Muon tomography for re-verification of spent fuel casks (the MUTOMCA project)

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Summary

- The problem
- The MUTOMCA project
- The Grafenrheinfeld test
- First data analysis
- Conclusions

The MUTOMCA project was funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection under the funding code 02W6279.

THE PROBLEM

the problem

Spent fuel from nuclear reactors is stored in thick-walled strongly shielding casks (e.g. CASTOR® V/19). These casks are hosted in dry Spent Fuel Storage Facilities (SFSF)

Assuring Continuity of Knowledge (CoK) of the spent fuel for the upcoming decades is a cornerstone of Safeguards

In case of self-shielding spent fuel casks, the nuclear material is currently not accessible for traditional non-destructive assay (NDA) techniques based on the ionizing radiation detection

A method to detect the diversion of spent fuel assemblies in shielded casks for safeguards re-verification purposes in case of temporary failure of monitoring systems is thus crucial.

The development of an adequate non-destructive (re)-verification method for casks, proving that the verified spent fuel remained unchanged, would be a real advantage for safeguards

Muon tomography is a promising technology for re-verification of casks

The MUTOMCA (MUon TOMography for CAsks) project aims to verify the real potential with a field-test

The MUTOMCA project was funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection under the funding code 02W6279.

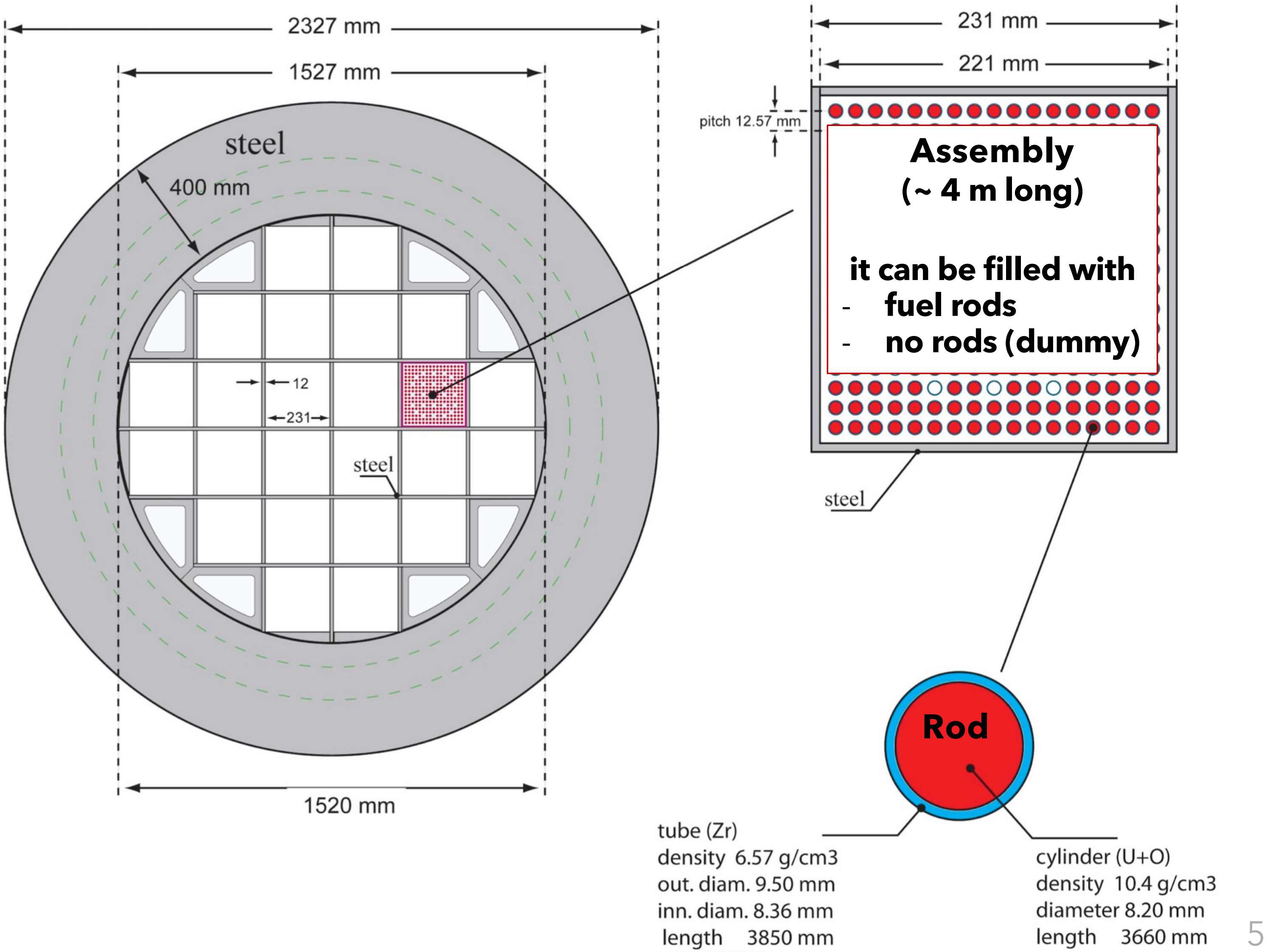
The aim of the MUTOMCA project was to (1) build a specific detector and (2) test it for muon tomography as a re-verification technique in case of loss of continuity of knowledge of spent fuel casks

INFN BGZ Gesellschaft für Zwischen-lagerung mbH JÜLICH Forschungszentrum European Commission

Spent Fuel Storage Casks in an interim storage facility in Germany

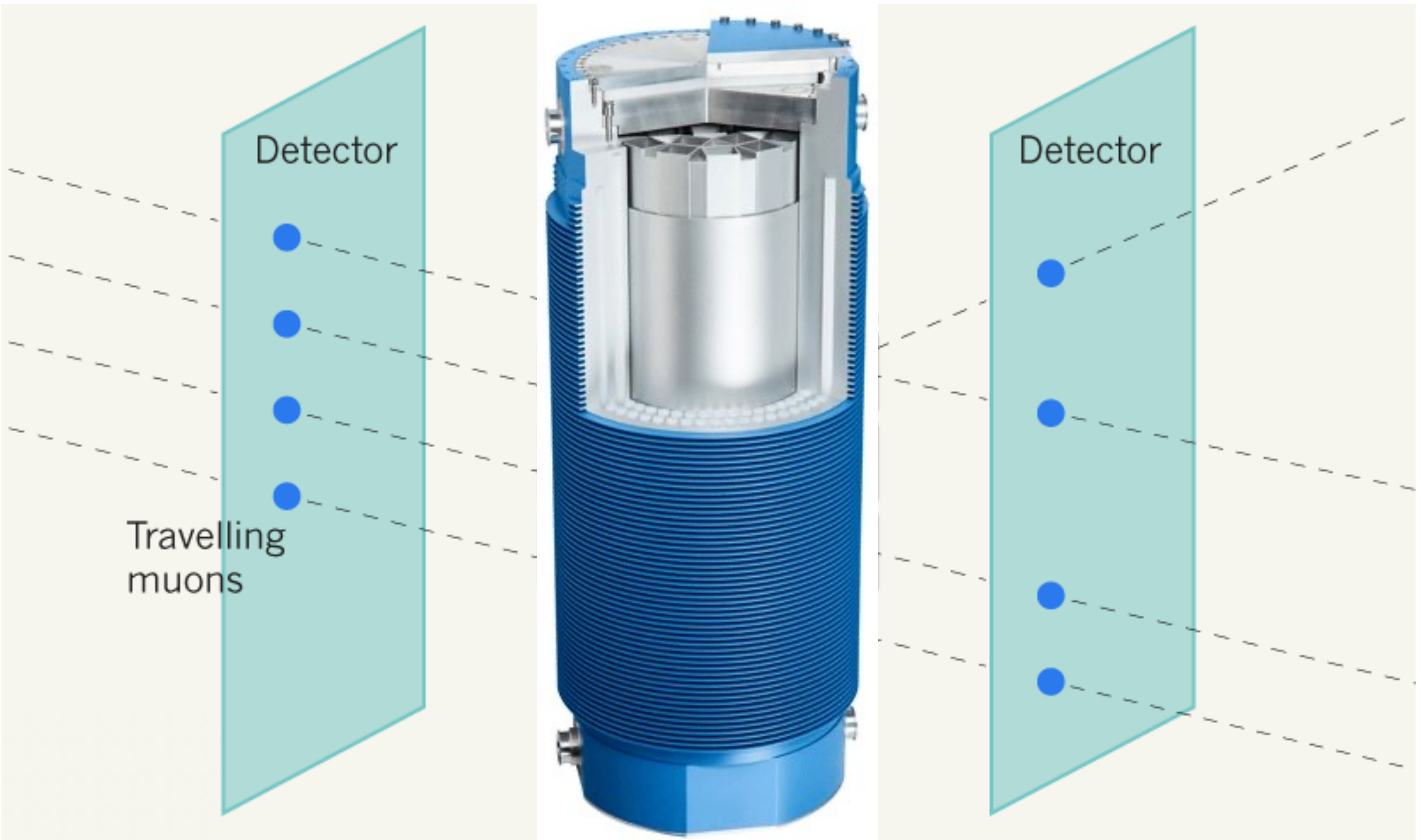
Schematic overview of the composition and size of a spent fuel cask (Castor®)

TECHNICAL DATA		
Cask Contents		
▪ Up to 19 spent fuel assemblies from PWR (total length max. 4950 mm, edge length max. 233 mm)		
▪ Total thermal power:	39	kW
▪ Total activity:	1900	PBq
Dimensions and Weight in the Storage Configuration		
▪ Overall height:	594	cm
▪ Outer diameter:	244	cm
▪ Cavity height:	503	cm
▪ Cavity diameter:	148	cm
▪ Cask weight empty:	≈ 108	t



