli Siltanen, University of Helsinki

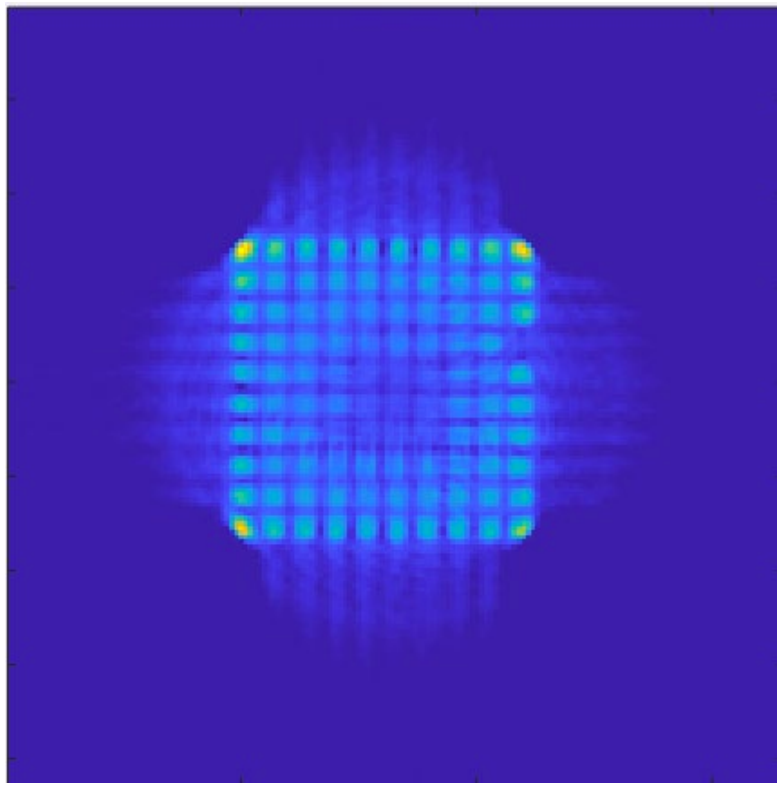
Sinogram


Detector no
Measurement angle


Detector no
Measurement angle

