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Muon Tomography solutions by GScan: From bridges to nuclear system

Presented by Andi Hektor (Co-founder & CSO)

On behalf of Madis Kiisk (Co-founder & R&D lead), Märt Mägi (Co-founder & CTO), and GScan's R&D team

ELI Workshop, Mar 2025

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Non-Destructive Testing & Structural Health Monitoring

<u>Team:</u> 40 employees + 25 collaborators in joint projects

<u>Located in the Estonia, UK, and Germany</u>

<u>Biz domains:</u>

- NDT for critical structures in the built world
- Nuclear decommissioning and waste classification
- NDT for large composite objects:
    - Energy and O&G systems
    - Defence
    - Naval

<u>Investments:</u> €13mln grants + €4mln private investments

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Partner network

Uni. of Tartu (Estonia), €1.2m+
CAEN (Italy), €1m
DLR (German aerospace agency), €0.8m
Foundation Bruno Kessler (Italy), €0.8m
Imperial College London (UK), €0.5m
UCLouvain (Belgium), €0.5m
Uni. of Cambridge (UK), €0.42m
Uni. of Sheffield (UK), €0.4m
DESY (Germany), €0.3m
University of Cambridge (UK), €0.3m
KBFI/NICBP (Estonia), €0.2m
European Space Agency (ESA), €0.3m
CERN (Switzerland), €0.07m
Uni. of Tokyo (Japan), Uni. of Exeter (UK), Taltech (Estonia)

Recognized business partners

Jacobs
national highways
SGS
AtkinsRéalis
NRS Nuclear Restoration Services
Sellafield Ltd
ALARA As Low As Reasonably Achievable
Republic of Estonia Transport Administration

Our motivation: Built Environment Not Properly Managed

Majority of decision about assets (demolish, limit usage, defining reconstruction scope) are made based on conservative assessments and not clear facts

50% of built infrastructure is >50 yrs old

- = 2 mln bridges
- <13% in good condition
- 50k bridges/year reach their lifespan

75% of 2050 the infrastructure not yet built

- 3 tons of concrete used / year / every human
- 8% of global Co2

No good tools & methods to see inside

- >40cm of inhomogeneous materials (like reinforced concrete or timber)
- see inside shielded materials

4x

Investment overspend

2x

Deficient maintenance

5x

Excessive CO2 emissions

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Client requirements

Non-Destructive Testing

- Imaging resolution sufficient for rebar and tendon ducts – **a few millimeter spatial resolution**
- Discrimination of corrosion and chemical changes, e.g., carbonisation – **automated material classification**
- **Reasonable cost**

Our approach

- Develop hardware with tracking performance and operational requirements that meet the requirements of these applications
- Deploy scattering and transmission based imaging and material classification.
- Our approach is to solve first the inverse problem, detect objects and its boundaries and classify material of each object

GScan's scanner / tracker technology

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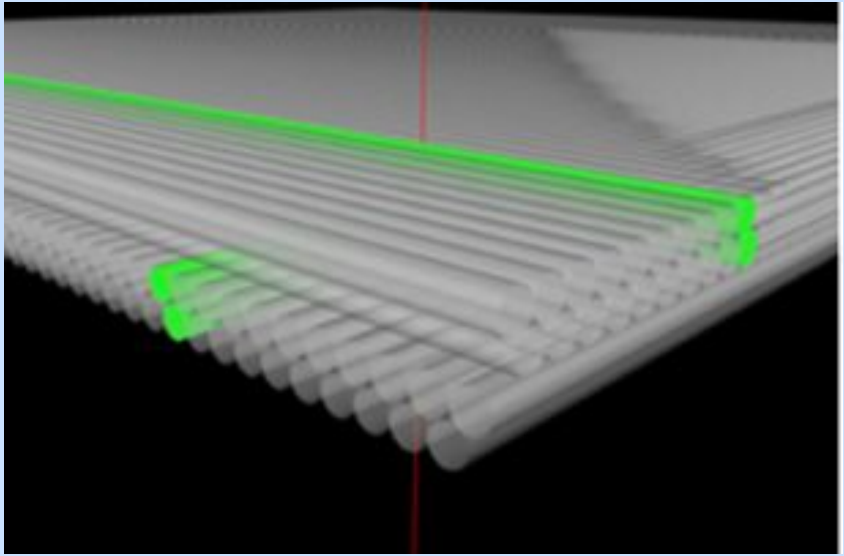
Design requirements and decisions

- Tracking accuracy - 1 mrad
- Spatial resolution - 100 um
- Field-work requirement – robust, user friendly, compact lightweight
- Our selection - fibre mats out of plastic scintillation fibres



The layout of two double-layered fiber-mats, assembled orthogonally to form a x-y detection plane.

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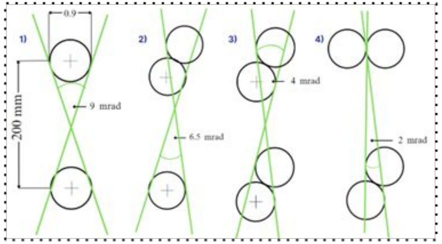
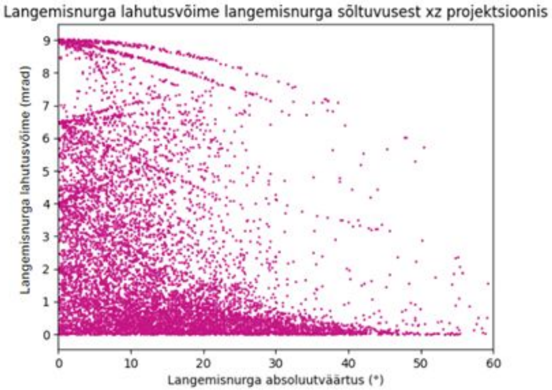
The tracker



Possible combinations of the fibres/clusters lit by the passing particles.



Tracking resolution as a function of the inclination angle of the particles, expressed in full width of the cone visualized above.

An image of a three-detector plane tracker, an assembly of 6 fibre-mats.

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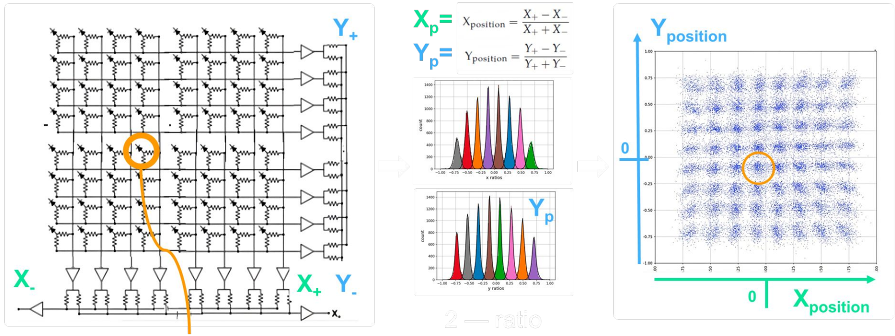
Front-end readout