THE PROJECT

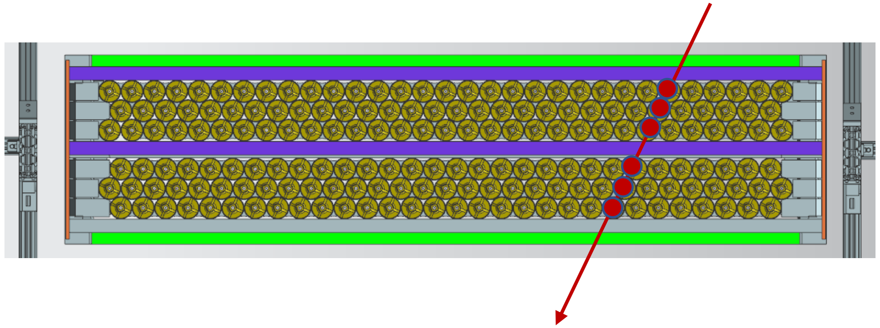
The basic idea is to place two detectors at the two sides of a spent fuel cask and to produce an *image* of the cask content, *detecting entering and exiting (or not exiting) muons*



A small detector module prototype has been constructed and tested in the vicinity of a spent fuel cask

the MUTOMCA detector

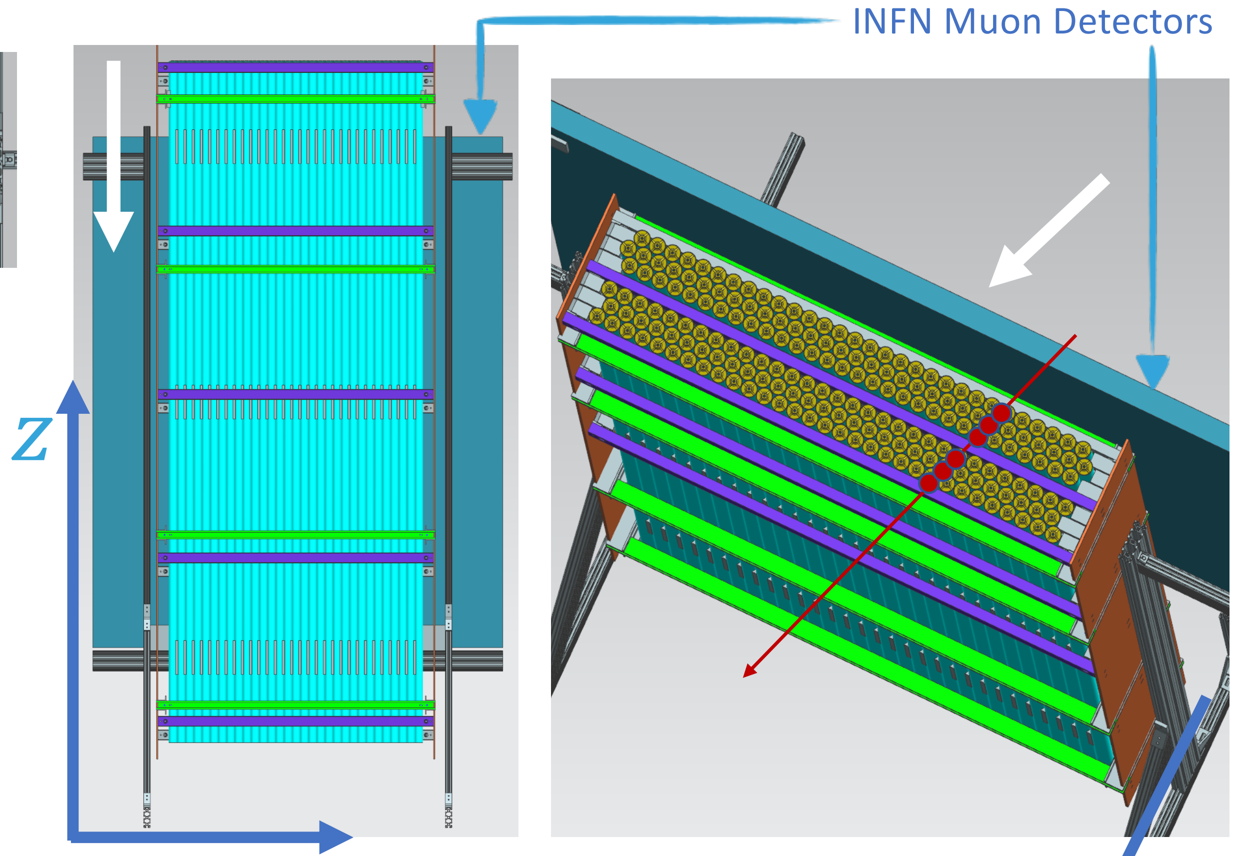
The project consisted in the construction of a couple of Drift Tubes (DT) modules that could be installed in the proximity of a cask and can be rotated around it



Two modules: each module has 183 tubes distributed in 6 layers of 30/31 tubes each.

Aluminum tubes:
4500 mm high
50 mm diameter
1.5 mm thickness

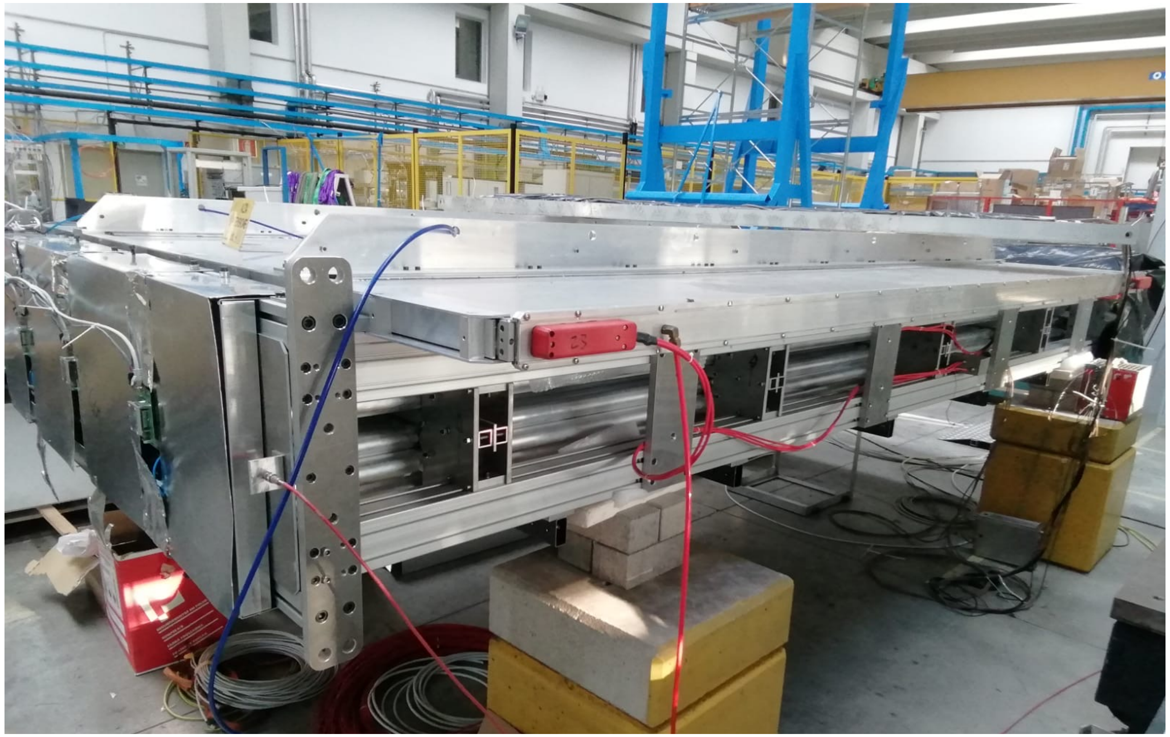
Precise measurement of the "y" coordinate
Rough measurement of the "z" coordinate



Two additional INFN Muon Detectors [consisting in 4 drift cell planes] were added to also measure the z coordinate (and consequently the zenith angle)

the MUTOMCA detector

Both modules have been completely constructed [at the INFN Laboratori Nazionali di Legnaro (LNL) in], instrumented and operated at high voltage (HV ~3000V) and gas flux (85%-15% Ar-CO_2)



A support structure has been designed and realized to move all modules around the cask to obtain a full coverage of the CASTOR.

The structure is holding also the two additional INFN drift cell modules

Given the two tracks of the muon in the two detectors (at the two sides of the CASTOR), two algorithms were selected to reconstruct 3D images:

MLEM algorithm [L. J. Schultz et al., IEEE Transactions on Image Processing (2007) 16, 8]
For each unit of the inspected volume, it finds the parameter values that maximize the likelihood function given the observations of the scattering angle and displacement of the muon collection.

µCT algorithm [S. Vanini et al., Phil. Trans. Of the Royal Society A (2019) 377, 2137]
It is based on the comparison of the measured fraction of absorbed muons along a so-called Line-of-Response (LoR, often used in PET tomography), and the theoretical absorption ratio derived from the muon energy distribution and the traversed material thickness.