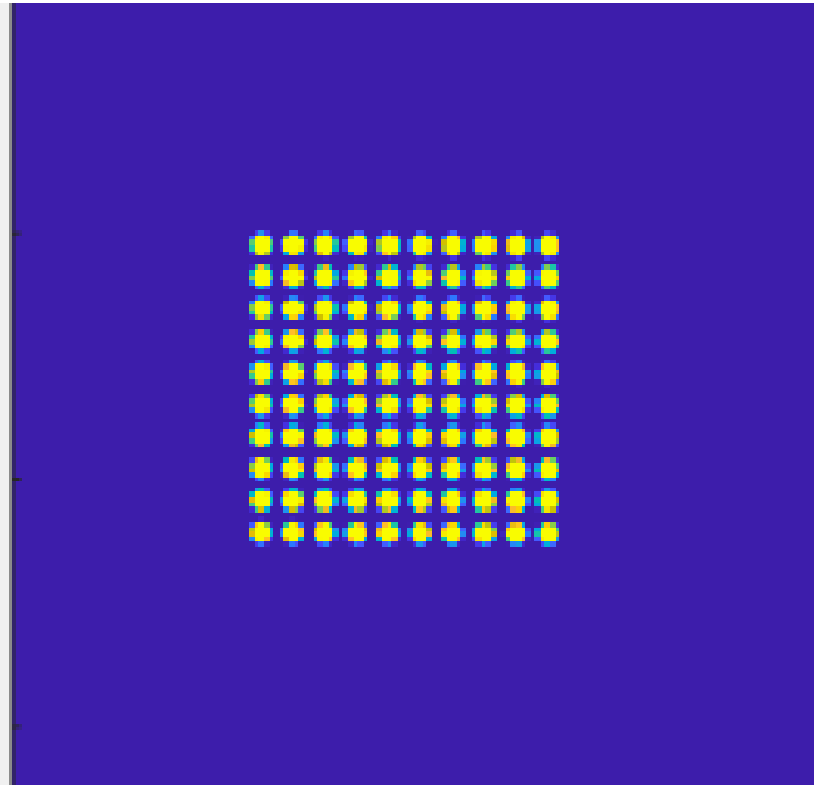
A priori information

Initial FBP



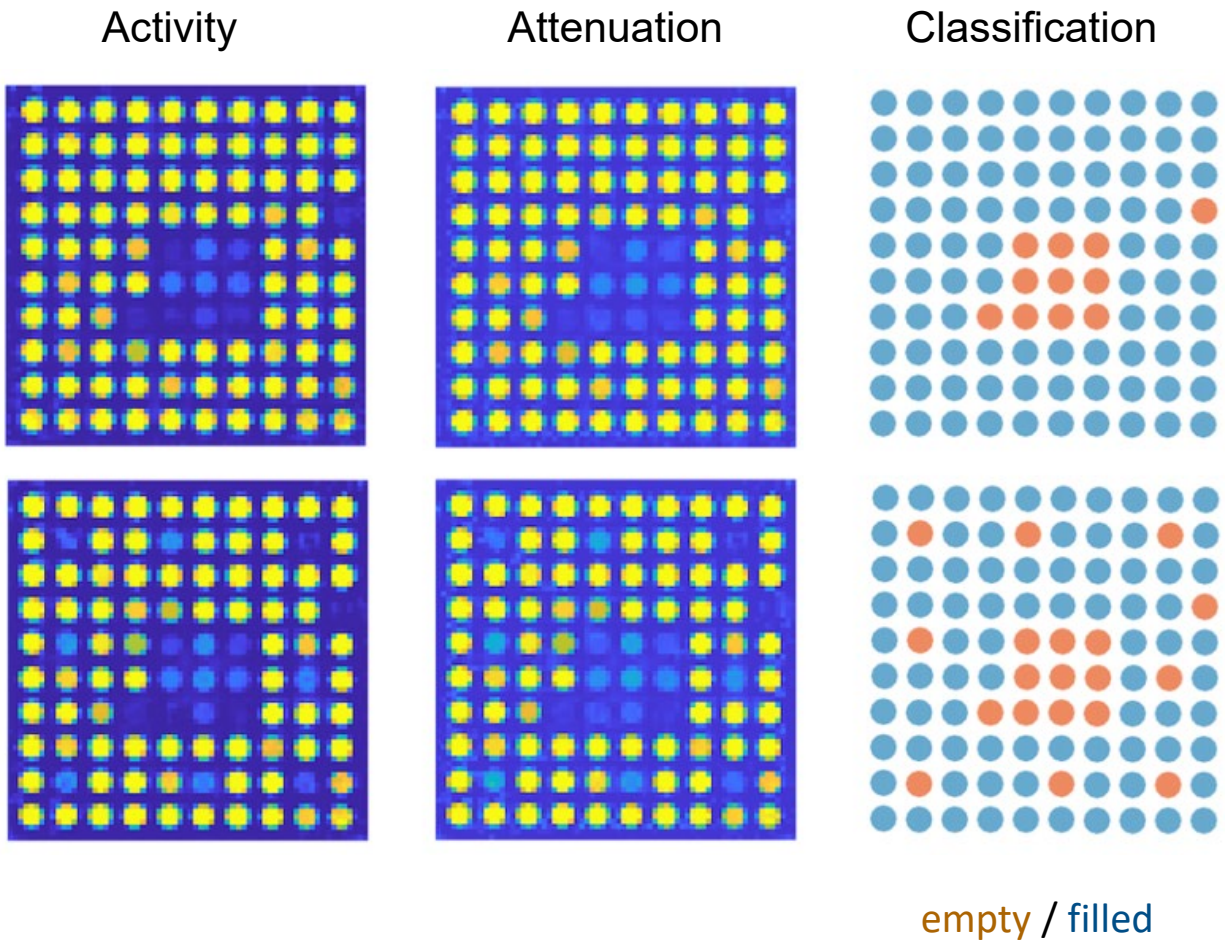
Known type:
rod dimensions
and locations

