Muography with Micromegas detectors:

Main features and results and future prospects in geophysics with new concept telescopes.

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S. Procureur

Outline

- ~~Muons and muon tomography~~
- Micromegas detectors
  - Muon telescopes
  - Evolution
- Muography applications @ CEA
  - G2G3
    - Towards 3D Muon Tomography
  - Metrology
- New Concept Telescope: D3DT
- Outlook and Conclusions

Thanks to previous speakers!

***Bulk** (Patent – Saclay – 2006)*
***Micromegas** (Patent – Saclay – 1996)*

Robust, well-known

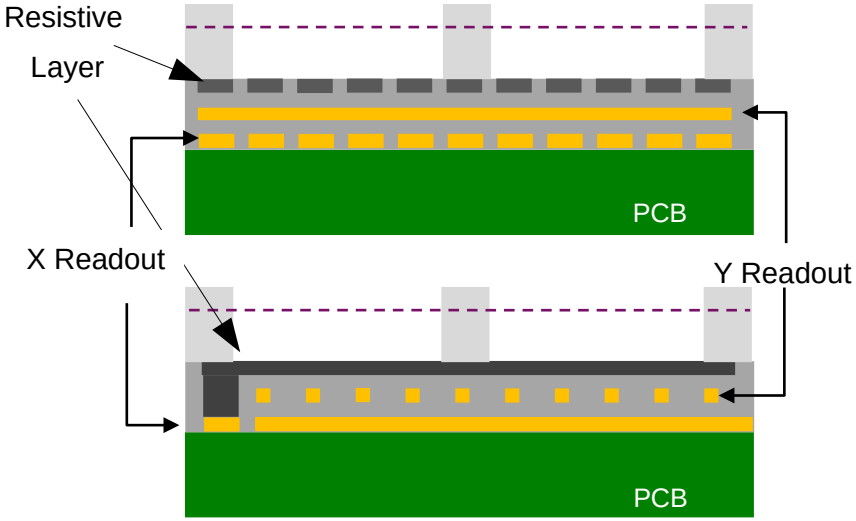
Big surface (50 x 50 cm^2)

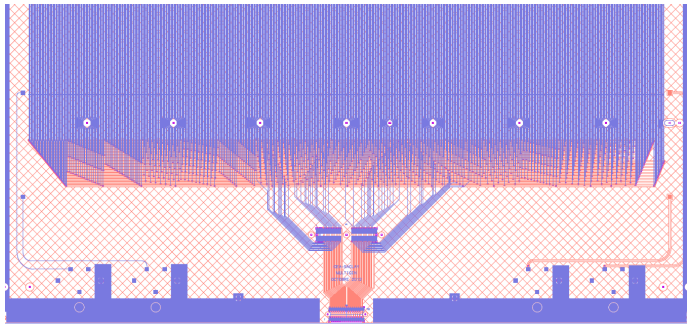
Continuous R&D

Resolution:

o100 μm spatial

o10 mrad angular





Resistive Strips

Avoid sparks → Detector protection

Charge Diffusion → Better spatial resolution

→ Multiplexing possibility

***Multiplexed Readout - V1** (Patent – Saclay - 2006)*

From 1037 to 61 channels both X and Y

→ 1/34 lines reduction

→ Simpler DAQ

Muon Telescopes

Main Features

50 x 50 cm² Micromegas detectors

- Multiplexed strips → Less DAQ
- ***Spatial resolution ~ 400 μm***
- ***Angular resolution ~ 4 mrad***
- ***Time resolution ~ 10 ns***

Miniaturized DAQ components

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

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***
  - ***~10 months for a 20 L bottle***

Slow control

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

→ ***Stability along time***

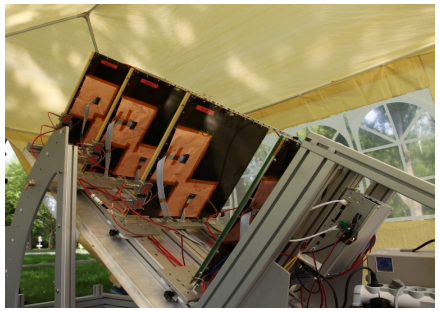
1st Gen (2015)

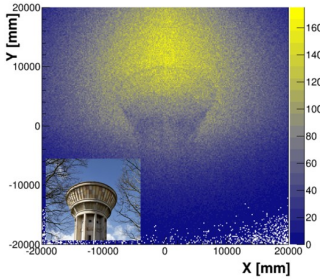
2nd Gen (2016)

3rd Gen (2017)

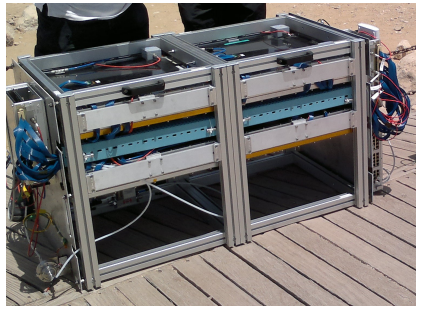
4th Gen (2018)

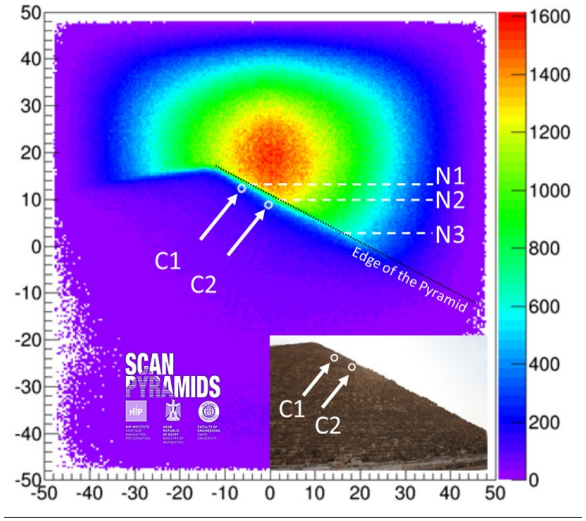
WatTo



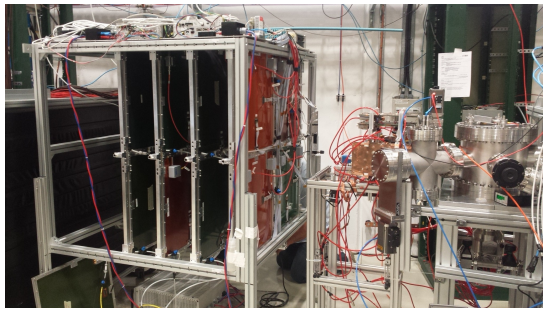


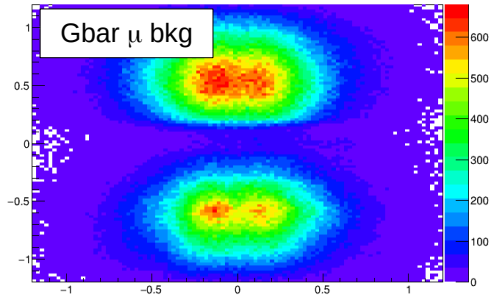
ScanPyramids





GBar





Improvements on:

- Size
- Autonomy
- Stability
- Less Multiplexing

Applications on:

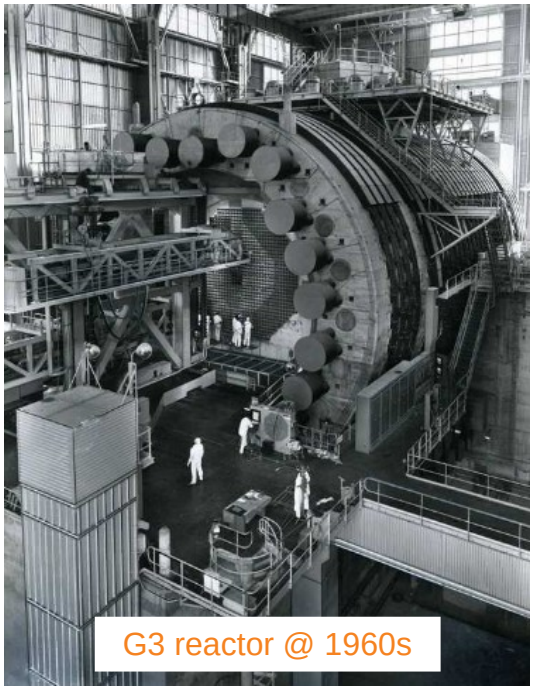
- Engineering
- Archaeology
- Fundamental Research
- ...

Main Goal:

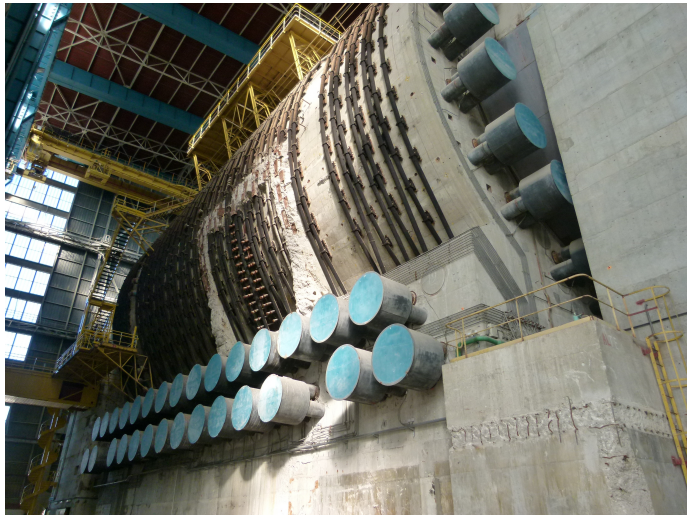
- Monitoring of the G2 and G3 nuclear reactors, located at CEA – Marcoule (South France), by muon tomography to:
  - Cross-check the validity of the existing plans / designs (they date from the 60's)
  - Check the internal structure and ageing of the reactors → ***Reactor Body***
  - Look for possible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

