The use of muon tomography in safeguarding nuclear geological repositories

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on behalf of

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BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG | JÜLICH Forschungszentrum | Radioactive Waste Management | The University Of Sheffield. | Geoptic

Muon tomography and GDFs

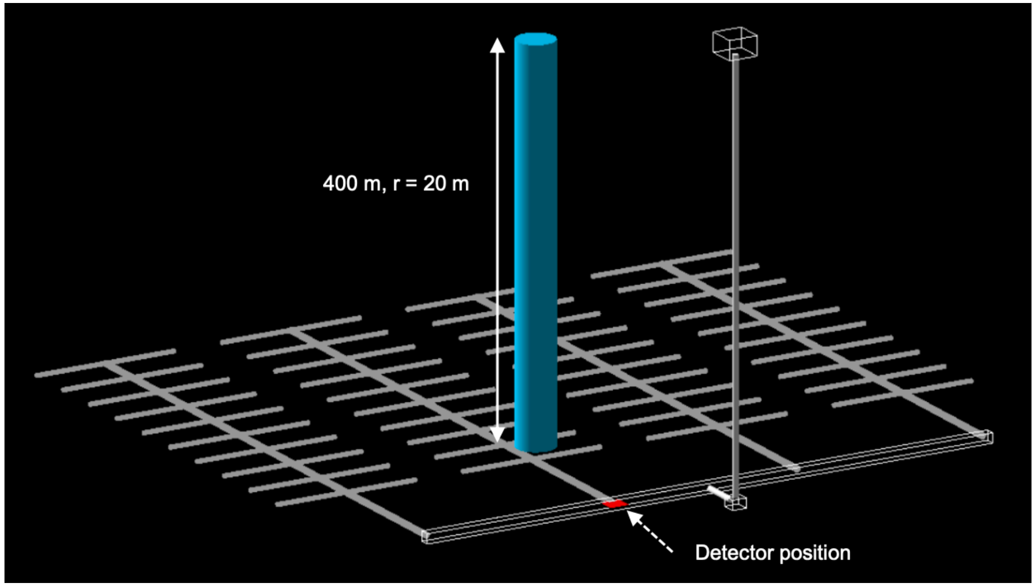
- Civil infrastructure imaging and imaging of ore bodies in mines with muons is already underway
- For example: in the UK the technique is being used to search for hidden shafts in railway tunnels (see Chris Steer's talk)
- Elsewhere in the world nickel and uranium ore bodies are being located without the need for drilling boreholes
- In general muon tomography is a powerful tool for locating irregularities in overburdens
- The following reports on a series of proof of principle simulation studies we have performed to assess the capability of muon radiography to detect a series of potential features that may need to be identified for *safeguards or safety purposes* in geological disposal facilities (GDFs)

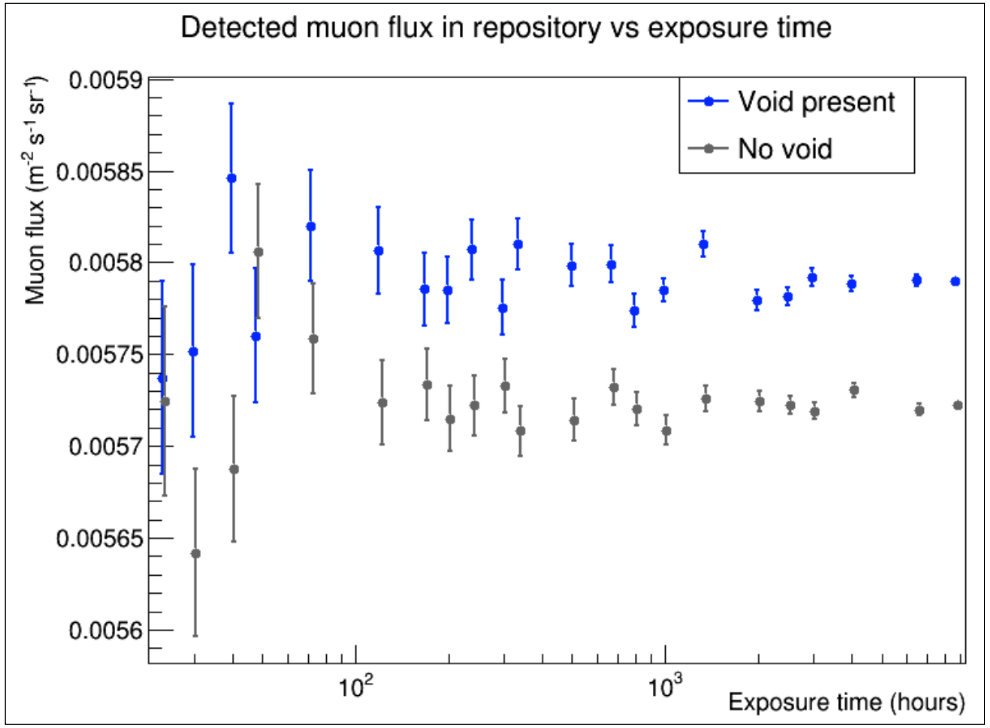
- An example list of the types of features that may need identification include:

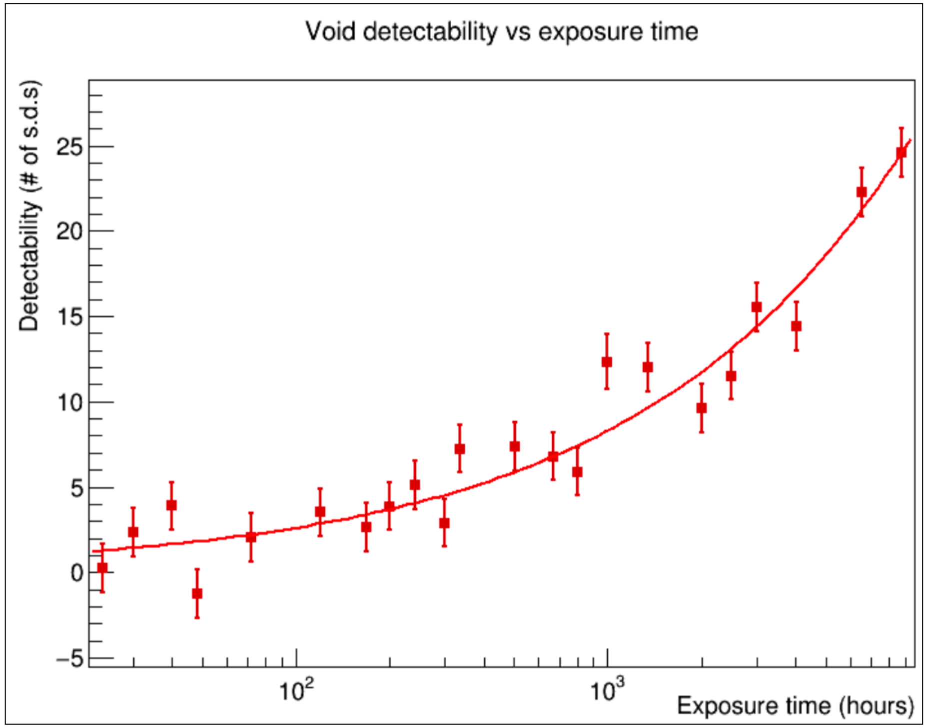
- design information verification
- continuous geological overburden monitoring for overburden change detection
- understanding the condition of the host rock geology
- searching for undocumented voiding
- checks of backfill integrity in the vaults
- tunnel lining system checks/ monitoring
- sensitivity to water ingress and movement in the overburden
- long-term monitoring of the GDF post-closure