Fit a fuel grid



Reconstructed images

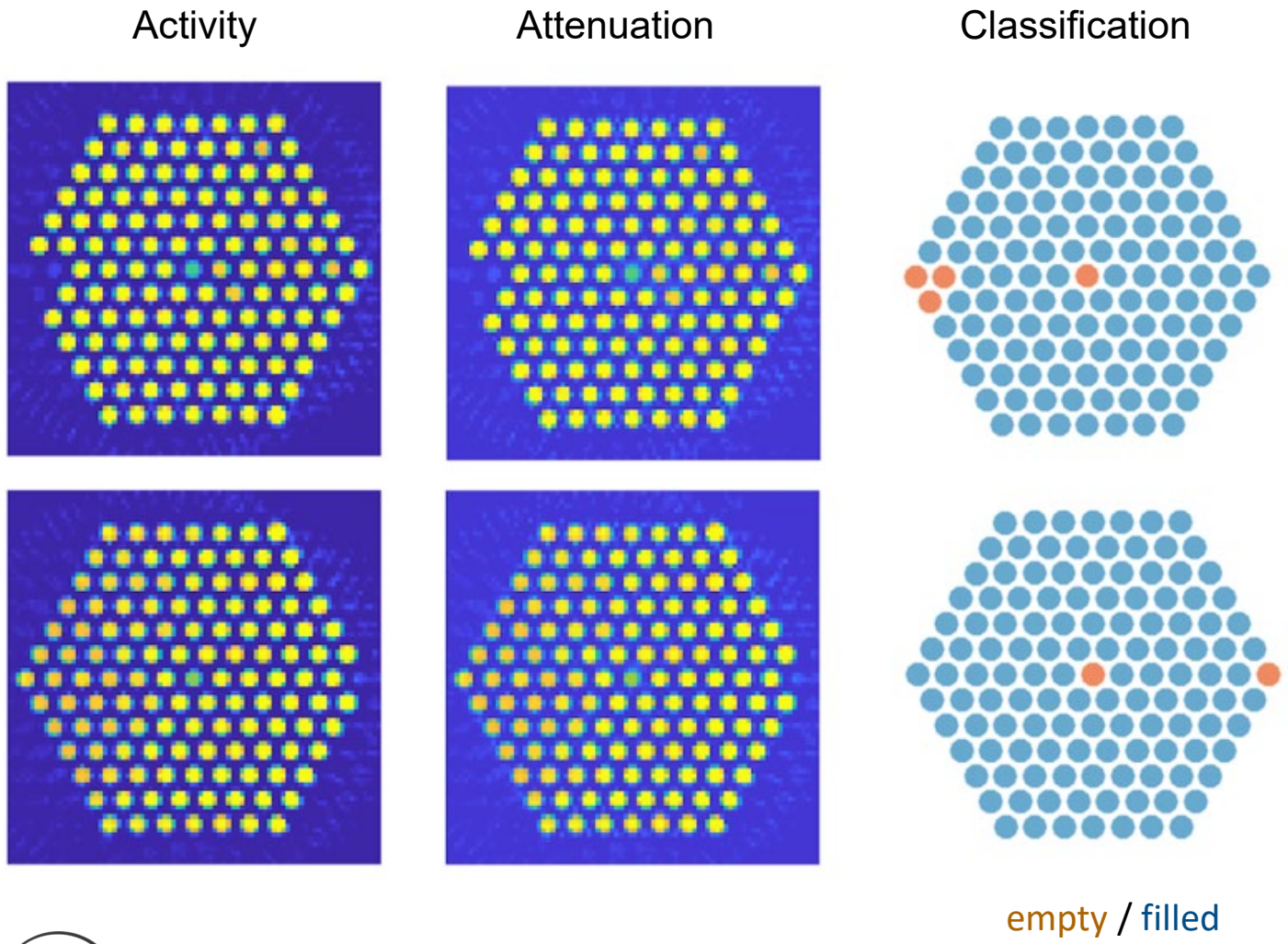
- ATRIUM10 assembly from two measurement heights