Ready for dismantling

G2 – G3 buildings @ CEA Marcoule



G3 reactor @ 1960s



G2 reactor @ 2018

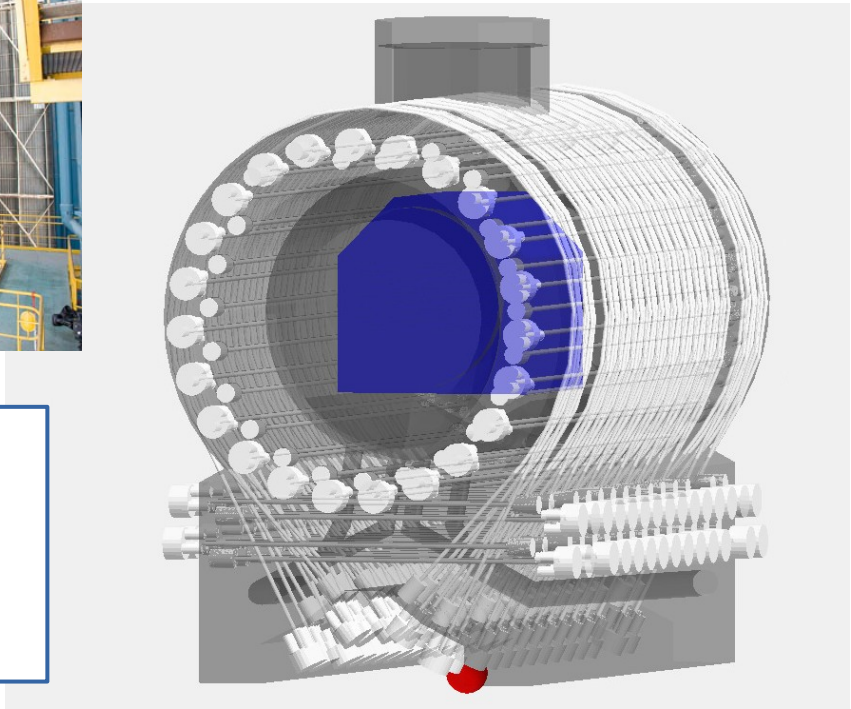
First analysis:

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

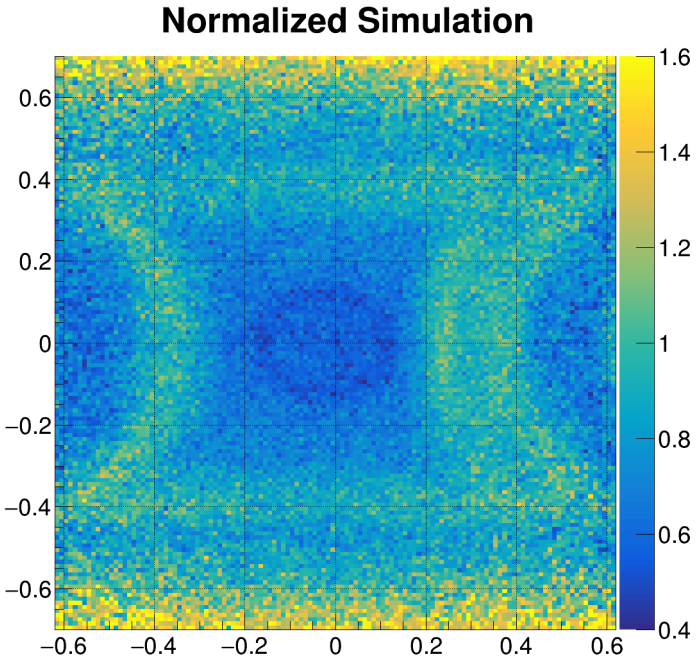
GDML Reactor Geometry (interpretable by Geant4):

>22000 Geometry files

~3.4 GB



Geant4 - GDML Model



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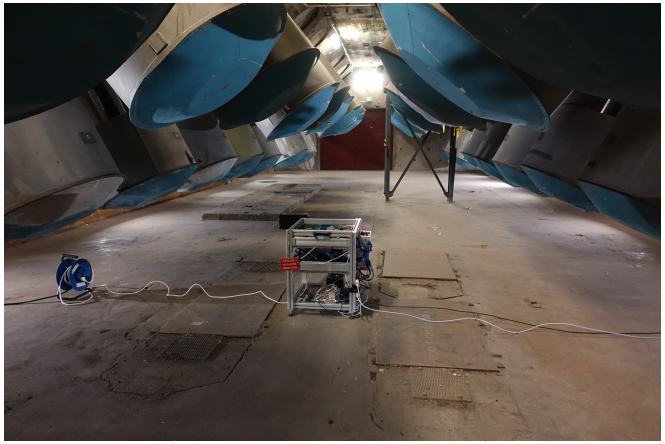
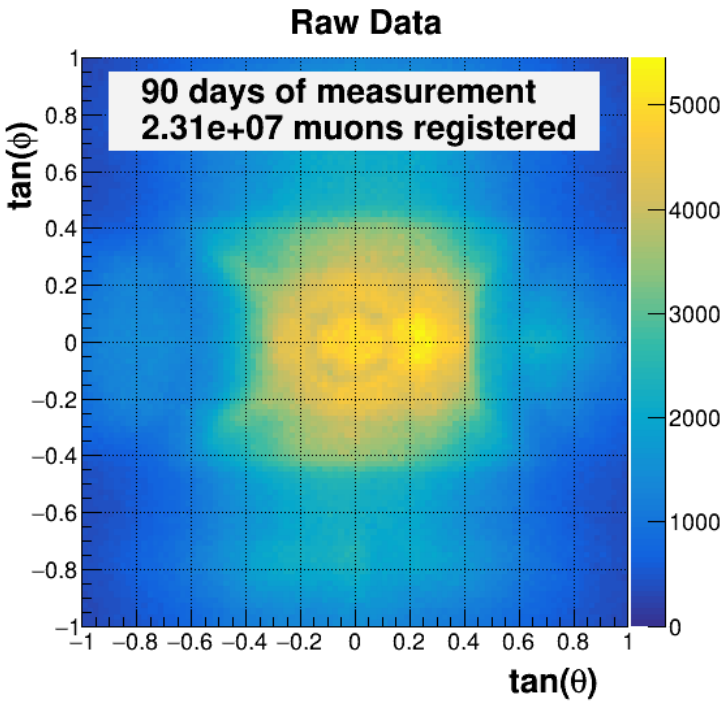
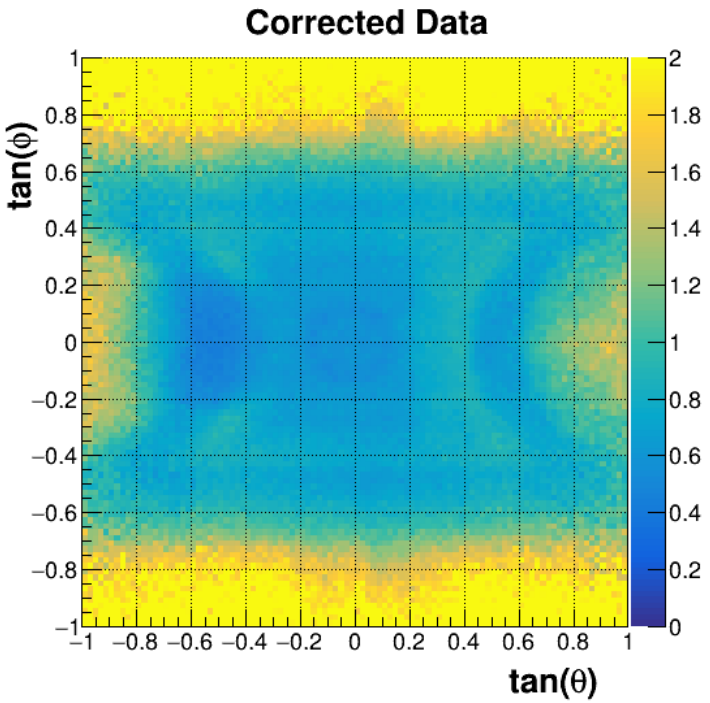


- Detector placed at the centre of the reactor (level – 0)
- Optimal position for a first overall image

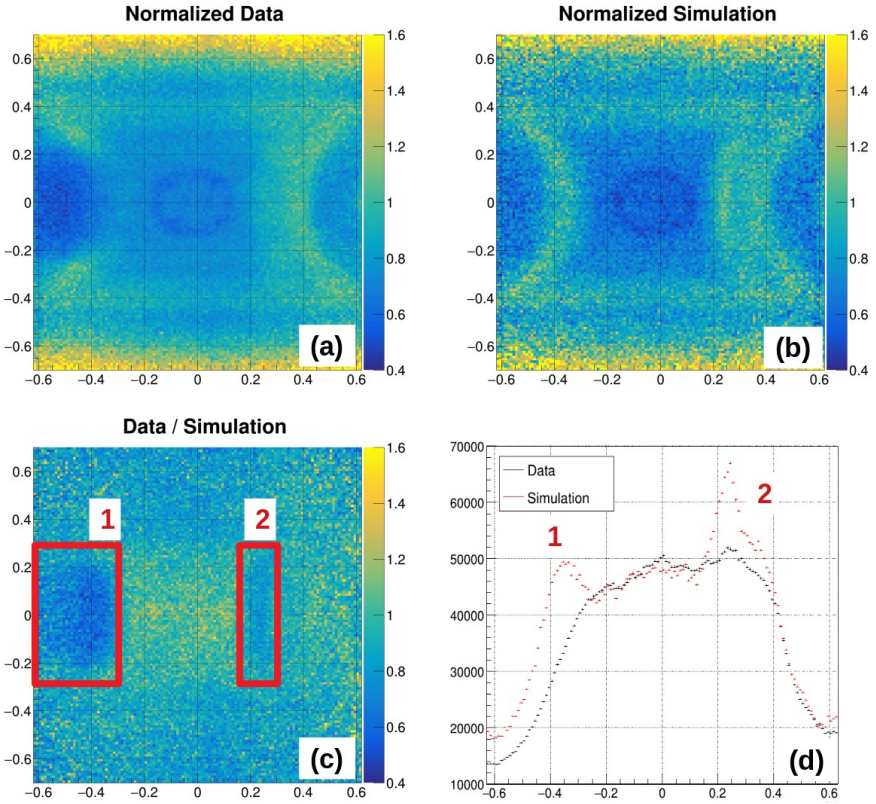


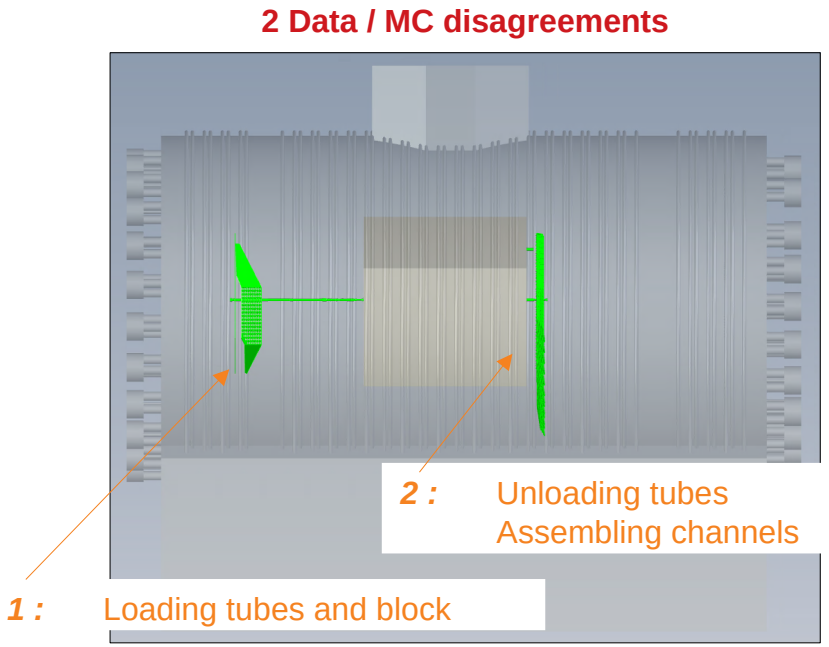


First analysis:

https://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast.php?t=fait_marquant&id_ast=4862

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





Second analysis:

- 3D reconstruction from Data → Resolution of the so-called **inverse problem**
  - No need of preliminary information neither simulations (only external shape)
  - Reconstruction algorithm from medical imaging (**S**imultaneous **A**lgebraic **R**econstruction **T**echnique)
    - Challenge: Much less number of images with lower resolution

$$[D]\vec{\rho} = \vec{o}$$

- Split the volume to study in n_v 3D pixels (voxels)
- Split each muography in n_m measurements (directions / pixelization / resolution)
- So for a given muography ...

