Muography Activities at CEA

New Advances in Nuclear Surveillance

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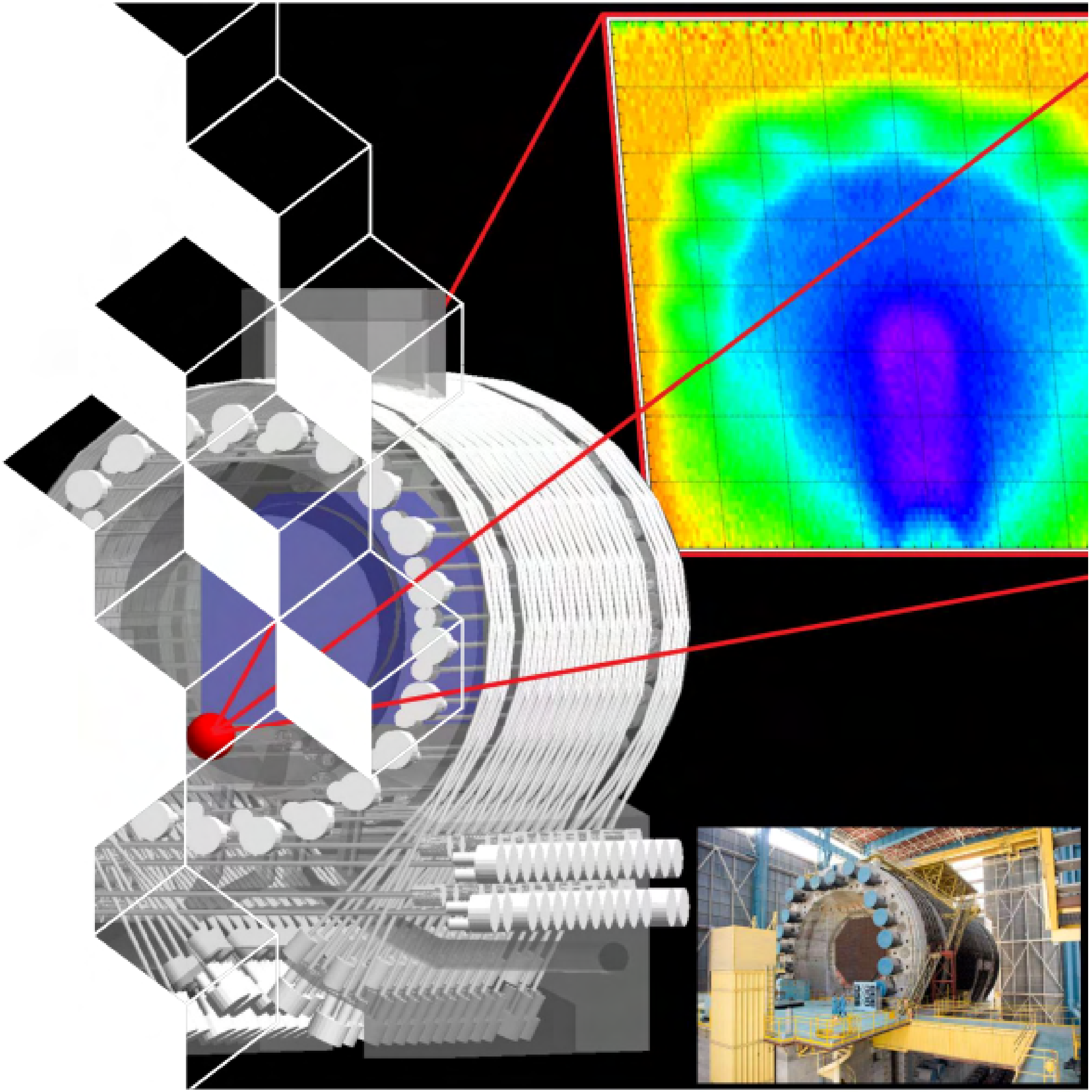
On behalf of Irfu's muography group



Outline

1.- CEA and Muography

- A bit of history
- General Aspects

2.- Nuclear Applications

- Context
- G2G3 Project
- Other Projects : Container scanning

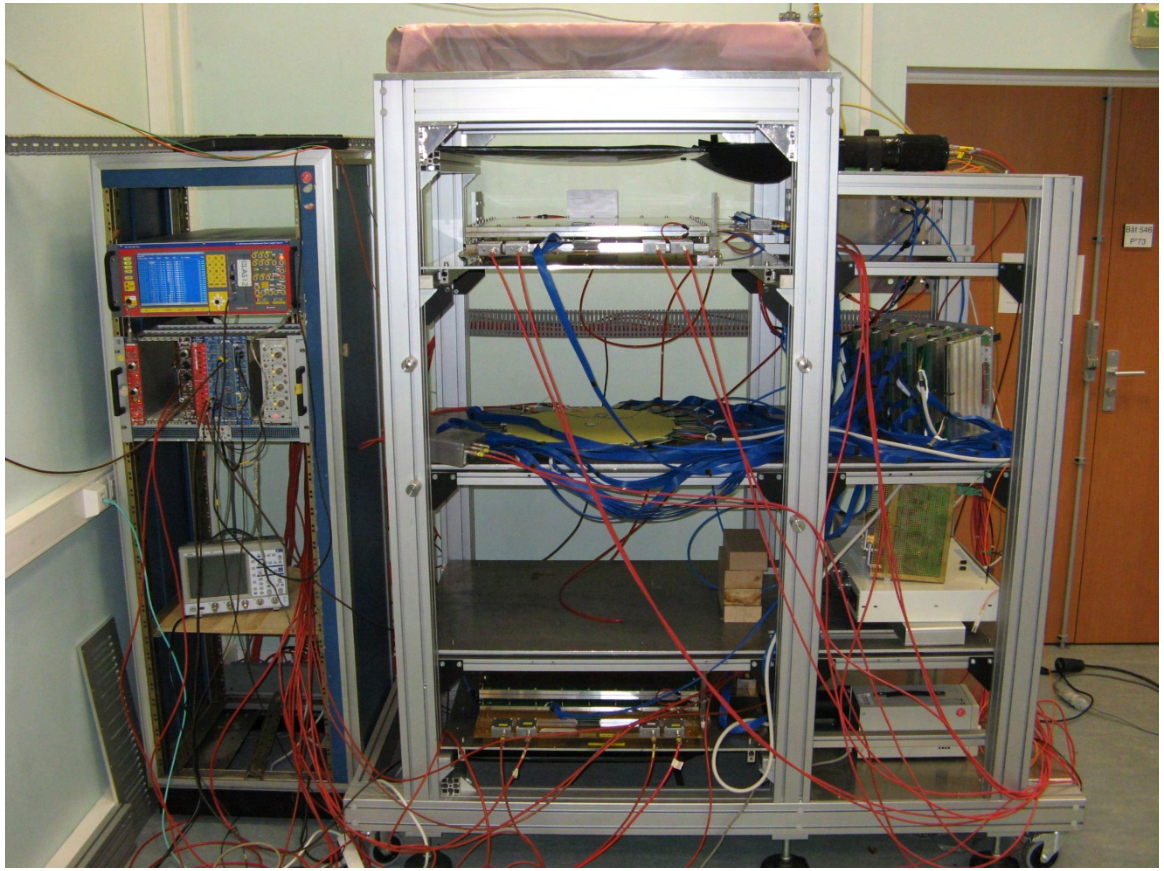
3.- Outlook

4.- Summary and Conclusions

1. CEA and Muography

CEA and Muography

Technological Transfer from IRFU's Cosmic Test Bench (From 2012)



