GSCAN

Commercialisation of muon tomography for security inspection and non-destructive testing

Madis Kiisk, Andi Hektor, Olin Pinto
on behalf of the R&D team, GScan

Imperial College London
November 2023

Outline

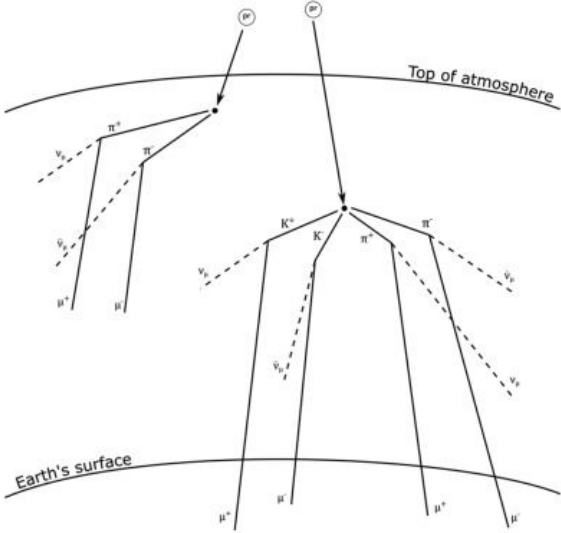
- Introduction on muon tomography (Andi)
- Introduction of GScan (Madis)
- What makes detecting low-Z possible
- GScan tracking detector development
- Results from the first tomographic measurements
- The CosmoPort project with Imperial (Olin)
- Summary & Outlook

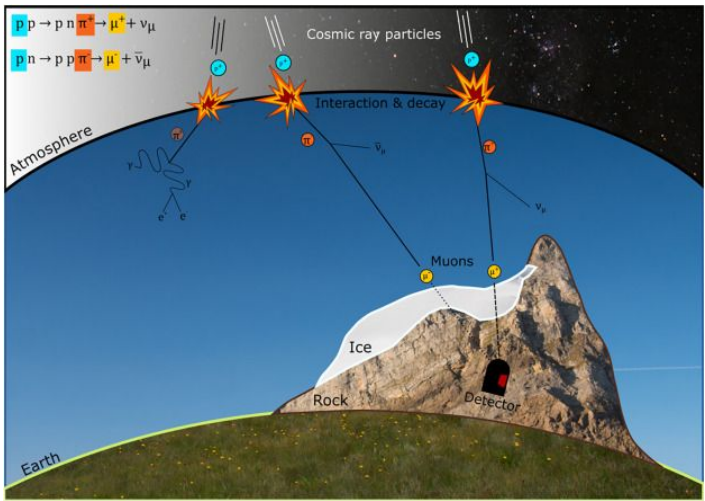
Assembly hall, GScan

Introduction to muon tomography

Muon tomography / Muography

- **Muon tomography** or **muography**: uses cosmic ray muons to generate 2D/3D images of volumes using information contained in the Coulomb scattering and absorption of the muons
- The devil is in the details:
  - High energy electrons/positrons
  - Particle classification: electron versus muon
  - Energy resolution
- How can we squeeze out all the information from the data? – **ML** & **AI**
- How can we build a **commercially viable** products?





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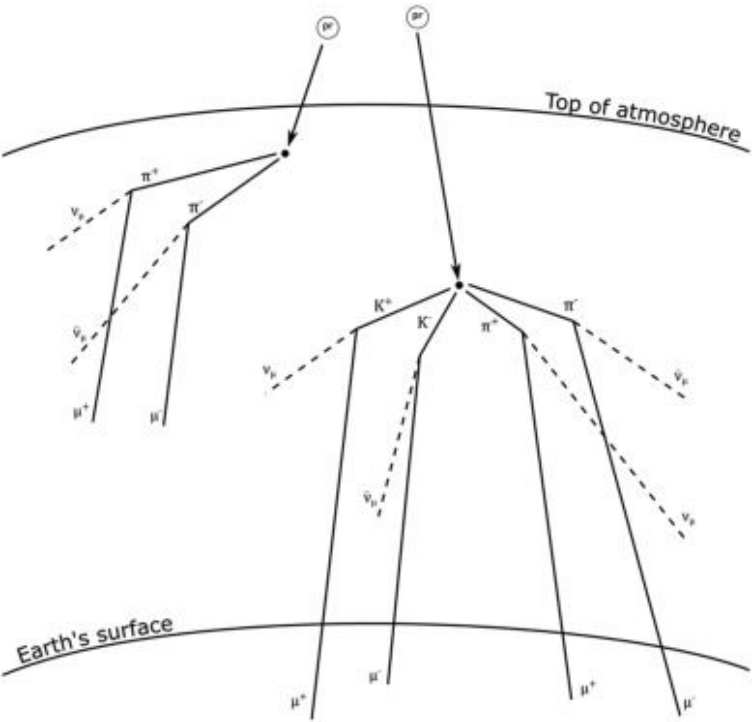
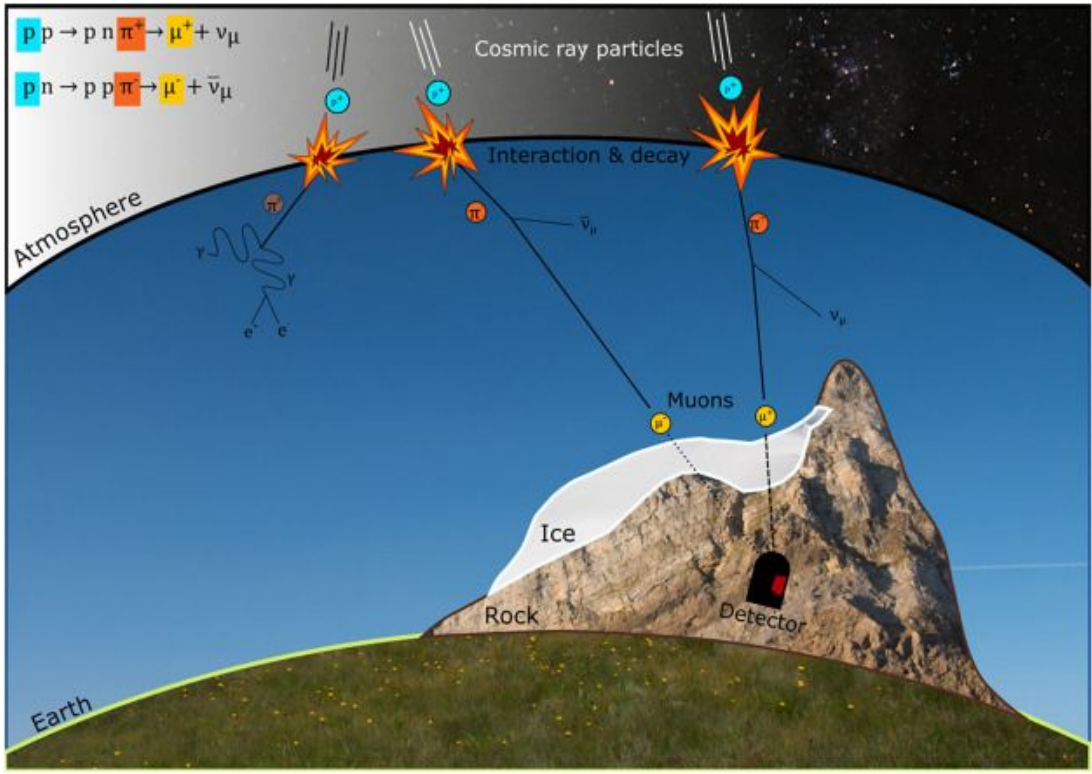
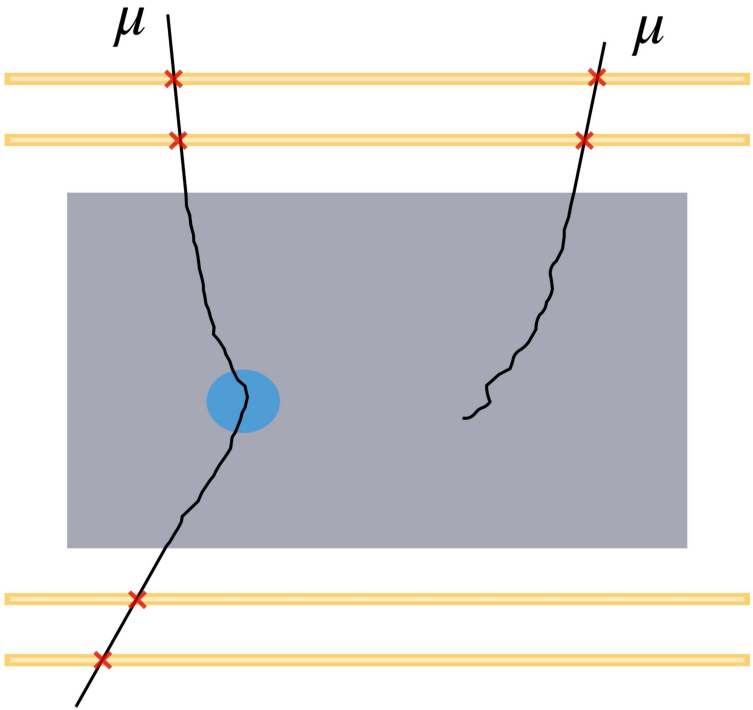
Muon tomography / Muography