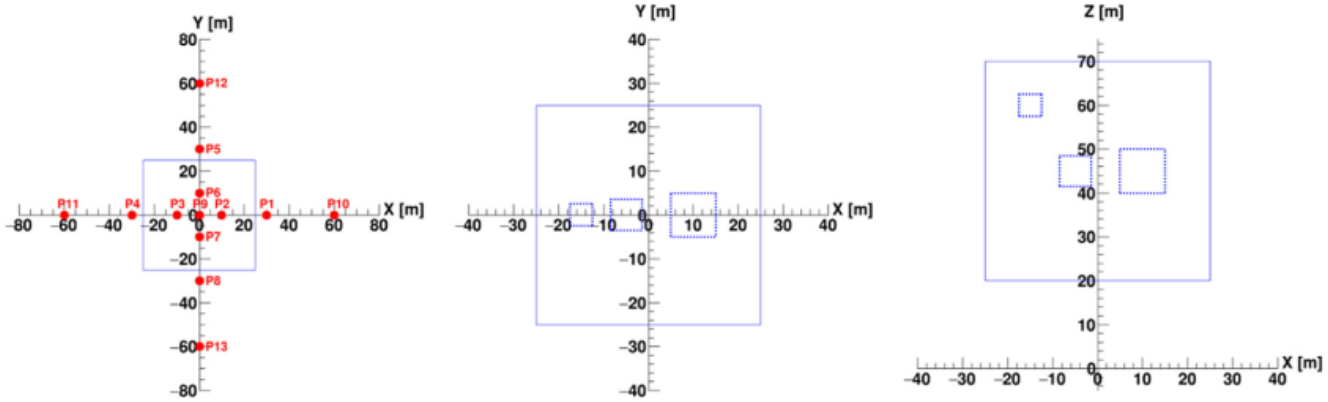
[D] Distance Matrix (n_v x n_m)
Mean distance traversed by muons for each voxel
Calculable theoretically

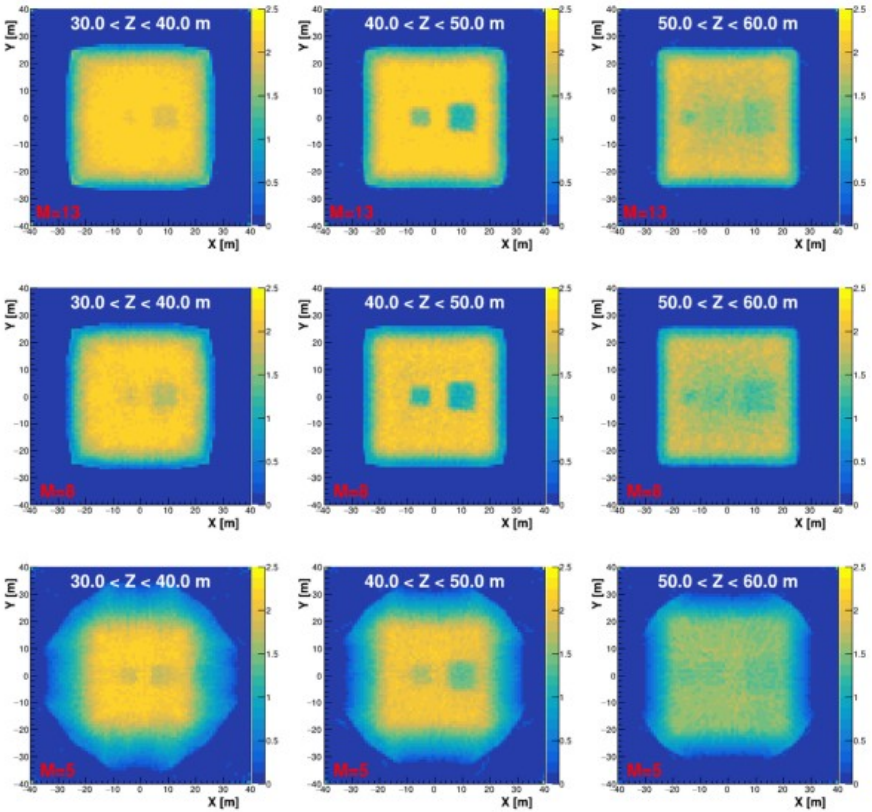
ρ Density vector (n_v)
Density of each voxel ***UNKNOWN***

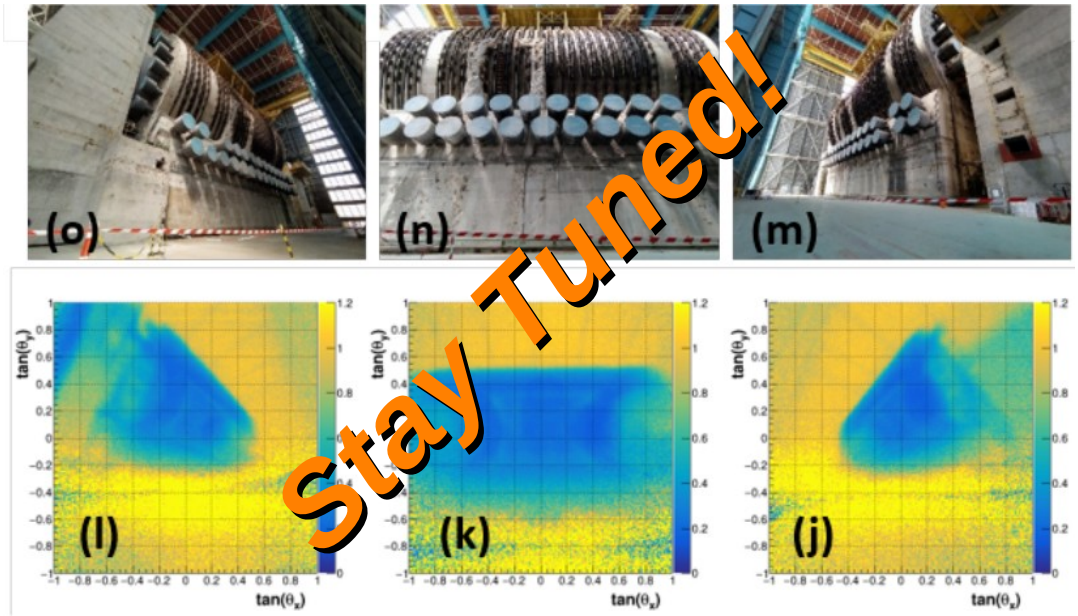
o Opacity vector (n_m)
Opacity for each measurement
Known from data (detected / expected)

S. Procureur; NIM A 1013 (2021) 165665

- Simulations:
  - Concrete Block (50 x 50 x 50 m^3)
  - Air cubes (5, 7 and 10 m side)
- Up to 13 projections (1 month)
  - Current 50 x 50 cm^2 telescope





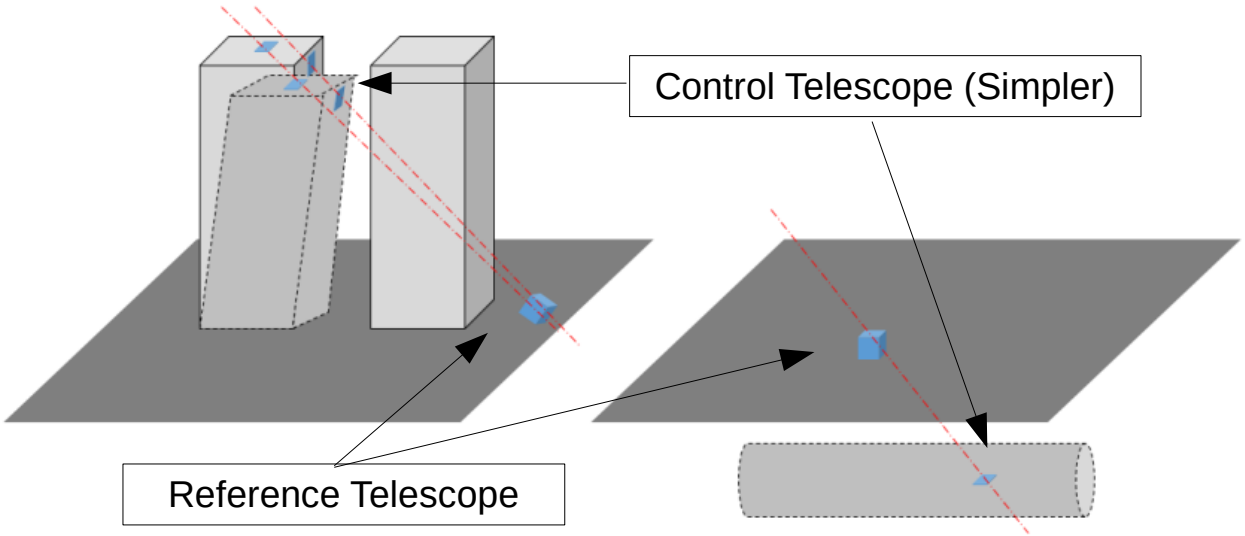


- Reactor divided in **245025** voxels (0.5 m side) → n_v
- 24 measurements splitted in 200 x 200 directions = **960000** measurements → n_m
- So **[D] has ~ 235 10^9 elements**