- Characterization of detectors
  - Initially CLAS 12 Vertex Tracker Micromegas
- Based on Bulk Micromegas detectors
  - Irfu's expertise (Invented + 2 patents)
- Some advantages w.r.t. accelerators
  - Free
  - No booking needed
- Successful operation at Laboratory
  - Several types of detectors characterized

CEA and Muography

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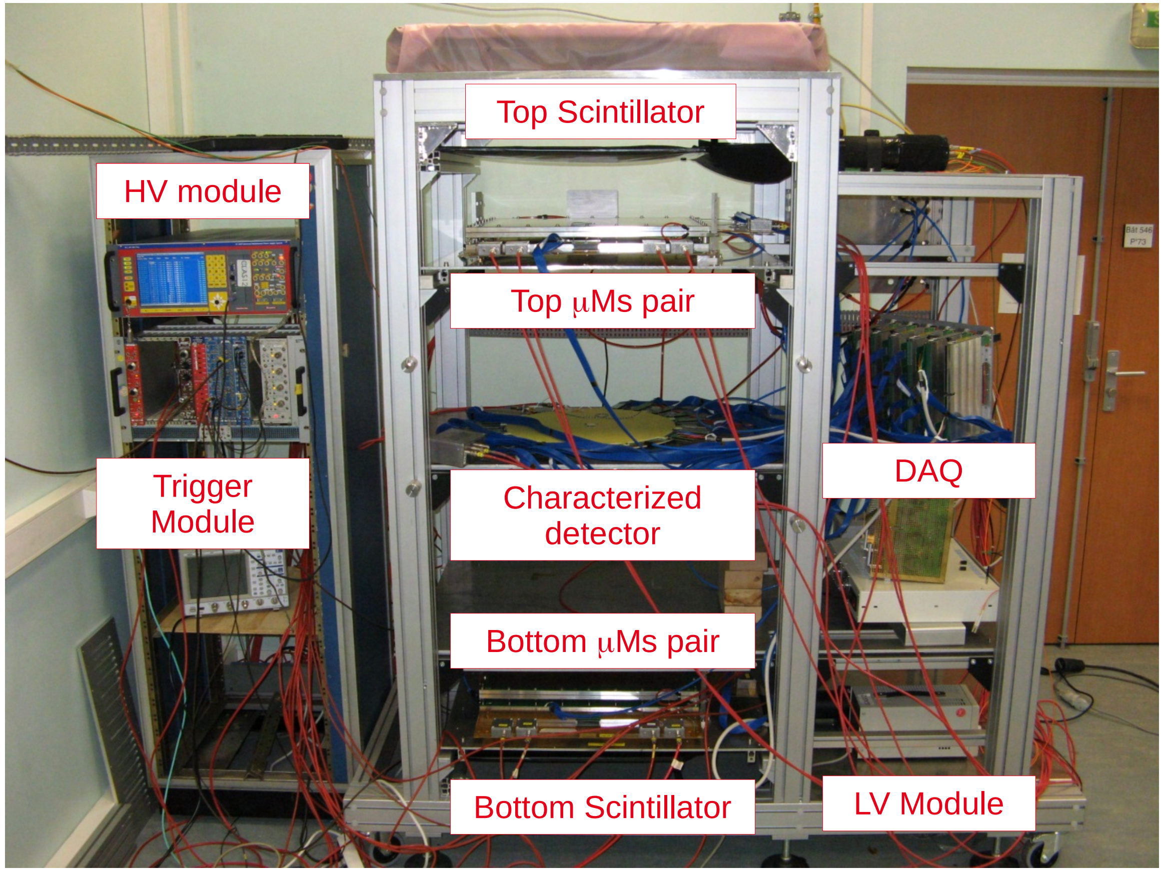

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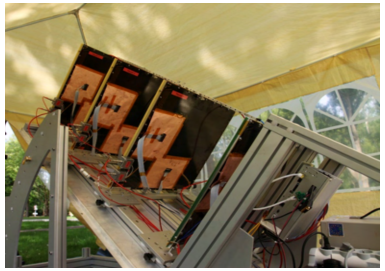
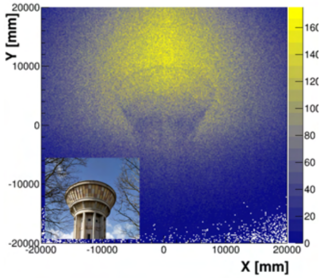
Muon telescopes at CEA: Historic

1st Gen (2015)

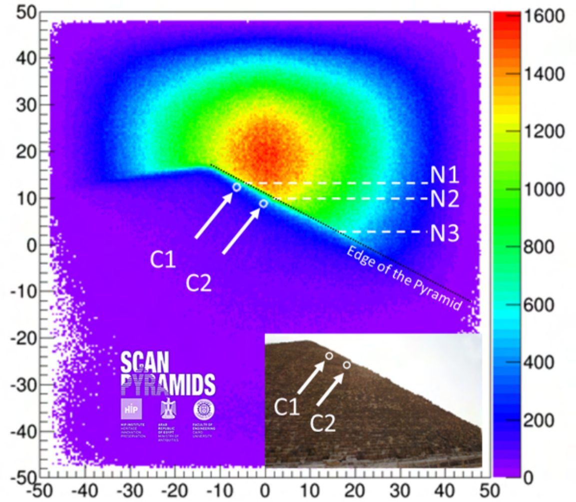
WatTo



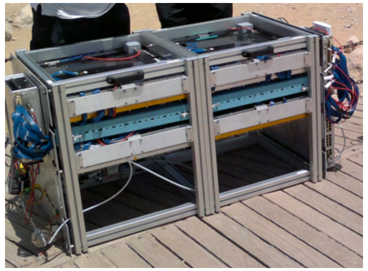


2nd Gen (2016)

ScanPyramids

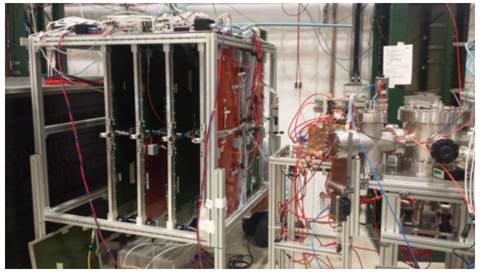


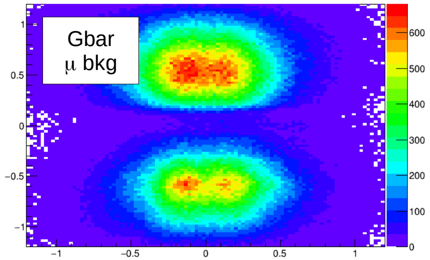
3rd Gen (2017)



4th Gen (2018)

GBar





Improvements :