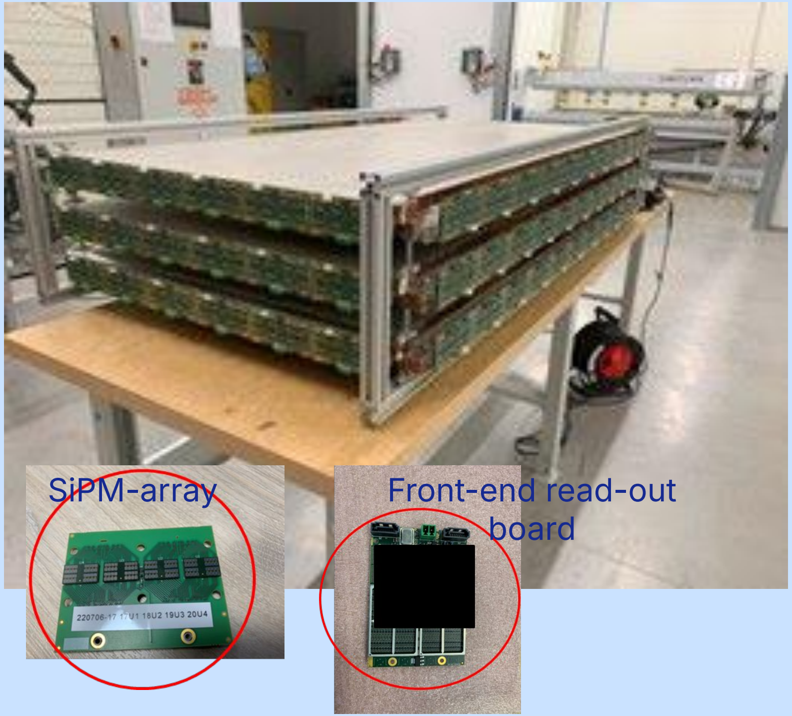
SiPM array readout is performed in two ways:

1. Via multiplexer - DAQ channel reduction 16X
2. Customised, home-made DAQ direct readout with strict-budget design condition

Below an illustration of the multiplexer schematics:



1 — SiPMs
2 — ratio calculations
3 — constellations



An image of a three-detector plane tracker, an assembly of 6 fibre-mats.

muonFLUX™ Infra & Nuclear

The muonFLUX Infra system in the in-field configuration measuring critical structures of an office building (Feb 2024)

The muonFLUX Infra system in-field configuration allows to rapid and mobile transit and set up at a measurement site

Deployment examples

Bridge element (UK)

Wind turbine towers

Scanning of a pillar

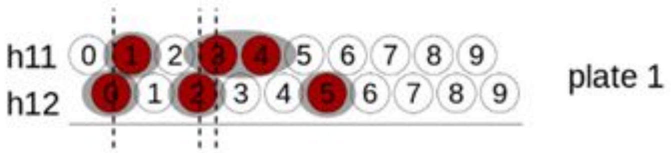
Scanning of an office wall

Nuclear reactors

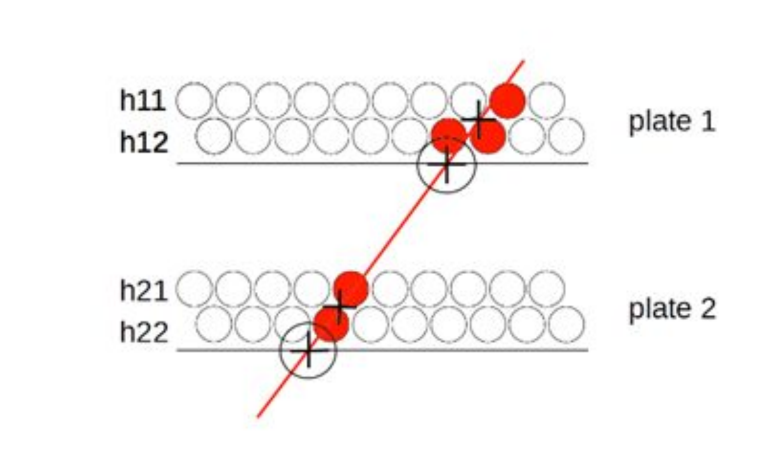
Data processing:

acquisition data, reconstruction, object and material recognition

Hardware fibre clustering + particle tracking



An illustration of the clustering logic. Lit fibres next to each other compose individual cluster. A fibre-mat may contain multiple clusters.

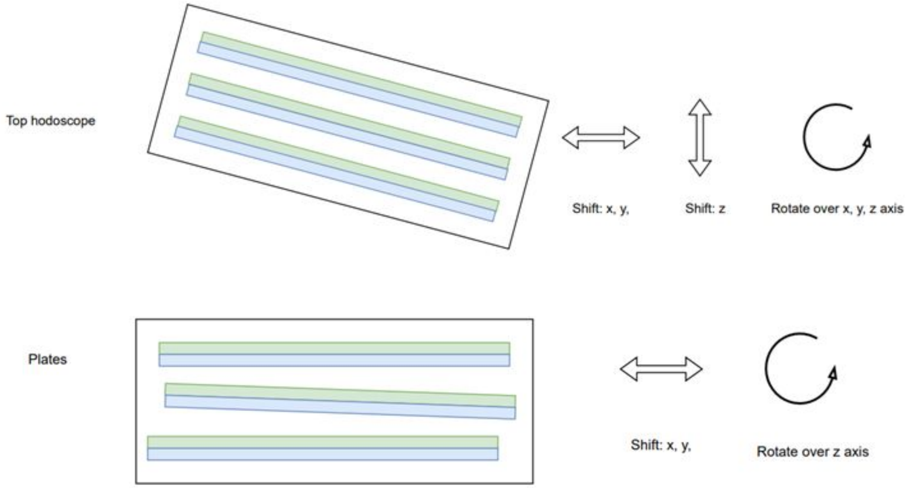


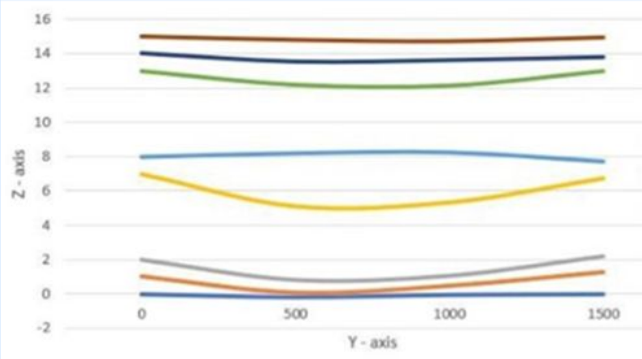
An illustration of the hit coordinate localisation in case of clusters with two- and three-fibre lit at separated x-plane and on an virtual x-y plane.

Hardware alignment

Our approach:

- Custom Unsupervised Physics Informed Neural Network
- Develop a custom model architecture that can learn physical build.
- Use the physical properties of muons behaviour to make corrections.



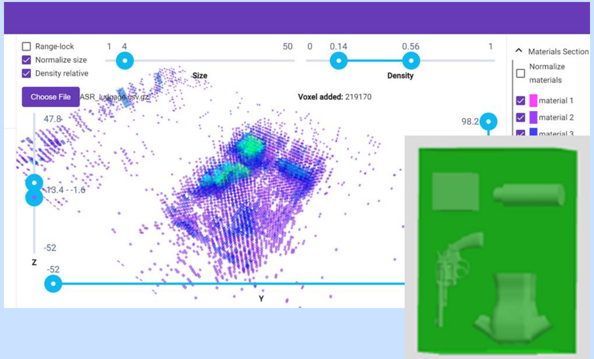


Learned curvature of a fiber mat

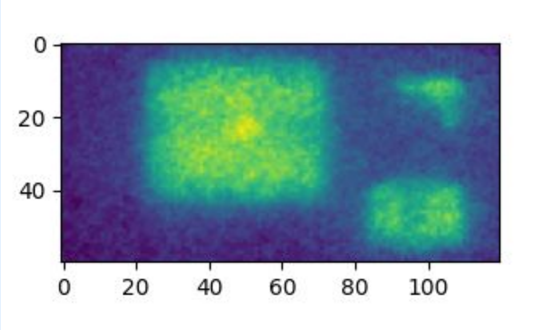
3D image reconstruction

Our approach:

- Started off with ray casting and proprietary iterative algorithm
- Increased the ML expertise within the company and through the collaboration with partner research institutions to switch over fully to ML-methods
- Work in progress on development of deep-learning methods
- Integration of physics informed neural networks



Reconstruction of 15 minute simulation of 10cm cube of RDX, 250ml bottle of water, revolver, clothes.