Metrology: Pomme experiment

JINST 16 (2021) P07013

Surveillance of the movement of (natural or artificial) structures



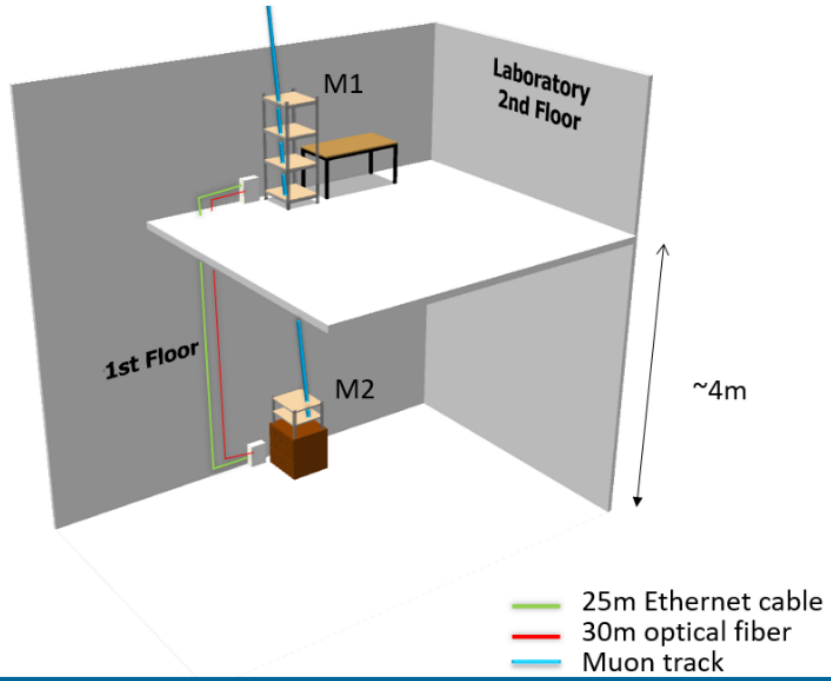
Better Resolution

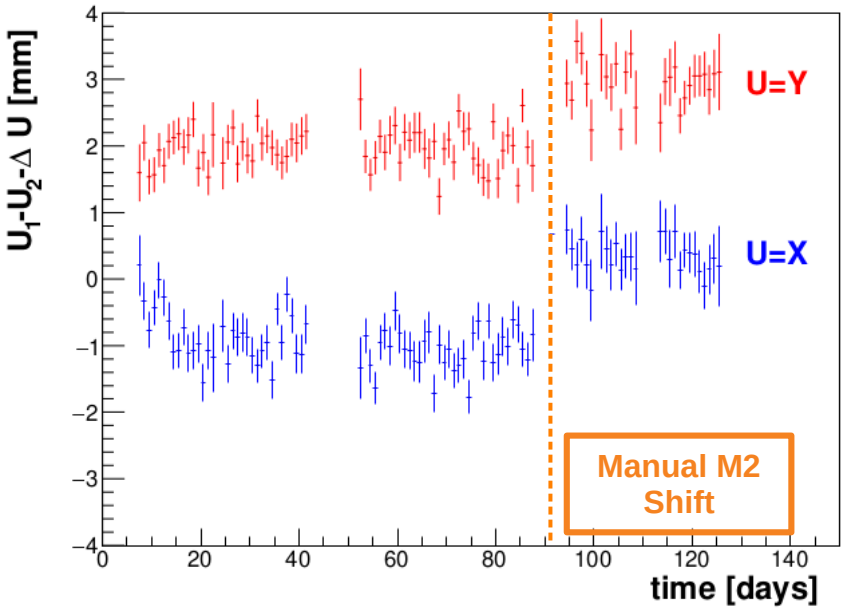
→ More precise Metrology

Micromegas are excellent candidates

→ Online analysis

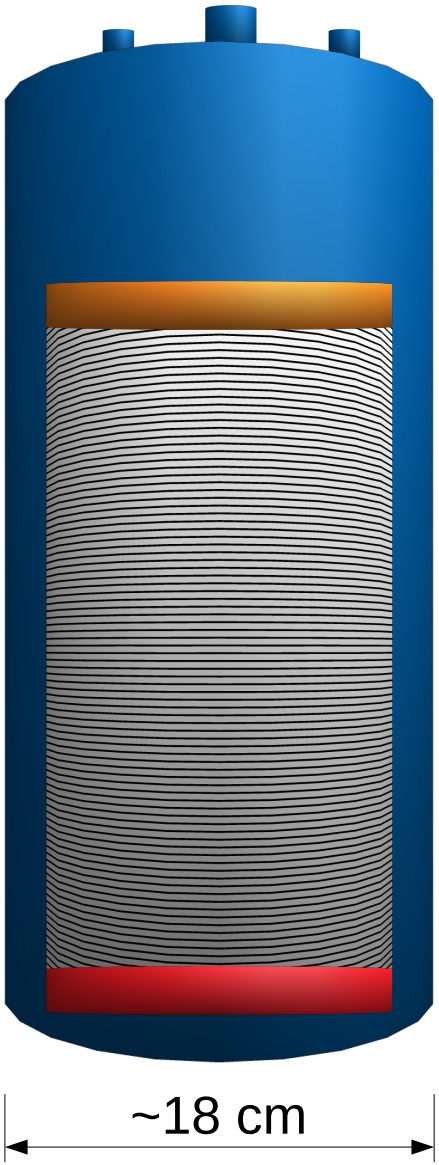
Pomme setup





Sub-millimetric precision

D3DT: Cylindrical TPC equipped with a 2D pixelized and multiplexed Micromegas



→ Services Feedthroughs

→ Buffer space (DAQ, HV, ...)

→ **Micromegas Detector**

Cylindrical Field Cage:

- Stripped Kapton – Copper foil
- Active t_0 measurement

→ Cathode (up to 10 kV)

→ 3D muon track reconstruction with a single instrument

→ $\Omega \sim 2\pi$ acceptance

→ Possibility of 3D tomography with a TPC network

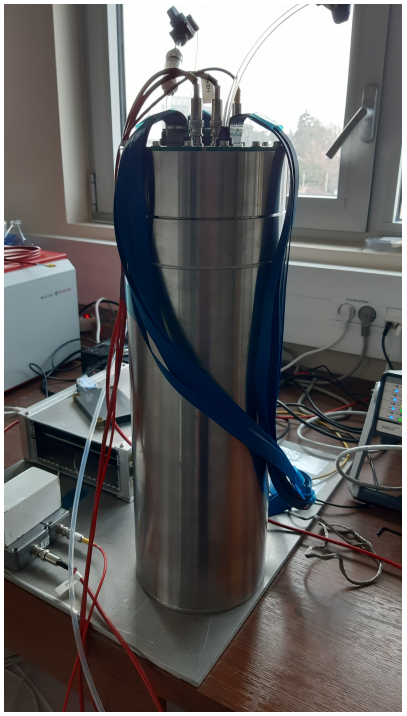
Potential applications on:

→ Boreholes

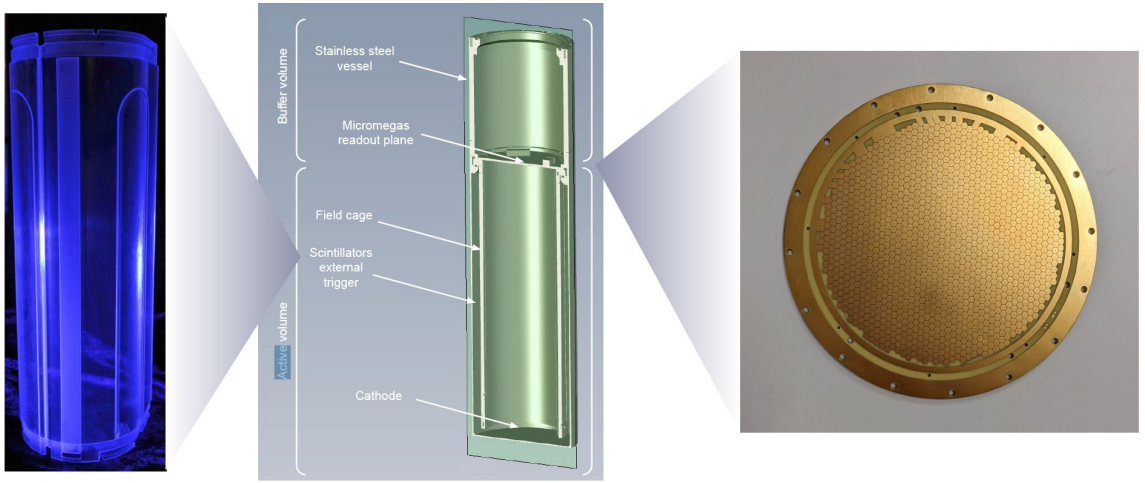
→ Mining

→ Geothermal fields sounding

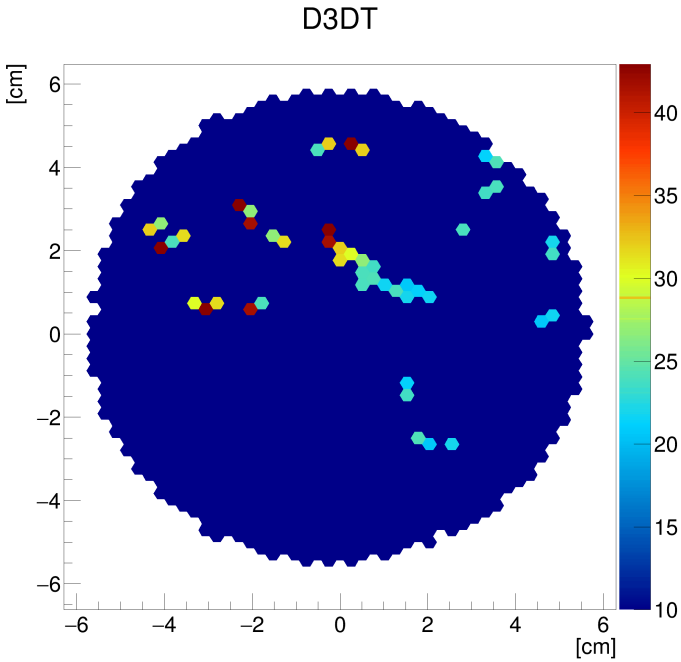
→ Civil engineering

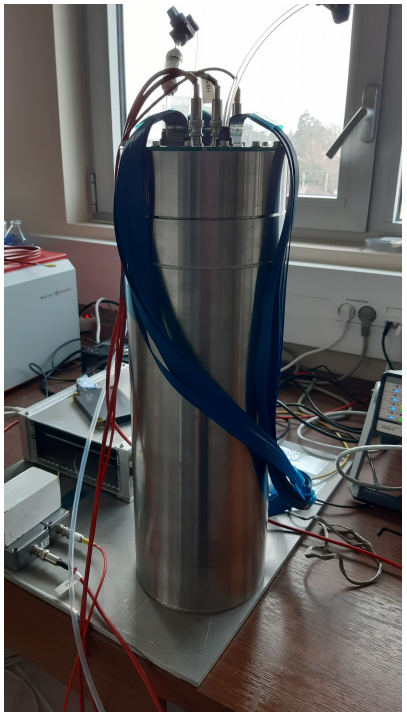


- First Laboratory Prototype (40 cm drift) already operative
  - First Muon Tracks registered
  - Still some work to do:
    - t_0 implementation
    - Data with higher Drift field
- But several previous prototypes have been developed ...