- Compactness
- Autonomy
- Stability
- Active Surface

Applications :

- Civil Engineering
- Archaeology
- Fundamental Research
- Nuclear Domain

Muon telescopes at CEA: Nowadays

50 x 50 cm² Micromegas detectors

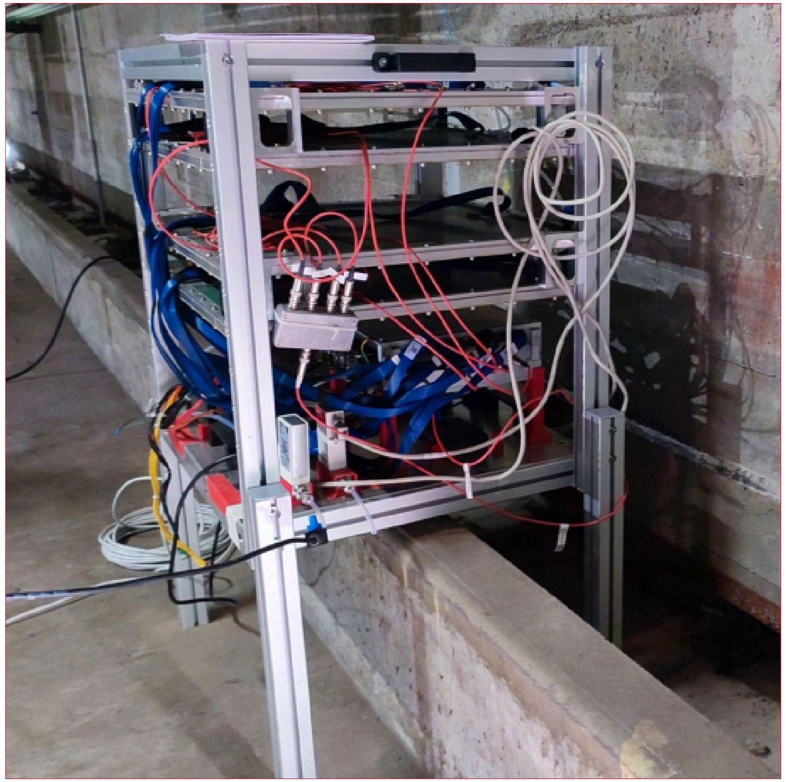
- 2D Multiplexed strips → Less DAQ
  - Patented
- Resistive Layer → Better reconstruction
- ***Spatial resolution ~ 400 μm***
- ***Angular resolution ~ 4 mrad***
- ***Time resolution ~ 10 ns***

Materials

- Mostly light: Aluminium, plastic...
- ***Overall weight ~65 kg***

Gas

- Non-flammable Ar-iC_4H_{10}-CF_4 (90:2:3)
- Recirculation system and filters
- ***Gas consumption ~0.3 L/h***



Miniaturized DAQ components

- Front – end cards
- HV modules
- All controlled by a Nano-PC
- ***Overall Consumption 35 W @ 12 V DC***
- Possible to supply by batteries / solar panels

Slow control

- Temperature, pressure, humidity, oxygen
- Accelerometer/inclinometer → Movement
- μMs gain corrected by Amplitude feedback
  → ***Stability along time***

Other developments

- Gas Tightness
- Gas mixtures
- Smaller hodoscopes and Cylindrical TPC

2. Nuclear Applications

Nuclear Applications: French Context

A key-industry in France with an important associated R&D

- CEA is a reference institution in this R&D

Safety Questions to Address

R&D @ CEA

- Construction and use of several ad-hoc facilities (large variety)
  - Necessity to dismantle after they use
  - Currently 36 CEA installations at clean-up and dismantling phase
    - **Previous monitoring mandatory**
- This R&D produces 25000 m^3 of nuclear wastes per year
  - Different types (solid, liquid, radioactivity…)
  - **Need to qualify and certify**

Nuclear Energy (world-nuclear.org)

- 70 Nuclear Reactors + Flamanville
- 19 Power Plants
- New Reactors Construction (??)

- Operation and **Dismantling**
  - Control and Monitoring
  - Safety plans in case of accident
  - **Waste management**

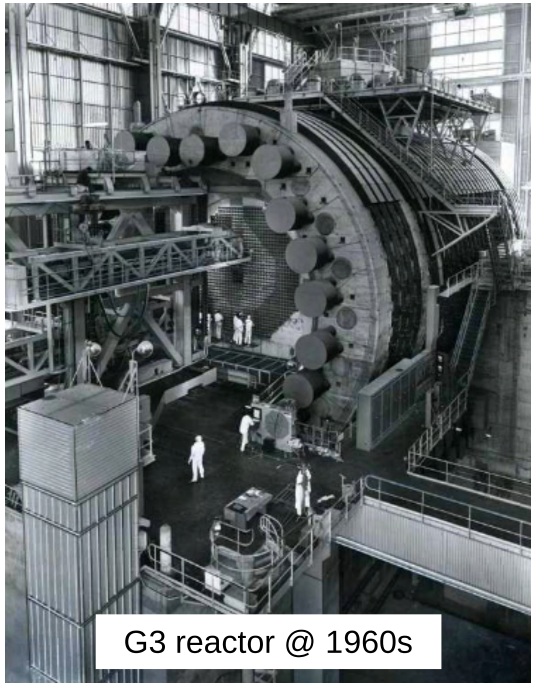
The G2G3 Project

Main Goal:

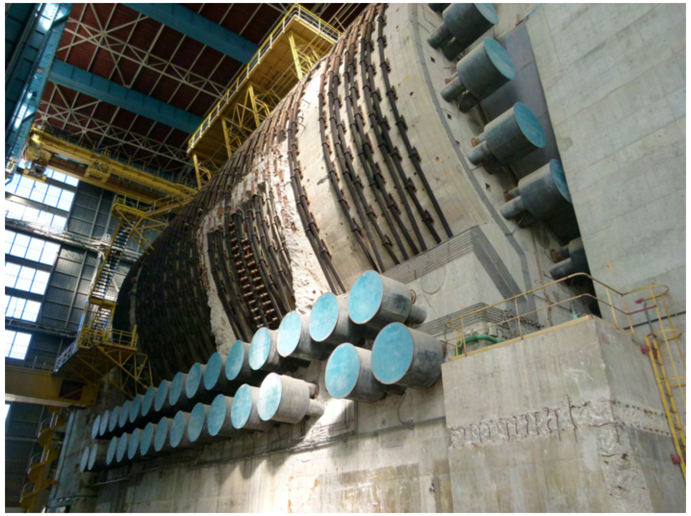
- Monitoring of the G2 and G3 nuclear reactors, located at CEA – Marcoule (South France), by muon tomography to:
  - Cross-check the validity of the existing plans / designs (they date from the 60's)
  - Check the internal structure and ageing of the reactors → Reactor Body
  - Look for possible damages (e.g. fissures) inside the concrete (is it possible?)