Real 15 minute measurement projection on vertical axis. Banana box, 1kg of salt inside it imitating cocaine, on right airsoft gun and below it bag containing two 1 kg sugar bags

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Object detection

- Started off with conventional and proprietary edge detection methods.
- 3D-UNET volumetric segmentation
- We utilize deep convolutional neural networks to detect objects within the volume of interest. Once the areas of attention are identified, we further enhance the information in these regions.
- Finally, a supervised classification neural network predicts the material types within the focused areas.

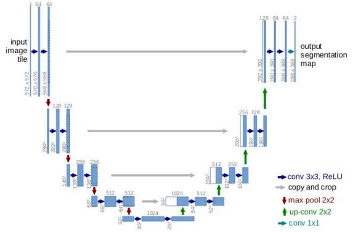
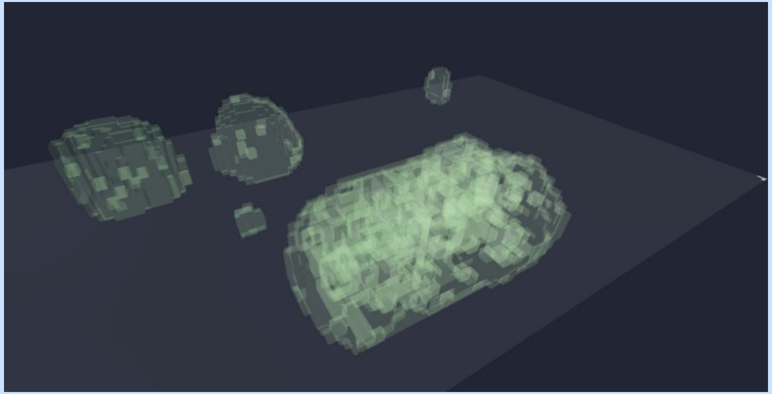


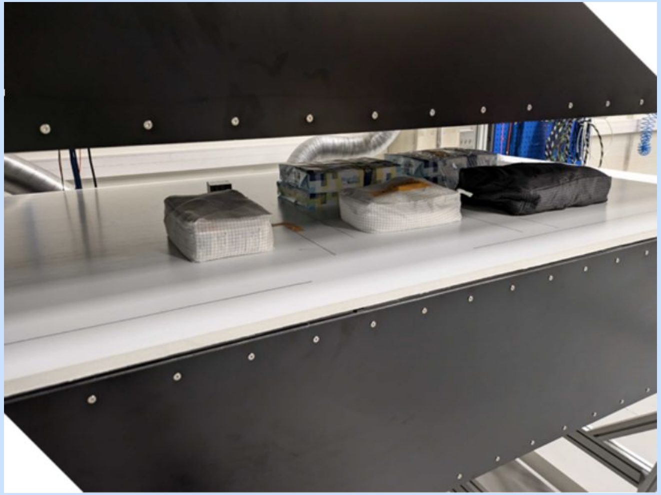
Fig. 1. U-net architecture (example for 32x32 pixels in the lowest resolution). Each blue box corresponds to a multi-channel feature map. The number of channels is denoted on top of the box. The x-y-size is provided at the lower left edge of the box. White boxes represent copied feature maps. The arrows denote the different operations.



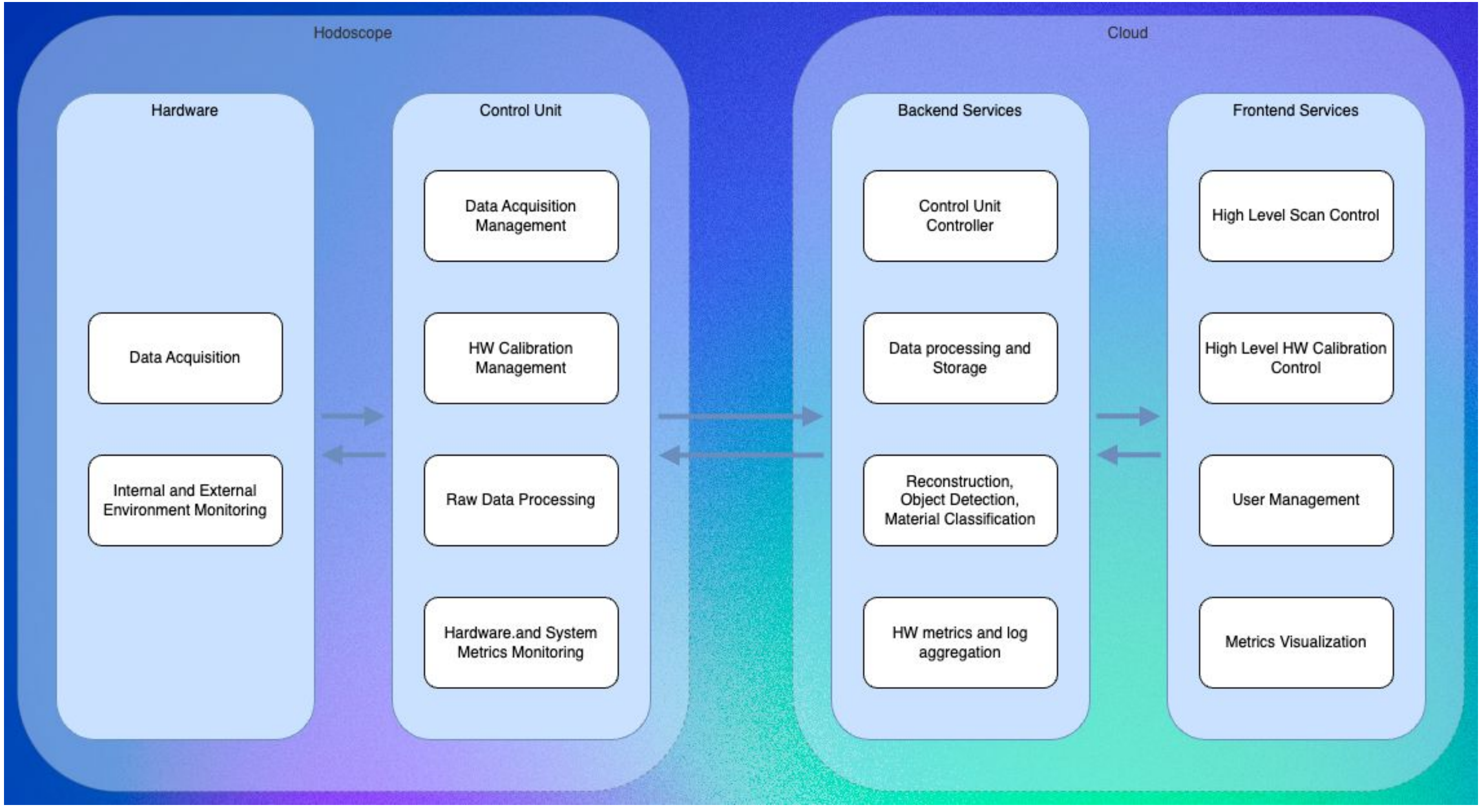
Object detection result. 3 bags with clothes containing various small 1×1 cm objects and two 3×3cm objects randomly placed objects in scanner.