D3DT 40 cm prototype layout





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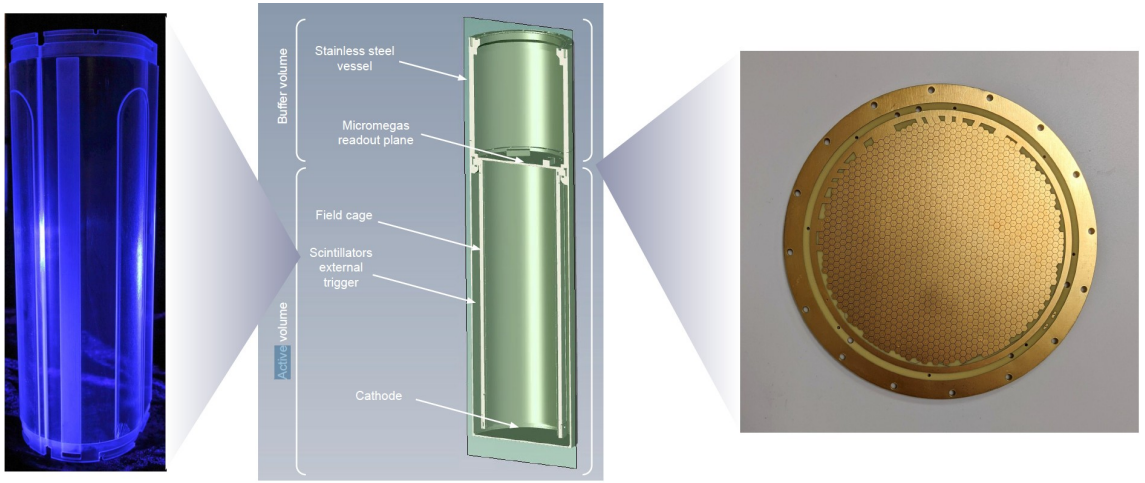

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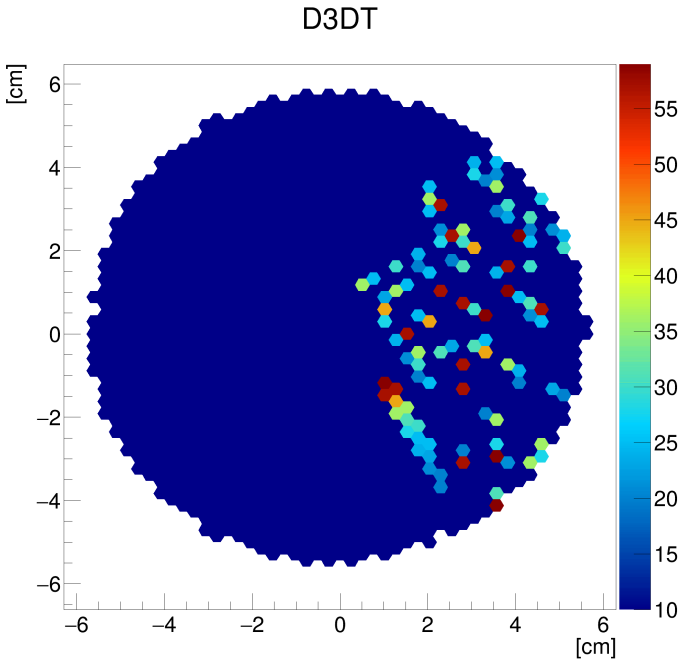

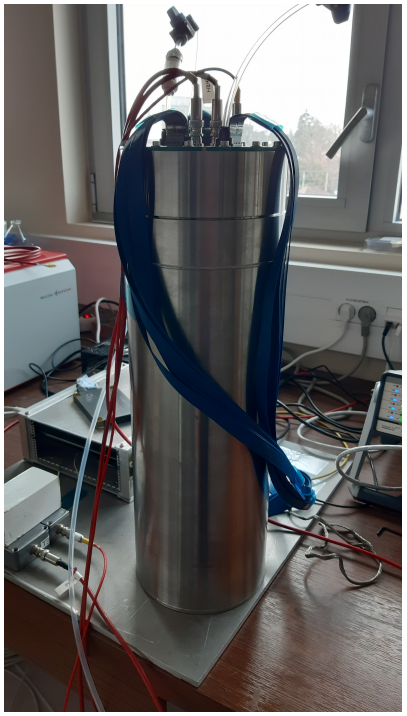

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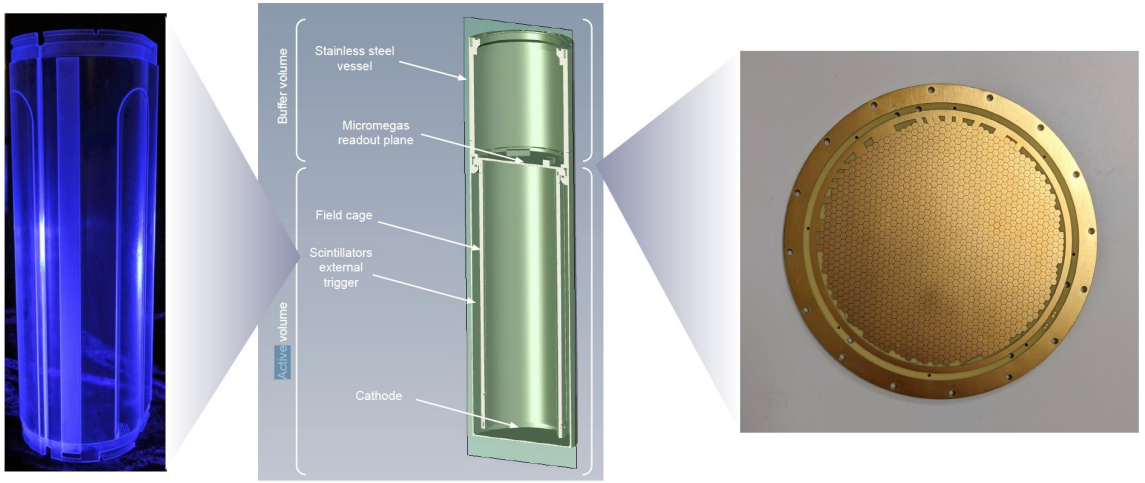

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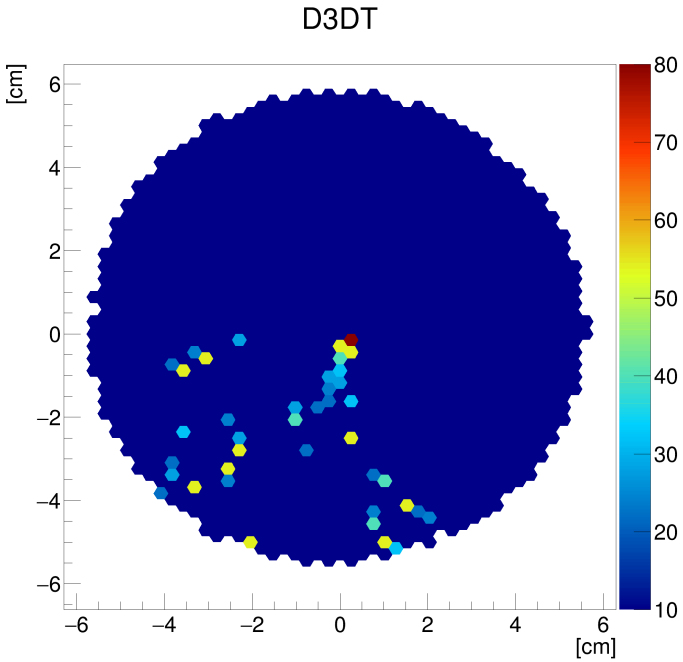

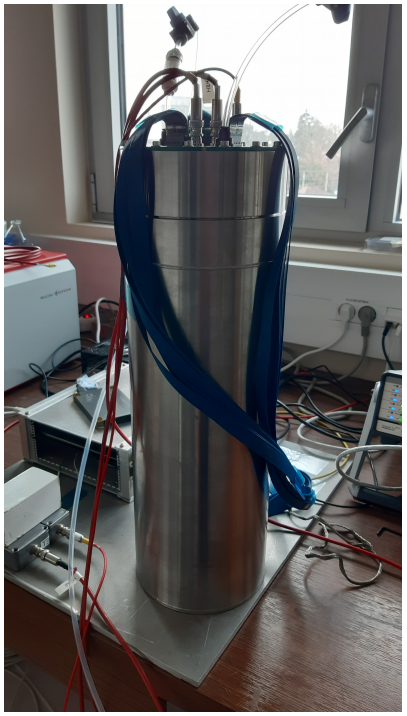

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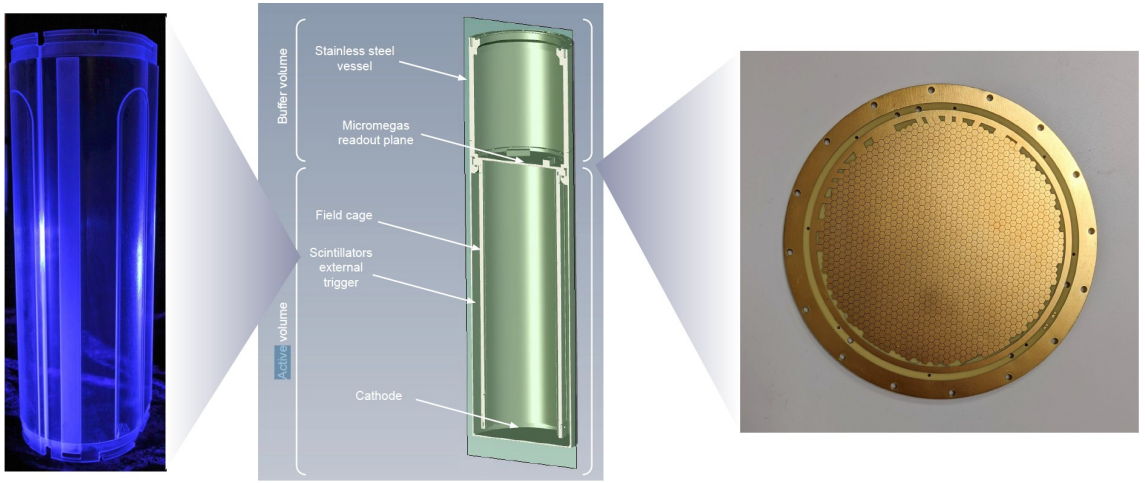