Ready for dismantling

G2 – G3 buildings @ CEA Marcoule



G3 reactor @ 1960s



G2 reactor @ 2018

The G2G3 Project

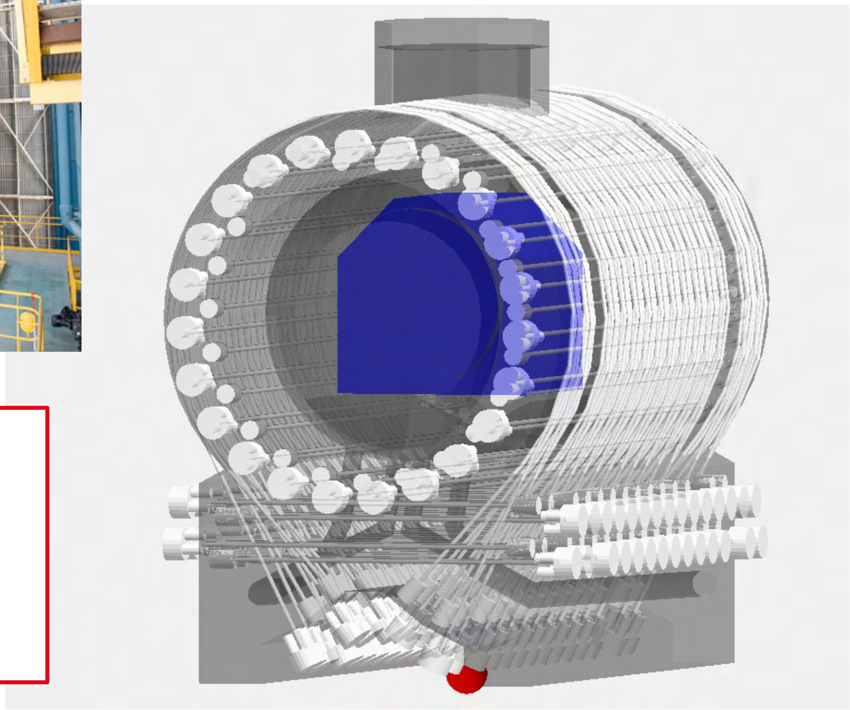
First analysis: Look for disagreements Reality – CAD Model

- Data / Monte Carlo comparison
  - Monte Carlo generated with the geometry from the 3D - CAD model
    - Any anomaly will imply differences between the model and the real structure

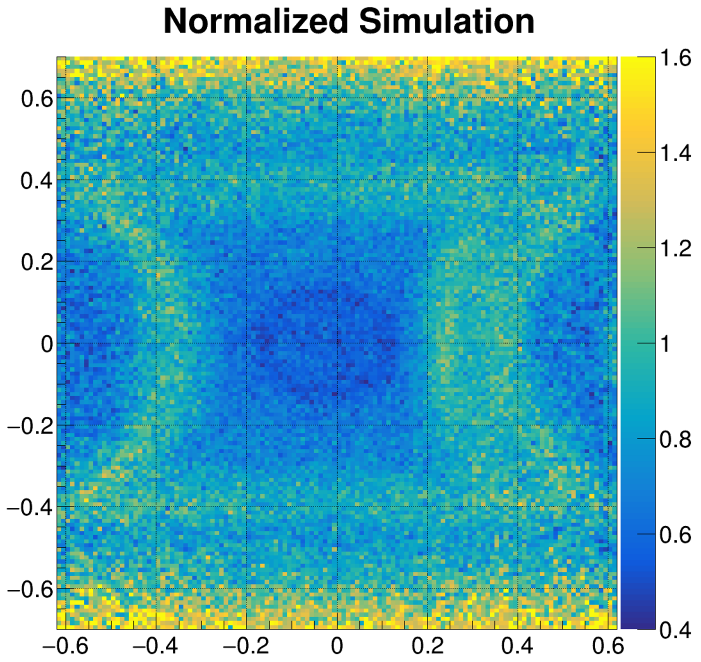
GDML Reactor Geometry (interpretable by Geant4):

>22000 Geometry files

~3.4 GB



Geant4 - GDML Model



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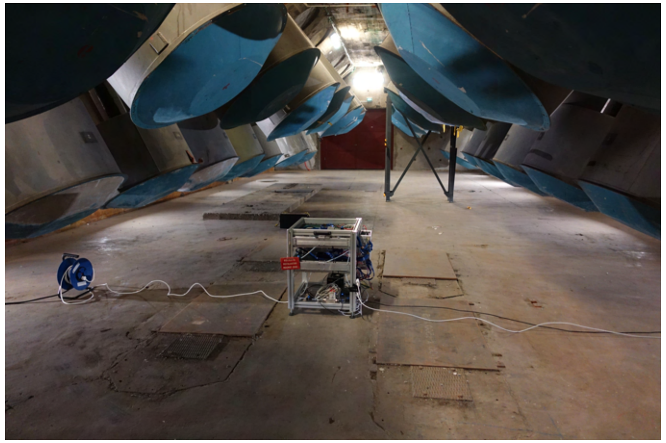
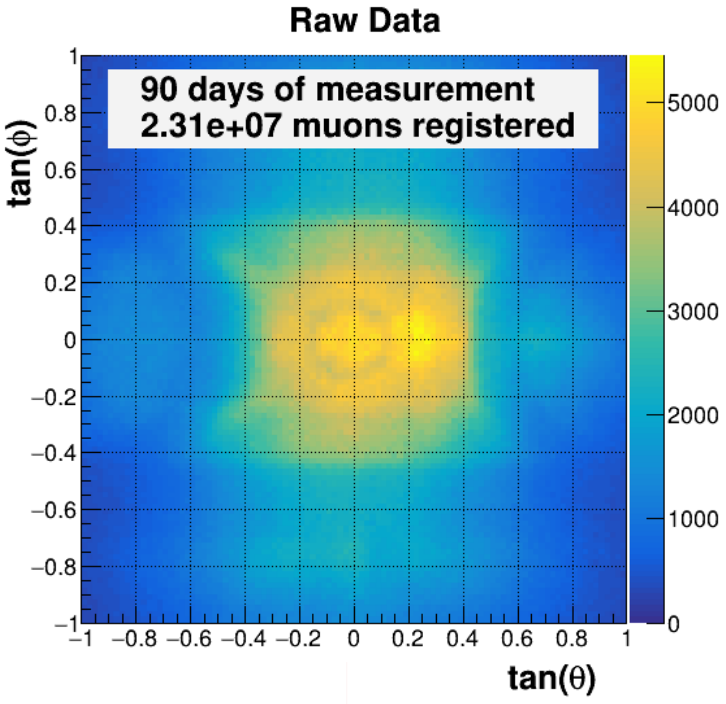
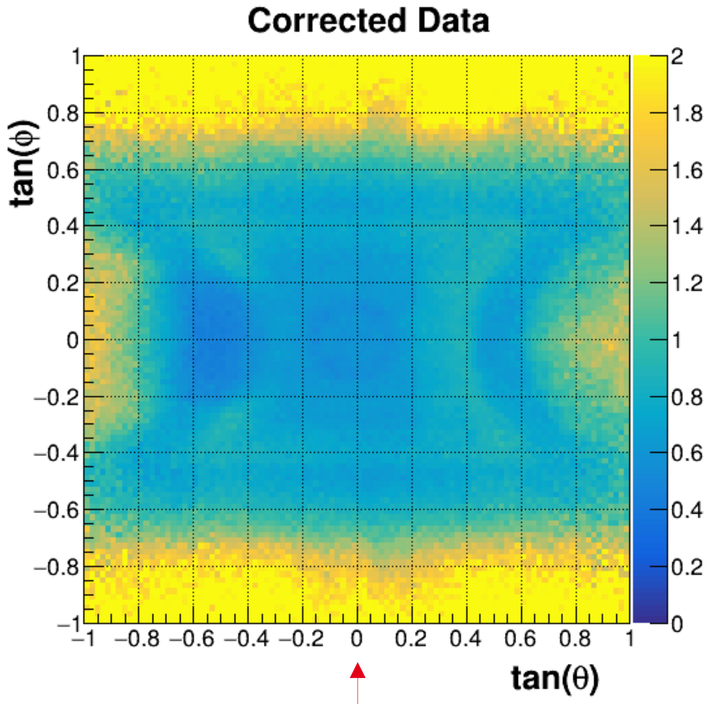