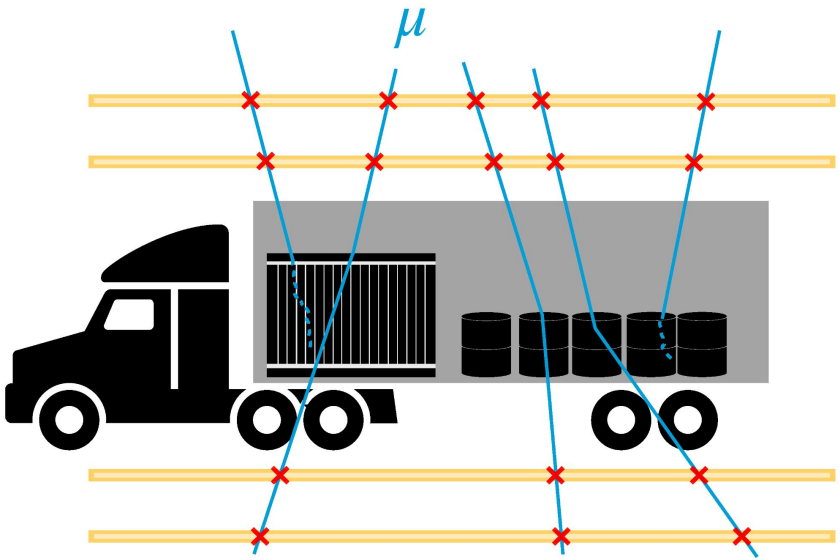




https://www.sciencedirect.com/science/article/pii/S0012825221003433

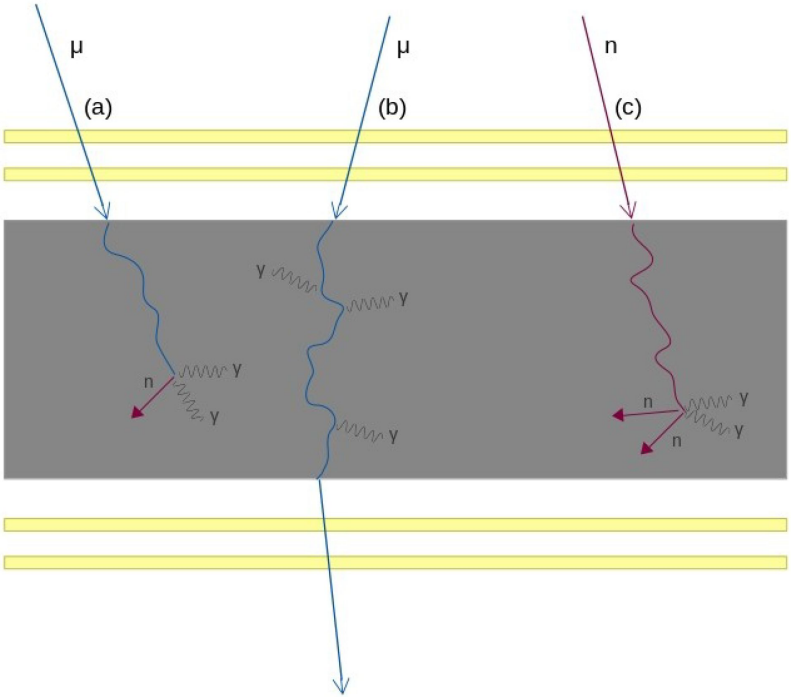
Principles of MT, vol 1

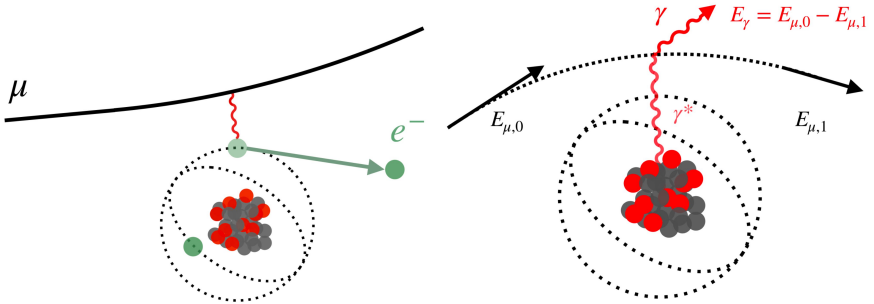




https://www.mdpi.com/2410-390X/7/1/13

Principles of MT, vol 2

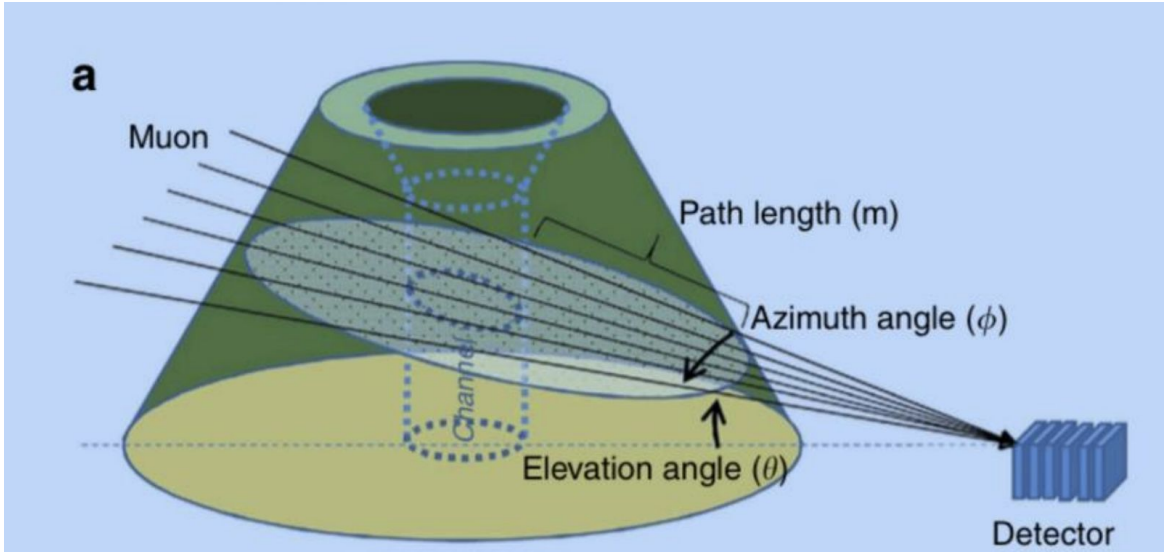




- Strong dependence on Z
- The muon scattering is much more “Z-sensitive” than X-ray absorption: classification of materials by Z
- It needs some energy resolution of detector system

https://www.mdpi.com/2410-390X/7/1/13

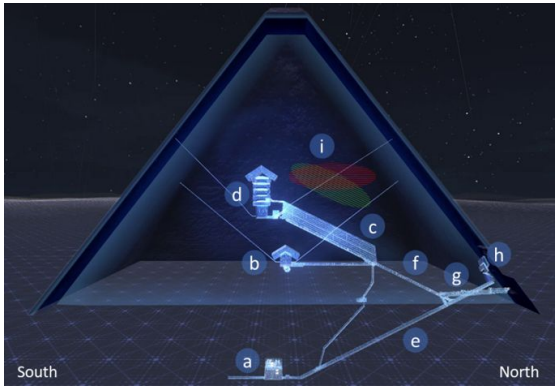
MT applications: Geology & Historical sites



HARD SCIENCE — MARCH 4, 2023

Cosmic rays passing through Great Pyramid help reveal hidden corridor

A non-invasive method for looking inside structures is solving mysteries about the ancient pyramid.