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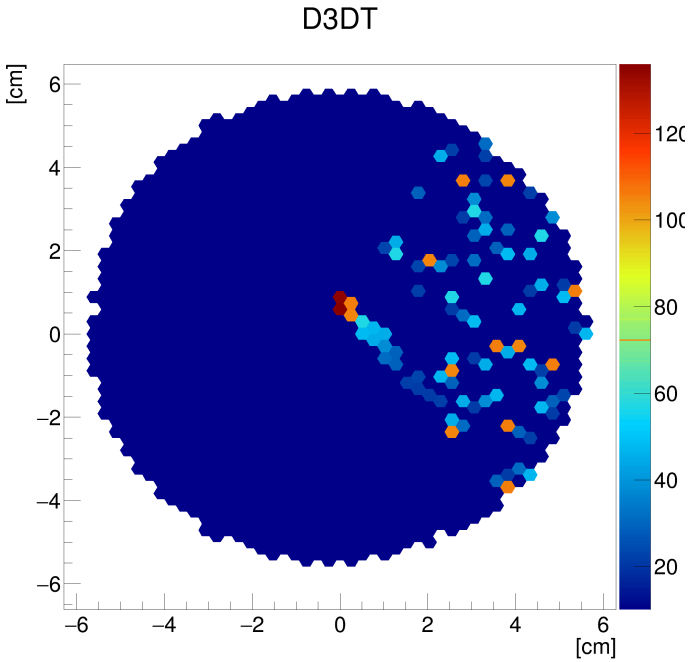

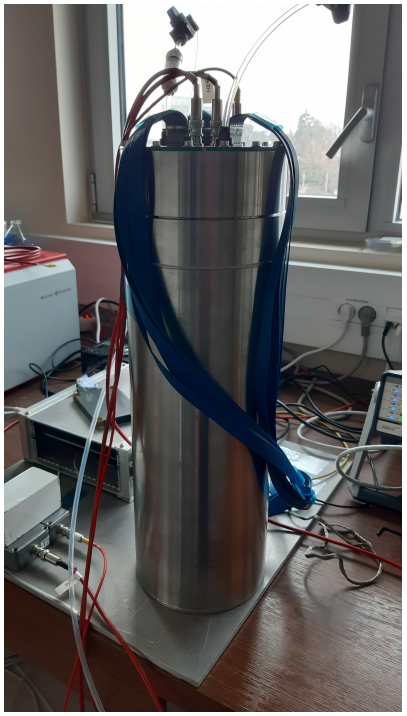

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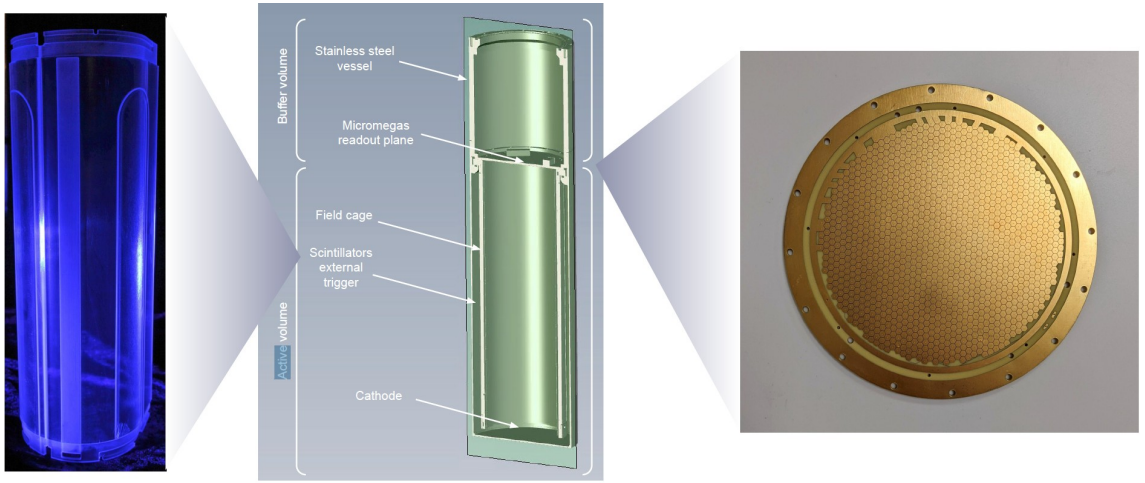

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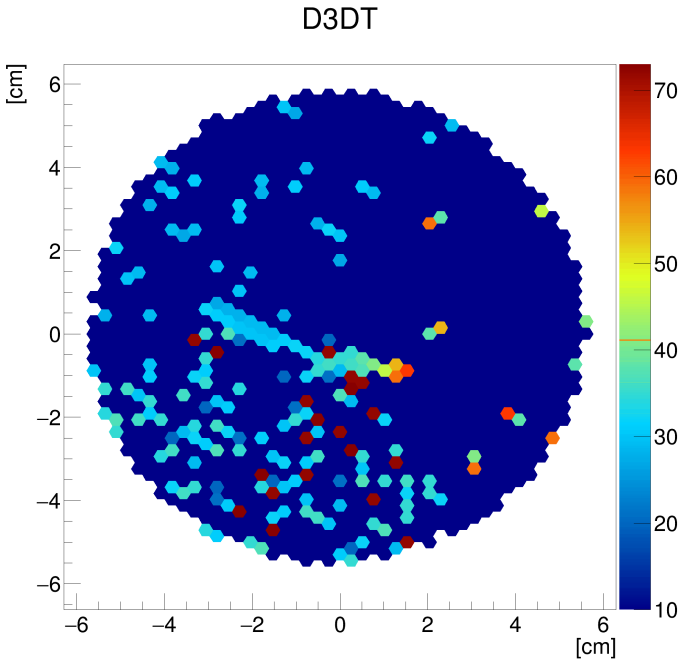
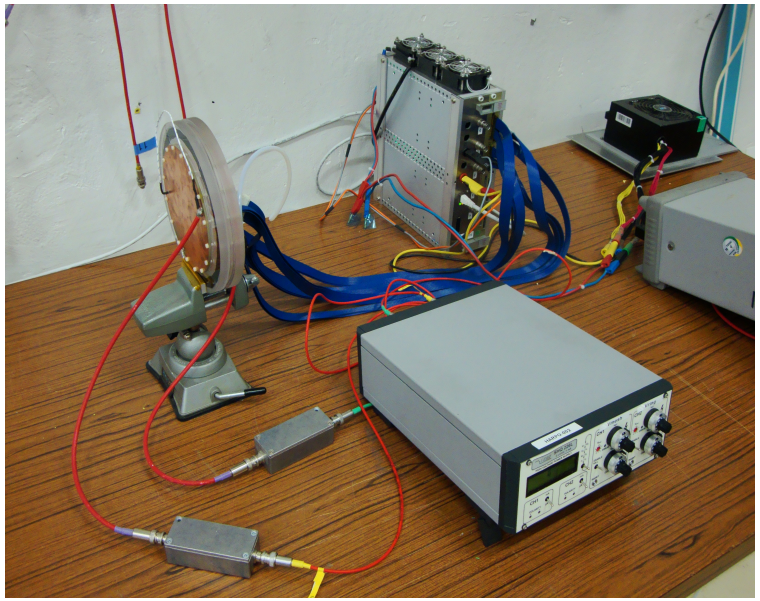
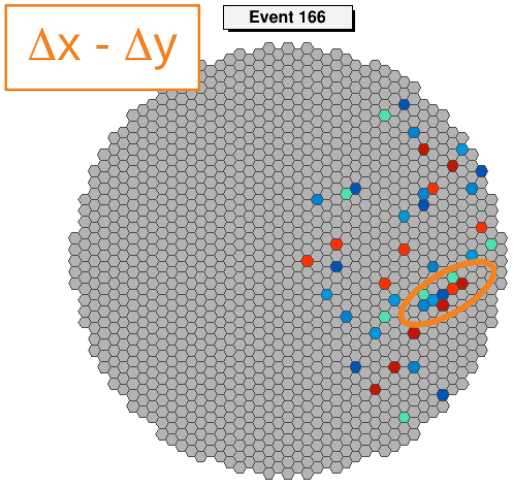


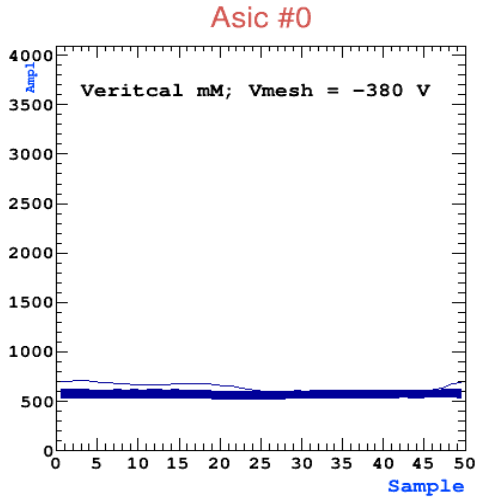
Cosmic muons with first prototype (mMs test bench)

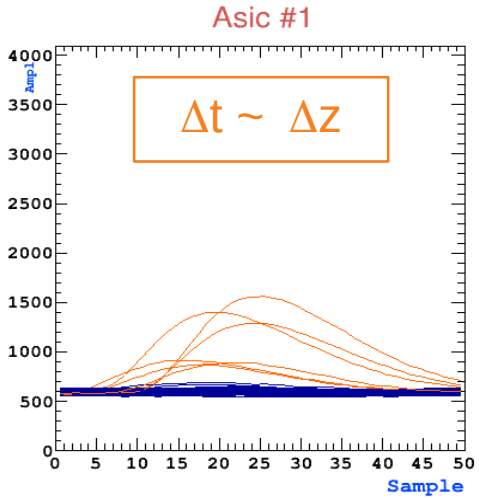
J. Phys.: Conf. Ser. 1312 (2019) 012013

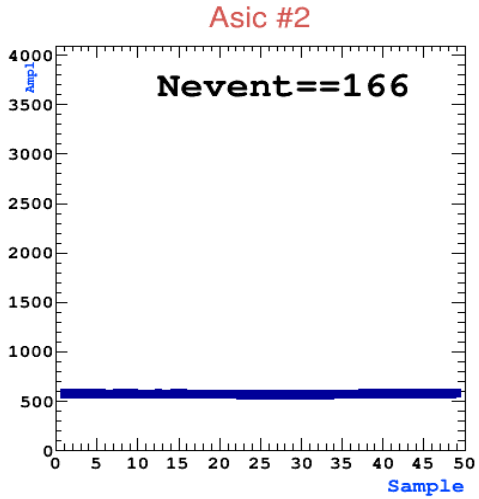


- Drift Volume: 12 cm Ø; 3 cm length
  - No field cage
- Gas @ Atmospheric Pressure
  - Continuous Flushing
  - Ar – iC_4H_{10} (95:5); Ar – iC_4H_{10} – CF_4 (95:2:3)
- Readout based on DREAM ASICs (Auto-trigger)
  - Same as current telescopes