The outcome of the reconstruction process is a grid of 3D voxels (cubic pixels with homogeneous density)

VMC Simulation Framework GEANT4 A SIMULATION TOOLKIT + ROOT Data Analysis Framework

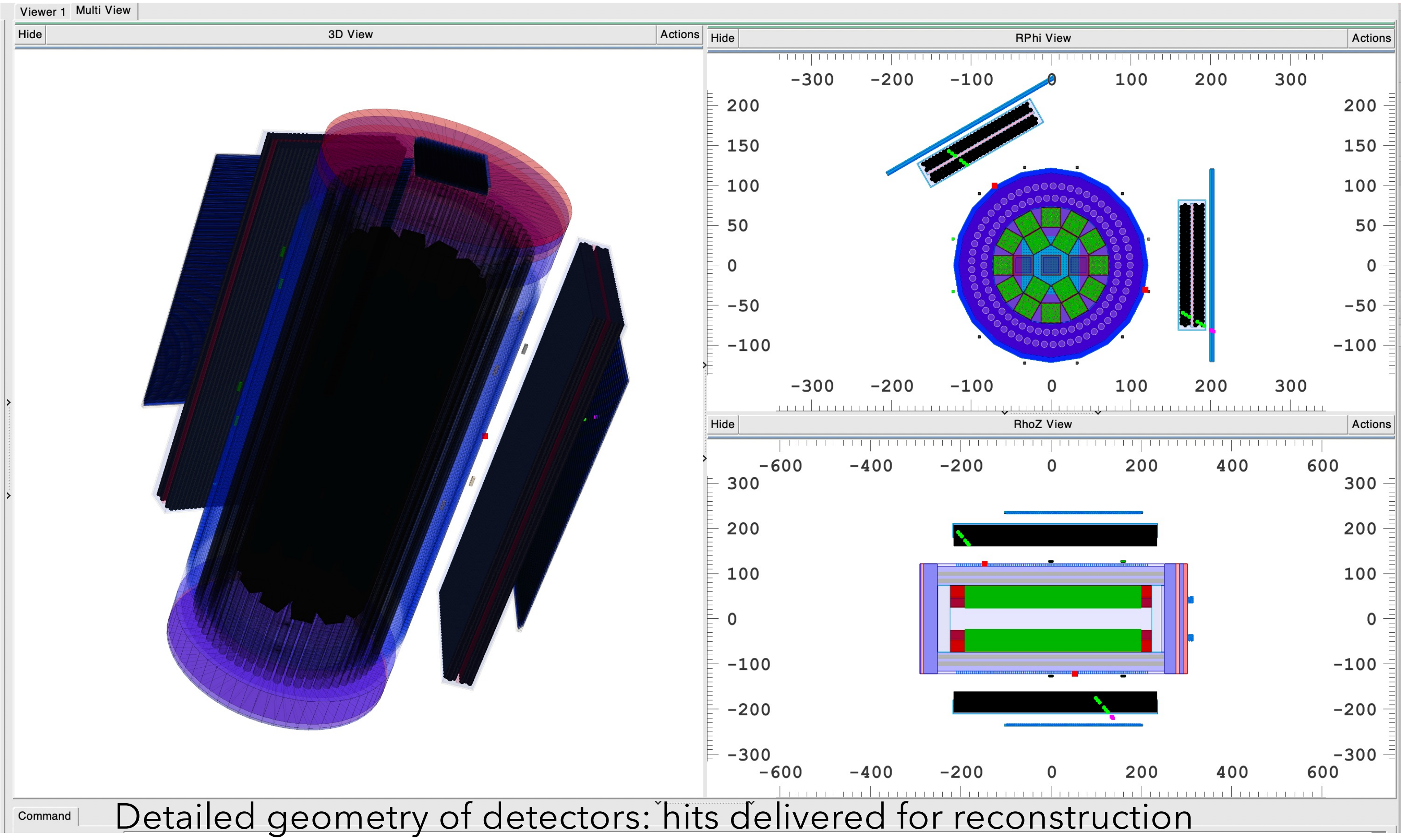
A versatile and highly-configurable simulator has been developed, together with tools for analysis and visualization.

Muons generated on a cylindrical surface: multiple options for generation available [**EcoMug** generator]

Detailed CASTOR® V19 structure with 3 options for assembly elements (fuel, dummy, void)
Layout fully customizable

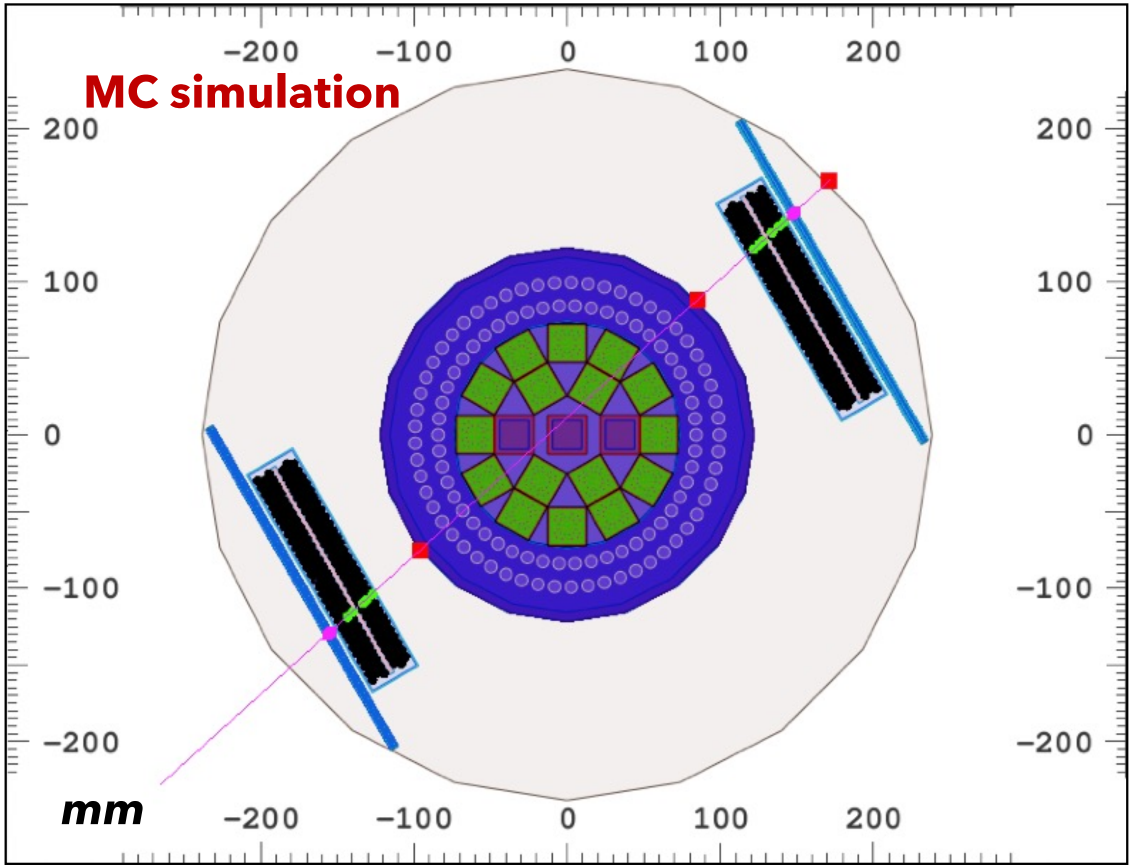
Detectors can be rotated and mis-alignments can be introduced too

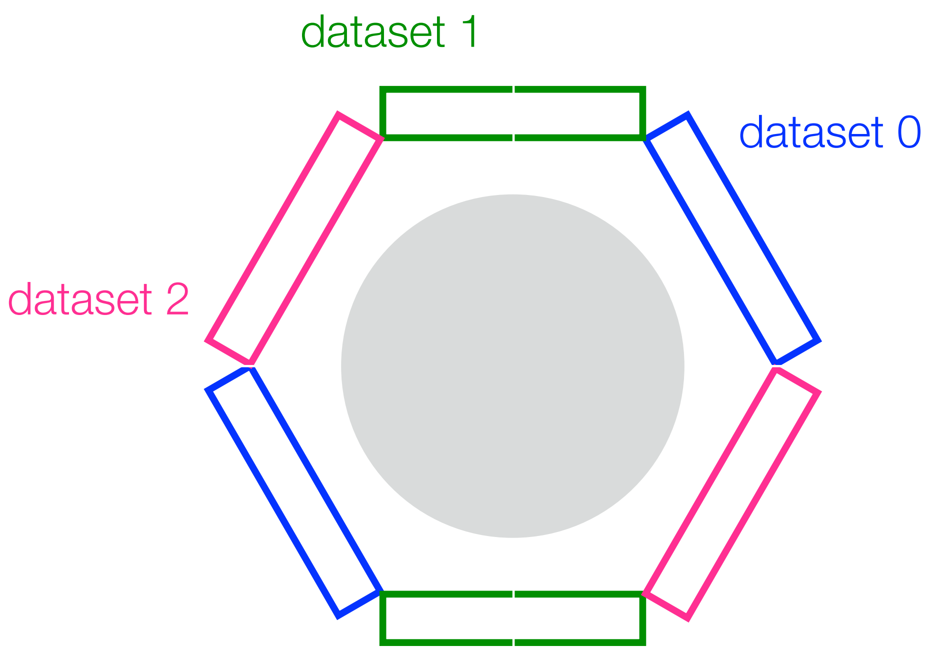
MC output very similar to Data output



Detailed geometry of detectors: hits delivered for reconstruction

One of the CASTOR V/19® used at the field test featured 3 dummy elements in the inner part.



