Passive Gamma Emission Tomography (PGET) for verifying spent nuclear fuel

Riina Virta

Radiation and Nuclear Safety Authority (STUK)
Helsinki Institute of Physics

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Background

Nuclear safeguards

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

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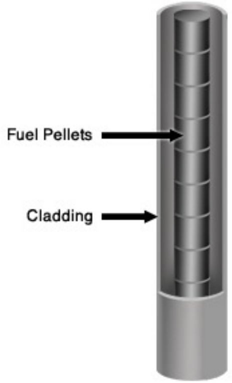
IAEA

European Commission

Picture: IAEA

Nuclear fuel

Pellet: ~ 1cm diameter



Fuel rod: ~ 4m in height

Fuel assembly

Images: TVEL, fema.gov

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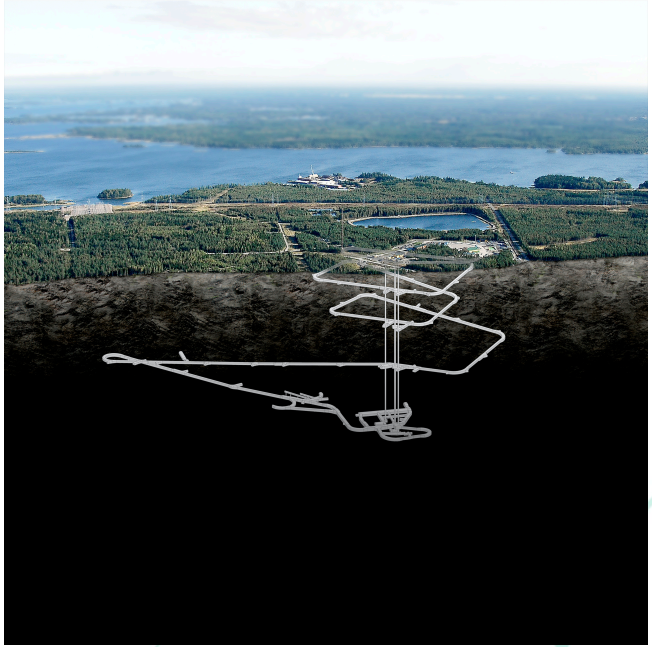
Spent fuel disposal in Finland

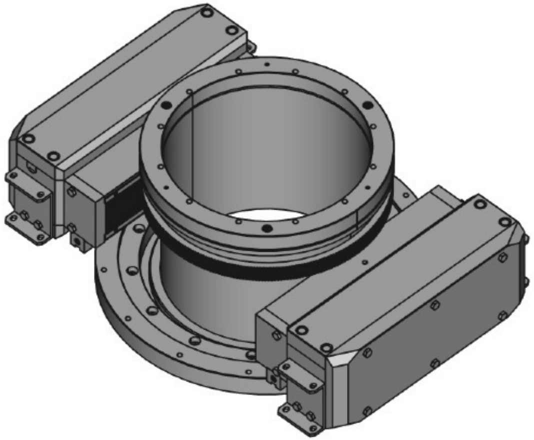
- Disposal in a geological repository starting in the mid-2020's
- Verification of fuel needed: not retrievable after disposal

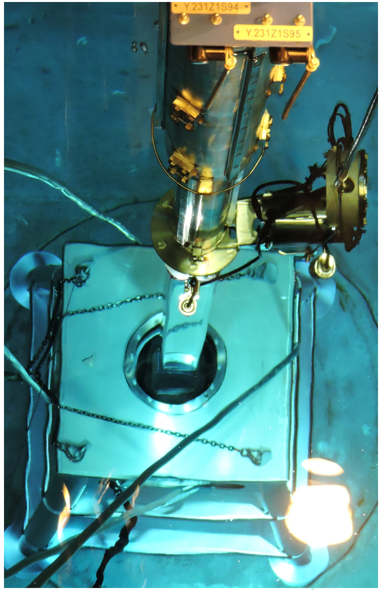


Pictures: Posiva

PGET device

- PGET – Passive Gamma Emission Tomography
- Approved for inspections in 2017 by the IAEA
- Rod-level detection of anomalies