[5] Virta et al. 2020

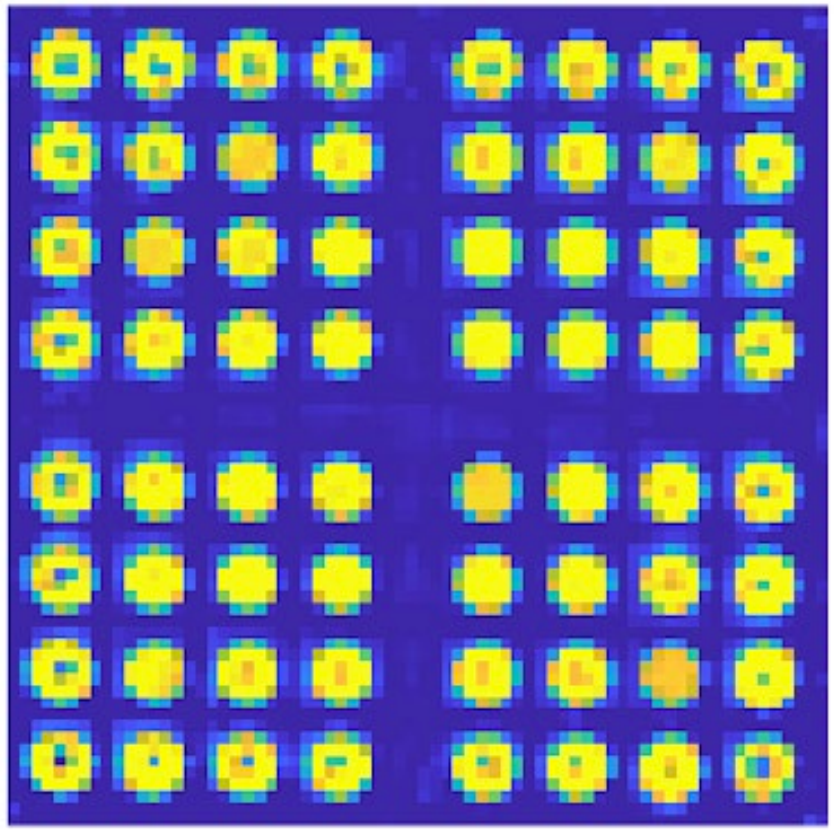
Reconstructed images

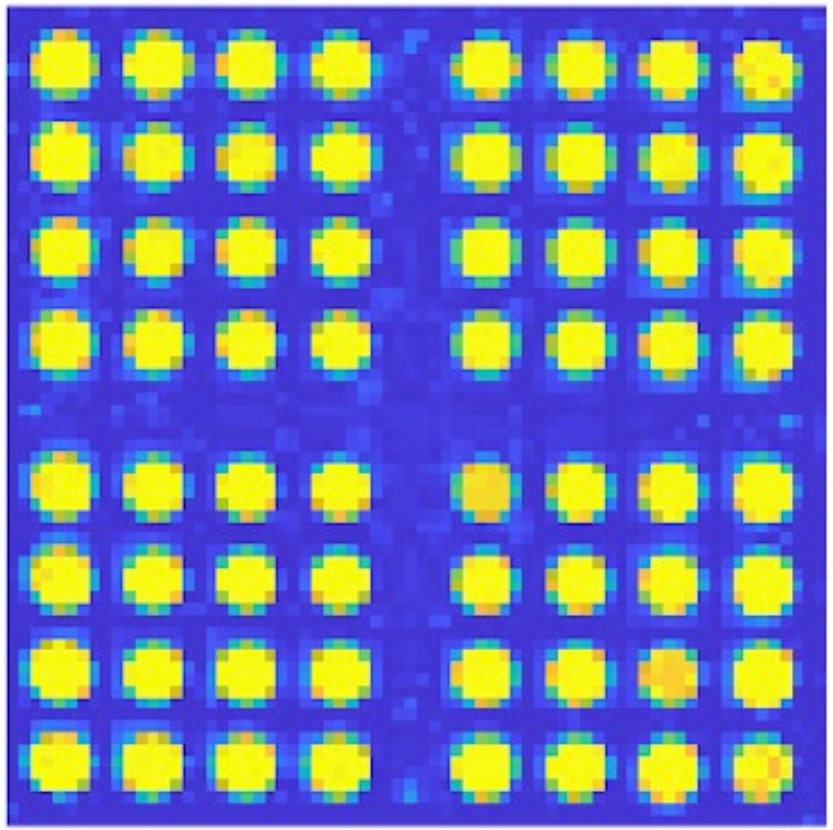
- VVER-440 assemblies with empty rod positions