GDF safeguarding - void detection

- Initial studies have simulated the ability to detect a large (unphysical) unknown shaft in a GDF with a single 2m x 2m detector with idealised resolution and efficiency (85%)

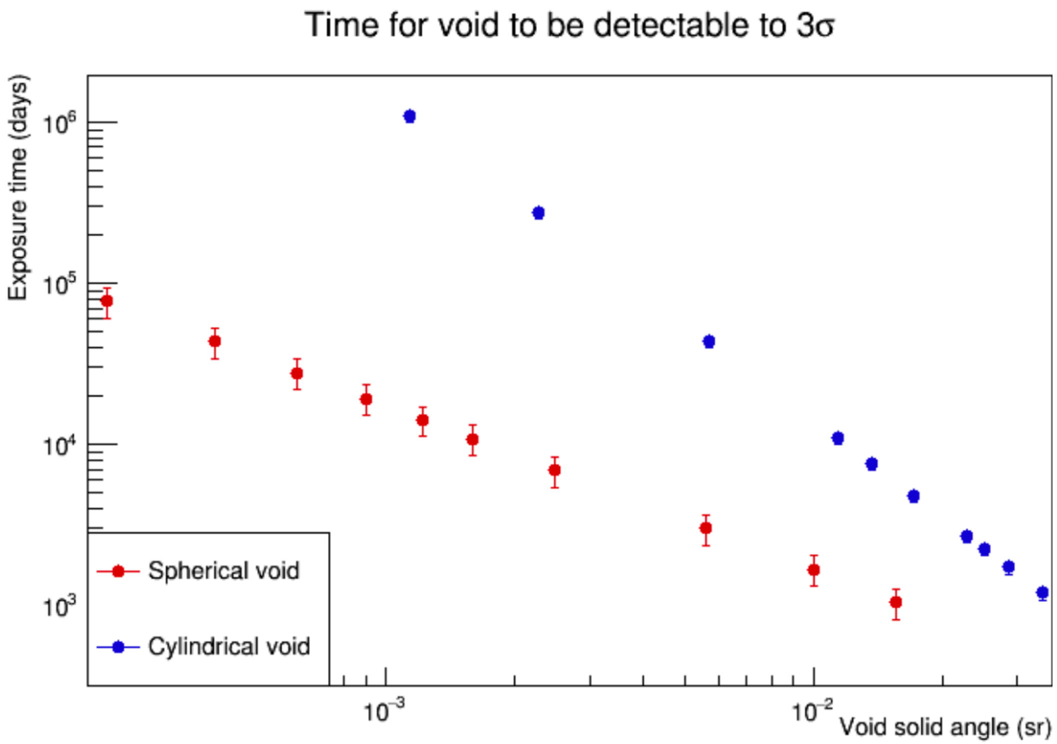


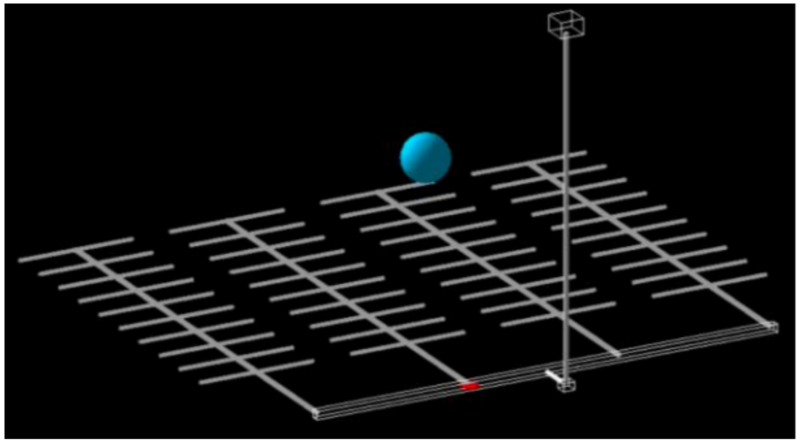


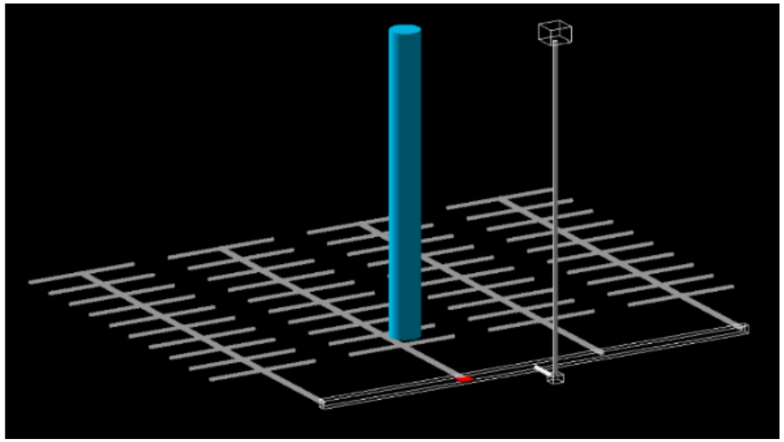


GDF safeguarding - void shape dependence

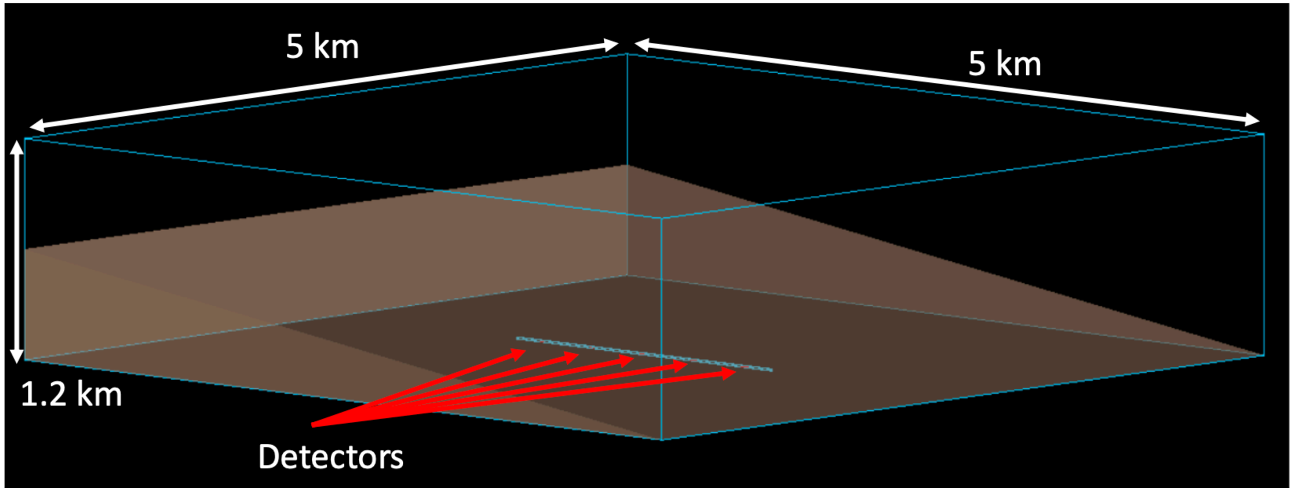
- Comparison of a series of cylindrical and spherical voids ("can we categorise sensitivity to a suite of object sizes and shapes?")