Picture: TVO

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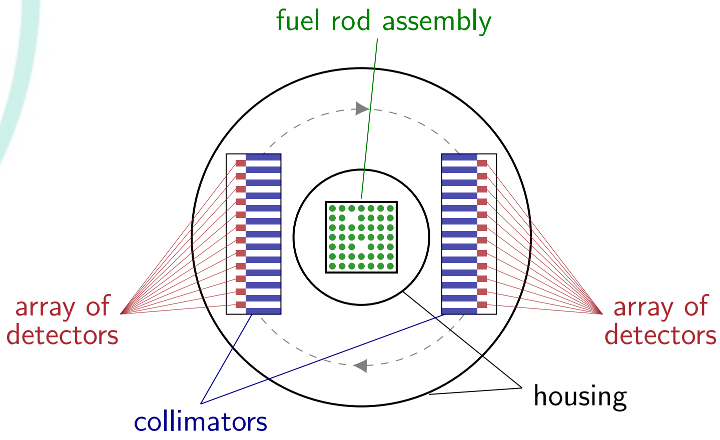
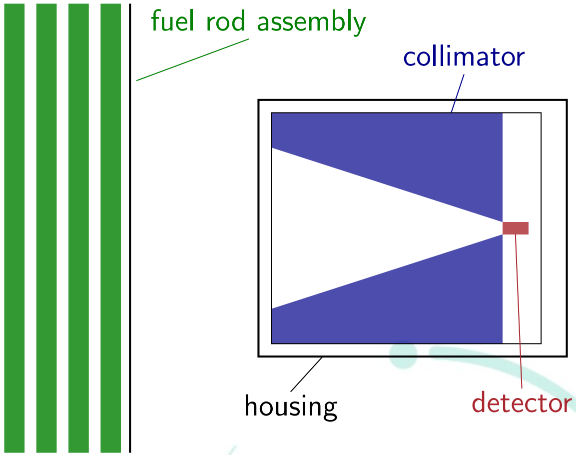
PGET device

- 182 highly collimated CdZnTe detectors, 2 linear banks
- 360 deg spin around the spent fuel assembly
- 5 min measurement time
- Interleaving of data allows for 2 mm effective pixel resolution



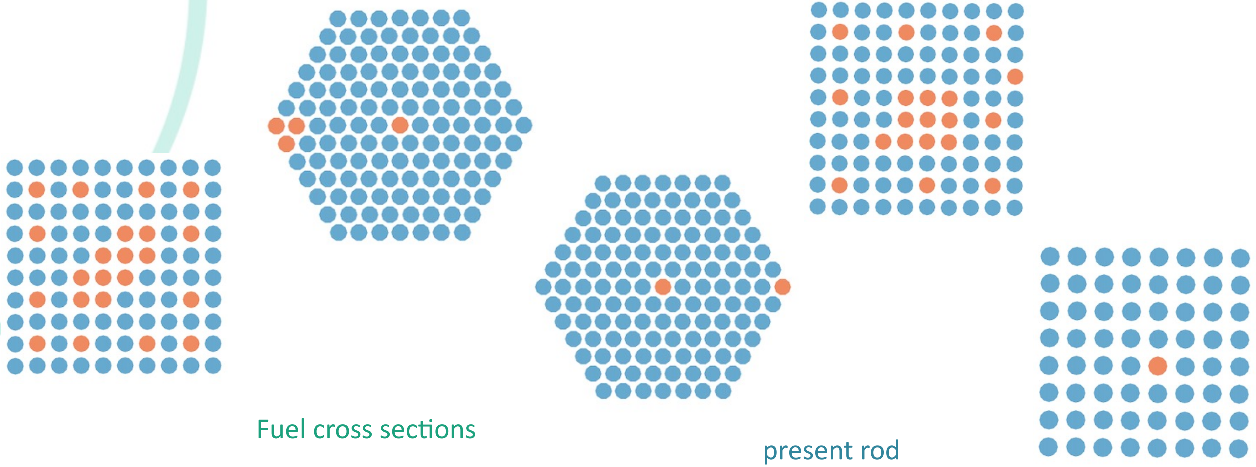
(a) Transaxial cross section, collimators in the horizontal direction