Intra-rod activity differences

- SVEA-64 assembly

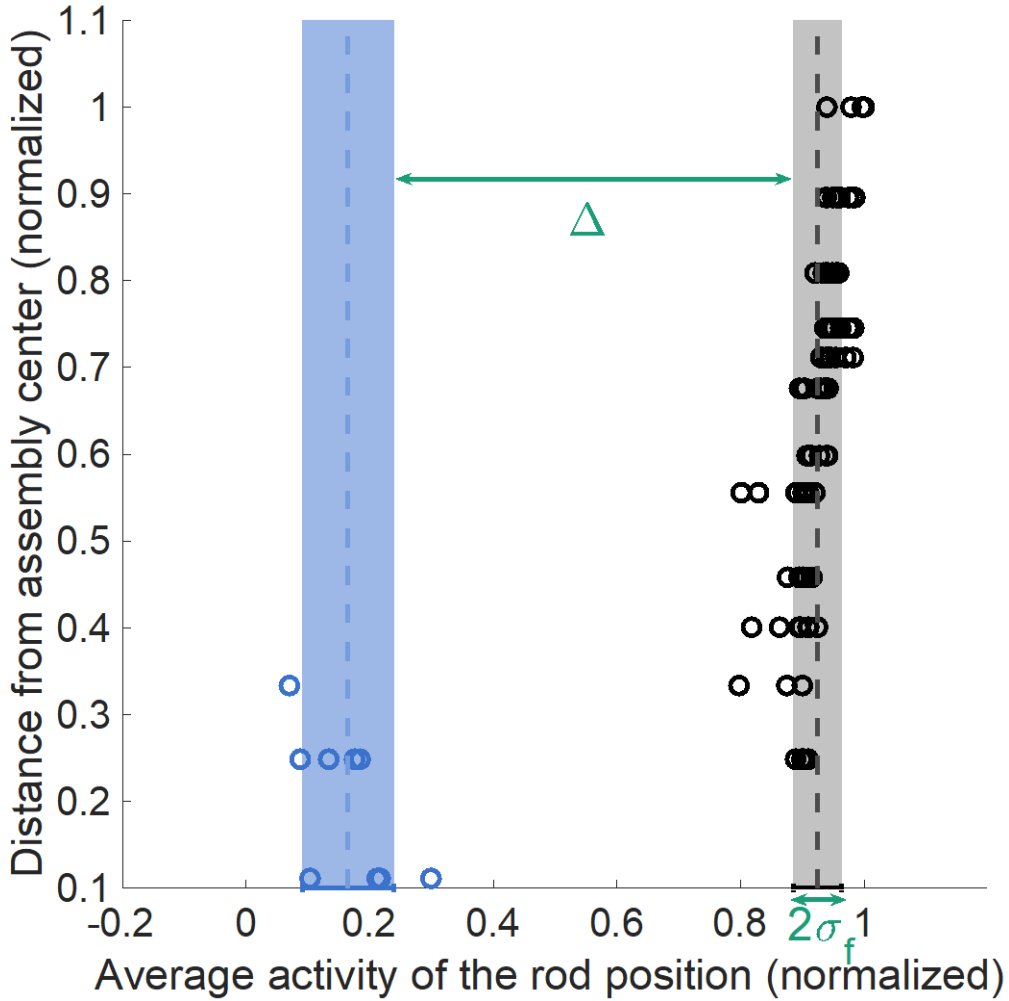




[5] Virta et al. 2020

Image quality index

- A metric for quantitative comparison of reconstructed images
- Assesses how well modified grid positions are distinguished from filled positions
- A pair of two values [Δ, σ_f]
- $\Delta \equiv (\mu_f - \sigma_f) - (\mu_e + \sigma_e)$
- Means and standard deviations of average activities of empty and filled grid positions are considered