- Note neither void volume nor subtended angle is enough to parametrise the problem, need, e.g. zenith angle too

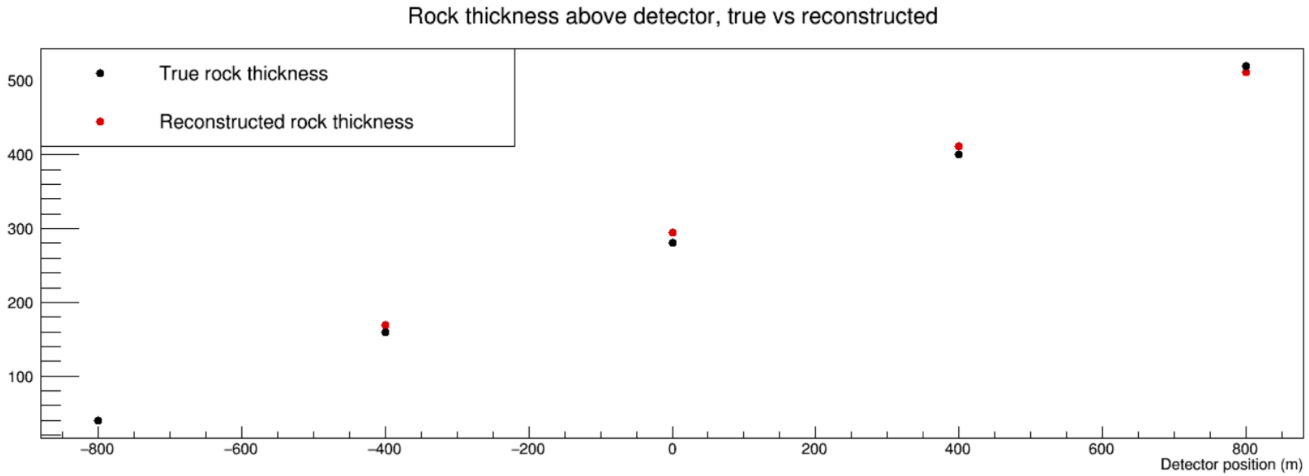


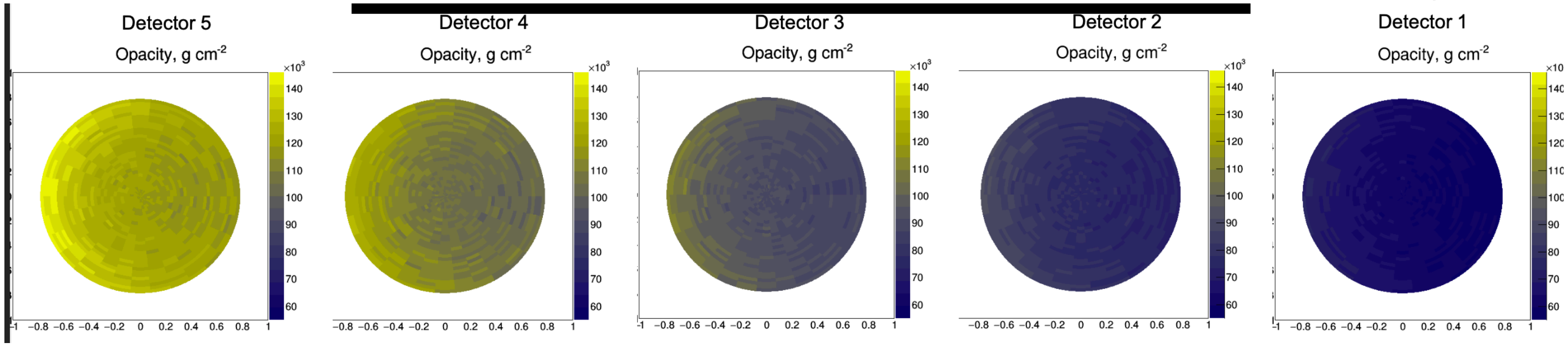




GDF safeguarding - opacity reconstruction





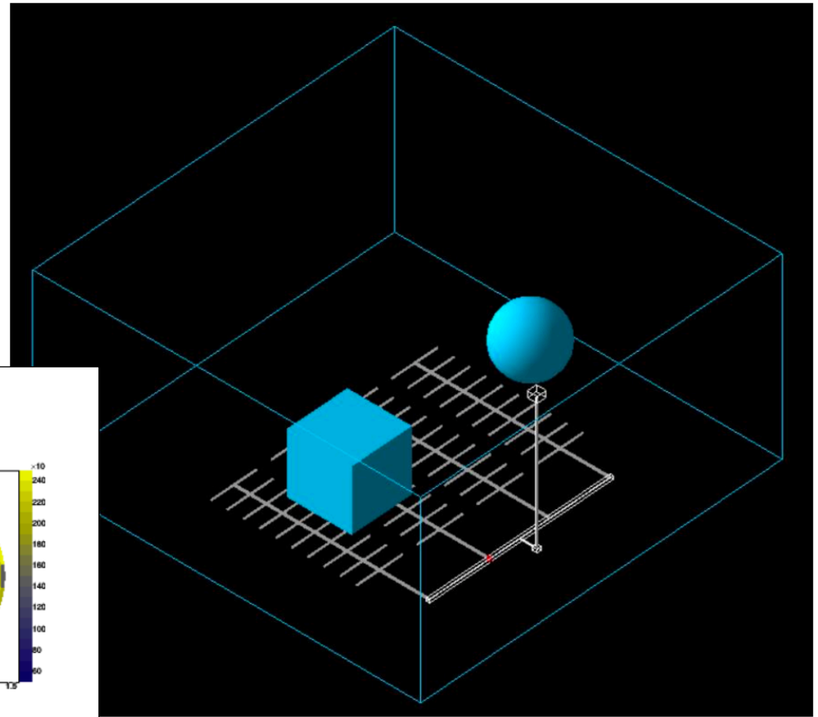


- Using muons to investigate the overburden:
- Here a simple granite slope and a system of 5 detectors is used
- Opacity data from 5 detectors in a tunnel under the slope, as a function of incident muon angle is shown
- The granite slope can thus be reconstructed using a suitable regression algorithm or SART