(b) Vertical cross section, collimators in the vertical direction

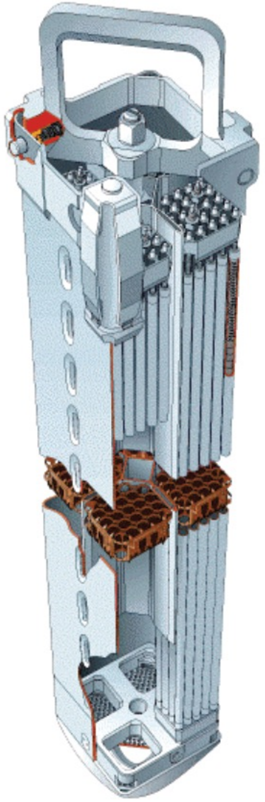
Imaged fuel

- Total of 94 individual fuel assemblies
- Varying geometries, burnups and cooling times



Fuel cross sections

present rod
missing rod



Fuel assembly

Mathematical model

- Constrained minimization problem
- Iterative image reconstruction, Levenberg-Marquardt type of algorithm [1]
- A priori information from an initial FBP image
- μ emission map, λ attenuation map

$$\min_{\lambda,\mu,c} \left\{ \underbrace{\|H(\mu)\lambda - C(c)s\|_2^2}_{\text{Data fidelity term}} + \underbrace{\alpha_\lambda \|R_\lambda \lambda\|_2^2 + \alpha_\mu \|R_\mu \mu\|_2^2}_{\text{Regularization terms, a priori information}} + \underbrace{\alpha_c \|\log(c)\|_2^2}_{\text{Data sensitivity correction}} + \underbrace{\alpha_s \|\mathbf{1}^T(s - C(c)s)\|_2^2}_{\text{Keep the same overall scale}} \right\}$$

Data fidelity term

Regularization terms, a priori information

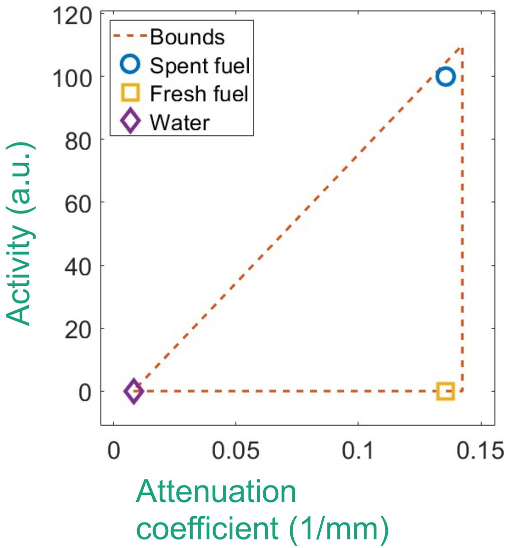
Data sensitivity correction, prefers solutions where corrections are close to 1

Keep the same overall scale of the sinogram

[1] 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.

Bounds

- The space of possible attenuation and activity values needs to be constrained
- Triangle bounds deliver most of the reconstruction quality (box bounds not sufficient)