Material classification

- Feature based classification approach - derived from using model developed NN
- Work in progress, as an example from exercise in summer 2024:
  - material classification performance 70%,
  - 20 materials in the library
  - 15 minutes scanning time
  - Objects varied in size between about 50 grams up to few kg.



Overview of system architecture



Data and process flow

Inout from hardware

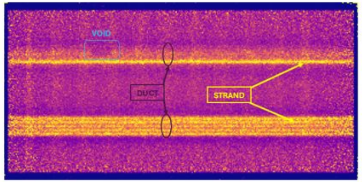
Particles' track data, apply limits and filters

GSCAN cloud server

Apply alignment ML model → Apply 3D reconstruction features → Apply object detection model → Apply object classification

Reconstruction configuration

Output: 4D array to visualization flow



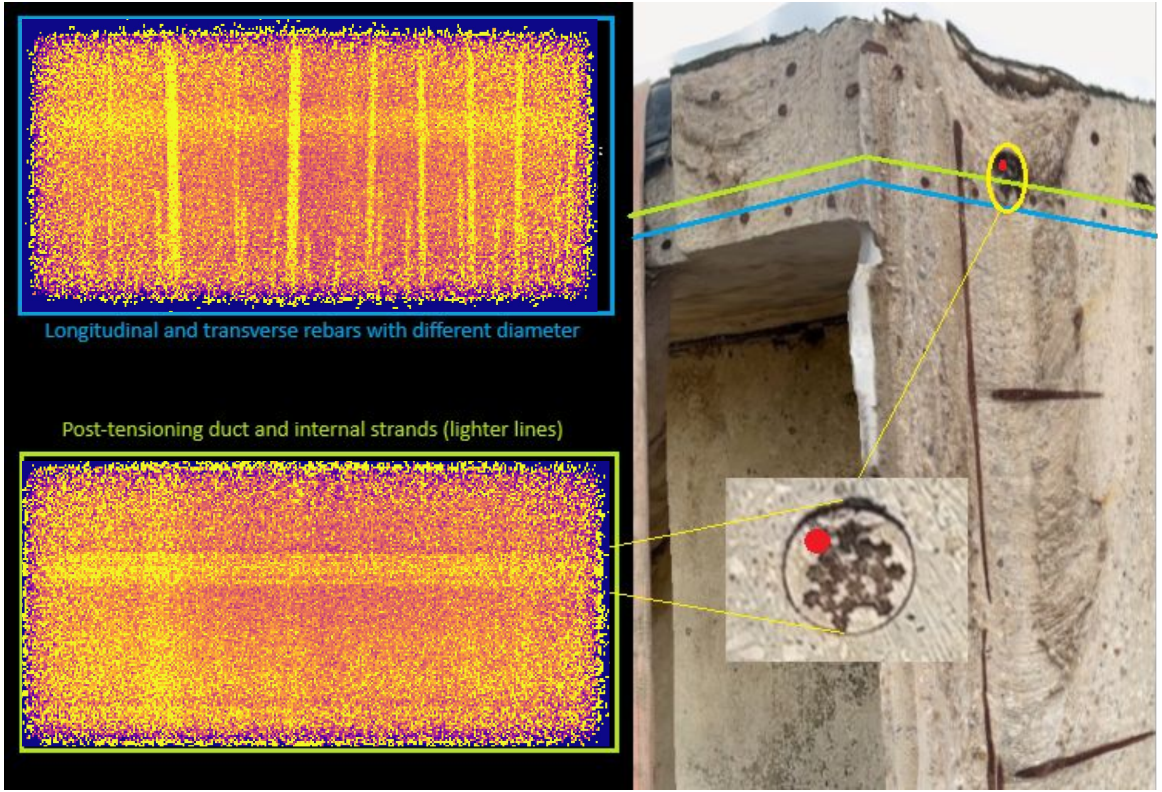
1. Defect detection
2. Identification and condition of the materials

Example 1:
Post-tensioned structures

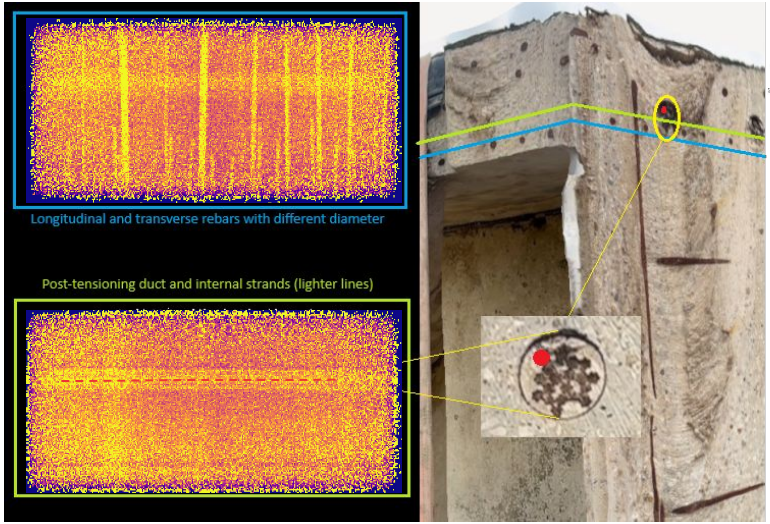
First potential use case: Post-tensioned systems

GScan muFLUX™
Bridge scan

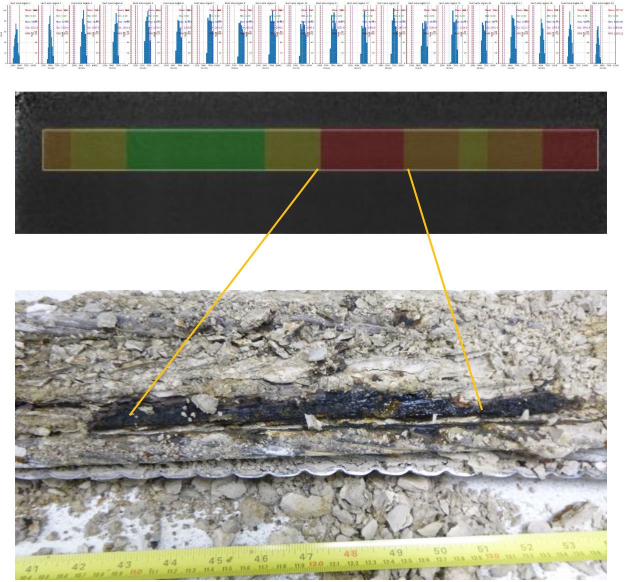
- Moonshot stage I completed 03.2024
- MS final trial with UK National Highways Q4 2024