- Detector placed at the centre of the reactor (level – 0)
- Optimal position for a first overall image





Geometrical acceptance and detection efficiency

The G2G3 Project

First analysis: Look for disagreements Reality – CAD Model

https://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast.php?t=fait_marquant&id_ast=4888

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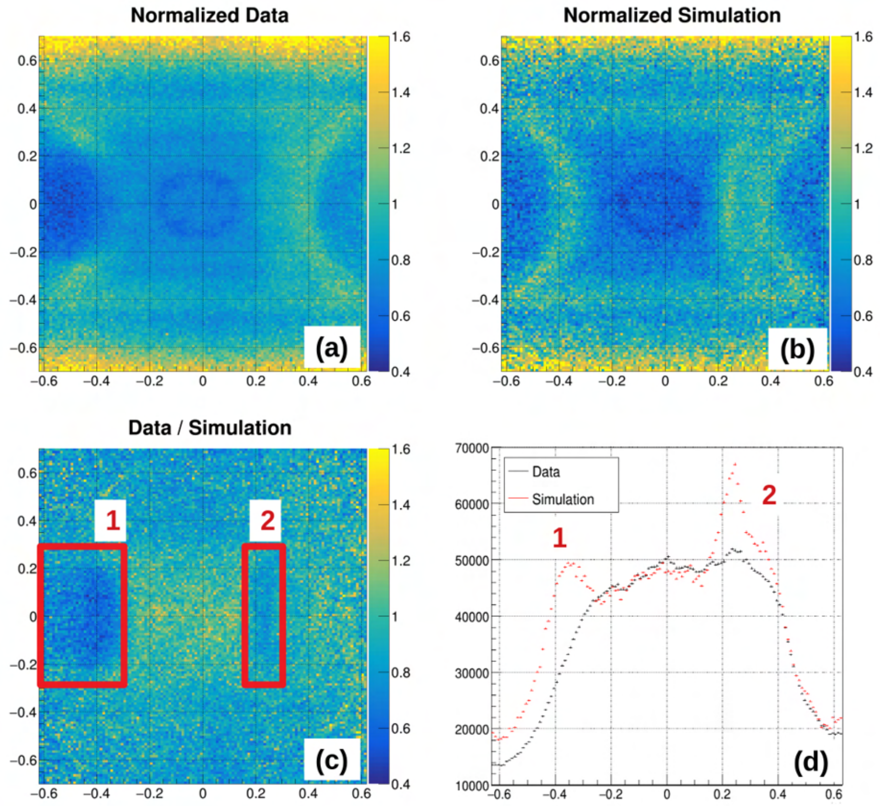
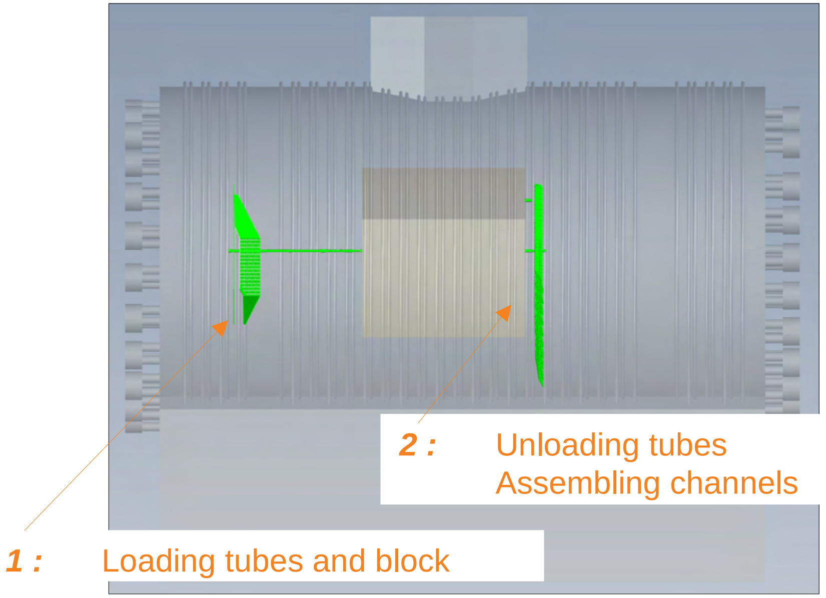