$$A \begin{bmatrix} \lambda \\ \mu \end{bmatrix} \leq b$$

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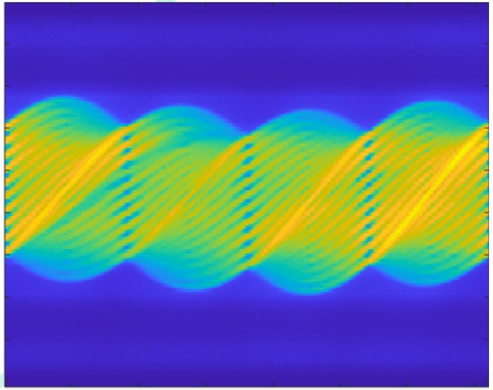
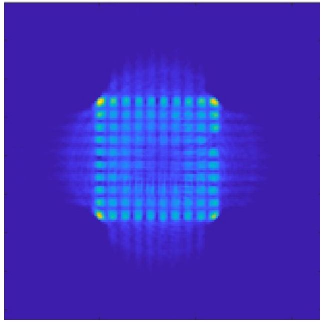
Reconstruction from data

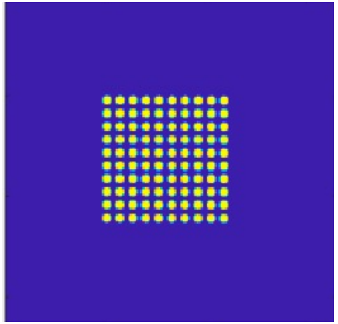
Sinogram



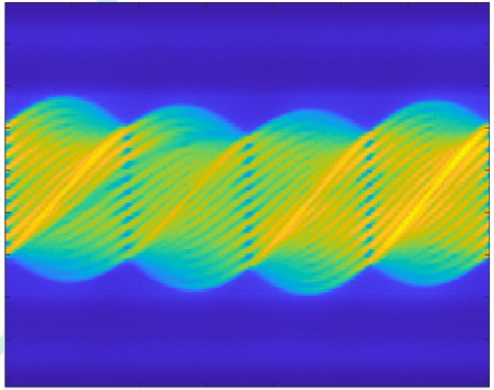
Initial Filtered Backprojection

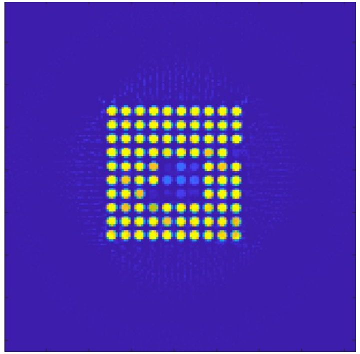


Fit known fuel grid

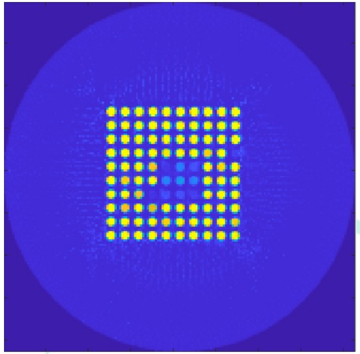


Reconstruction from data





Activity

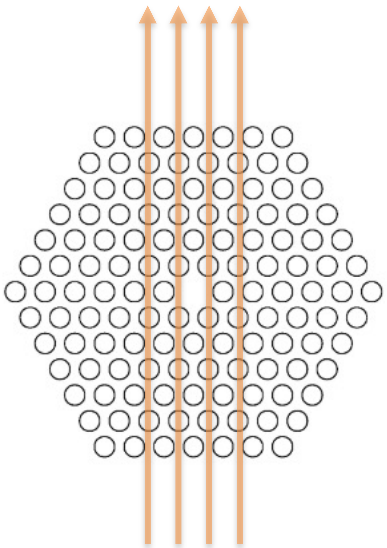


Attenuation

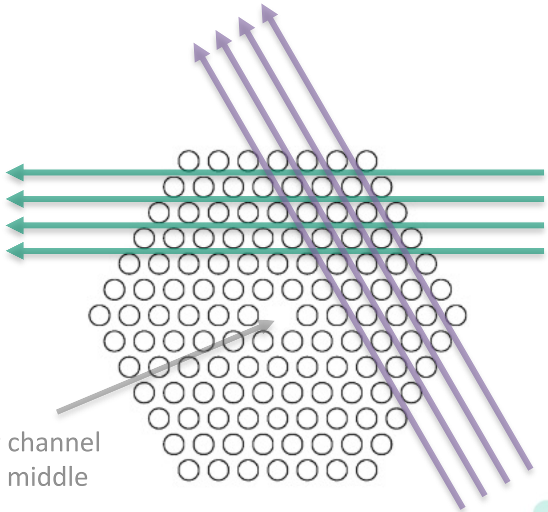
Heavy attenuation in fuel: attenuation map critical!