Determining the capability with Sample measurement

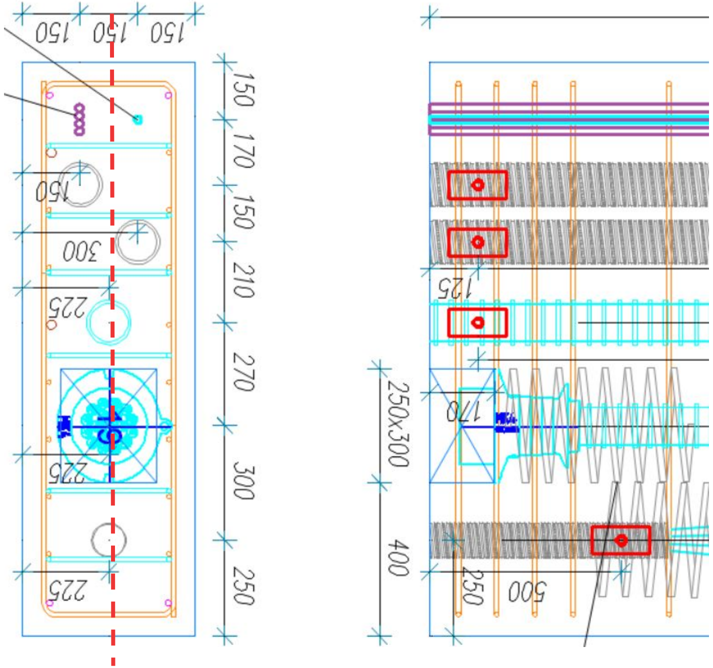


ML application

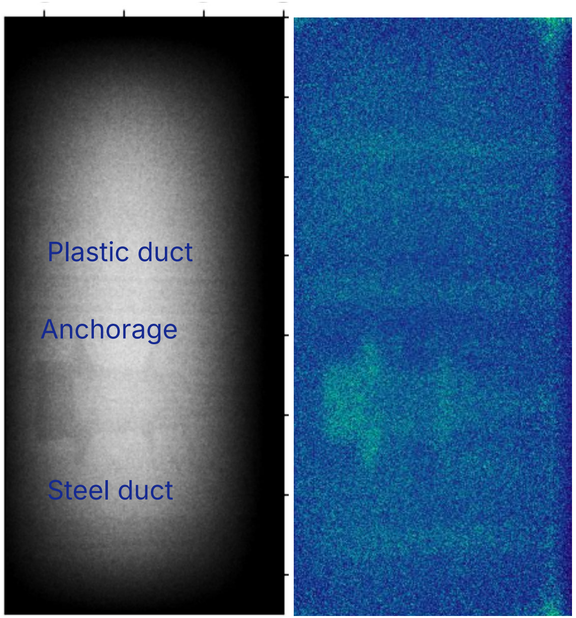


Variety of post-tensioned systems

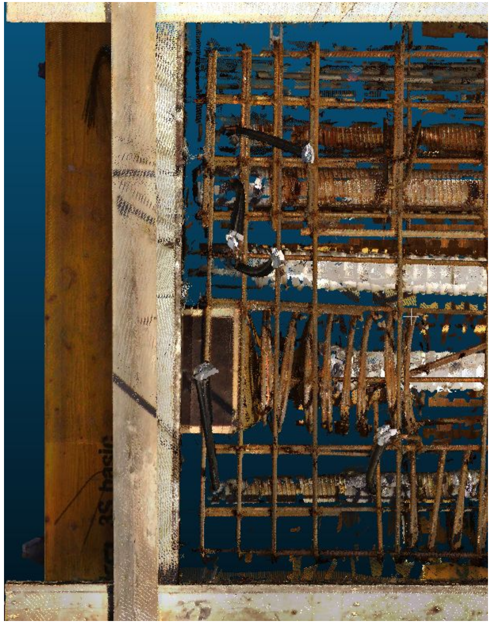
Design drawing



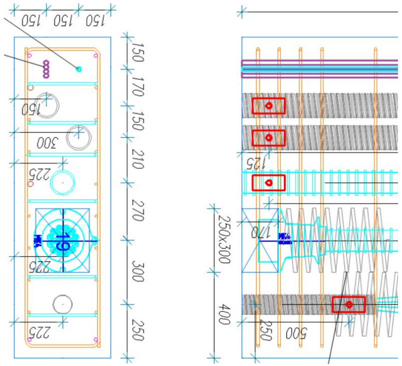
Raw reconstructions 100 h

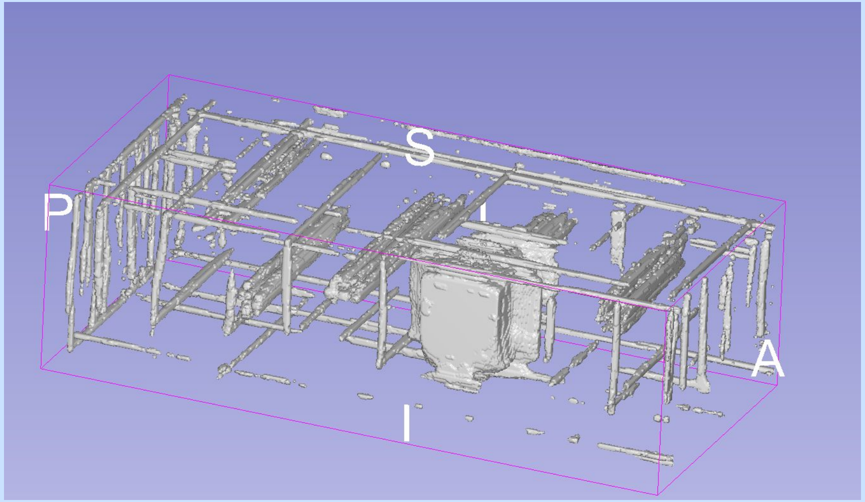


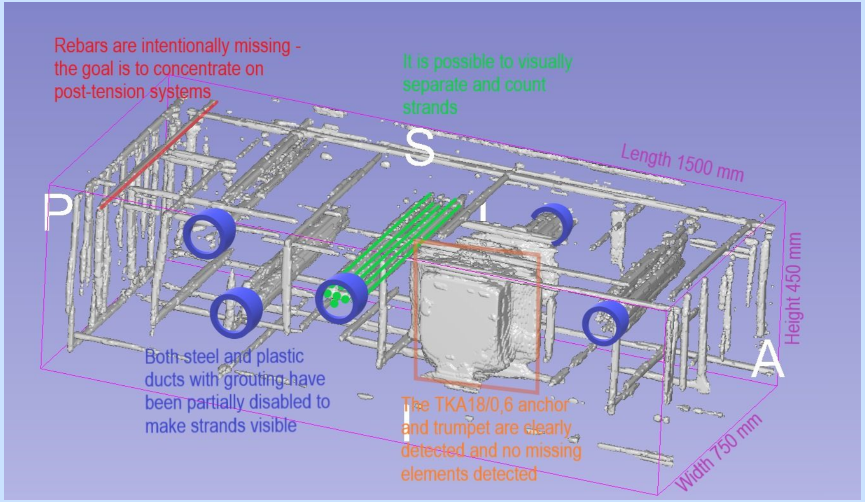
Pre casting point cloud

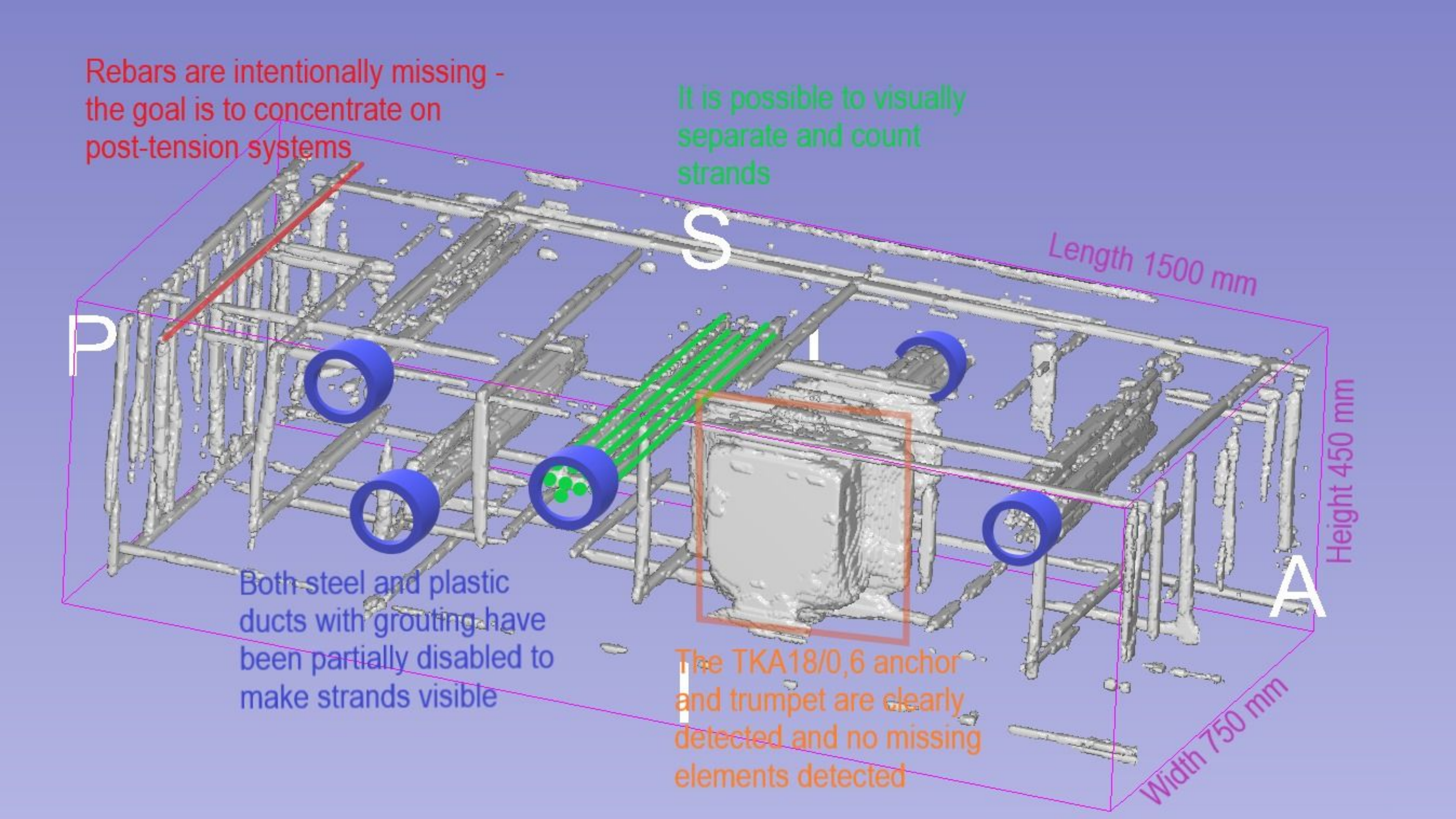


Results:
Moonshot Phase 2








Rebars are intentionally missing - the goal is to concentrate on post-tension systems
It is possible to visually separate and count strands
S
Length 1500 mm
P
Height 450 mm
A
Both steel and plastic ducts with grouting have been partially disabled to make strands visible
The TKA18/0,6 anchor and trumpet are clearly detected and no missing elements detected
I
Width 750 mm

Example 2:
3D imaging of nuclear submarine sections for decommissioning

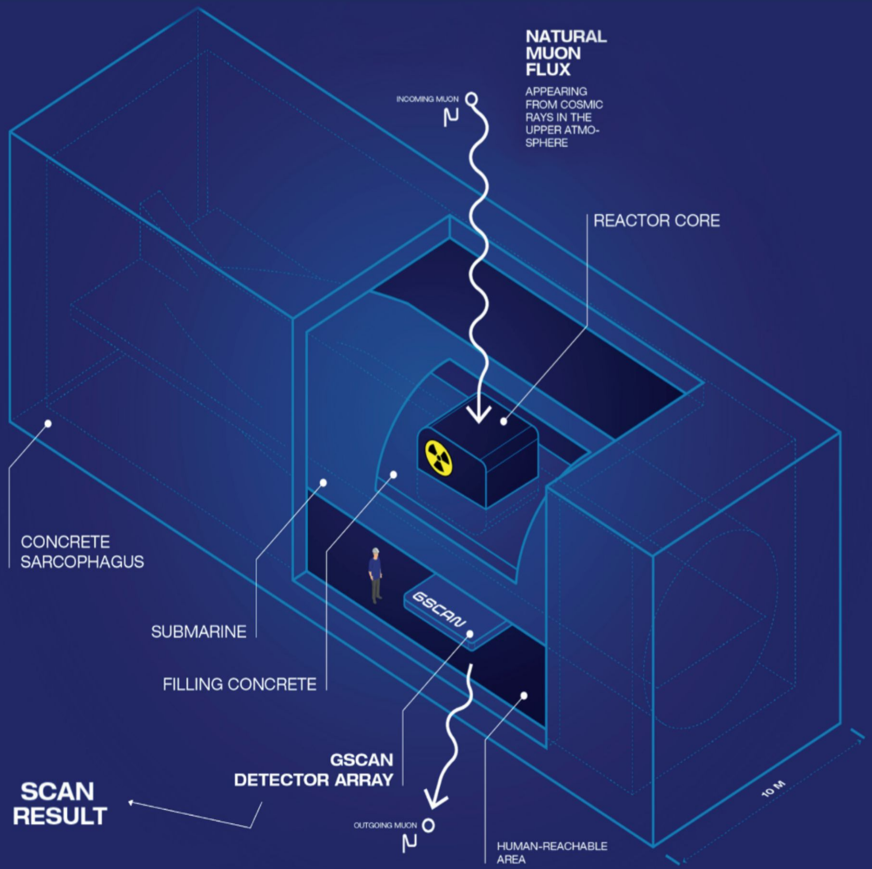
Use Case #1: The imaging of military nuclear reactors

Two abandoned submarine reactors