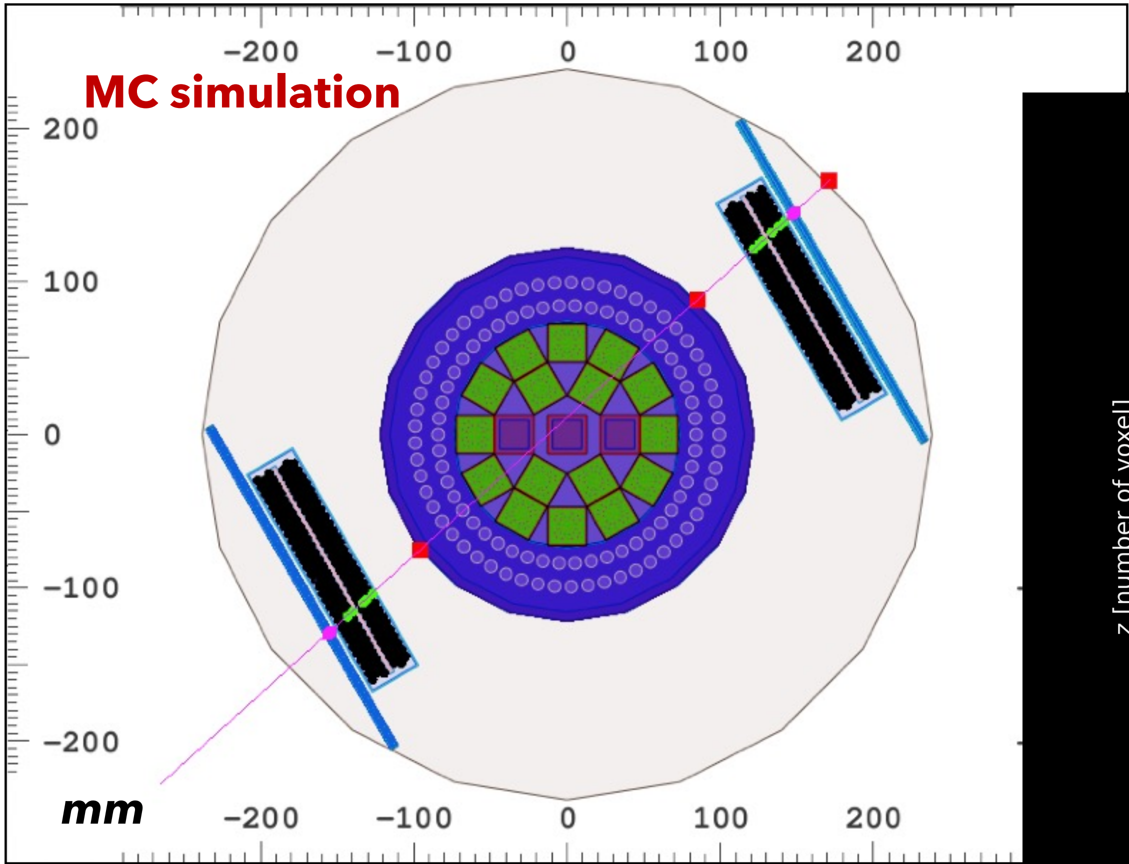


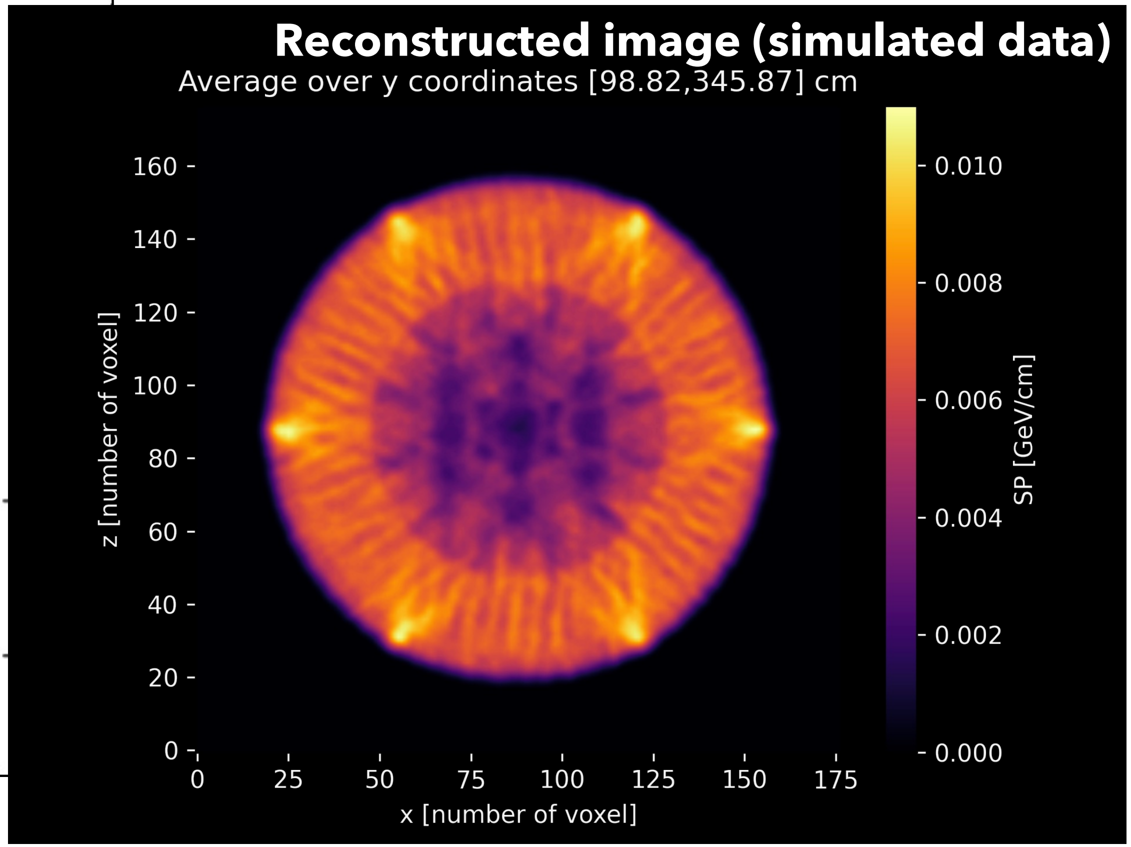
Data-taking strategy

One of the CASTOR V/19® used at the field test featured 3 dummy elements in the inner part.

Example of an image reconstruction based on MC simulated data

µCT reconstruction with three simulated datasets (~12 hours of equivalent data-taking per position)

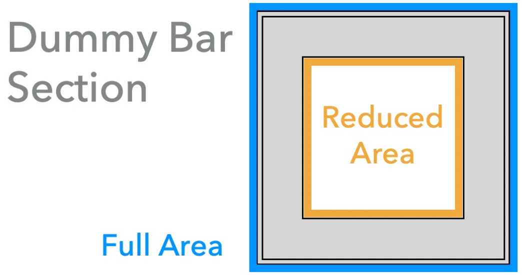


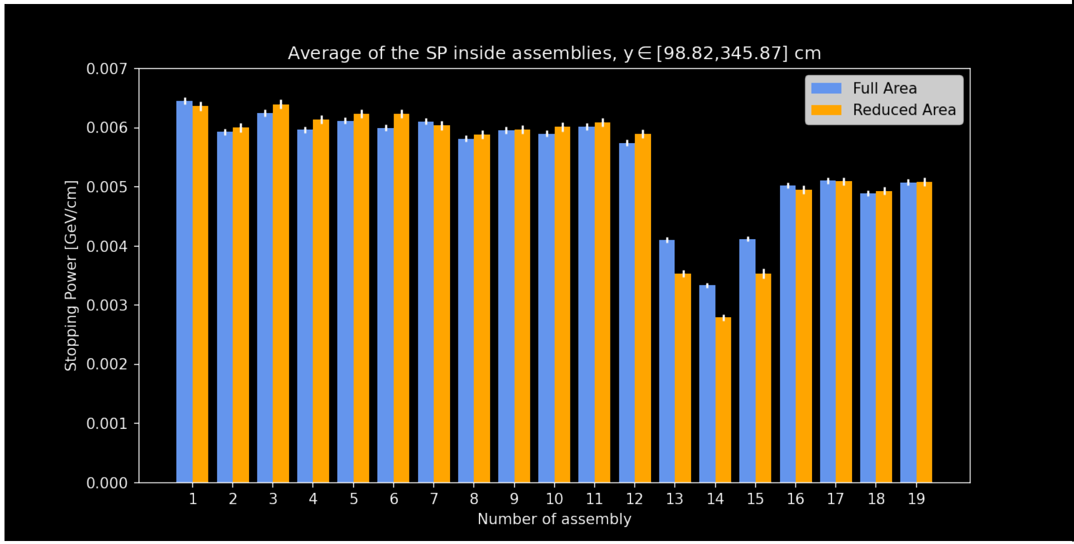


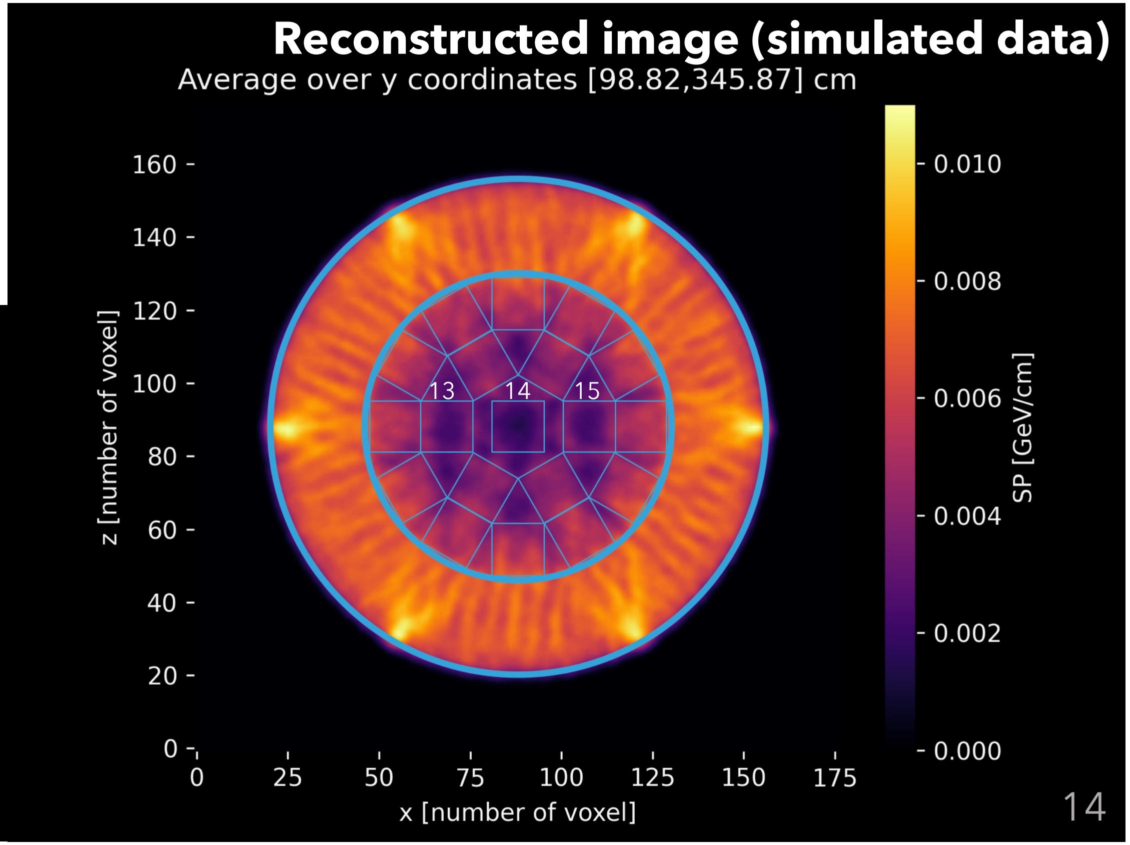
One of the CASTOR V/19® used at the field test featured 3 dummy elements in the inner part.