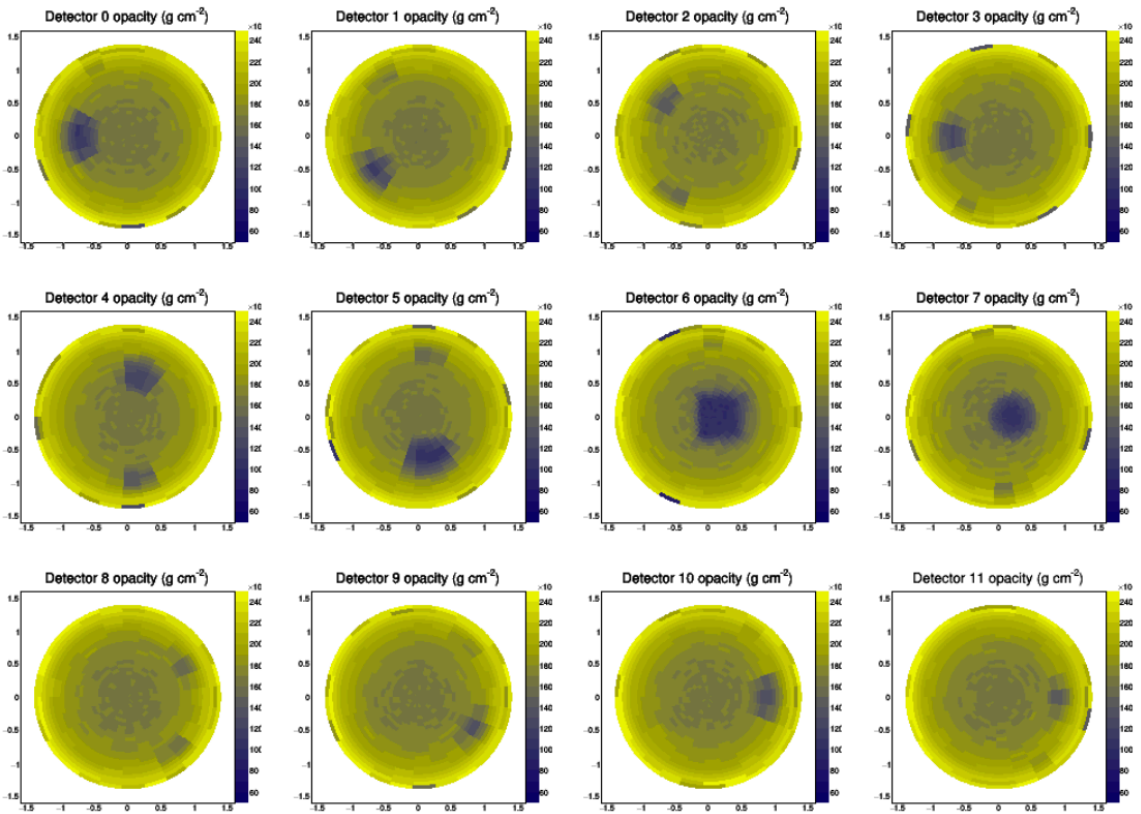
GDF safeguarding - void *imaging*

- Use of 3D techniques such as SART, enables *opacity* information from a multiple detector system to be combined to create a 3D image

Interactive view of simulated geometry (repository with 2 large voids)



Opacity data from 12 detector positions



- A simulated geometry with unphysically large voids is being used in the first instance to develop the software tools and to establish the technique

The CHANCE project

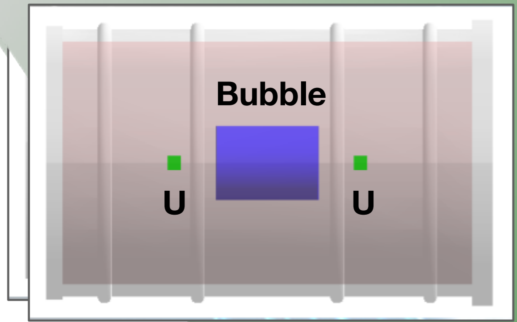
CHANCE
Characterization of Conditioned Nuclear Waste for its Safe Disposal in Europe

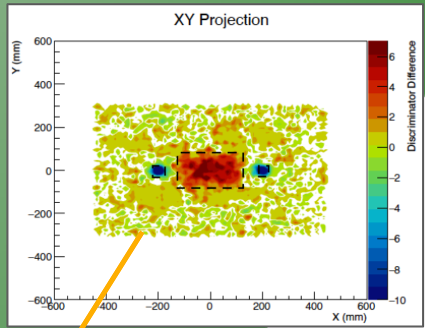
- CHANCE: “Characterization of conditioned nuclear waste for its safe disposal in Europe”
- EU Horizon 2020 project
- 4 years of funding, started June 1, 2017 - extended to March 2022
- 11 partners in 7 countries
  - universities, research institutes, government agencies and industrial partners
- 3 different techniques for non-destructive assay of nuclear waste drums:
  - Work Package 3: Calorimetry
  - **Work Package 4: Muon Scattering Tomography**
  - Work Package 5: Spectroscopy

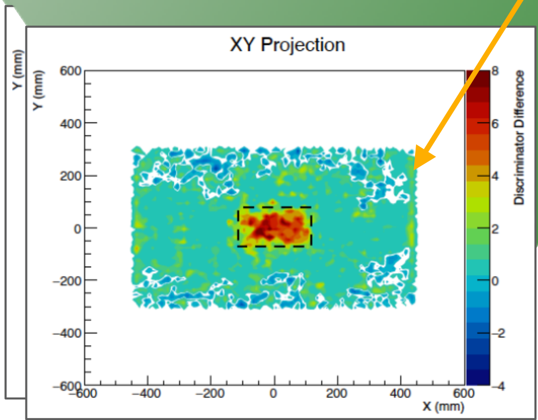
The University Of Sheffield. University of BRISTOL Politechnika Warszawska Warsaw University of Technology

Ahmad Alrheli, Dominic Barker, Chiara de Sio, Daniel Kikoła, Anna Kopp, Mohammed Mhaidra, Patrick Stowell, Jaap Velthuis, Michael Weekes