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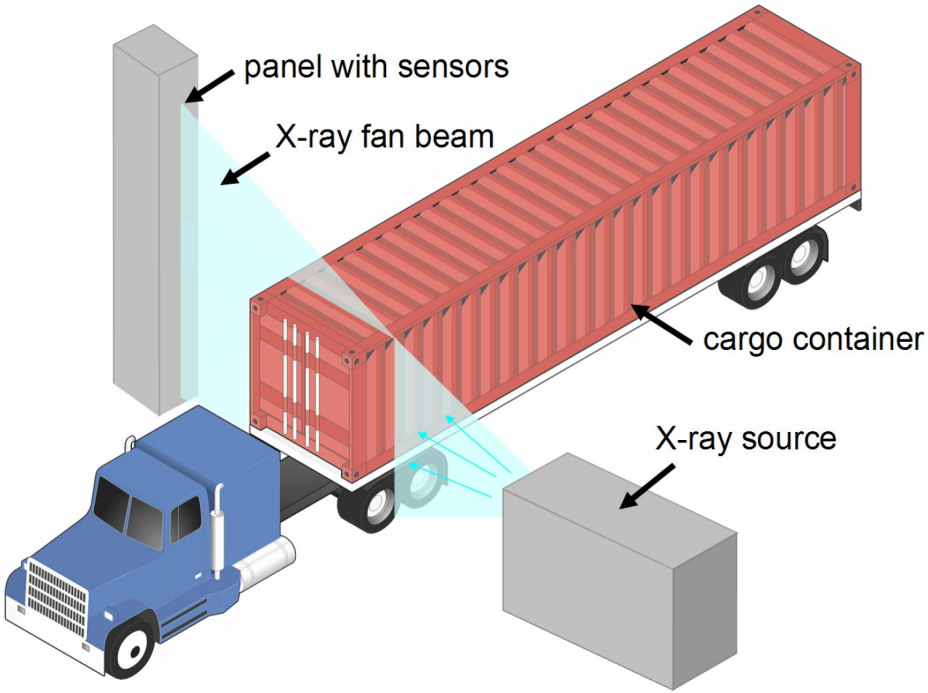
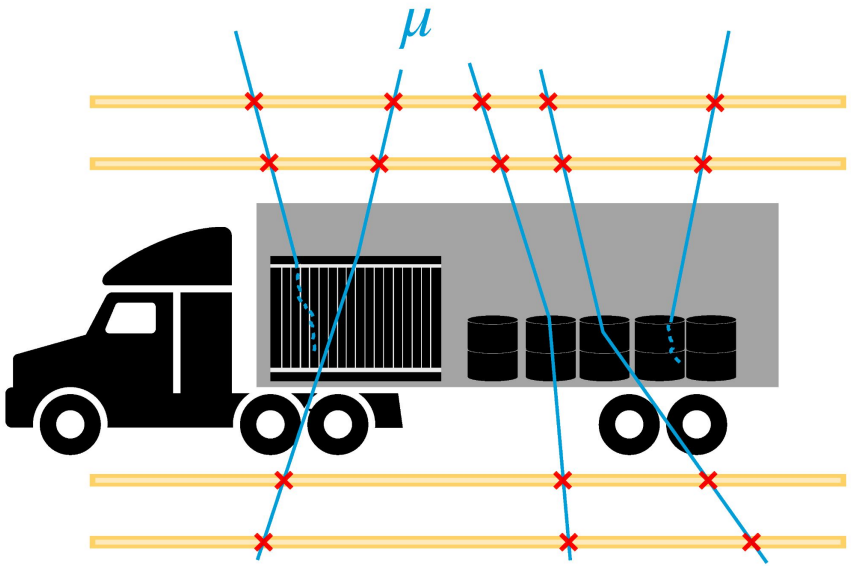
MT applications: Security & Customs





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Business domains for muon tomography

	MARKET ENTRY	NEXT VERTICAL		OPPORTUNITY	
VERTICAL	B2B	B2G		B2B	B2B
	INFRASTRUCTURE TESTING & INSPECTION	SECURITY & FRICTIONLESS TRADE	DEFENSE AND DUAL-USE	MEDICAL IMAGING	SECTOR AGNOSTIC
	$20bn	$15bn	$5bn	$40bn	$Xbn
USES	**Mobile scanners that local service partners deploy on-site worldwide** EaaS model TAM/SAM/SOM: 20bn/10bn/5bn	Automated border crossings, explosive-detection gates (vehicle & foot). Drug & weapons scanners.	Perimeter security (automated gates to detect weapons and explosives at mil. bases, schools, ports, etc.)	Harmless medical scanners for bone radiology, lung monitoring, MRT replacement	Tech supplier to large platforms and manufacturers (Siemens, Philips) where we opt to not compete directly with end product

Team

A team of 40+ brilliant, highly motivated and talented people

Founders and key people

Marek Helm
CEO

Ex-head of the Estonian Tax and Customs Board

Hannes Plinte
Co-founder

Border control, biz models, security agencies, IT

Andi Hektor
Co-founder, CSO

Detector tech, international network, tech evangelist

Märt Mägi
Co-founder, CTO

Tech management, leads high-tech programs

Madis Kiisk
Co-founder, R&D Lead

Expert in nuclear physics and radiation safety

Jüri Saarma
COO

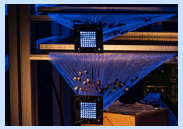
Helping Estonian tech companies to scale internationally

Edward Wilkinson
UK Lead

Excellent network in infrastructure and security domain in the UK, US, and Middle East

Timeline of GScan's technology

Product



Lab prototype completed, TRL3

WPO patent submitted

$7.9m pilot deal: SilentBorder project

First robotic production line launched

Silent Border

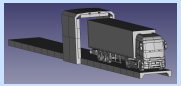
Q1: MVP1 muFLUX Infra

Q2: MVP2 muFLUX Small

Prep for new production line

New robotic production line launched

IT-cloud-solution for muFLUX Infra



New integration and maintenance site

muFLUX Medium launched

SilentBorder pilot ready

R&D programme for artificial muon beam

New production site

muFLUX Large launched

R&D programme for medical applications

New software products on NDT data

Products using artificial muons

Early phase products in medical radiology

2018-20	2021-22	2023	2024	2025	2026	2027	2028-30
GScan founded (spin-off from GoSwift) GScan takes over GoSwift IP and activities	First sale contracts signed, $1.5m $1.6m and $0.4m grants from Estonian Innovation Agency $2.1m seed investment	Funding round $1.5m $2.4m sales revenue Sales pipeline for 2023+ KSA, UK and Singapore missions	Funding round $15M $4.3m sales revenue First NDT pilots in UK/KSA First NDT contracts with global engineering companies	$30m sales revenue First larger contracts for security and customs scanners First NDT projects in US market	Funding round Series B $47m sales revenue Long term contracts on NDT in UK, GCC, Nordic region	$126m sales revenue Long term contracts on NDT and security markets Regional coverage: UK, US, Nordic region, EU	First pilot contracts in medical radiology

Business

Introduction to GScan, its tech, and some results

Multiple coulomb scattering

o) the inverse of the muon momentum p

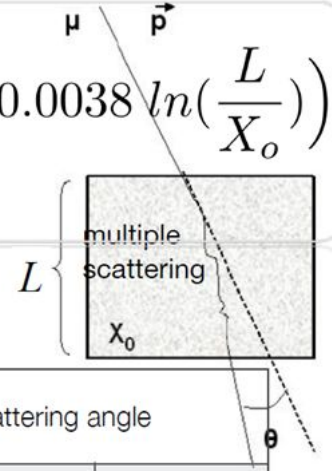
o) the √ of the material thickness L

$$\sigma_\theta = \frac{13.6\ MeV}{\beta cp\ (MeV/c)}\sqrt{\frac{L}{X_o}}\left(1 + 0.0038\ ln\left(\frac{L}{X_o}\right)\right)$$

o) the inverse of the √of the radiation length X_o (which depends on 1/Z)

$$X_o = \frac{716.4\ g\ cm^{-2}\ A}{Z(Z+1)\ ln(287/\sqrt{Z})}$$

X_o: the mean distance over which a high-energy electron loses 1/e of its energy by bremsstrahlung