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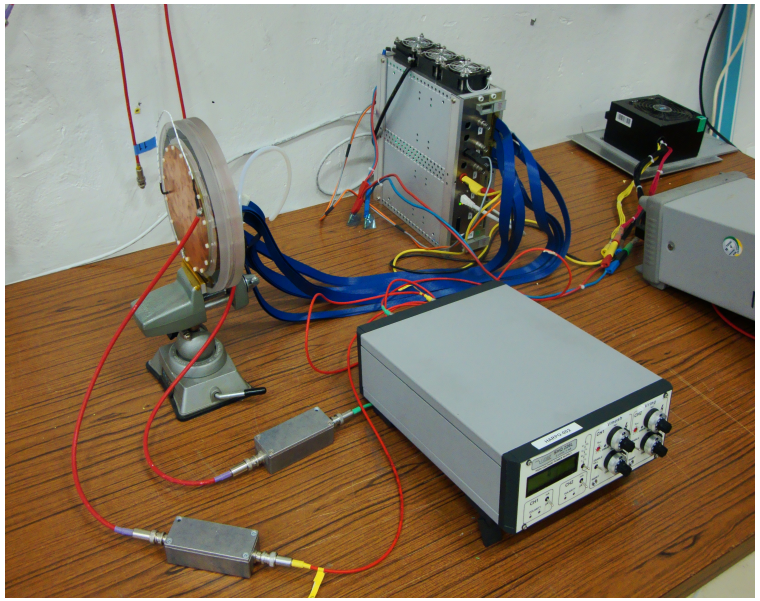

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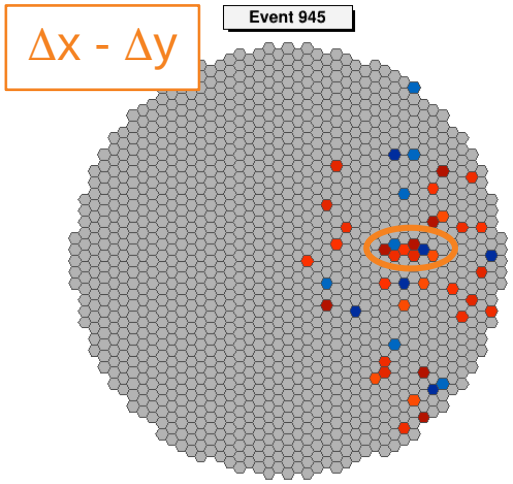
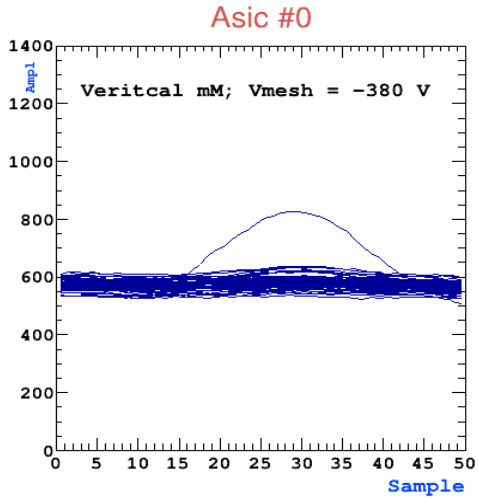
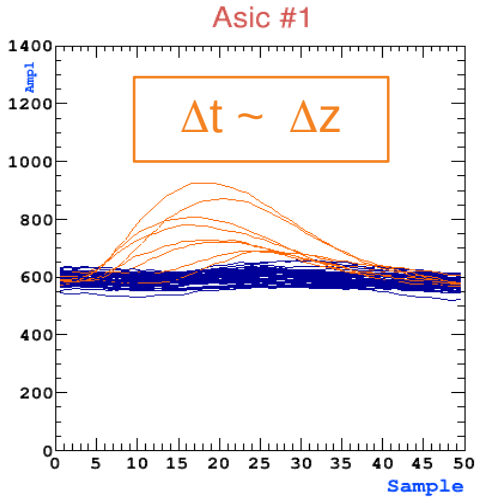
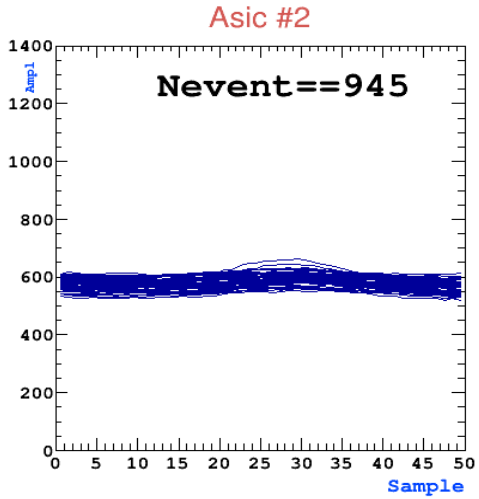
- Readout based on DREAM ASICs (Auto-trigger)
  - Same as current telescopes



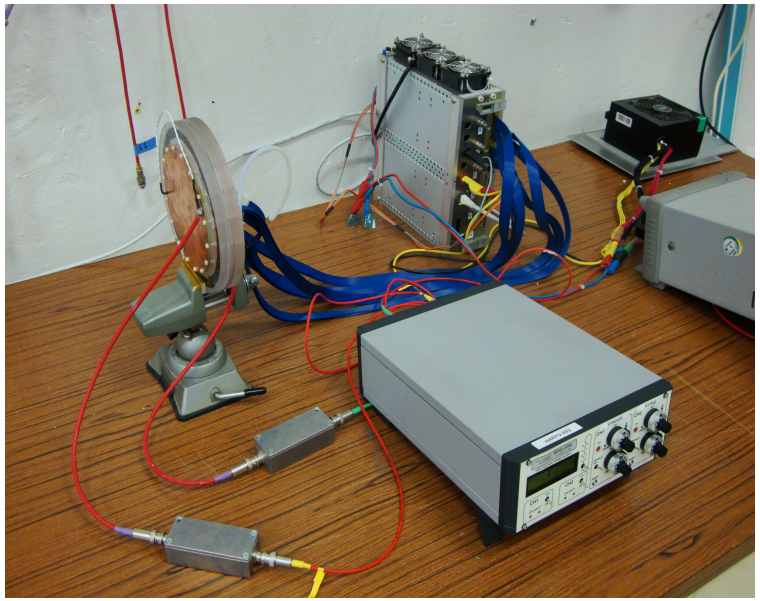




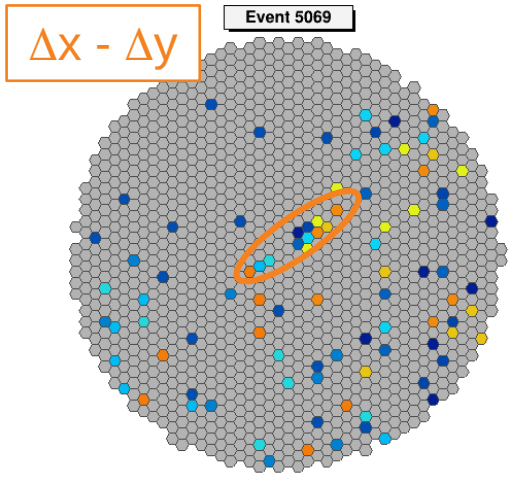


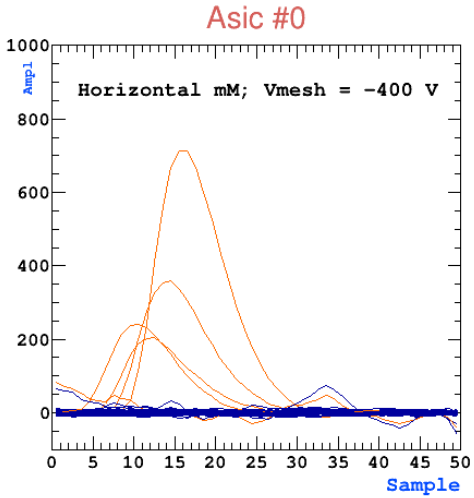
Cosmic muons with first prototype (mMs test bench)

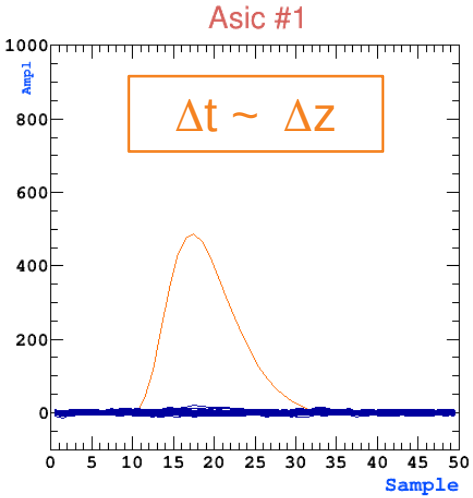
J. Phys.: Conf. Ser. 1312 (2019) 012013

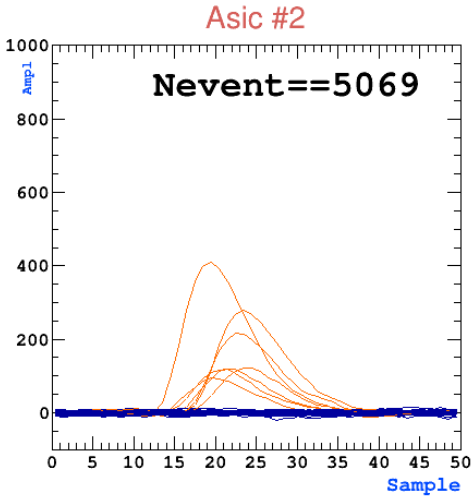


- Drift Volume: 12 cm Ø; 3 cm length
  - No field cage
- Gas @ Atmospheric Pressure
  - Continuous Flushing
  - Ar – iC_4H_{10} (95:5); Ar – iC_4H_{10} – CF_4 (95:2:3)
- Readout based on DREAM ASICs (Auto-trigger)
  - Same as current telescopes