A Soviet time training centre for sub-mariners at Paldiski, Estonia. The two reactors: 346A and 346B

No good documentation about construction, conservation, and <u>radioactive waste dumped</u> into the reactor sections and filled with concrete

Time is ticking
The sections have to be decommissioned by 2040

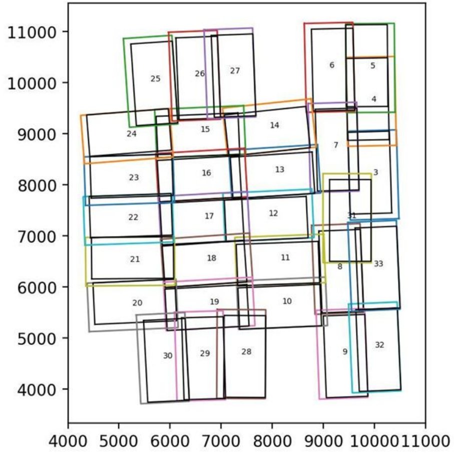
The main objectives:
(1) a more <u>exact 3D model</u> for decommissioning
(2) foreign objects (<u>dumped radioactive waste</u>)



Field work, methodology

- **Data acquisition:**
- 346A - 55 measurement locations
- 346B - 31 measurement locations
- Campaign period - 3rd of May until Sept. 22nd
- Combining 346A+346B ~4100h effective measurement time

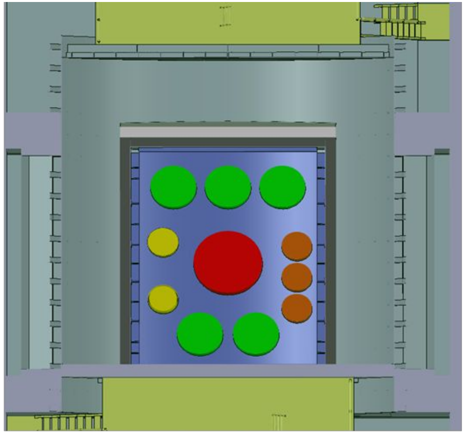
- **Imaging:**
- Formation of LIDAR coordinates based meta data and transformation single position muon trajectories into a united coordinates transformation
- Final selection - 1 cm voxel in order to ensure best image resolution
- The volume of interrogation: 346A - 15×9×10m3 and 346B - 10×9,5×10m3.