Example of an image reconstruction based on MC simulated data

μCT reconstruction with three simulated datasets (~12 hours of equivalent data-taking time)







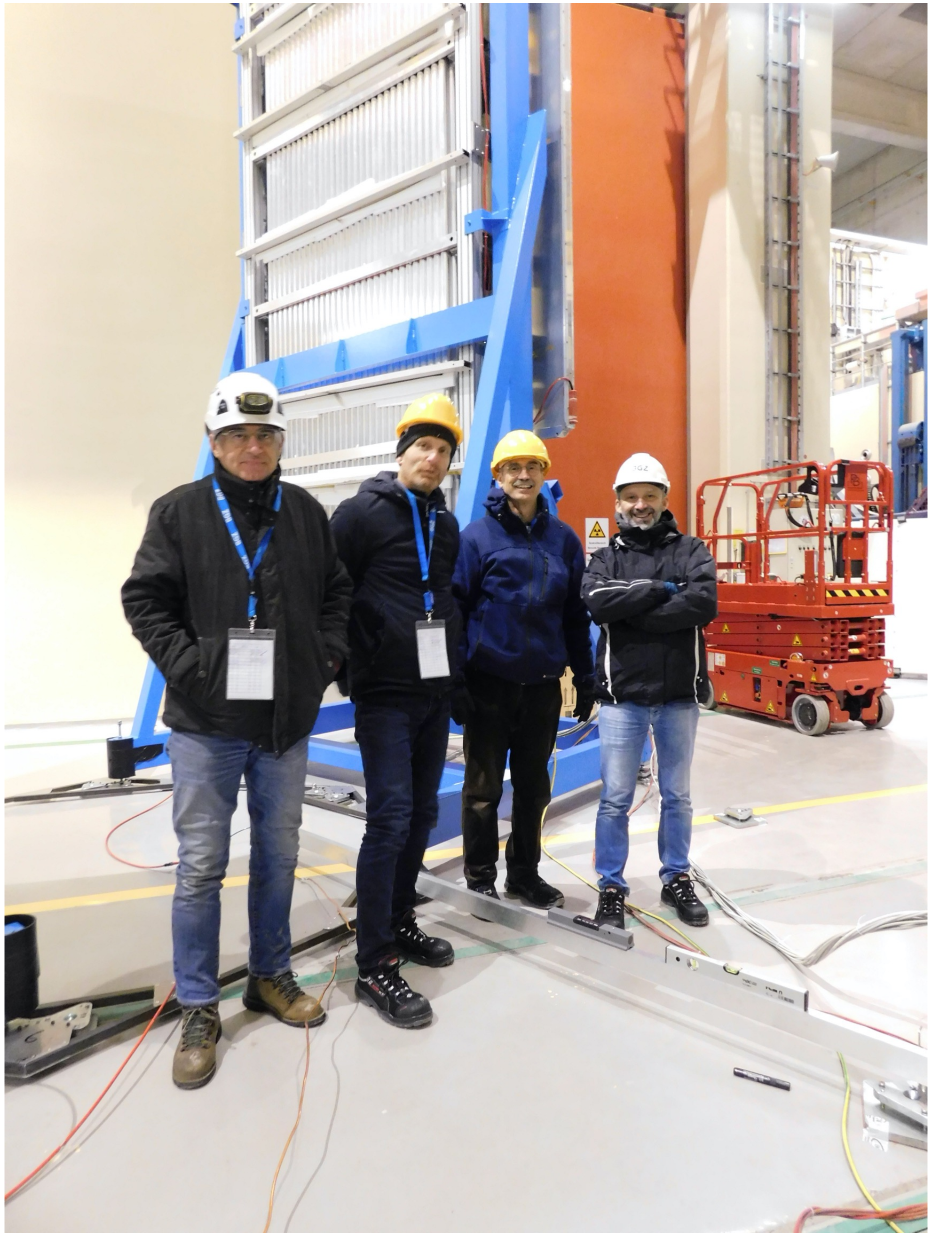
THE FIELD TEST

the Grafenrheinfeld field test

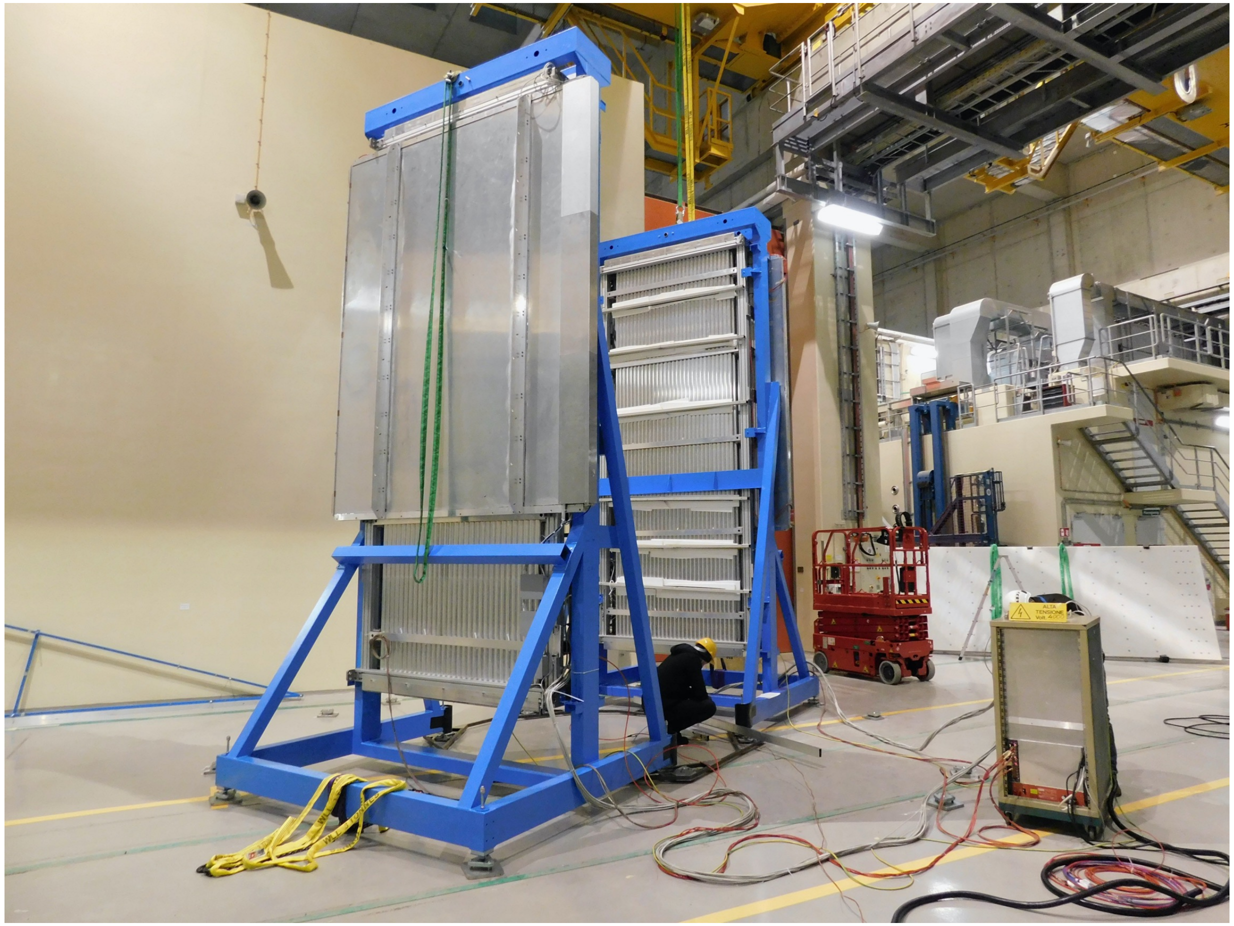
The field test in the framework of the MUTOMCA project took place in the SFSF of the Grafenrheinfeld site, Germany, from January 18th to February 24th 2023.

The detectors were delivered with a special transport in Grafenrheinfeld.

It was installed in the reception area of the SFSF.