Results

See-through directions



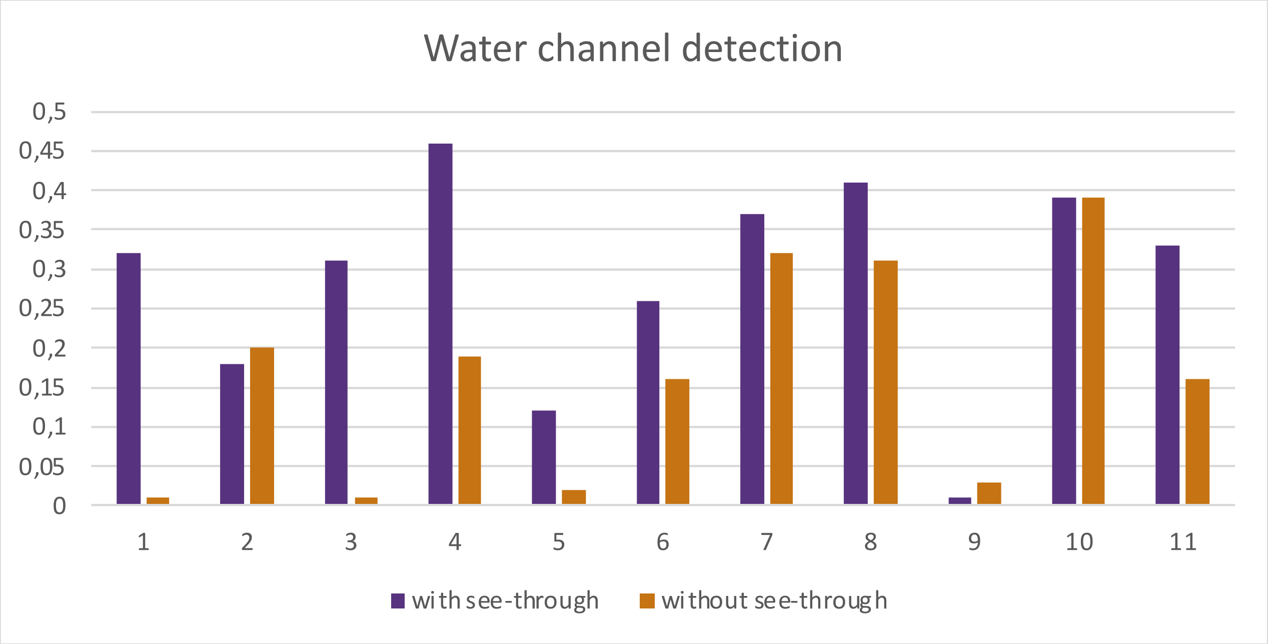
Not a see-through direction



2 out of 6 see-through directions

Water channel detection

- 11 assemblies, reconstructions with and without see-through projections in the angle set
- Water channel detection index describes how well the central water channel is visible compared to present rods



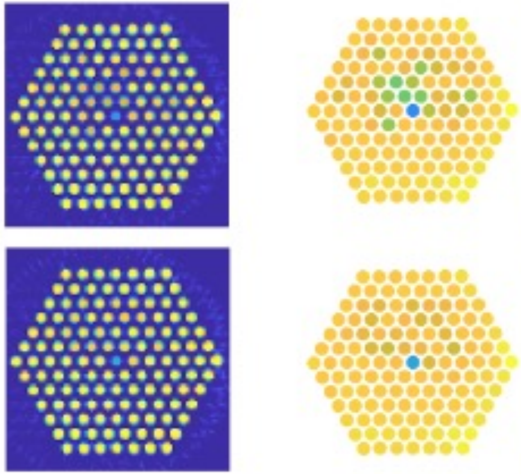
Value range: [0,1]