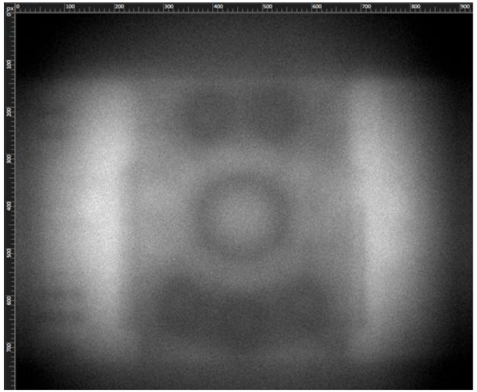


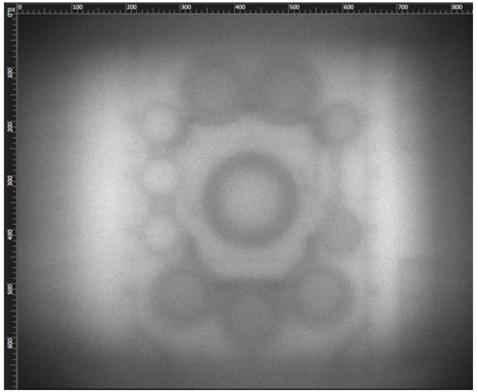
346B results

In the construction part, there are significant differences compared to the existing technical data:

- Reactor room rotated
- Placement of steam generators
- Internal biological barrier with lead lining
- Many other discrepancies with existing technical data





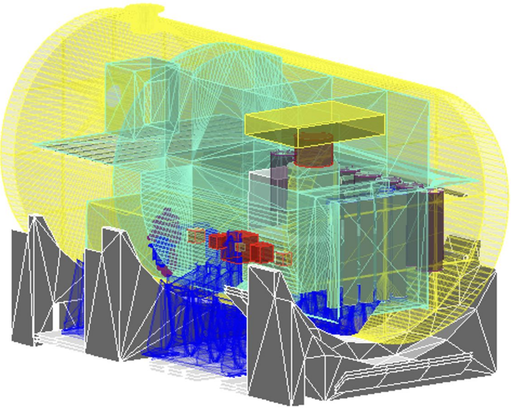


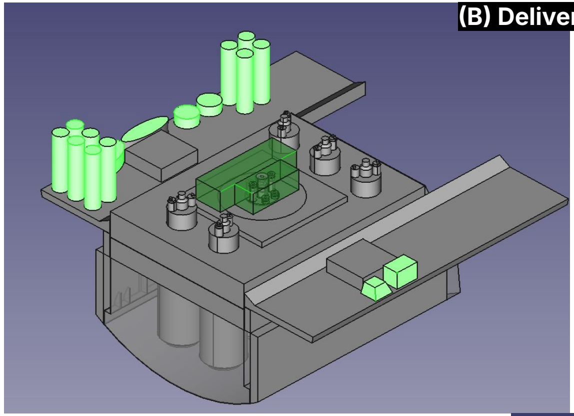
[ALARA_346B_z-plane_slices_1cm_voxel_size 2.avi - Google Drive]

346B results

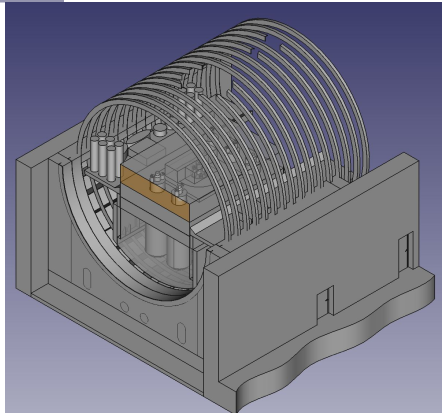
Provided:

- Updated existing 3D models with the findings and
- Foreign objects (marked as green objects on top right image)





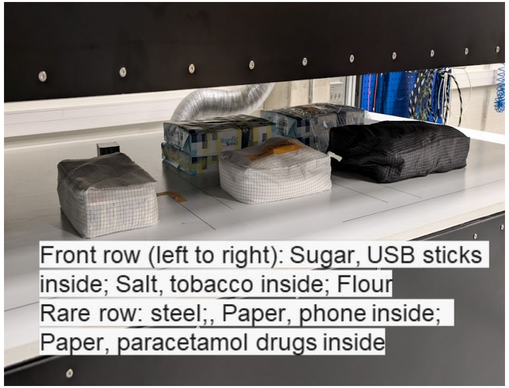
(B) Delivered 3D model

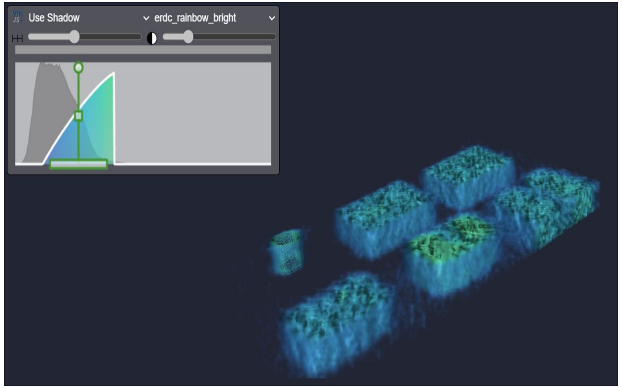


Example 3: Security & Customs applications

Data analysis with the User Interface: Turning the scattering and absorption data to classifying materials

Image of objects to be scanned → Reconstructed images of objects → ML based objects and material classification





Comment: SilentBorder project technology demonstration day test done in June 2024
Exposure time 15 min, objects in objects scenario, mainly carbon based substances, contraband mode
Project homepage: https://silentborder.eu/

Silent Border

2021 — 2025

The world's first modular ART-system for measuring containers and vehicles to be used by customs agencies from Estonia, Finland, Spain

Currently producing the custom hardware

COSMOPORT

2023 — 2026

The world's first mobile ART-system (TRL7) for measuring parcels and letters to be used by customs agencies from 5 different countries.

Currently designing the custom hardware

Beyond cosmic ray muons: Artificial muon sources

Artificial muon source: why?

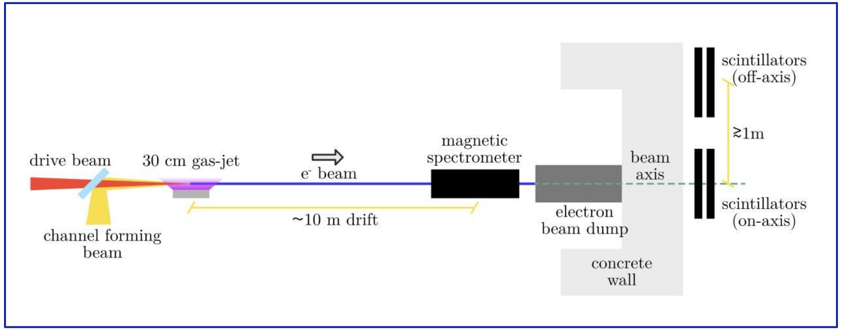
- To produce muons one needs 1GeV+ accelerator source of primaries, e.g. 100m linear accelerator in the case of electrons
- Laser Plasma Accelerator (LPA):
  the game changer in the case of muon tomography!
- Our dream: **a sea container size muon source**
- DESY: Dr. Kristjan Poder et al
- Other groups: Berkeley Lab