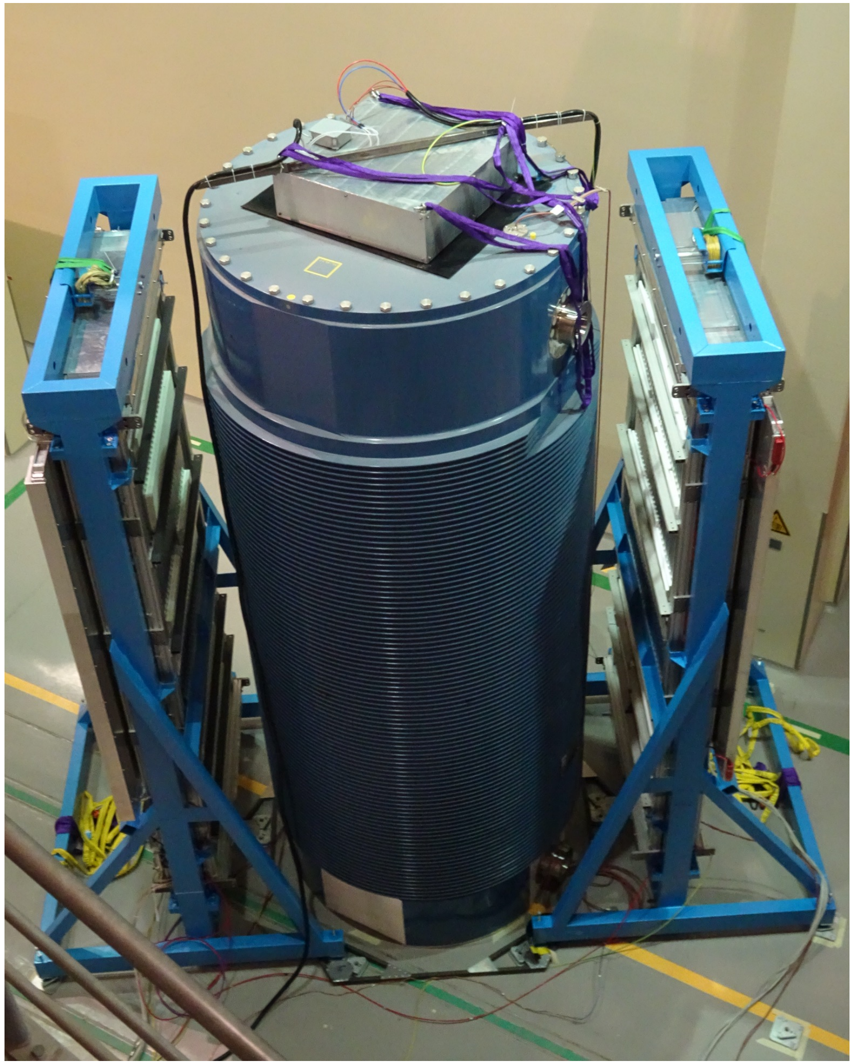


the Grafenrheinfeld field test



Two casks with different inventories were measured: the Grafenrheinfeld field test

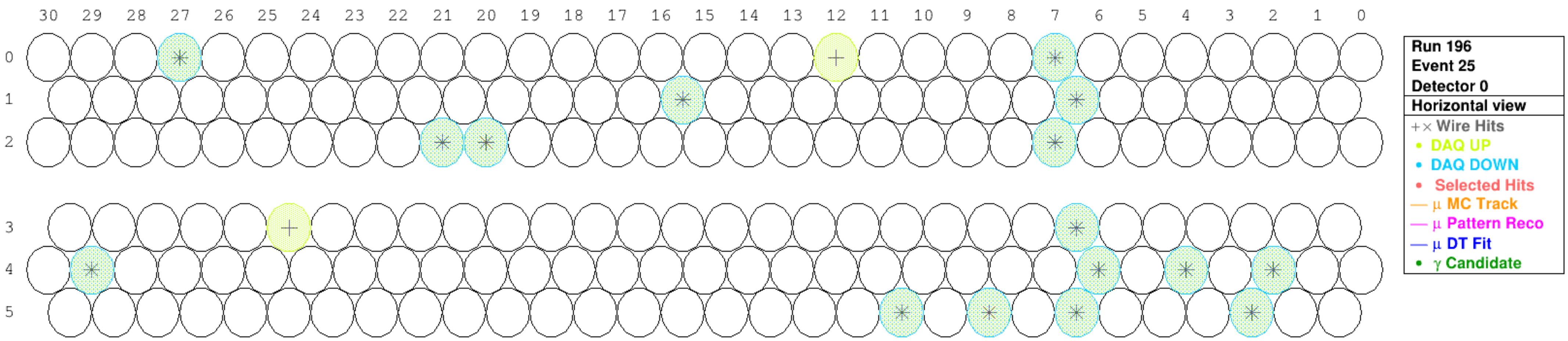
A cask with 3 dummies



A cask fully loaded

Cask with 3 dummies	Fully loaded cask
18 Days of data-taking	**11 Days** of data-taking
450 GB of data files	**300 GB** of data files
~10^7 useful tracks	**~6×10^6** useful tracks

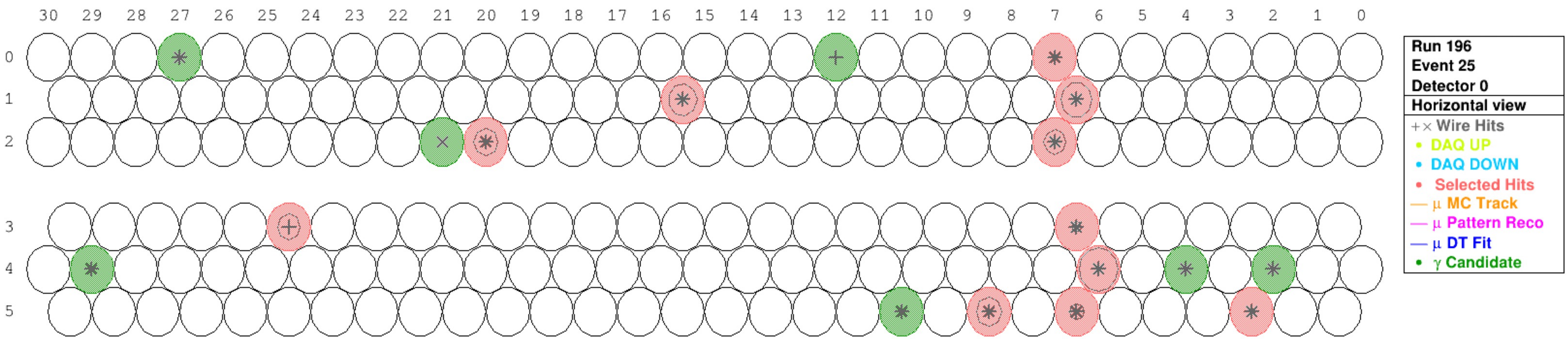
- The main difficulty of such a measurement was represented by the radioactivity emitted from the cask.
- An average number of ~11 noise signals from cask radioactivity was found for each saved event.
- A robust noise cancelling strategy was implemented in the track reconstruction software to remove the random radioactivity hits recorded together with muon tracks



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

Noise cancelling strategy includes different filters:

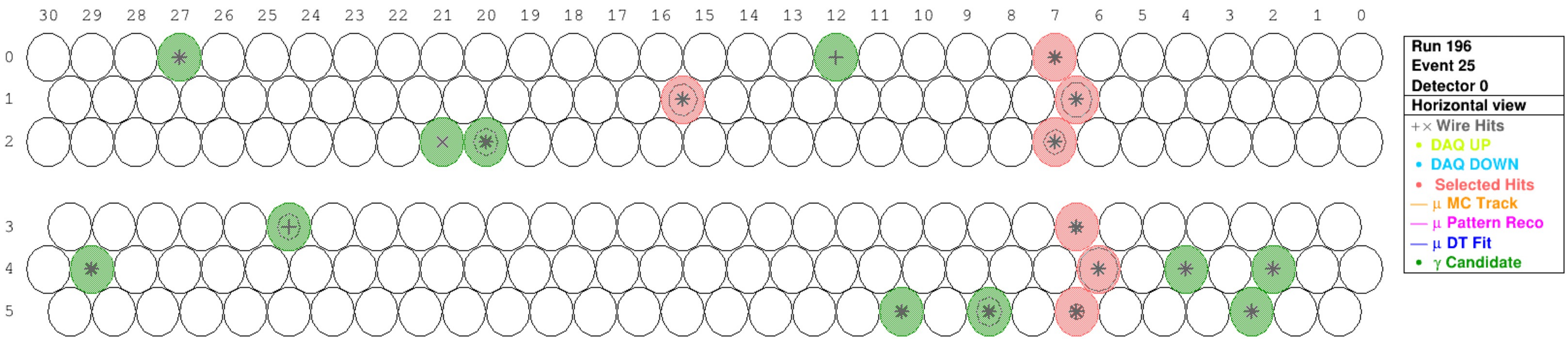
1. Time Filter
   Assumption: hits coming from a muon track are correlated in the arrival times, while hits coming from neutrons or gammas are randomly distributed in the time window open for the acquisition.



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

Noise cancelling strategy includes different filters:

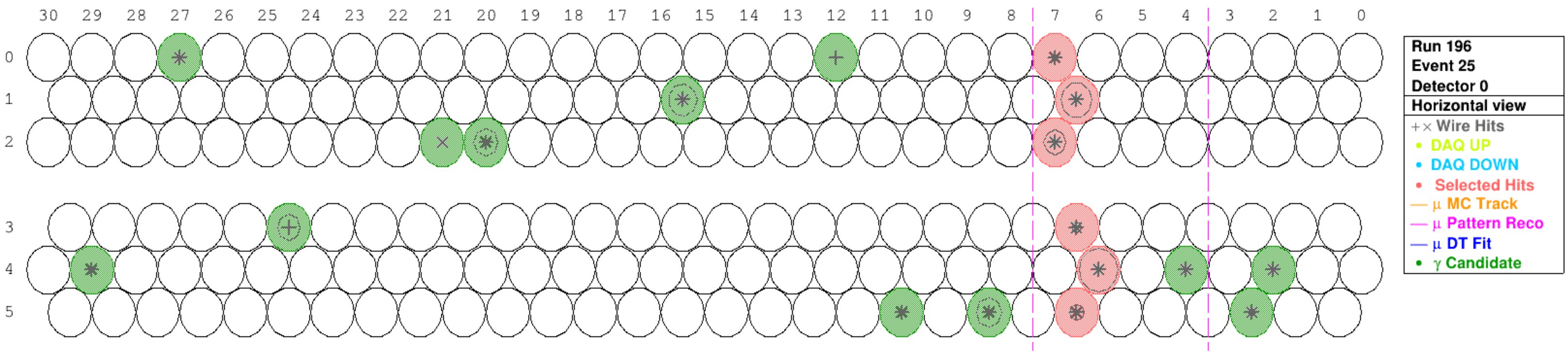
2. Space Filter
   Assumption: while the muon hits forming a track are connected, noise hits are more likely to be isolated.