Reconstructions

With see-through directions

90
Index 12.1

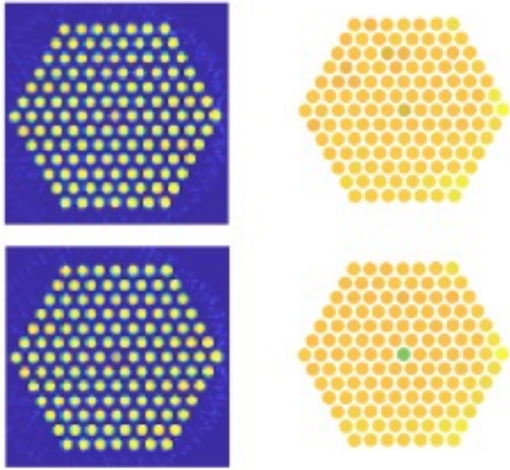
120
Index 16.5



Without see-through directions

90
Index 4.9

120
Index 13.0



Activity reconstructions and rod activity averages

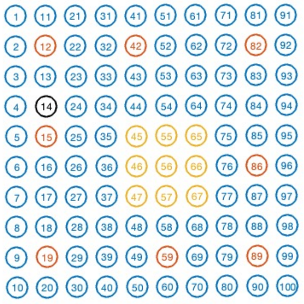
Partial rod edge detection

ATRIUM10
BU 44 QWd/tU, CT 13.2 a
1 dummy rod

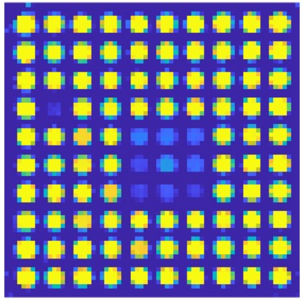
Measurement position where the partial rods are in the field of view of the device

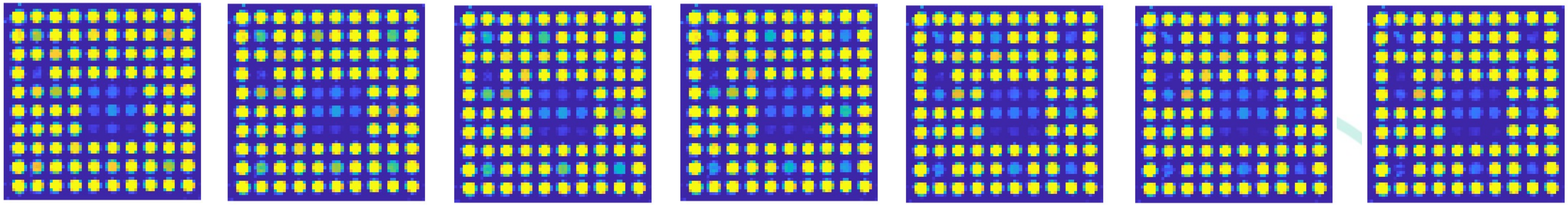
Scans every 2 cm showing the partial rods disappearing from view

Full length rods: 82
Partial length rods: 8
Water positions: 9
Burnable absorber rods: 0
Missing rods: 1