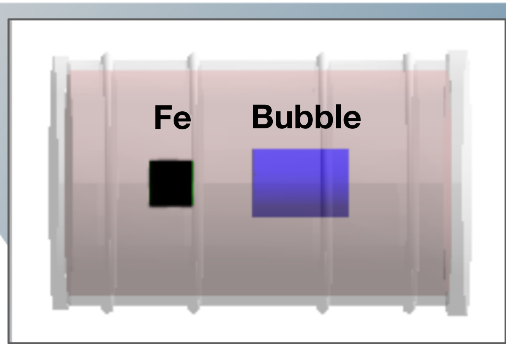
Bubble ID in heterogenous waste drums

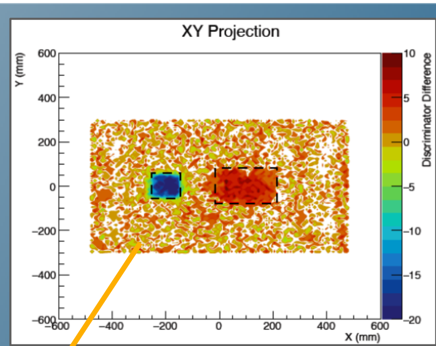


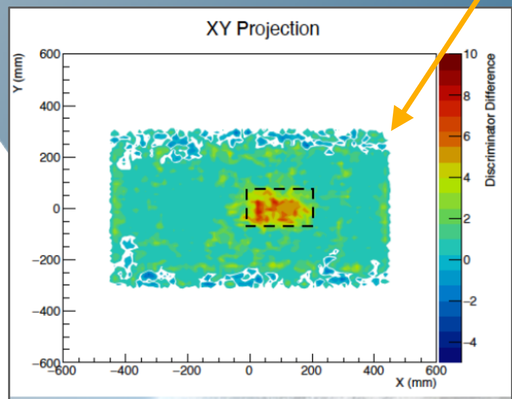




- Gas bubbles can form within the matrix of a waste drum and are a concern. Using muon scattering tomography bubbles can be identified and their volume accurately determined





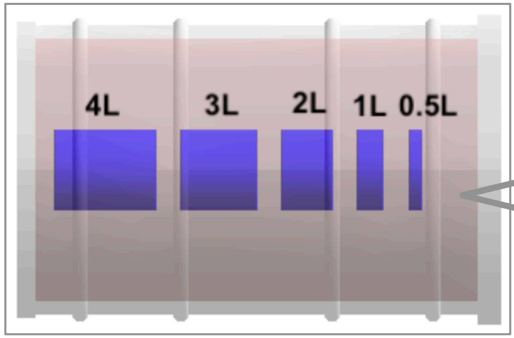


<u>Possible application to GDFs:</u>

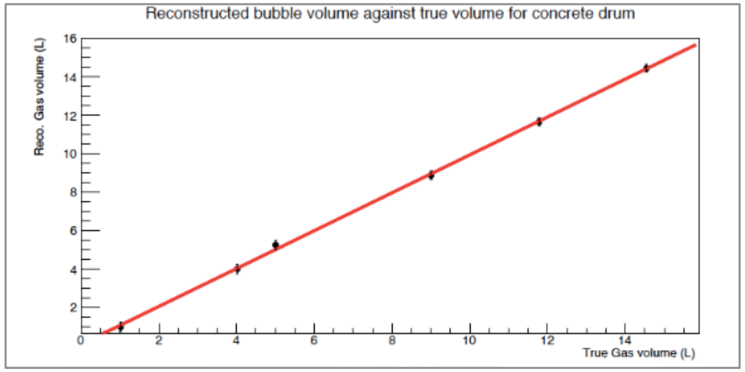
- monitoring of in-package voidage within nuclear waste drum which may result as a consequence settlement in the package during transportation

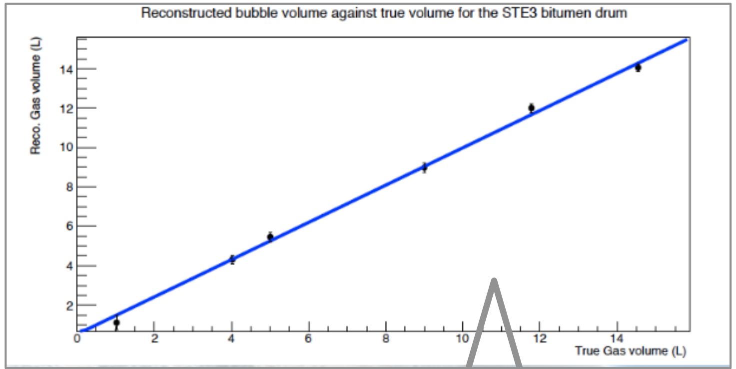
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 755371.

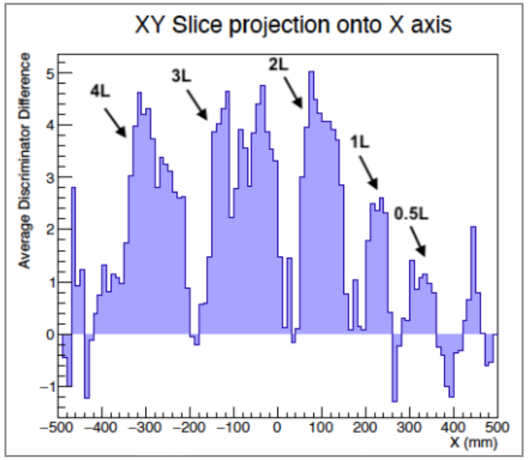
Bubble ID in heterogenous waste drums

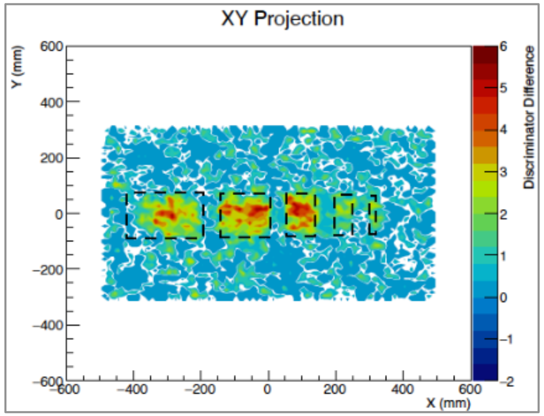


- The limitations on this method have been evaluated using a “figure of merit” technique
- Different sized bubbles, 5cm spacing, 4 week exposure









- Once the bubble has been identified it needs to be measured
- Simulate cylindrical bubbles in centre of the Eurobitum/STE3 bitumen filled drum, aligned with the drum’s central axis
- Distributions indicate how the mean of the discriminator gives a very accurate measure of the bubble volume