$$\sigma \simeq \frac{1}{p}\sqrt{\frac{L}{X_o}}$$

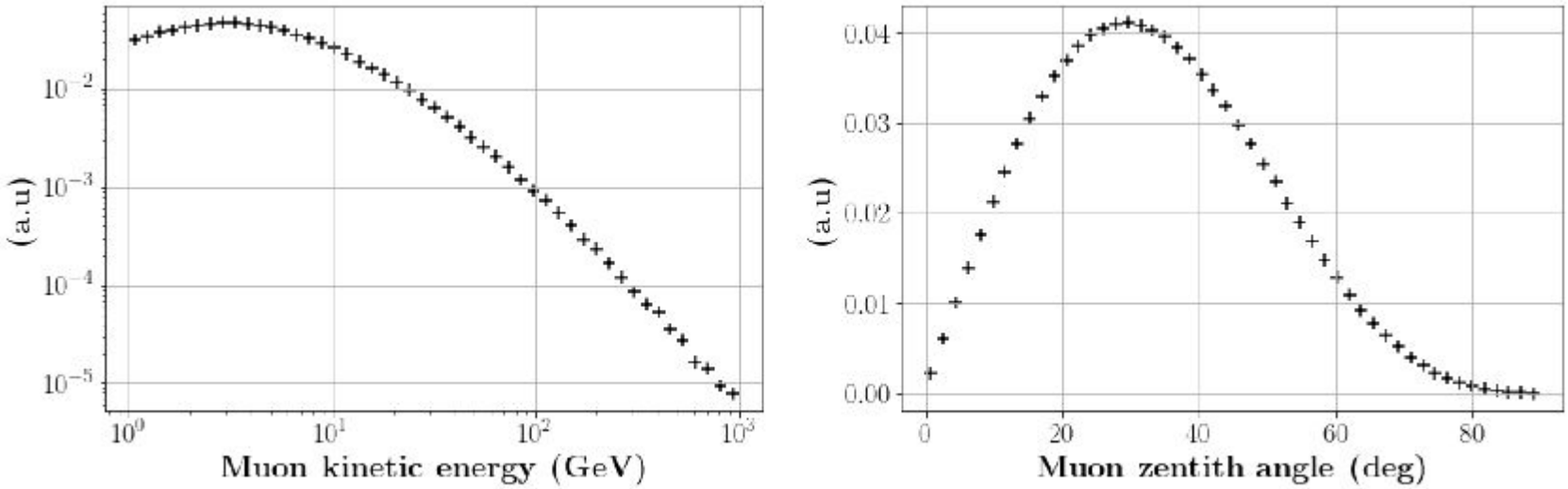
p = momentum
X_o = radiation length
L = material thickness

Multiple scattering for muons passing through 10 cm of various materials				RMS of scattering angle		
Material	Z	ρ (g/cm³)	X_o/ρ (cm)	0.3 GeV/c σ (mrad)	3 GeV/c σ (mrad)	30 GeV/c σ (mrad)
Water	-	1	36,1	26,3	2,6	0,3
Concrete	-		10,7	48,3	4,8	0,5
Iron	26	7,87	1,76	119,2	11,9	1,2
Lead	82	11,34	0,56	211,3	21,1	2,1
Uranium	92	18,97	0,32	279,5	28	2,8

Extracted from: G.Bonomi, *Progress in Muon Tomography*, EPS Conference on High Energy Physics, 5-12 Juuli. 2017.

The natural muon source characteristics

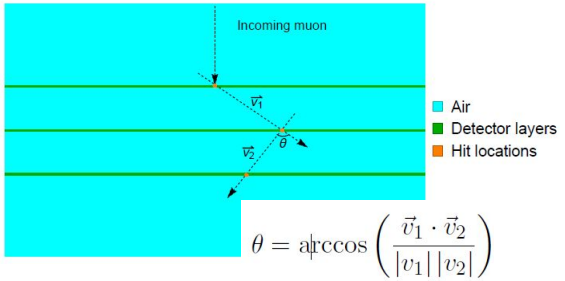
- About 10,000 particles/m2 hit the ground per minute (600 of them pass through our body)
- At sea level, the average muons energy is 3 - 4 GeV
- The particle flux is maximum at the zenith and is approximately proportional to cos2 (θ)



Example of simulated muon energy distribution (left) and zenith angle distributions (right).
(from: Barnes, S.; Georgadze, A.; Giammanco, A.; Kiisk, M.; Kudryavtsev, V.A.; Lagrange, M.; Pinto, O.L. Cosmic Ray Tomography for Border Security. Instruments 2023)

Why we believe we can meet the needs of our clients

1. **High tracking resolution (mrad-range)**
2. **Filter the incident particle flux**
3. **Multi-modal imaging for material classification**



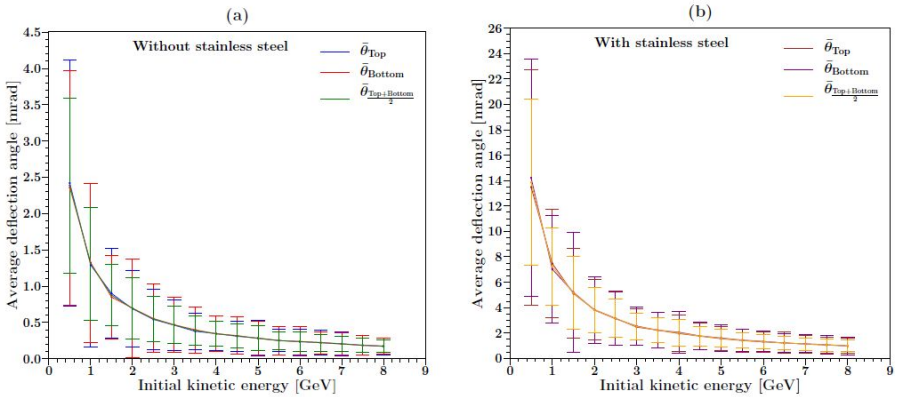


Table 4: Misclassification probabilities for the cases without stainless steel layers and with stainless steel layers, respectively.

Without stainless steel				
E pairs [GeV]	$\bar{\theta}_{\frac{\text{Top+Bottom}}{2}} \pm \delta\theta$ pairs [mrad]	OVL	P_{Gaussian}	P_{Linear}
0.5 - 2.25	2.612±1.700 - 0.716±0.526	0.278	0.161	0.080
2.25 - > 3	0.716±0.526 - 0.248±0.153	0.330	0.197	0.180
With stainless steel				
E pairs [GeV]	$\bar{\theta}_{\frac{\text{Top+Bottom}}{2}} \pm \delta\theta$ pairs [mrad]	OVL	P_{Gaussian}	P_{Linear}
0.5 - 2.25	14.925±8.310 - 4.104±2.800	0.251	0.144	0.013
2.25 - > 3	4.104±2.800 - 1.422±0.766	0.304	0.179	0.141

A.I Topuz. et.al (2022). *JINST*, *17*(02), C02008

A.I Topuz. et.al (2022). *Journal of Physics: Conference Series* (Vol. 2374, No. 1, p. 012185).

Patent application: PCT/EP2019/055333, granted in Japan, in process - Europe, US, China

Tomographic reconstruction

- In the voxelize interrogation space, algorithms need to reconstruct in addition to the material characteristic parameter space of scattering density also the momentum
- Particle path estimation becomes relevant in certain applications
- Due to the vertical flux domination, vertical axes object reconstruction is distorted
- Especially in security application voxel population is low. If populated, few tracks per voxel is typical.
- Different algorithms have been tested and used:
  - POCA
  - Ray-casting (backprojection)
  - Algebraic reconstruction algorithms and its modifications
  - Probabilistic
- We seek for deep-learning based approaches that use input in the form of particle hit coordinates
-

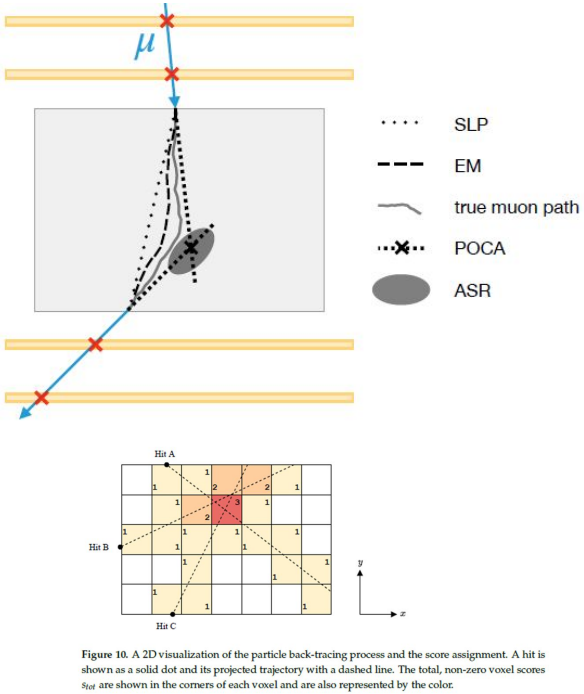


Figure 10. A 2D visualization of the particle back-tracing process and the score assignment. A hit is shown as a solid dot and its projected trajectory with a dashed line. The total, non-zero voxel scores s_{tot} are shown in the corners of each voxel and are also represented by the color.