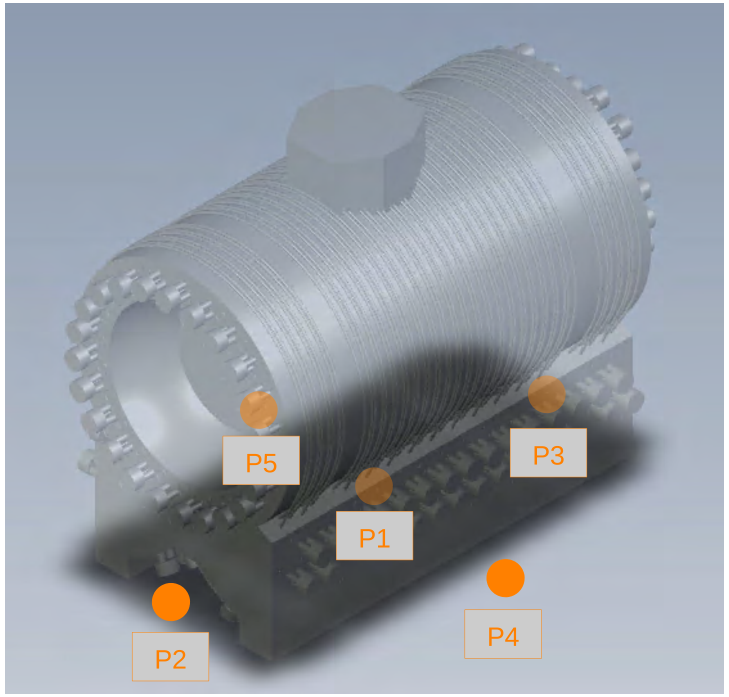
2 Data / MC disagreements



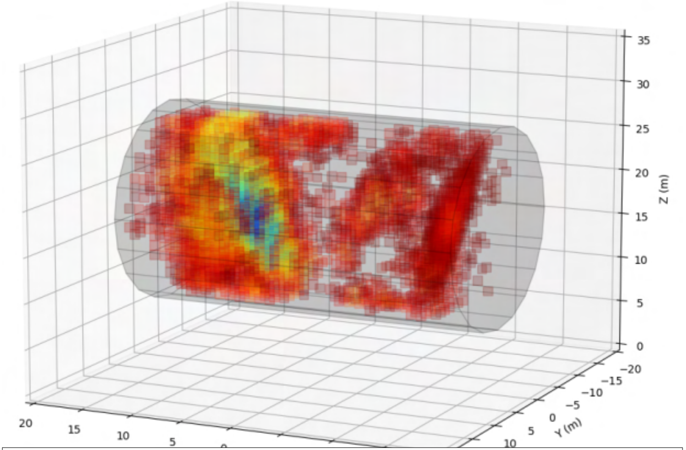
The G2G3 Project

Second analysis: Anomalies location in space

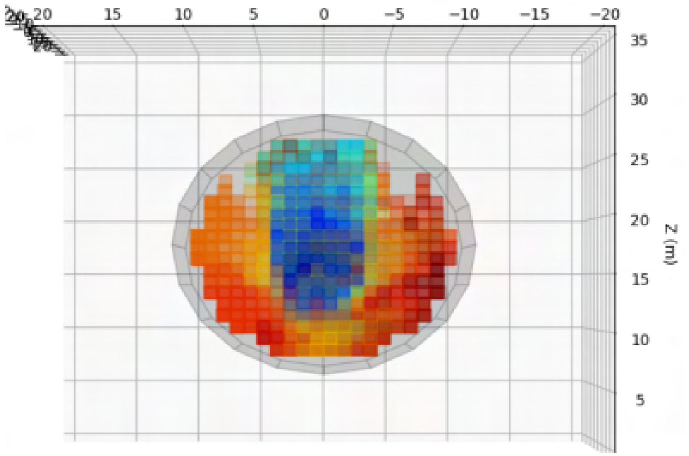
- Triangulation of different measurements

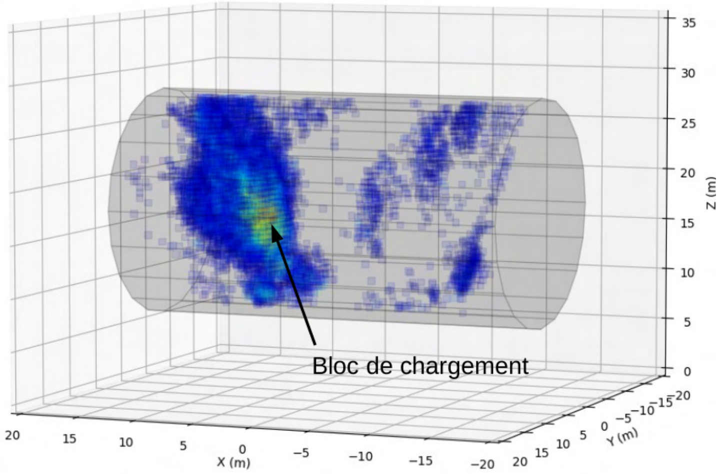


5 measurements combination



Anomlaies triangulation

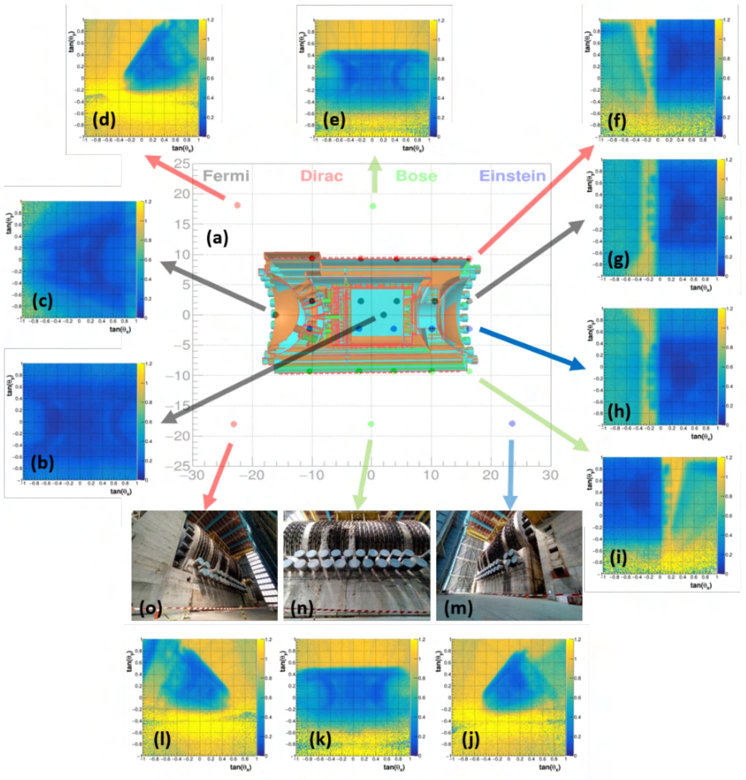




Fine tuning :
Compatible results with identified elements
@ 1st analysis

The G2G3 Project

Third analysis: 3D Muon tomography



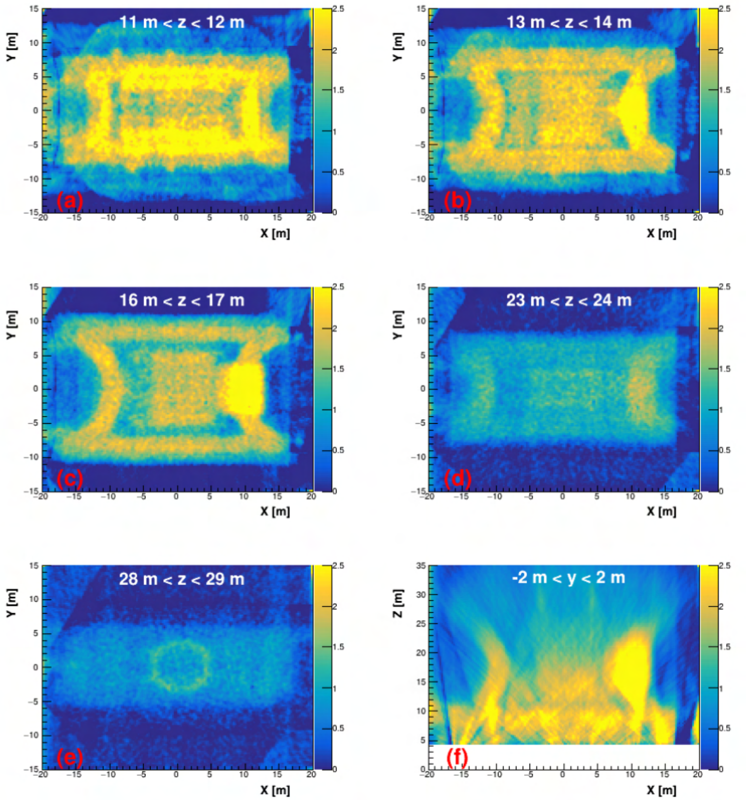
SART Method

[D] (n_v x n_m) **[ρ]** (n_v) = **[o]** (n_m)

n_v : Voxels number 2688000
25 cm side

n_m : 27 positions with
200 x 200 directions per 2D muoography
(1080000 mesurements)