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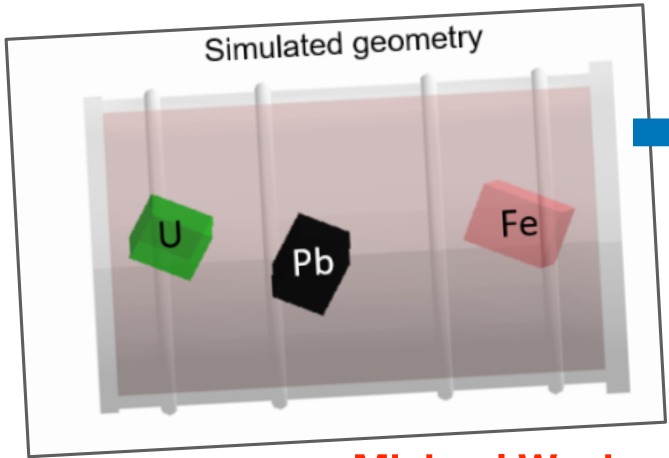
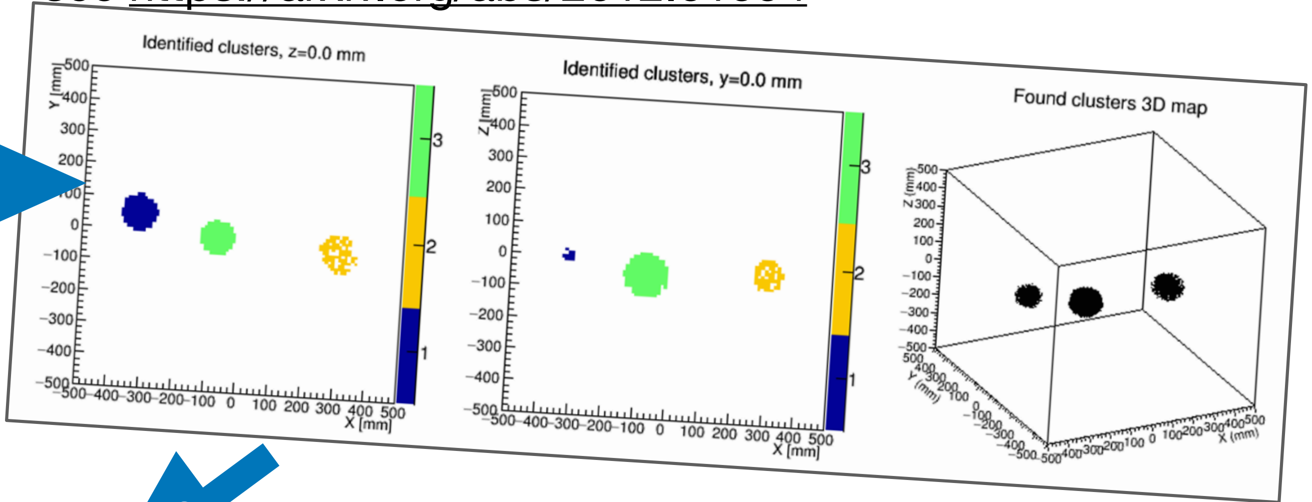
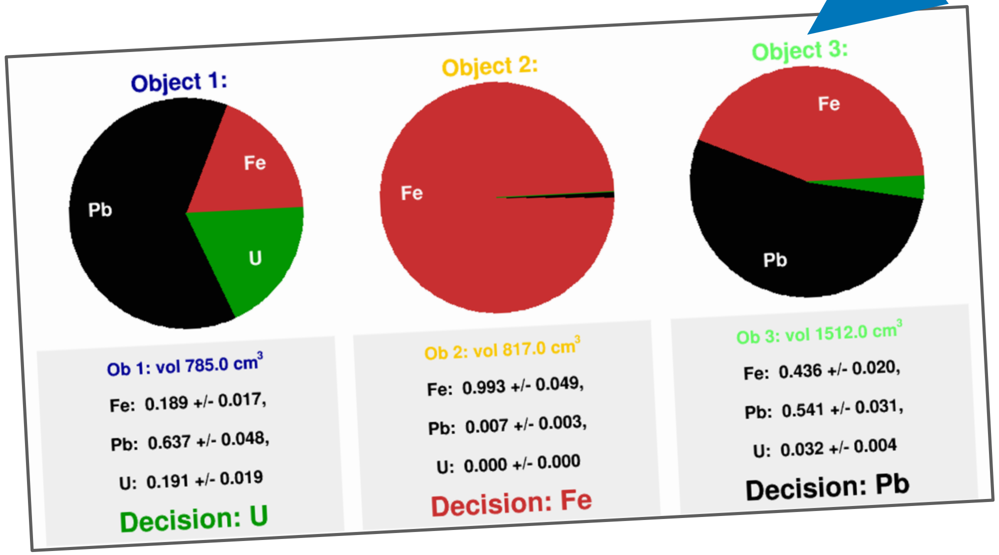
Material ID in heterogenous waste drums

- A method has been developed to perform material identification using **machine learning techniques**
- **STEP 1:** identification of material boundaries in the waste drum which has a concrete matrix
- **STEP 2:** uses machine learning MVA algorithms to assign a probability for each identified object being a particular material - see https://arxiv.org/abs/2012.01554





see Michael Weekes' poster



Possible applications to GDFs:

- safeguarding any outgoing potentially-empty package (e.g. MST would be able to confirm, quickly, any presence of high-Z material in the outgoing package that shouldn't be there)

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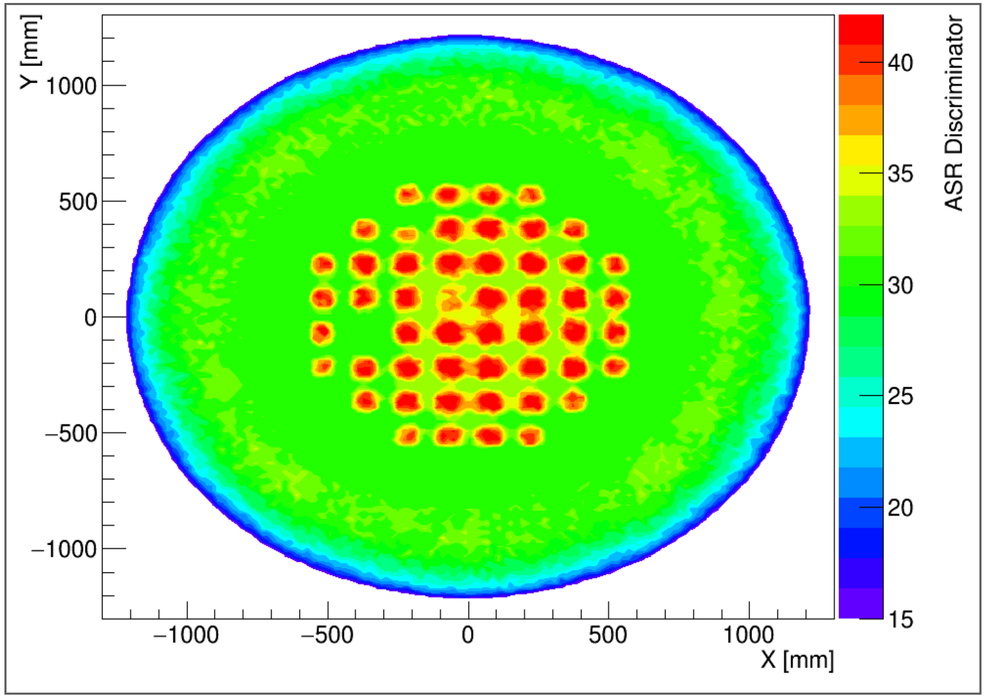
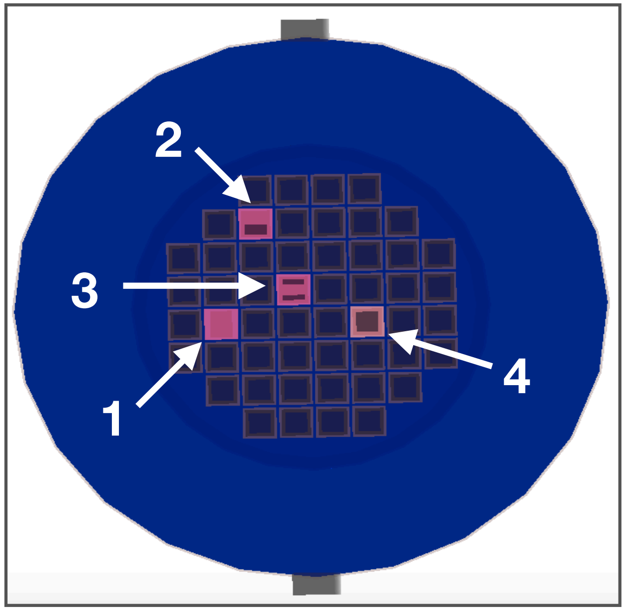
Waste container imaging