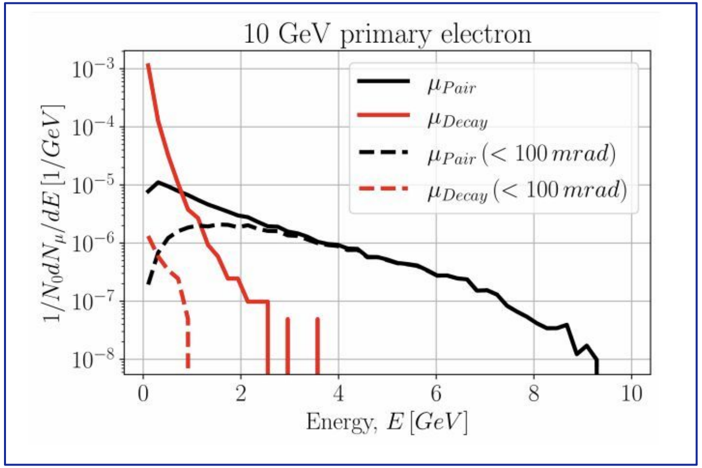
Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator

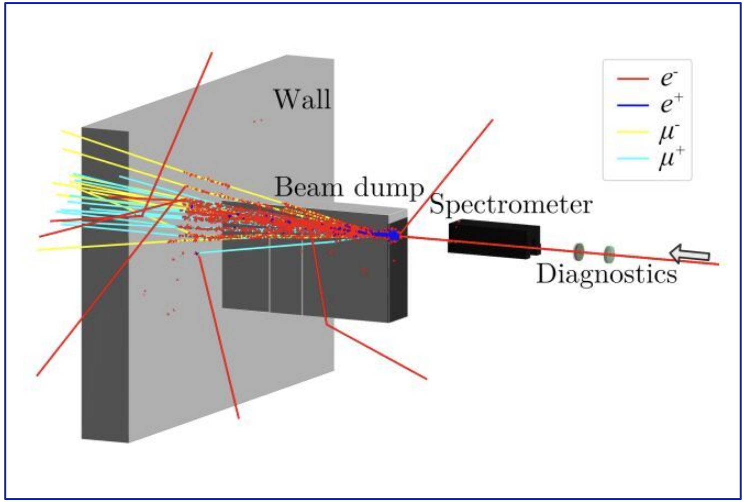
Davide Terzani,[1,*] Stanimir Kisyov,[1] Stephen Greenberg,[1,2] Luc Le Pottier,[1,2] Maria Mironova,[1] Alex Picksley,[1] Joshua Stackhouse,[1,3] Hai-En Tsai,[1] Raymond Li,[1,3] Ela Rockafellow,[4] Timon Heim,[1] Maurice Garcia-Sciveres,[1] Carlo Benedetti,[1] John Valentine,[1] Howard Milchberg,[4] Kei Nakamura,[1] Anthony J. Gonsalves,[1] Jeroen van Tilborg,[1] Carl B. Schroeder,[1,3] Eric Esarey,[1] and Cameron G. R. Geddes[1]

https://arxiv.org/abs/2411.02321

Artificial muon source: how?







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https://arxiv.org/abs/2411.02321

Takeaway messages

- We have successfully implemented the technology so far
- We expect ML implementation throughout the all data processing chain double our performance parameters
- Home-made DAQ gave a huge leap
- Continue with ASIC design for front-end readout: the energy consumption and waste heat the main reasons
- Last but not least: we are looking for the R&D partners
    - **Open invitation of a EU EIC Pathfinder project** on an artificial muon source, related detector tech and tomography algorithms

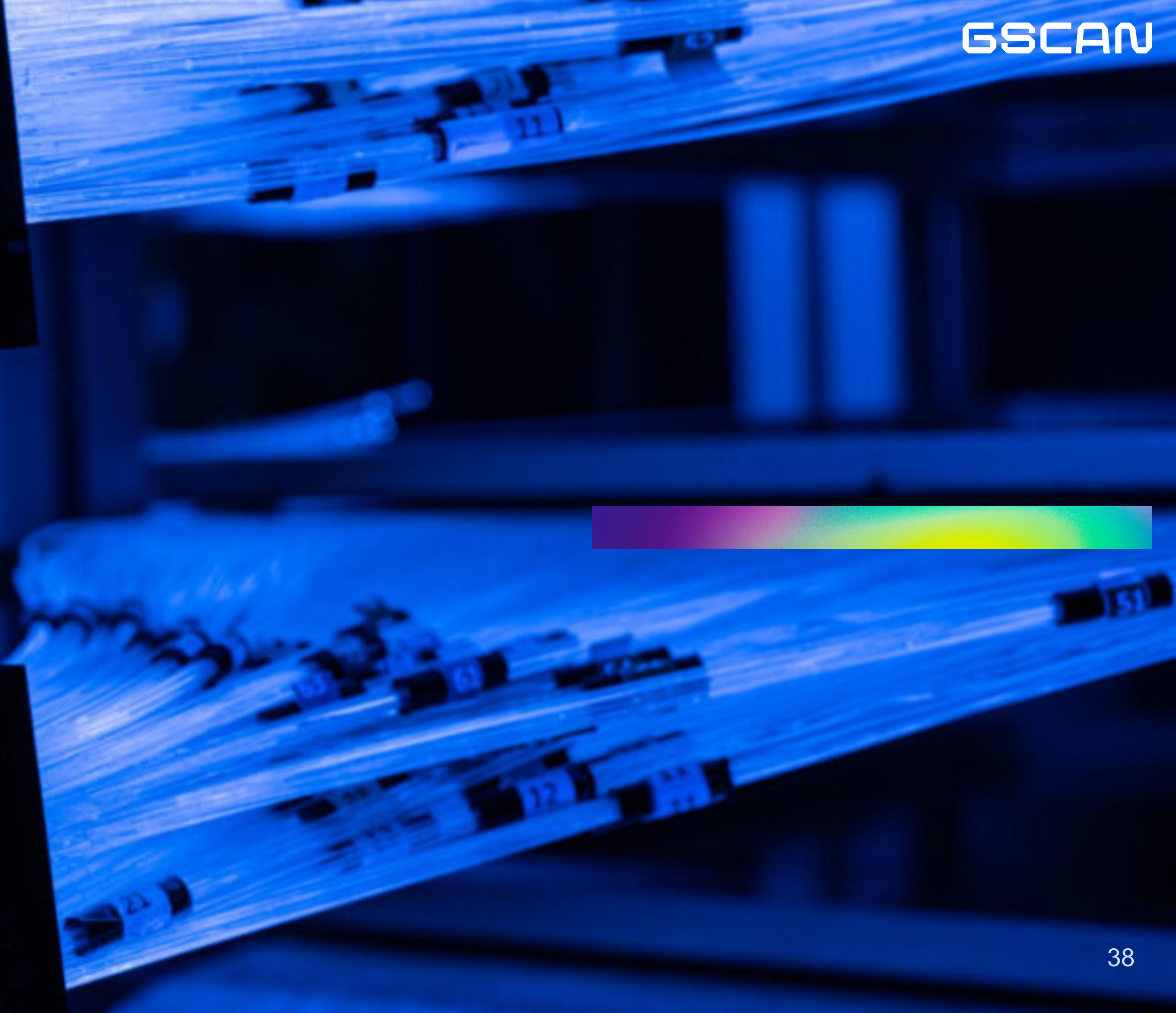
GSCAN

Thank you!

Questions?

Like to test?

Please, contact:
madis.kiisk@gscan.eu



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