→ **[D] has ~ 2,9 10^{12} elements**



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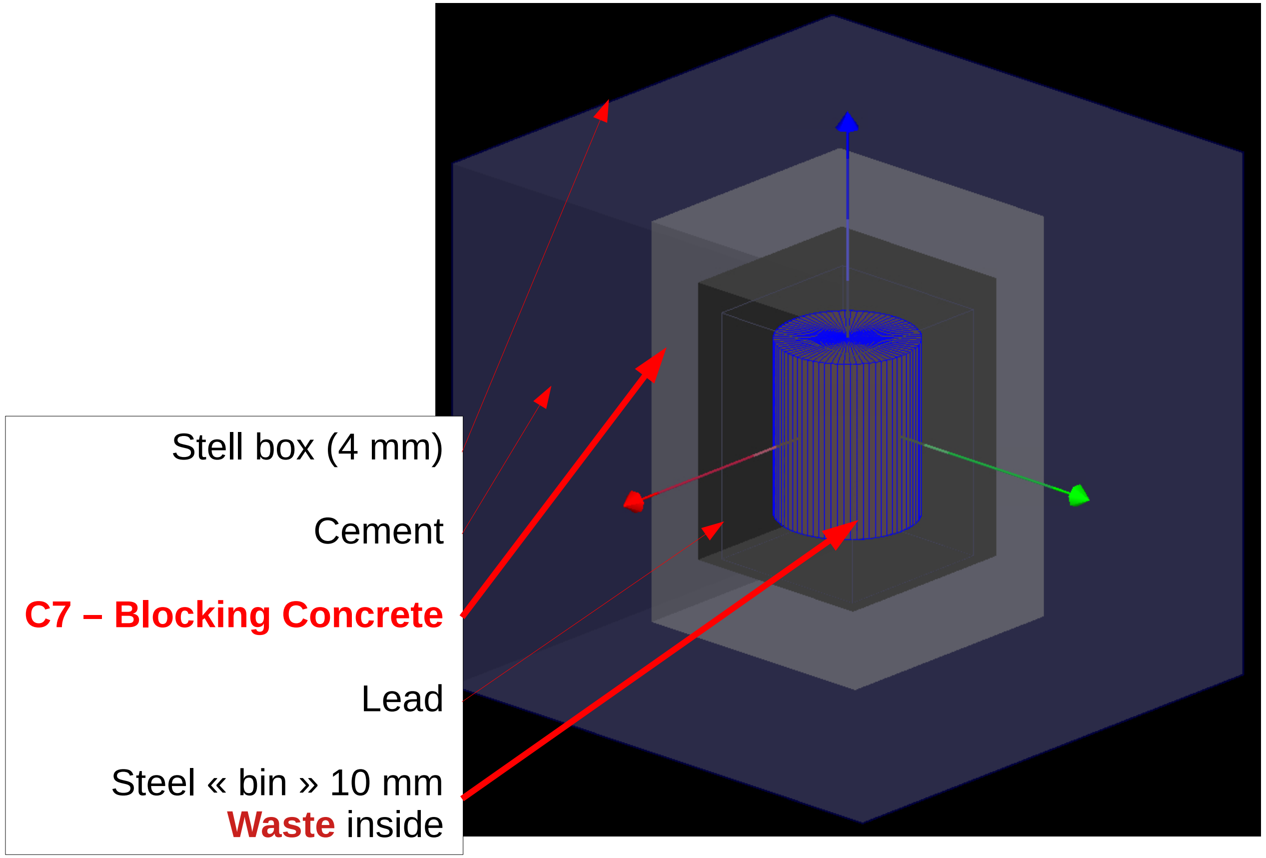
Video available here

Container scanning

Main goal

- Container verification (not precise characterization)
  - First order density of waste (~water, heavy metals, …)
  - Integrity of the blocking concrete



IP2 Type containers
1.7 m side (5 m^3)
12 tonnes overall weight

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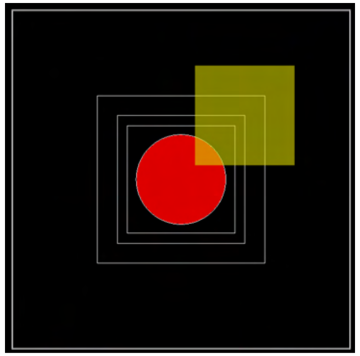
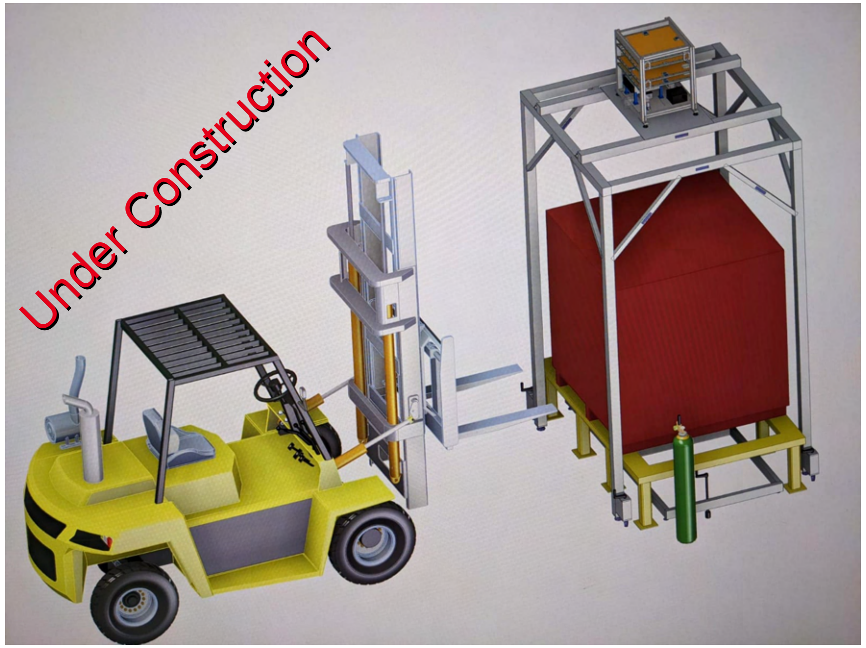
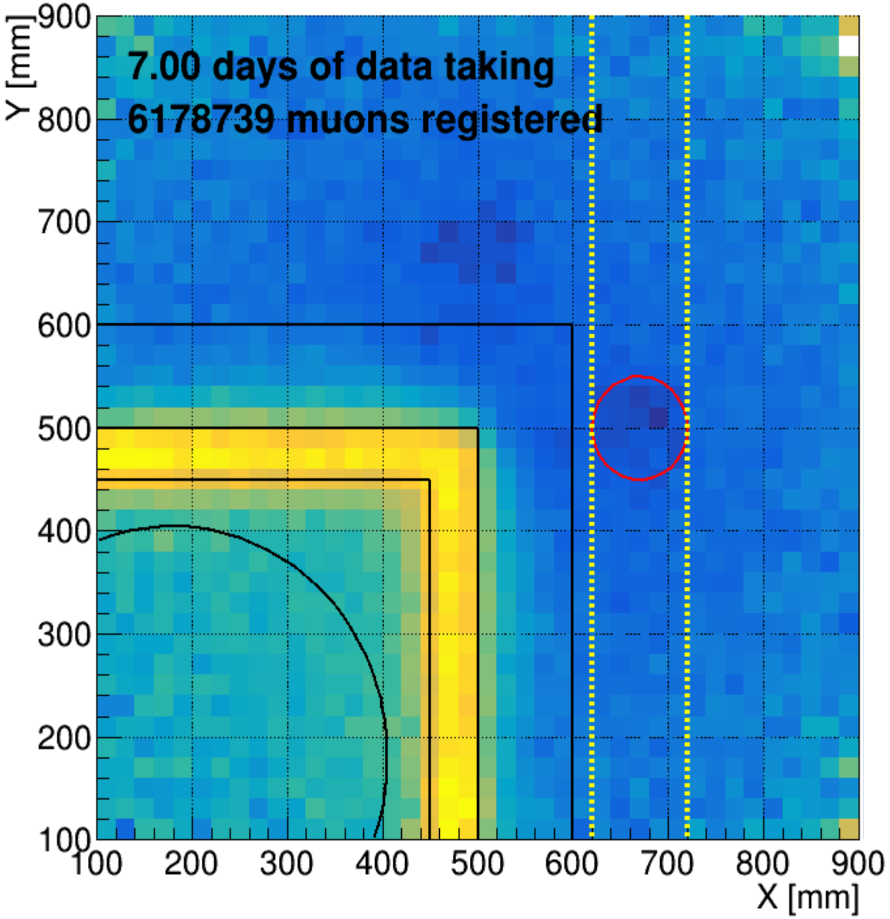