- Looking at the potential for muon scattering tomography to identify possible changes to a CASTOR drum

<u>Possible applications to GDFs:</u>

- confirming that a full complement of in-package components is present (no unauthorised diversion of materials)
- confirmation that out-going packages are truly empty





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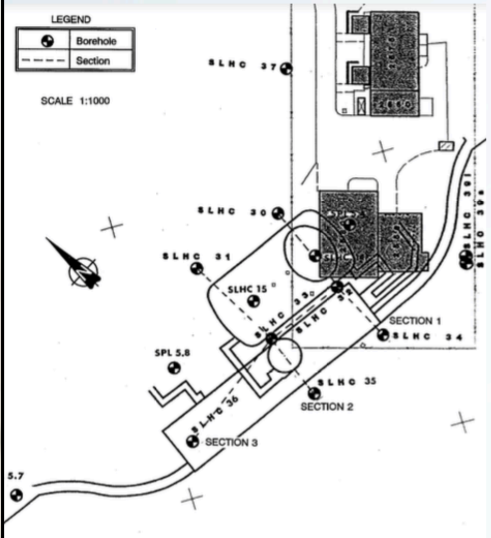
- Various diversion scenarios considered
  1. Empty basket
  2. Half-loaded basket (Unloaded side fuel assemblies)
  3. Half-loaded basket (Unloaded central fuel assemblies)
  4. Pb pellets basket (UO_2 pellets replaced by Pb pellets)

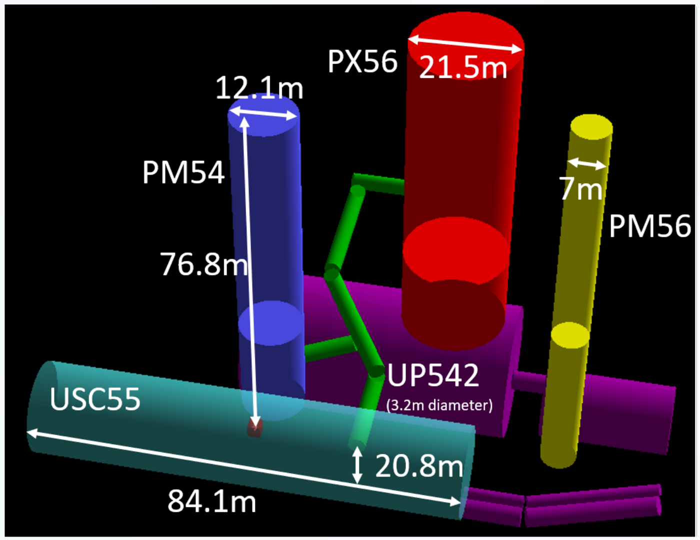
MT imaging @ CERN

- Next week we will be imaging a complicated tunnel system around the CMS experiment at CERN, 80 m below ground
- The focus is on the imaging of complex subsurface structures, e.g. having multiple objects of interest in the field of view, etc.
- Will also be deploying a low power, semi-autonomous long-term monitoring system for 3+ months
- As well as a powerful proof of principle it also helps to validate our workflows, i.e. geotechnical information >> detailed simulation >> projected sensitivity/imaging time