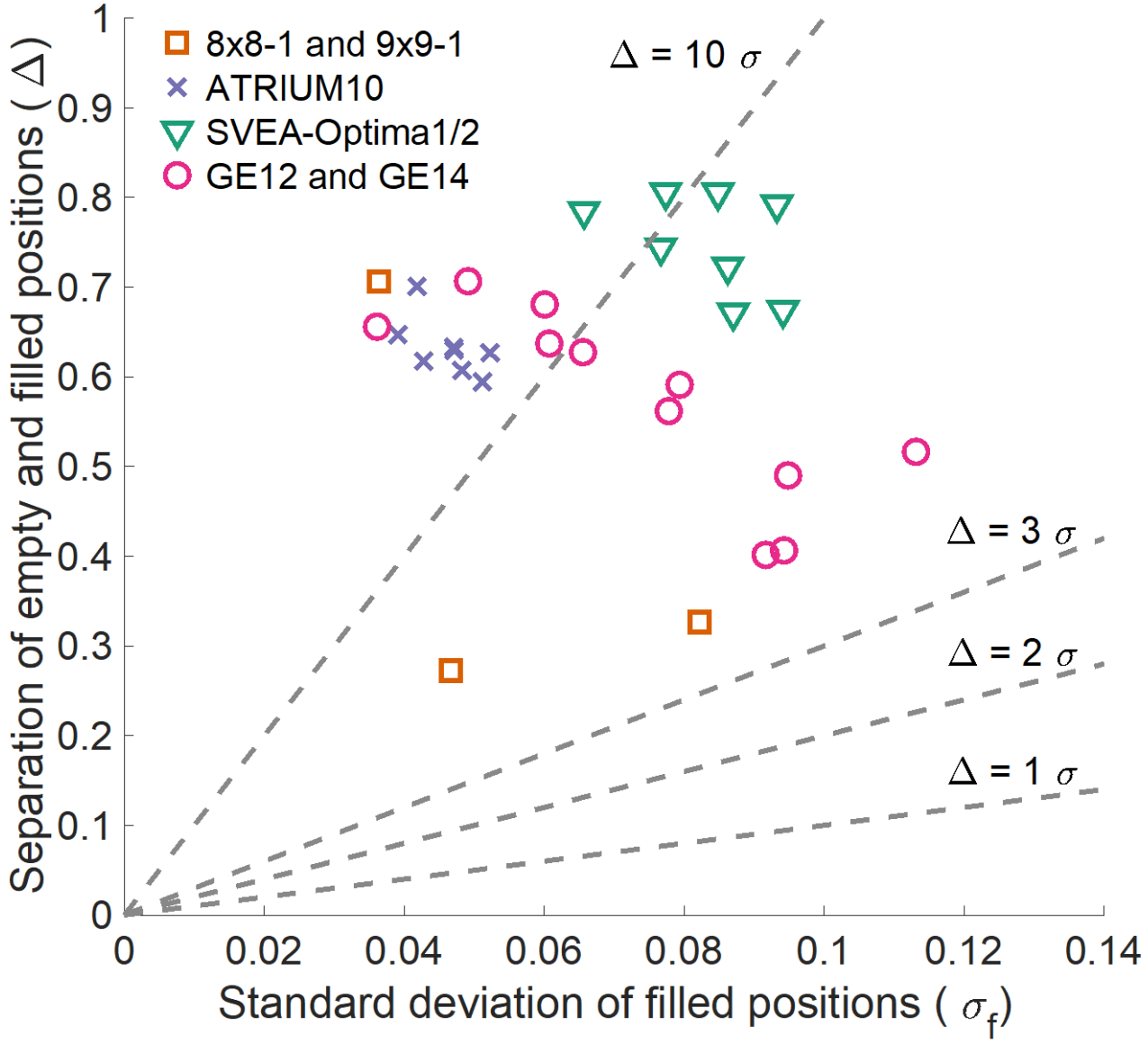


Black circle filled grid position
Blue circle empty grid position

[6] Virta et al. 2022

Image quality comparison

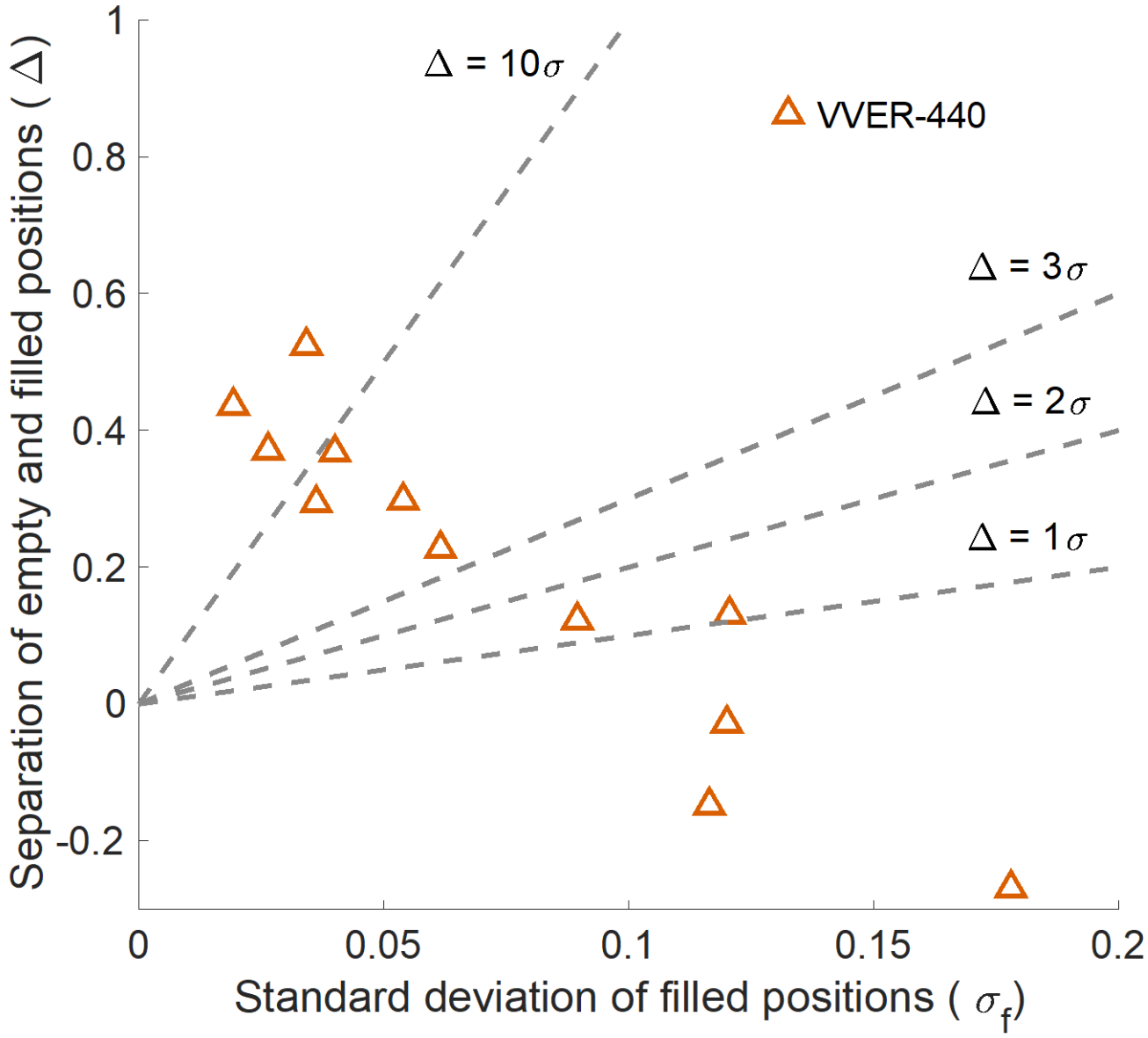
- Olkiluoto assemblies



[6] Virta et al. 2022

Image quality comparison

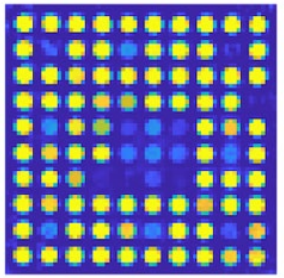
- Loviisa assemblies



[6] Virta et al. 2022

Conclusions

- A gamma emission tomography method has been developed for verifying spent nuclear fuel prior to geological disposal
- The method demonstrates rod-level detection of anomalies and has been evaluated with a wide range of measurement data
- Safeguards verification protocols are ready for start of operations around 2025



References