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

Noise cancelling strategy includes different filters:

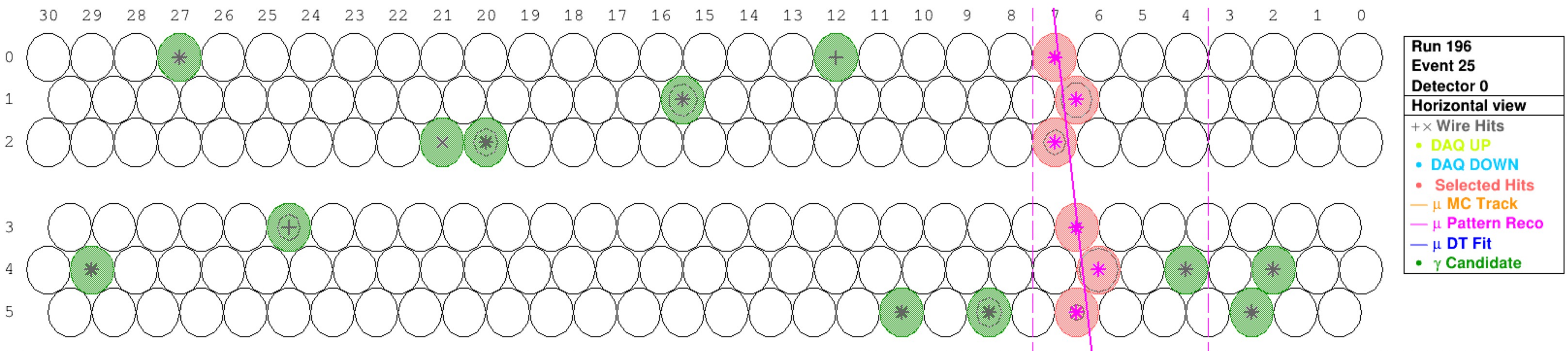
3. Clustering Filter
   Based on the same assumption of the space filter, it allows to identify the area of the detector where a major cluster of hits can be found.



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

Track reconstruction strategy includes two steps:

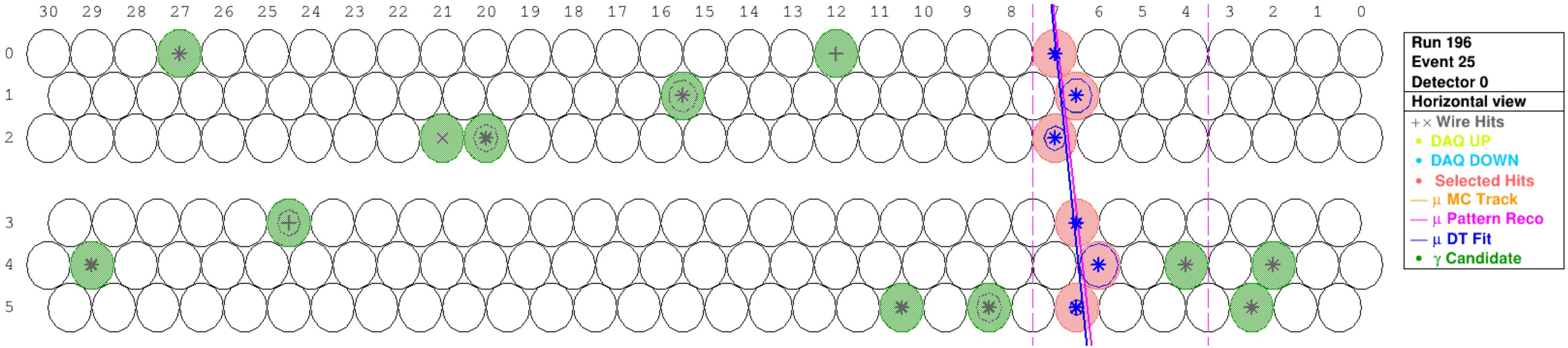
1. Pattern Recognition
   It is linear regression of the wire coordinates of selected hits: it is useful to identify track candidates.



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

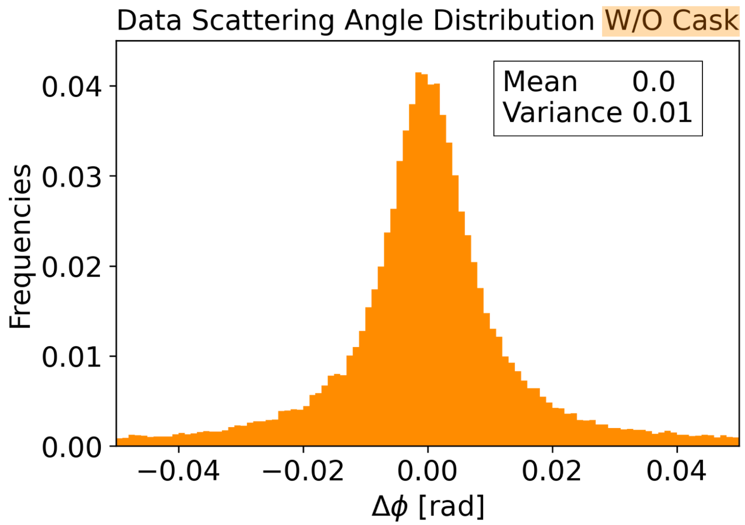
Track reconstruction strategy includes two steps:

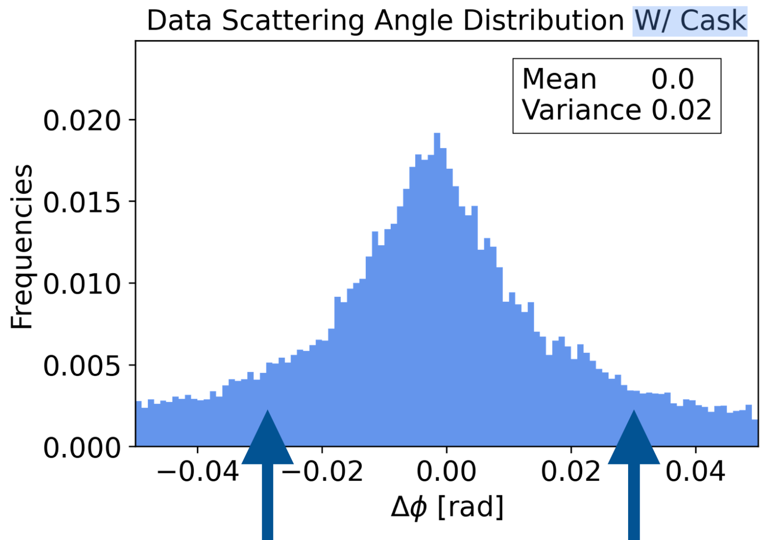
2. Drift Time Fit
   It is used to find muon trajectories, by calculating the best tangent to the drift time circles of the selected track candidates.



Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars.

Once the the tracks on the two sides of the Castor have been reconstructed, different distributions were checked





Effect of the heavier materials

- All these tests were performed on a small subsample of the data

- Last week the first "full production" has been launched and is on-going

- In the next days/weeks the first images should be available (🤞🏼🤞🏼🤞🏼🤞🏼🤞🏼)

Conclusions

Muon tomography technology seems promising for spent fuel casks (re)-verification

The MUTOMCA project built two specific detectors and performed a field test measurement at the Grafenrheinfeld (January-February 2023)

A lot of effort was dedicated to the noise reduction and to pattern recognition/track fitting in presence of a high background

Data analysis is ongoing – all the statistics is being processed
The first images should be soon available to verify the potentiality of the technique

Thank you for your attention

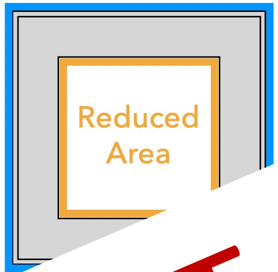
One of the CASTOR V/19® used at the field test featured 3 dummy elements in the inner part

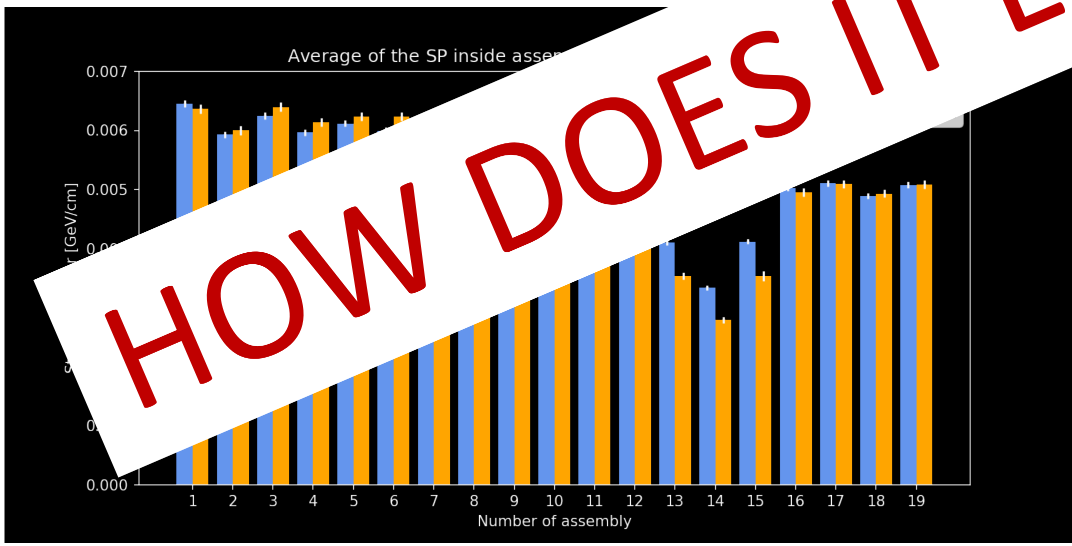
Example of an image reconstruction based on MC simulated data