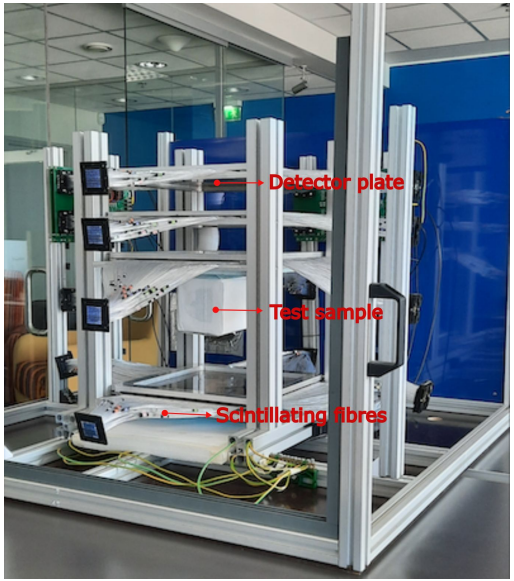
Examples of an reconstruction result -Geant4 simulation of the industrial tomographic prototype

Material Classification exercise with lab prototype

- **Objective**: Evaluate the accuracy of machine learning (ML) algorithms in classifying low-Z materials commonly found in security applications

- The detector system was employed to measure various cube-shaped materials, 20 mm below the third detector plate

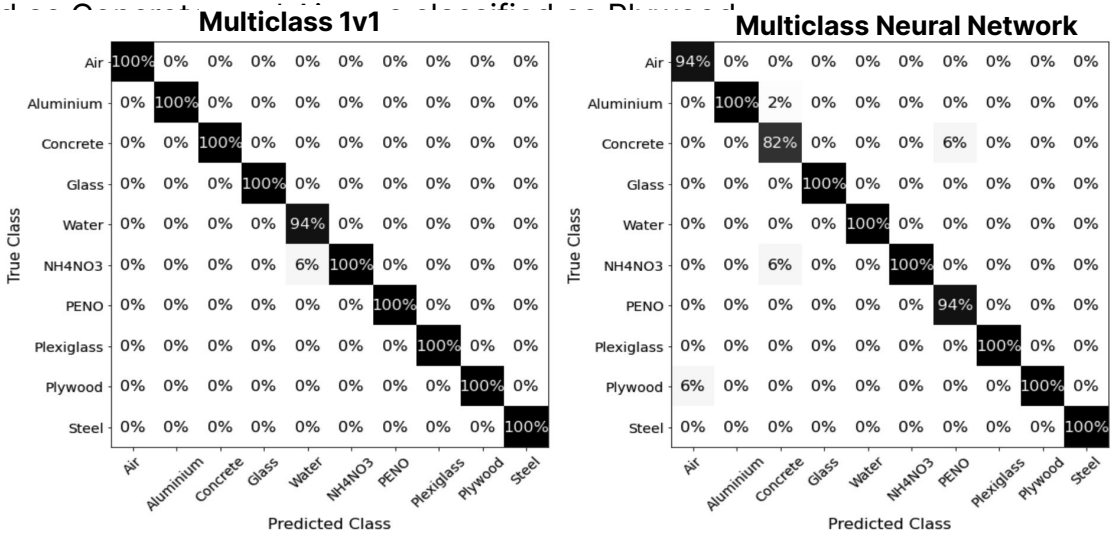
- **ML Models Utilized**: Linear Discriminant Analysis (LDA), Neural Network (NN) and LDA One-vs-One (1v1)



Material Classification Results

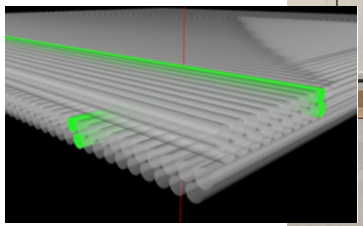
Patent application EP23154494.1, 01.02.23

- **LDA achieved a peak accuracy of 80%** using global features (15-fold cross-validation)
- **LDA Multiclass 1v1** with selected features and 5-fold cross-validation achieved a **peak accuracy of 99.33%**
  - One false positive case: Ammonium nitrate with sulphur pellets misclassified as water
- **Multiclass NN classifier** demonstrated a good classification **accuracy of ~97%**
  - Few objects classified as false positives: Aluminium and Ammonium nitrate with sulphur pellets were predicted as Concrete, Aluminium classified as Plywood

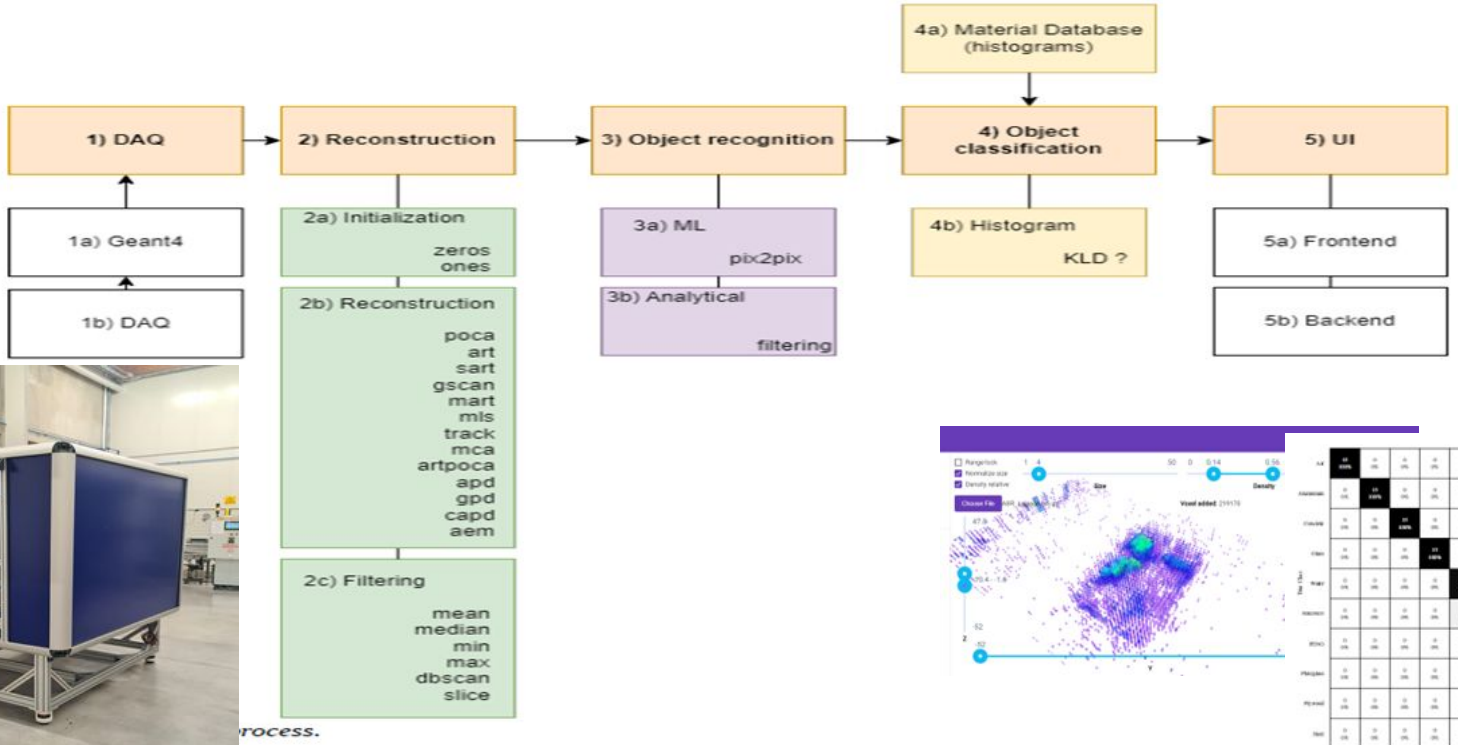


Detector technology

1. Double-layered mats Plastic scintillation fibre-mats
2. Active surface area - approx. 1500×750 mm
3. 2×1536×830 mm of fibre
4. Customized SiPM-arrays from Hamamatsu for signal conversion
5. Fibre - up to 1 mm diameter (Kuraray)
6. DAQ - currently PETSys and CAEN, home made DAQ prototypes available the end of 2023.
7. Modular solution for scale up



The block-scheme of the data processing steps



First product: muFLUX AI Infra

Launched **March 16, 2023**

First three systems produced are already fully booked for commercial projects in 2023

Technicalities:

Consists of 6 fibre-mats

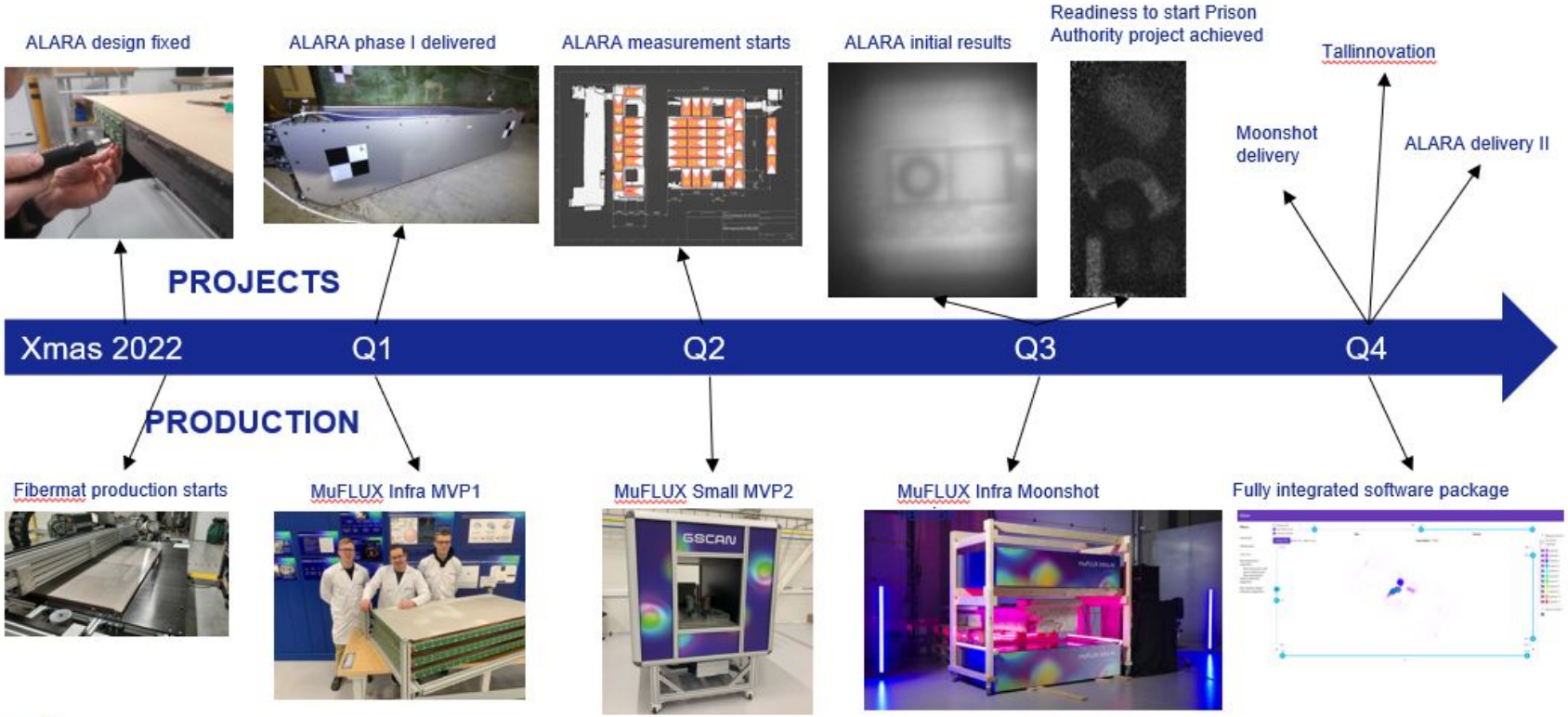
Weight: 90kg

Dimensions: 1m x 1.8m

Power consumption: 150W

External power and data management units

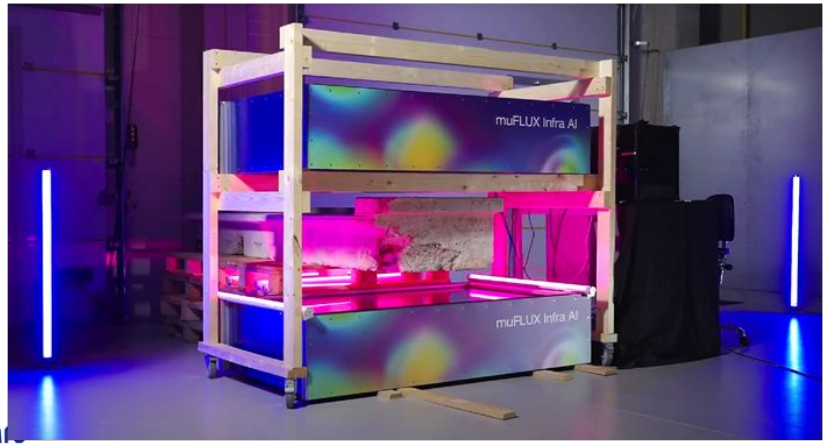
Highlights from 2023



Status of the hardware

muFLUX Small: The physical upgrades and testing started for tomographic reconstruction and material classification

muFLUX Infra: The completed construction of Moonshot equipment (a pair of hodoscopes)

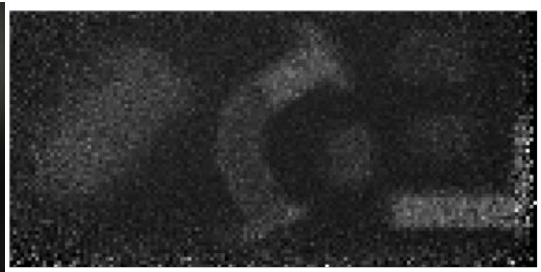


Status of the tomographic prototype

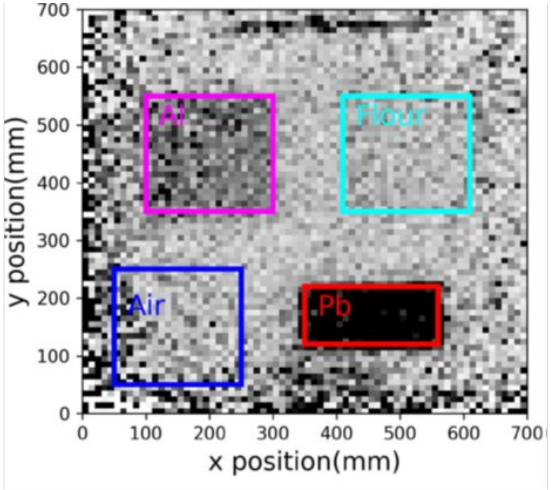
Harnessing the power of muons, we've achieved what's never been done before!

- Reconstruct of low Z standalone materials like sugar, salt, flour in few kilograms
- Automagical identification between low Z materials with unparalleled efficiency in minuscule quantities
- From lab to production prototype we have shown to produce consistent, reliable results at every step.

We have fulfilled all the prerequisites to consider muon tomography as viable technology for security applications



Measurement of 6 hours with detector system with efficiency of below 20%. Objects: 1. concrete block 2. steel pipe 2a. Lead in steel pipe 3. salt 4.flour (2x2kg bags) 5. sugar 6. lead

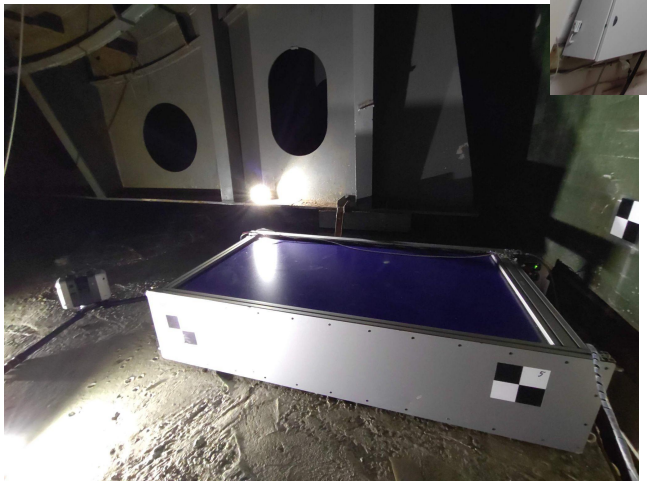


Chinese experiment TUMUTY Measurement of 10 days with detector system with efficiency of 26%.Even with 10 days of exposure the 20cm side-length cube of flour is not visible *https://doi.org/10.1007/s41365-019-0649-4*

3D Imaging of submarine nuclear reactor section - Paldiski site

- On-site (Paldiski, Estonia) scanning started in March 2023

- Scanning in transmission mode with one detector module under the object of interest - 4-month scanning period to cover approx 10×10 m2 floor area.