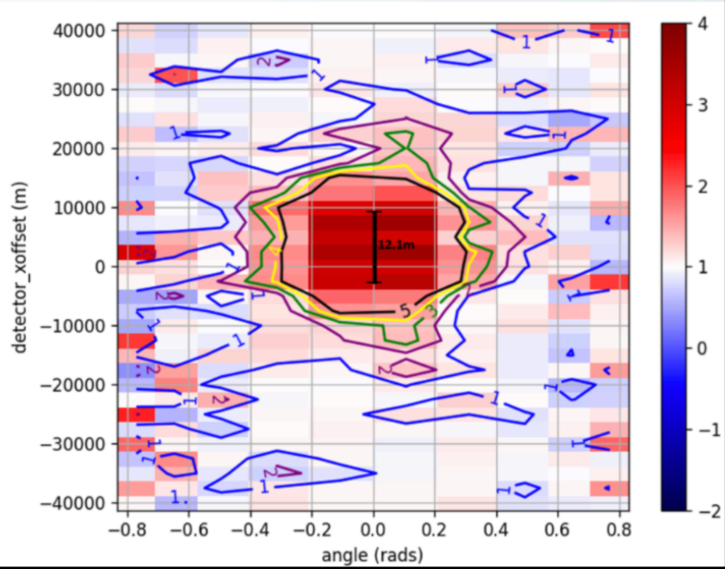
Early geotechnical boreholes data



Simulation geometry



5-Sigma Simulation of a Statistical test of CERN shaft detection



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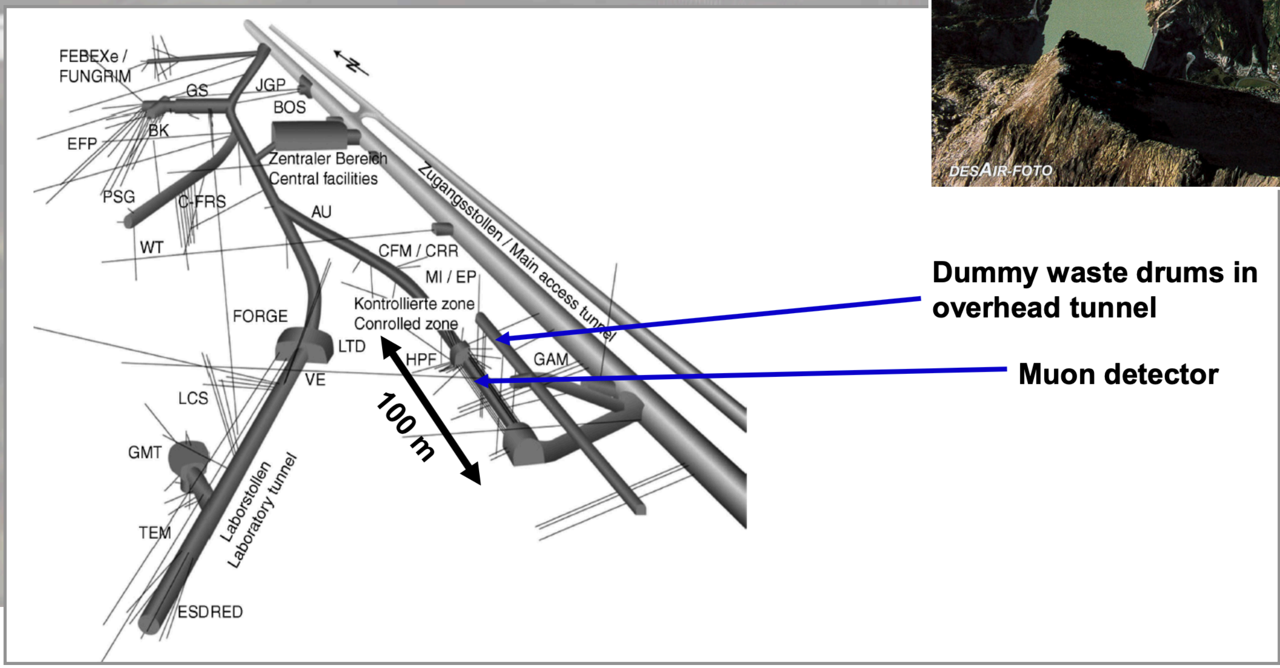
MT imaging @ Grimsel

- The possibility of performing further proof of principle tests at Grimsel in Switzerland is under discussion
- Grimsel is a GDF analogue operated by NAGRA at a height of 1700m in the Aar Massif



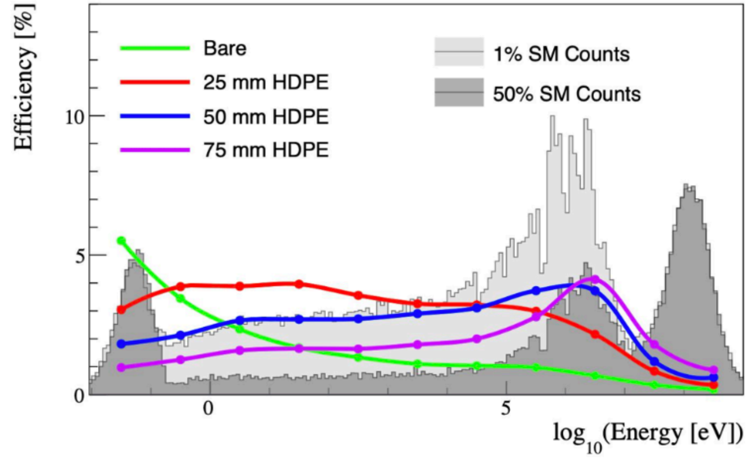
- Opportunities include, e.g. imaging dummy waste drums in tunnels that can be observed from infrastructure below

Neutron sensors for ground water monitoring

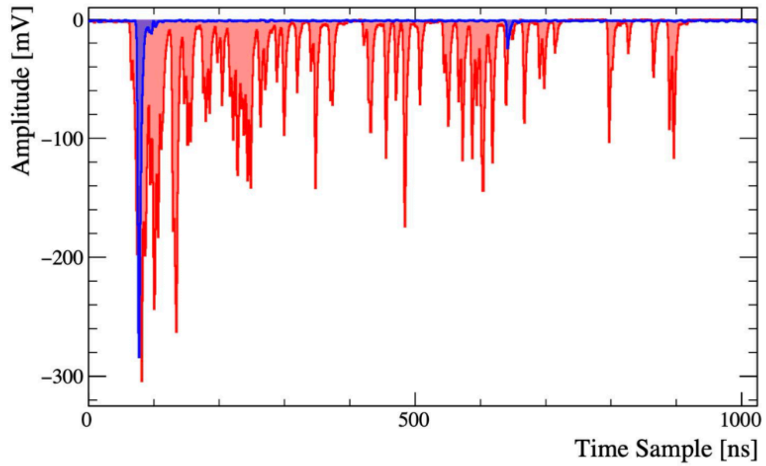
- Cosmic ray neutron sensor based on scintillating thermal neutron foils
- Count rates similar to typical Helium-3 soil monitors at ~50% of the cost
- Completely integrated remote monitors
  - 1.5W power consumption
  - GSM remote data transmission
  - Automated water content processing pipeline and dashboard interface
- See arXiv:2106.06757 (accepted for publication in JINST)

Peat bog trial, Scotland

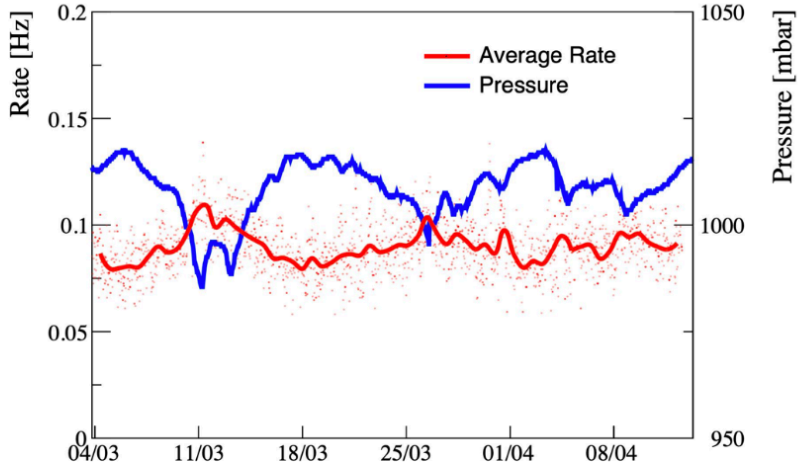
Capture efficiency as a function of neutron energy



Comparison between **gamma** and **neutron** induced pulses



Measured system rate over a one month test deployment



Conclusions

- Muon tomography is a powerful tool that exploits naturally occurring radiation to form images of objects in a non-invasive and non-destructive way
- It has been famously used to search for hidden chambers in pyramids and to image the magma chambers in volcanoes
- The technique is currently considered globally to a huge range of applications including imaging of civil infrastructure, mines, nuclear safeguards and material control, homeland security
- Considering the management of nuclear waste disposal there are a number of areas where muon radiography is a promising technology to address specific problems such as GDF design information verification, integrity assurance and long-term monitoring
- Similarly, muon scattering tomography offers the possibility to identify issues such as material diversion, package voiding and material identification.