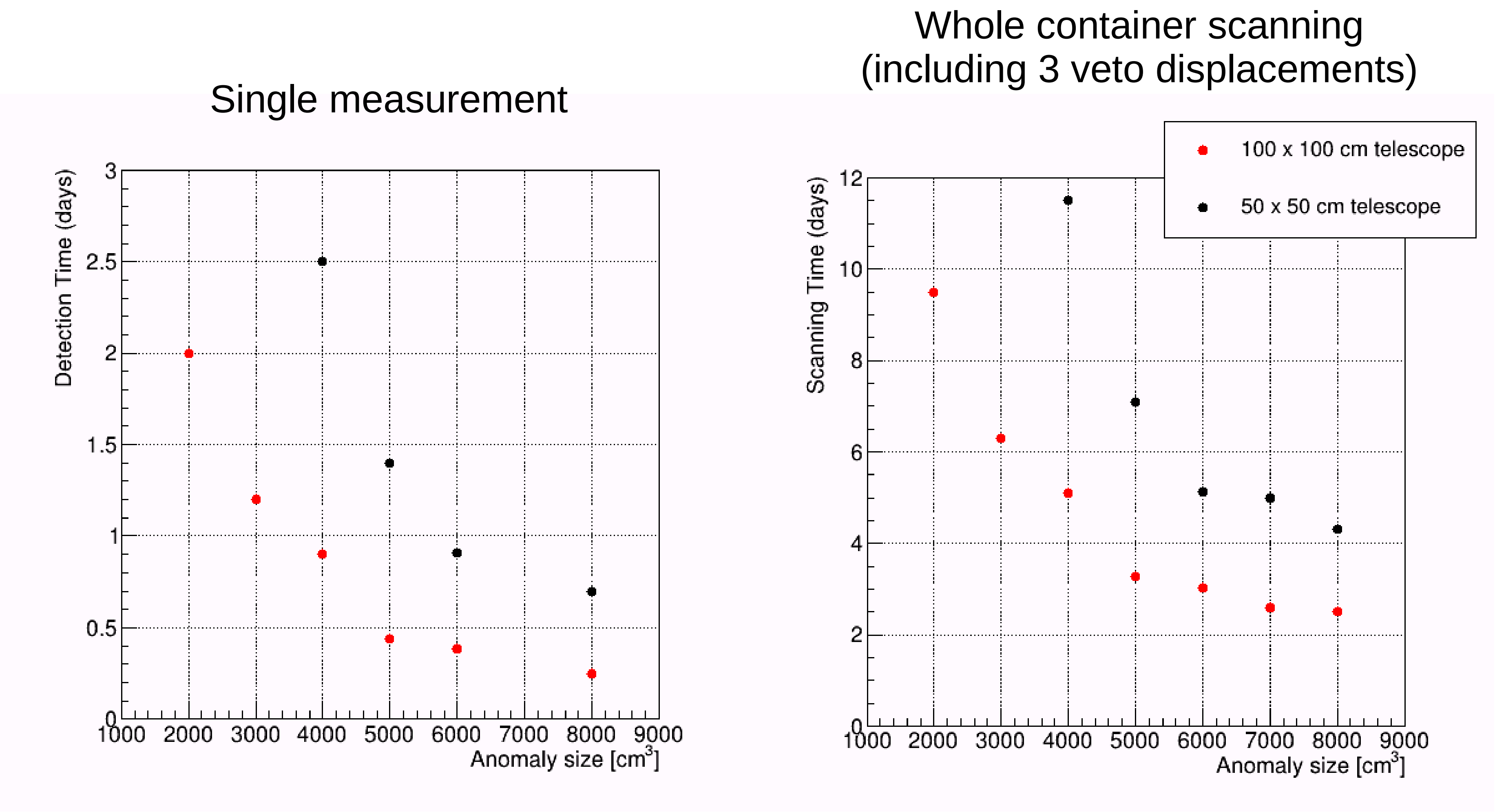
50 x 50 cm telescope





- Absorption set up (1 Top Tracker + 1m^2 bottom veto)
  - Simpler instrumentation
  - More adequate for verification

Container scanning



First proof of concept measurements expected by the end of 2023

3. Outlook

Outlook

- G2 → **G3 (PhD work ongoing until November 2024)**
  - 3D reconstruction focused on the graphite block
    - Measurement position and time optimization
    - Improvement of the 2D individual muographies
      - Muon track reconstruction / demultiplexing (CNN)
      - Muography denoising
    - Optimize 3D reconstruction process
      - Evaluate precision and accuracy (w.r.t. 3D model)
- Container verification
  - Proof of concept measurements
  - Fast anomalies identification (Image processing)

R&D

Tightness
(Autonomy)

Packaging
(Nuclear env.)

Safe and
green gas
mixtures

Deployment,
autonomy …

Analysis
Techniques

4. Summary and Conclusions

Summary and Conclusions

- CEA/Irfu group developed a muon telescope based on Micromegas detectors
  - Robust technology, good performance (angular and spatial resolution)
- This telescope has been used in the last years in different muography applications
  - Archaeology
  - Engineering
  - Nuclear domain
- Among the different projects related to nuclear domain, several applications have been proven
  - Reactor model verification → FIRST 3D MUON TOMOGRAPHY OF A REACTOR
  - Nuclear waste containers inspection
- New ideas and projects ongoing

Thanks!

This talk has been possible thanks to the work of:

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