Numerical modeling vs experimental images

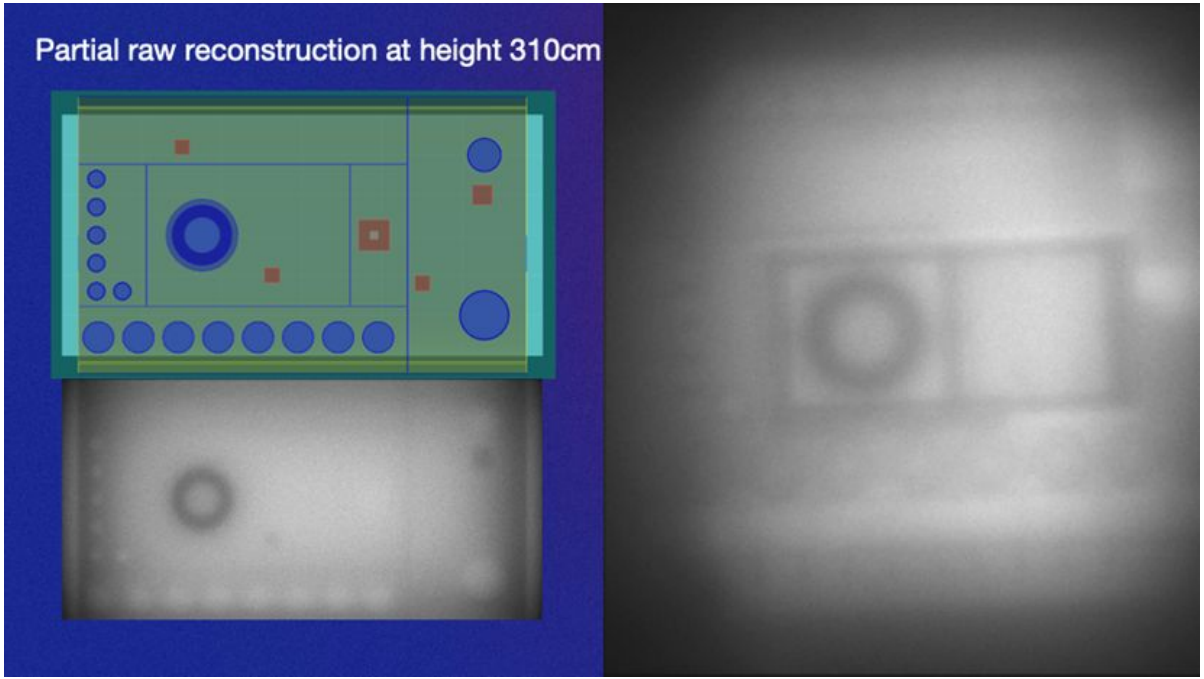
Measurement campaign completed as planned

We demonstrated a **considerably higher image resolution** than stated in the client contract

Results

Left: The image (bottom) of the reactor computer generated based on the virtual model and data (top)

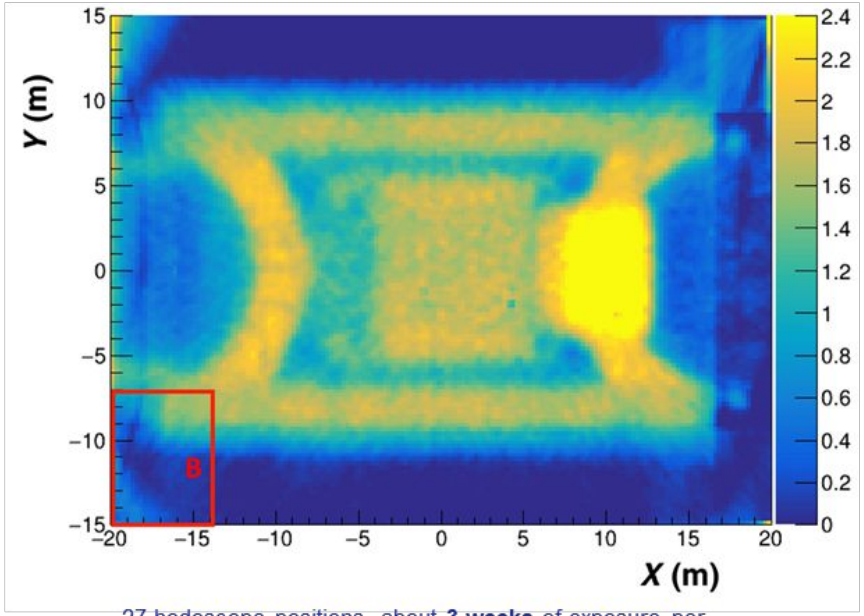
Right: The image of the reactor from the measurement data: reactor pressure vessel (largest object), pressurizes, steam generators and internal structures clearly visible



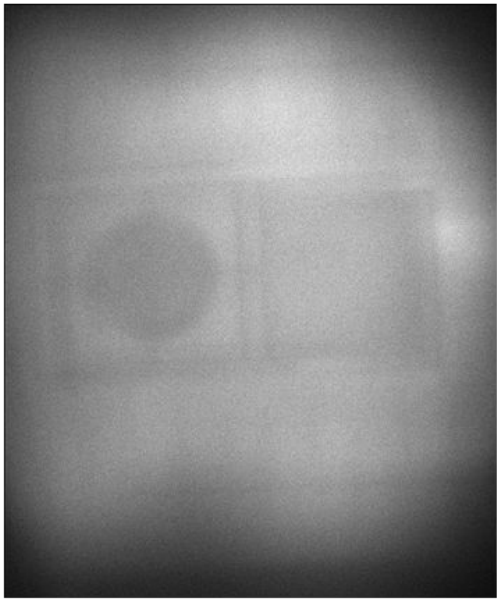
State of technology- Superiority across the board

NDT domain

We have shown unparalleled resolution and time needed for reconstructing in NDT scenarios. Below two reactors- on left reactor measured recently by French scientists, on right initial ALARA results by GScan



27 hodoscope positions, about **3 weeks** of exposure per position. Reconstruction covers 30x40m area with **25cm pixel**
https://www.science.org/doi/10.1126/sciadv.abq8431



30 hodoscope positions, **2-3 days** of exposure per position. Reconstruction covers 6x8m area with **1cm pixel**

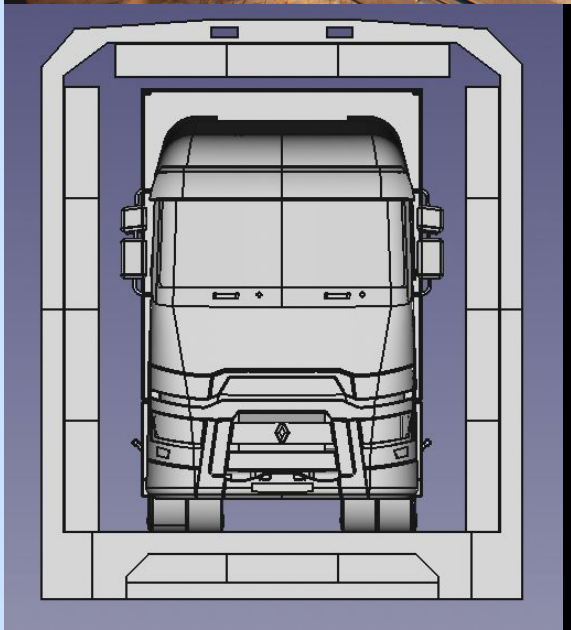
GSCAN

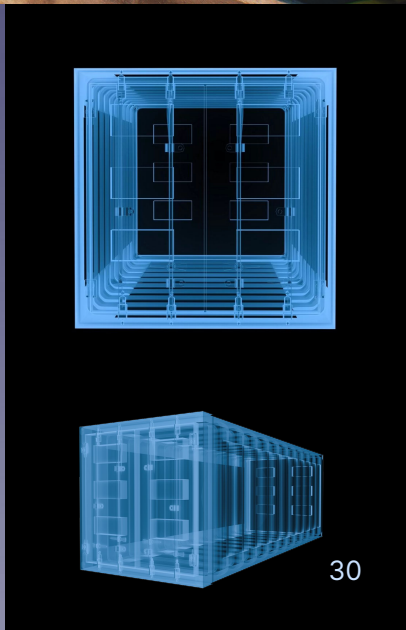
SilentBorder project

$8.0m the European Union pilot project for muFLUX AI Large: scanning trucks and sea containers.

Signed in 2021, delivery in 2025.
silentborder.eu

Technical partners: SGS Inc., German Space Agency DLR,
Uni. of Sheffield, CAEN, etc
Beneficiaries: Estonian, Finnish and Turkish customs agencies, etc





CosmoPort project with Imperial

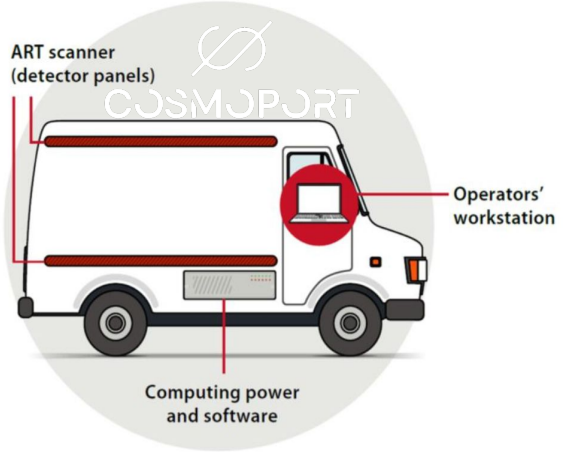
European Commission

Horizon 2020
European Union funding
for Research & Innovation

PROJECT FUNDED BY EUROPEAN COMMISSION
HORIZON-CL3-2022-BM-01-03

Cosmoport

- Develop the next-gen detection technologies using ART
  - Creating mobile scanning system
  - Achieve enhanced efficiency in detection (> 99%)
  - Self-calibration, advanced ML and robust mechanics
- **Achieve Technology Readiness Level 7 (TRL7)**
  - Evolve from proven prototype to mobile application