[1] T. Tupasela, P. Dendooven, S.J. Tobin, V. Litichevskyi, P. Koponen, A. Turunen, M. Moring, T. Honkamaa, ”Passive neutron albedo reactivity measurements of spent nuclear fuel”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 986, 164707, 2021.

[2] T. Honkamaa, F. Levai, A. Turunen, R. Berndt, S. Vaccaro, and P. Schwalbach, “A prototype for passive gamma emission tomography,” Proceedings of Symposium on International Safeguards, 2014.

[3] T. White, M. Mayorov, A. Lebrun, P. Peura, T. Honkamaa, J. Dahlberg, J. Keubler, V. Ivanov, and A. Turunen, “Application of Passive Gamma Emission Tomography (PGET) for the Verification of Spent Nuclear Fuel,” in Proceedings of 59th Annual Meeting of the Institute of Nuclear Materials Management, Baltimore, MD, USA, 2018.

[4] R. Backholm, T. A. Bubba, C. Bélanger-Champagne, T. Helin, P. Dendooven, and S. Siltanen, “Simultaneous reconstruction of emission and attenuation in passive gamma emission tomography of spent nuclear fuel,” Inverse Problems and Imaging, vol. 14, no. 2, pp. 317–337, 2020.

[5] R. Virta, R. Backholm, T.A. Bubba, T. Helin, M. Moring, S. Siltanen, P. Dendooven, and T. Honkamaa, "Fuel rod classification from Passive Gamma Emission Tomography (PGET) of spent nuclear fuel assemblies”, ESARDA Bulletin, vol. 61, pp. 10–21, 2020.

[6] R. Virta, T.A. Bubba, M. Moring, S. Siltanen, T. Honkamaa, and P. Dendooven, "Improved Passive Gamma Emission Tomography image quality in the central region of spent nuclear fuel, Scientific Reports, 12, 12473. https://doi.org/10.1038/s41598 022-16642-0 (2022).

Thank you for your attention!

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