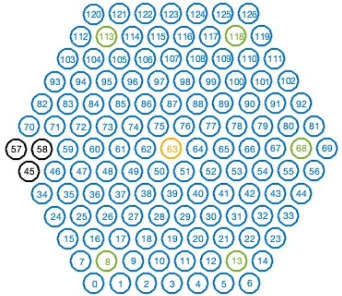
Activity reconstruction





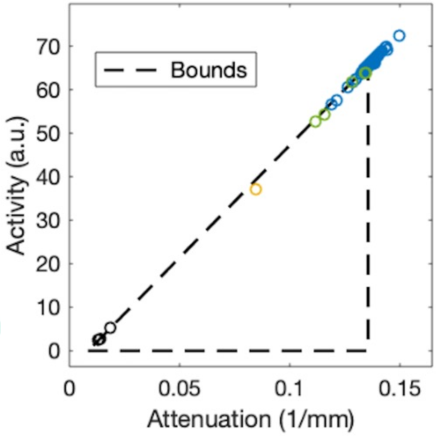
0 cm | 2 cm | 4 cm | 6 cm | 8 cm | 10 cm | 12 cm

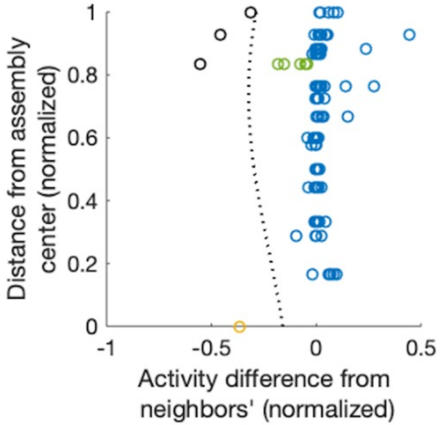
Classification



VVER-440 assembly

Support Vector Machines (SVMs) trained to produce the classification border





Circles: individual rods

Full length rods: 118

Water positions: 1

Burnable absorber rods: 5

Missing rods: 3

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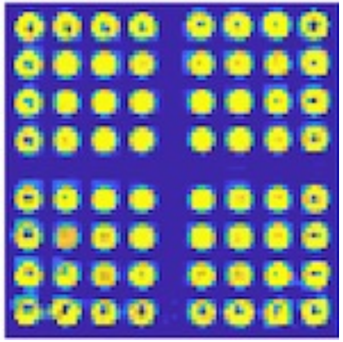
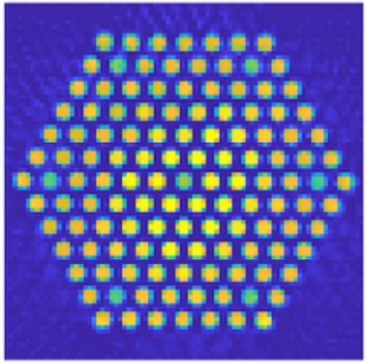
Conclusions

- Rod-level detection of anomalies is demonstrated with the method
  - Even intra-rod activity differences seen
  - Partial deviation in the axial direction also detected if measurement position is favourable

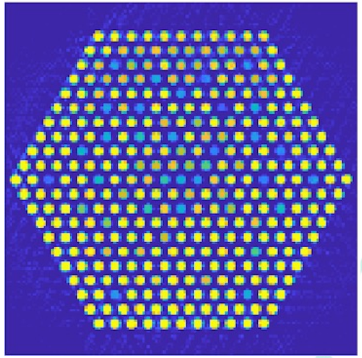
- Future challenges include
  - Further improvement of the method: even larger fuel to be measured in the future
  - Quantitative GET imaging: Bq/cm^3?



SVEA-64



VVER-440



VVER-1000

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Collaborators

- M.Sc. Student Rasmus Backholm, Department of Mathematics and Statistics, University of Helsinki, Finland
- Dr. Tatiana A. Bubba, Department of Mathematics and Statistics, University of Helsinki, Finland and presently at Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK
- Prof. Peter Dendooven, Helsinki Institute of Physics (HIP)
- Prof. Tapio Helin, School of Engineering Science of LUT University, Lappeenranta, Finland
- M.Sc. Tapani Honkamaa, STUK (Radiation and Nuclear Safety Authority in Finland)
- M.Sc. Mikael Moring, STUK (Radiation and Nuclear Safety Authority in Finland)
- Prof. Samuli Siltanen, Department of Mathematics and Statistics, University of Helsinki, Finland

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Thank you!

Contact at
riina.virta@helsinki.fi