COSMOPORT

GSCAN

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

TULLI

Imperial College London

Republic of Estonia
Estonian Tax and Customs Board

KEMEA

State Revenue Service
Republic of Latvia

ΑΑΔΕ
Independent Authority for Public Revenue (IAPR)

Border Force

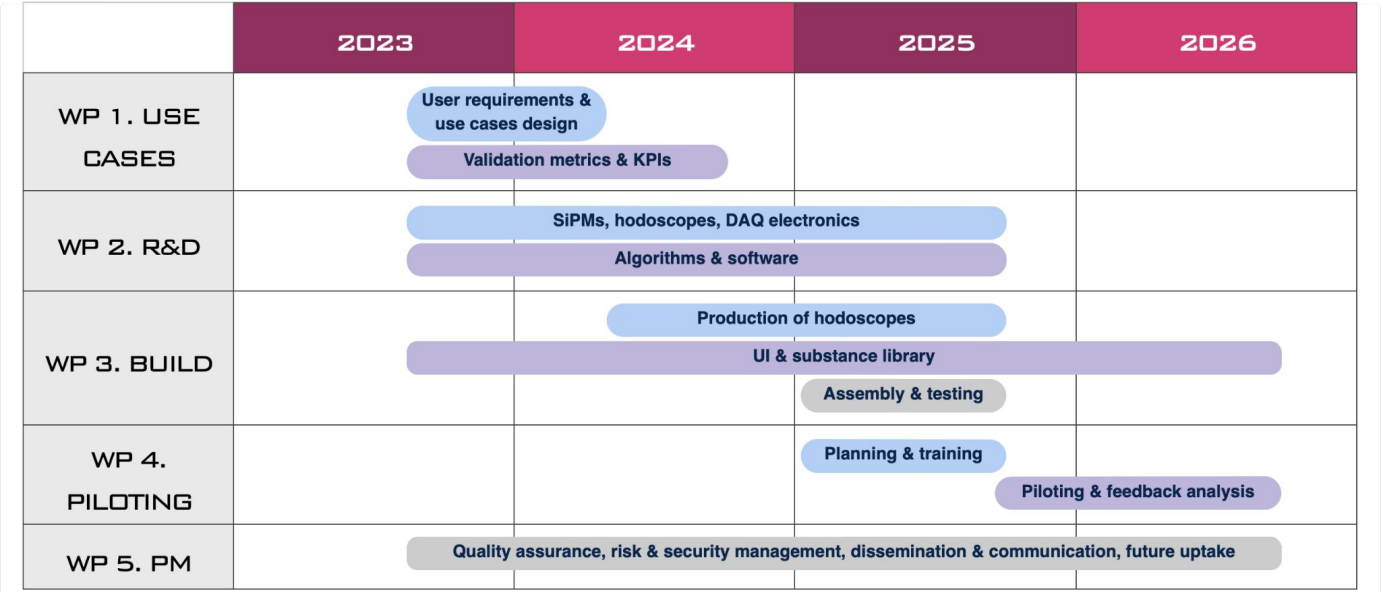
Work Packages and Roadmap

WP1 – Design of the system, User Requirements, Use Cases and Framework Design

WP2 – R&D of the components of the system (SiPMs, hodoscopes, DAQ, algorithms & sw)

WP3 – Construction of the system, Development of CosmoPort system and verification activities

WP4 – Piloting with the Customs & Border Forces



WP1– Bus/Trailer

Ensure the scanning system meets customs needs, refining requirements iteratively, and developing a technical framework

T1.1

Stakeholder engagement user requirements and use cases design

T1.2

Requirements engineering and design of CosmoPort technical framework

T1.3

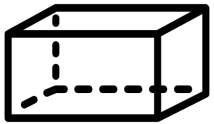
Definition of validation metrics and KPIs

WP2– Research & Development

R&D of the components of the system

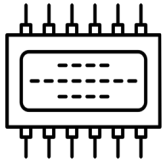
T2.1

R&D of silicon photomultipliers (SiPMs)



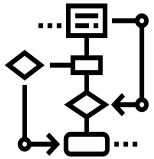
T2.2

Development of the compact hodoscopes



T2.3

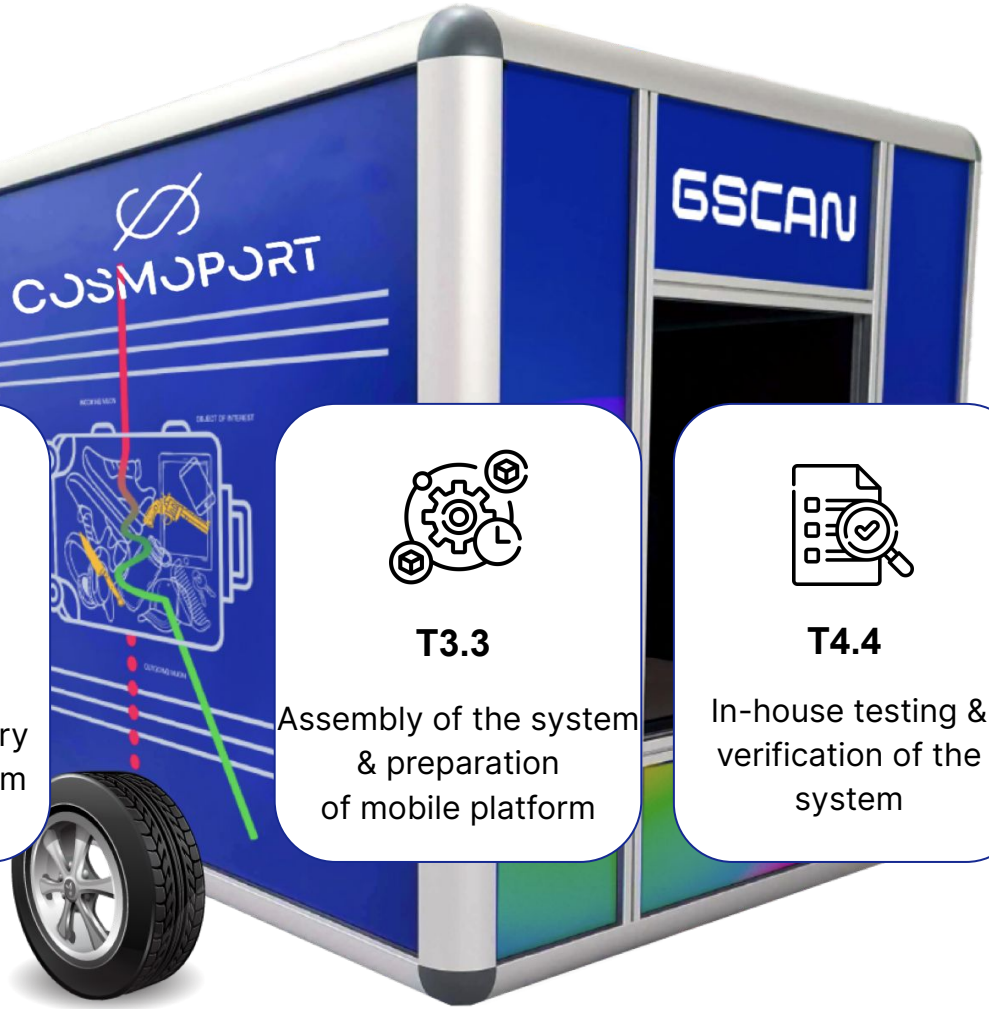
Development of the Data Acquisition (DAQ) electronics



T2.4

Development of the algorithms and software for the mobile system

WP3– Build



T3.1

Production of hodoscopes

T3.2

UI & substance library for the mobile system

T3.3

Assembly of the system & preparation of mobile platform

T4.4

In-house testing & verification of the system

WP4– Piloting

T4.1
Planning, monitoring, training activities, validation methodology

T4.2

Logistic centres of smaller courier companies

T4.6

Random checks for airports

T4.3

Random checks for yacht harbours

T4.5

Optimization of the usage of stationary x-ray system

T4.4

Sustaining customs activity and boosting LEAs' response to crime and emergencies

T4.7
Piloting feedback, analysis and conclusions

Summary & Outlook

- GScan is developing the technology for NDT and security applications
- We have chosen plastic scintillation fiber as a bases for particle tracking hodoscopes and tomographic systems
- We have developed a production technology for fibre-mat production in large volumes
- We are about to validate industrial prototypes
- First commercial project on submarine reactor sections started in January 2023, validation experiments for concrete constructions and security scanners are foreseen on the second half of 2023
- CosmoPort, a collaborative project is advancing security with next-gen ART scanners

Thank you!

gscan.eu

info@gscan.eu

linkedin.com/company/GScan