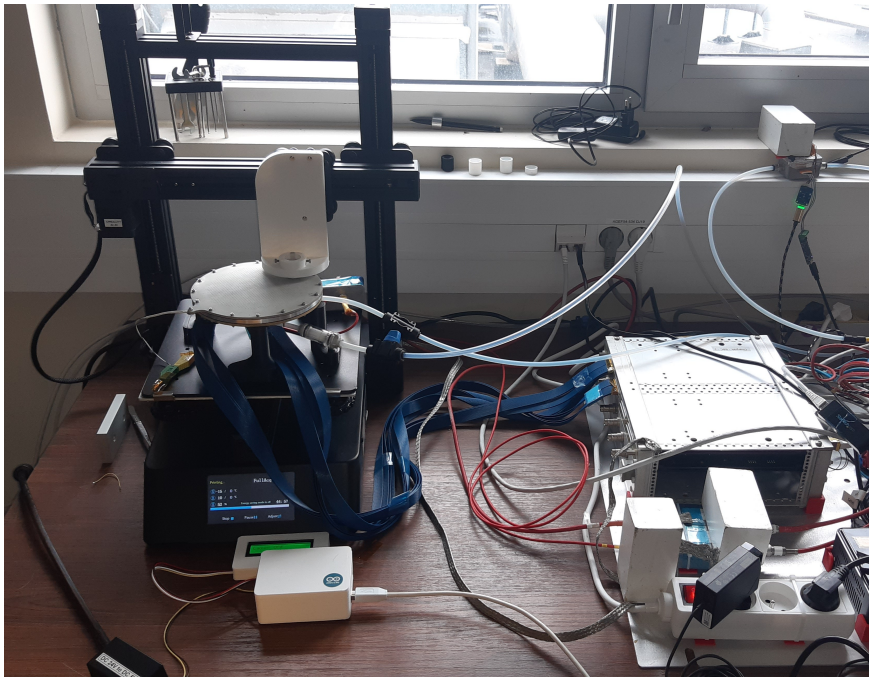


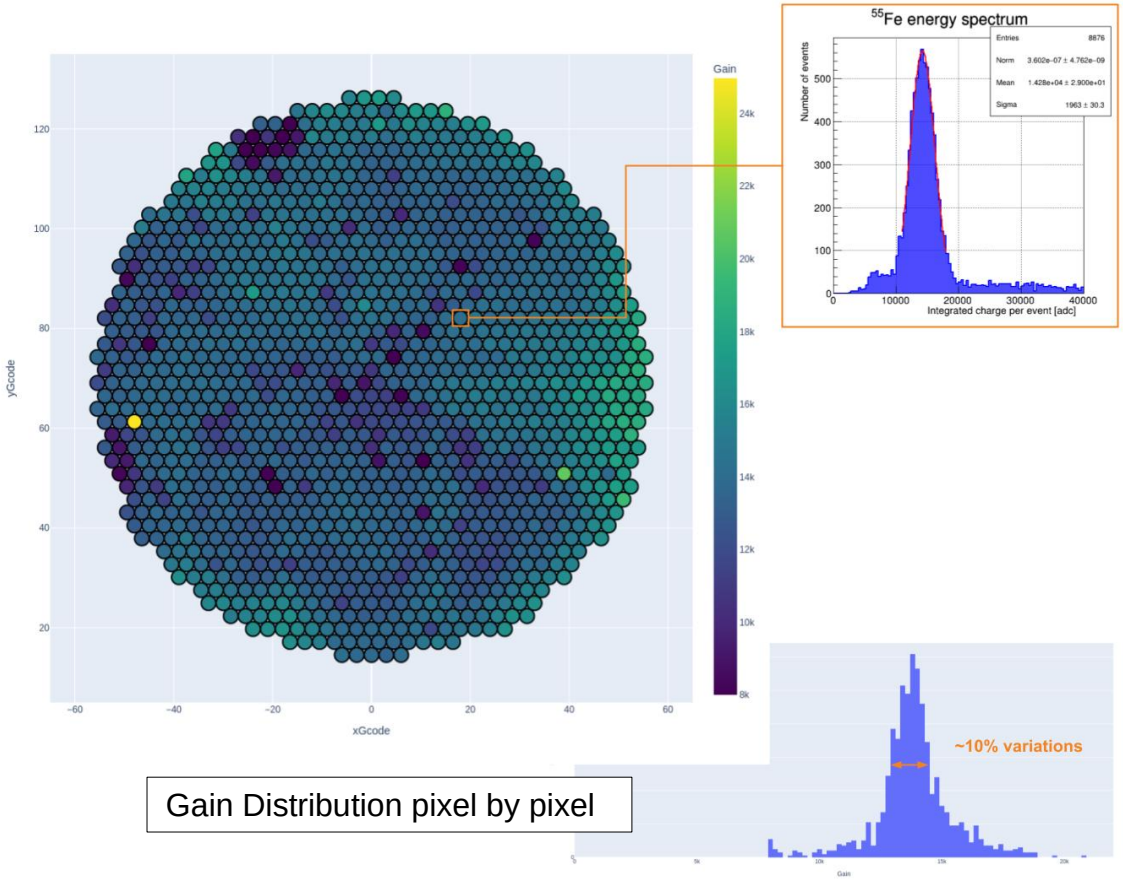




Automated calibration system pixel by pixel for Micromegas characterization

- Drift Volume: 12 cm Ø; 0.5 cm length
  - No field cage
- Ar – iC_4H_{10} – CF_4 (95:2:3) @ Atmospheric Pressure
  - Continuous Flushing
- DREAM ASICs (Auto-trigger)
- 3D printer to align the source (^{55}Fe) with each pixel





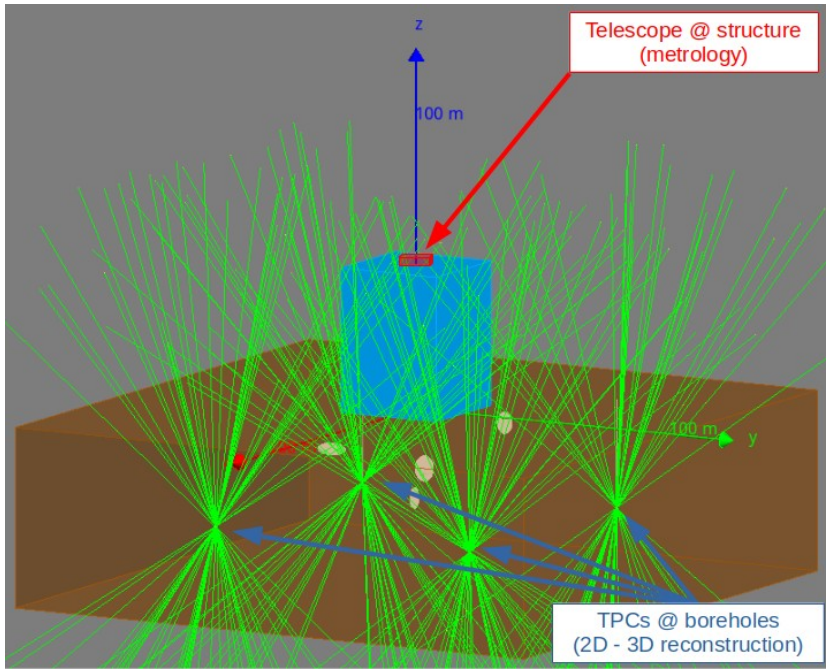
Gain Distribution pixel by pixel

M.Lehuraux PhD (CEA / IRFU / DEDIP)

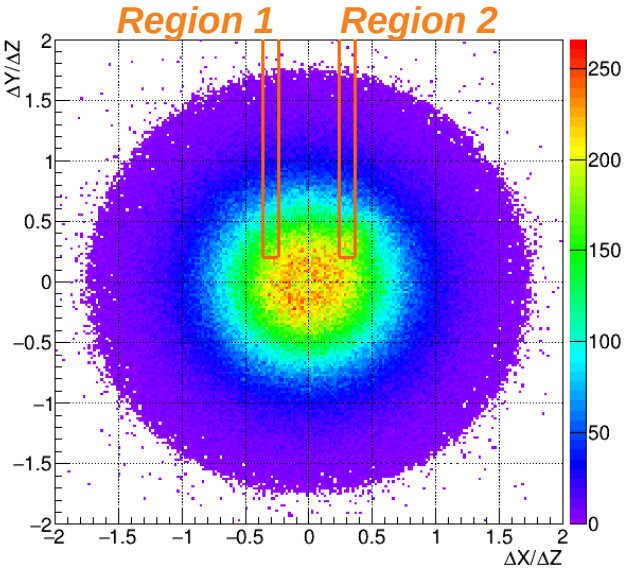
Homogeneity (Gain, Resolution, ...)

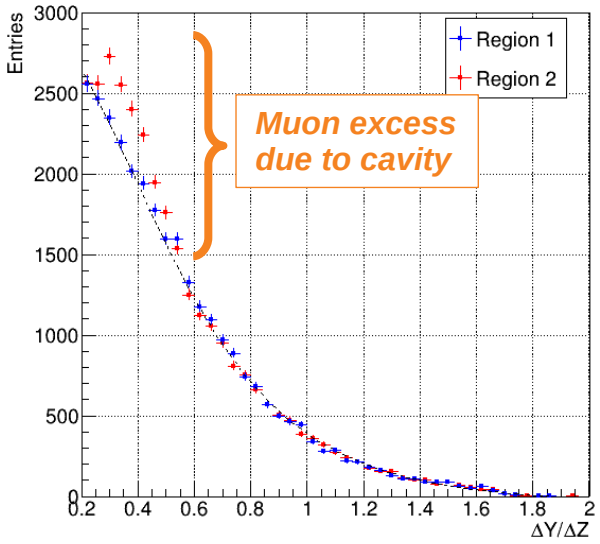
Dependence with Multiplexing Factor, Capacity, ...

On-site applications (Prospects)



- 1 month measurement @ 30 m depth
- Capability to identify with a single instrument:
  - → Ø ≥ 2.1 m Air cavities
  - → Ø ≥ 3.8 m Water cavities
- With an instruments network
  - → More sensitivity by triangulation
  - → 3D tomography capabilities





+ Metrology

APOGEIA

@ LSBB

Outlook and conclusions

- **Muon tomography** reveals as an interesting method for the **internal scanning of big objects**
  - Cheap, non-invasive, versatile, hazard-less
- Among the different techniques to carry out the measurements, **Micromegas-based** telescopes stand out
  - Robust technology, good performance (angular and spatial resolution)
- **CEA/Irfu group** has work in the last years in **different R&D** areas to improve the telescopes performance
  - Multiplexed Micromegas
  - Miniaturized DAQ
  - Gas system

Portability — Autonomy (low consumption)

Stability — Safety

- Different projects and measurements
  - Capabilities of the instruments proven
- **New ideas** and **projects** are ongoing
  - Metrology
  - **3D Tomography**
  - **Micromegas-read TPCs**

Archaeology

Engineering

Mining

Nuclear domain

Geophysics

Muography with Micromegas detectors:

Main features and results and future prospects in geophysics with new concept telescopes.

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B. Lefevre, M. Lehuraux, I. Mandjavidze, P. Mas
S. Procureur