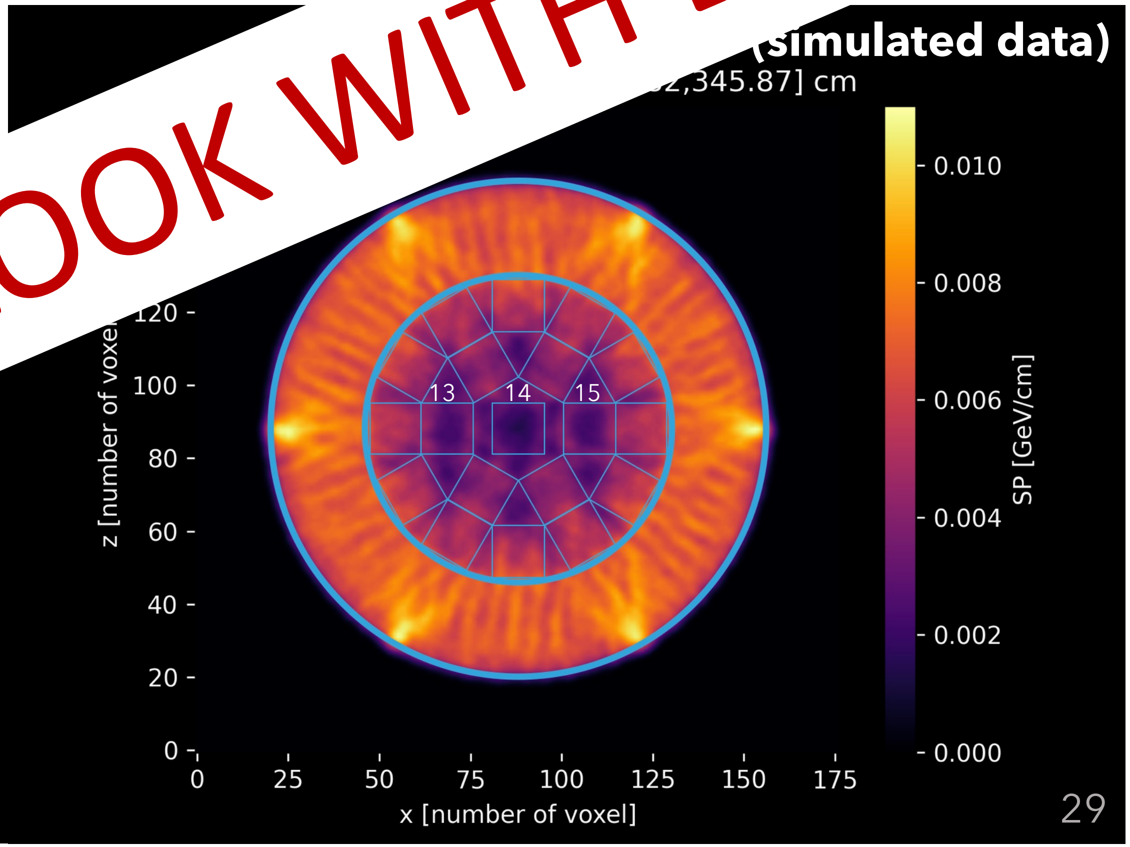
μCT reconstruction with three simulated datasets (~12 hours of equivalent data-t

Dummy Bar Section

... STAY TUNED ...





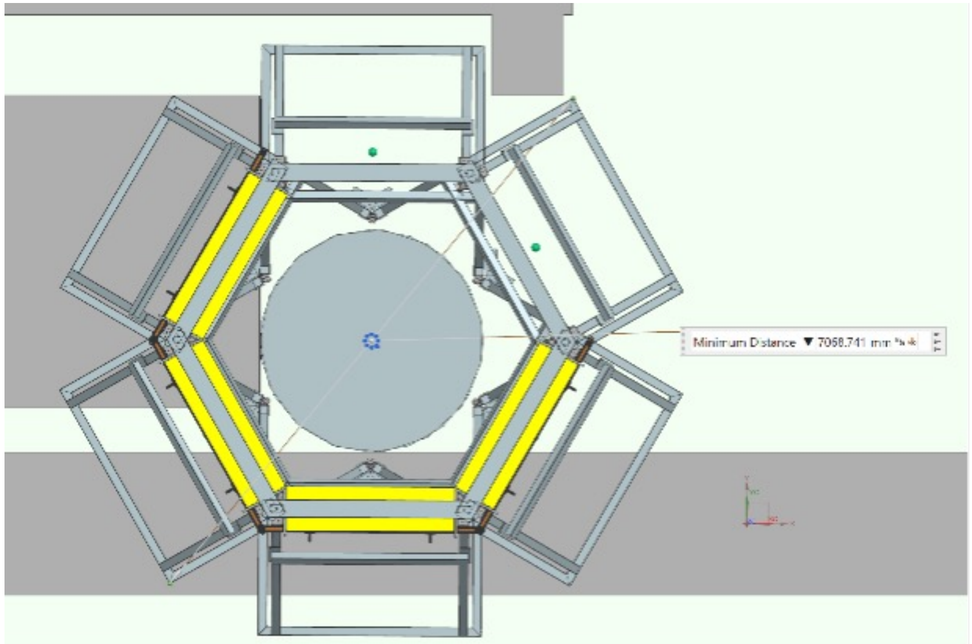


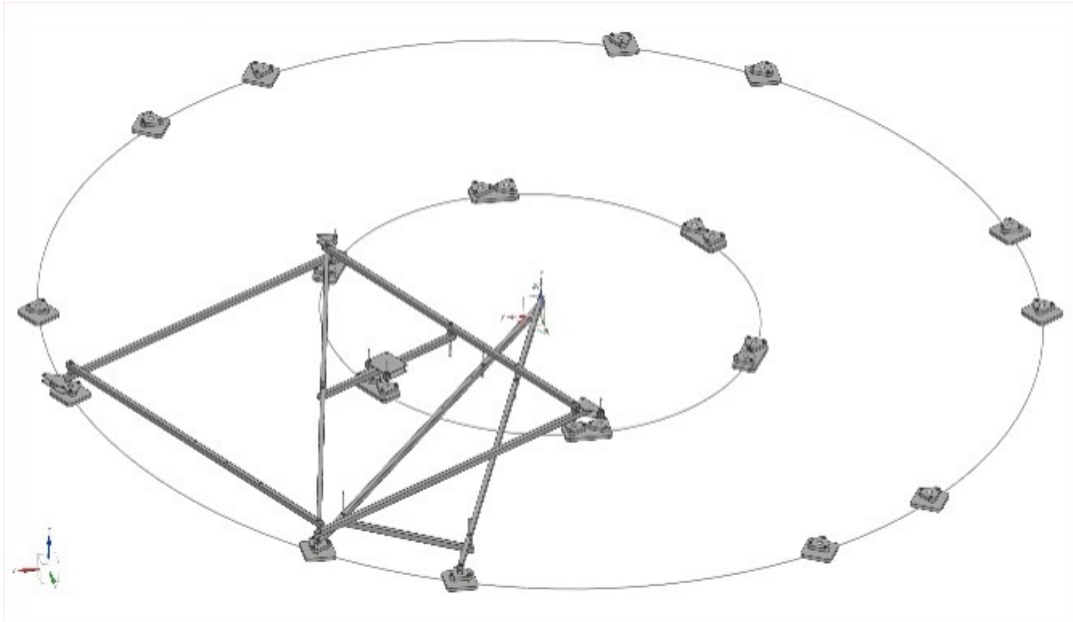
HOW DOES IT LOOK WITH DATA?

BACKUP

BACKUP

In order to determine the position of the two detectors with sufficient precision and to simplify and speed up movement operations at the field test, a system of support pads and tools has been produced.





A couple of smaller drift chambers may be placed in a fixed position above the cask for the whole data-taking period to allow also self-alignment with cosmic ray muons

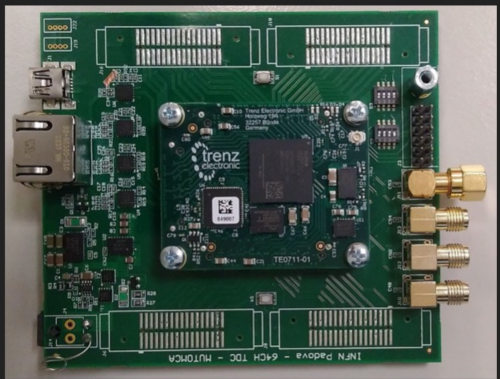
BACKUP

ELECTRONICS

- The data acquisition system is built over 4 types of cards based on FPGA (Field Programmable Gate Array) Artix7 (28 nm) and System On Chip (SoC) Zynq UltraScale+ (16 nm) from XILINX technologies (the major 3 are shown below).

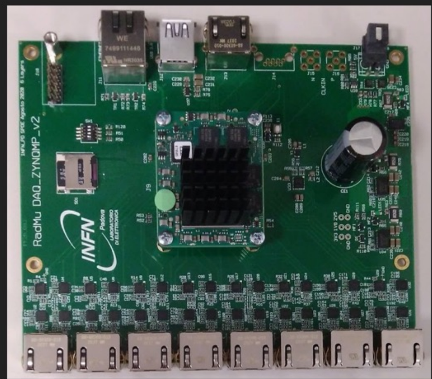
"TDC" card (Artix7 based)

- Each card implements 64 channels each instrumented with a TDC with LSB of 1 ns.
- The TDCs ReadOut takes place via a 1 Gbs ethernet link.
- Up to 64 of these cards can be used for a total of 4096 channels.



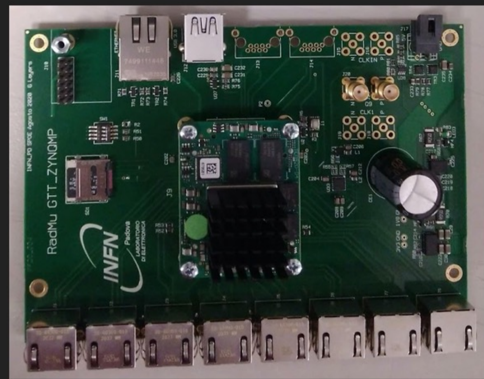
"DAQ" card (Zynq UltraScale+ based)

- Collects up to 512 channels receiving the related TDC data and processes a TRIGGER signal on them.
- Up to 8 of these cards can be used.

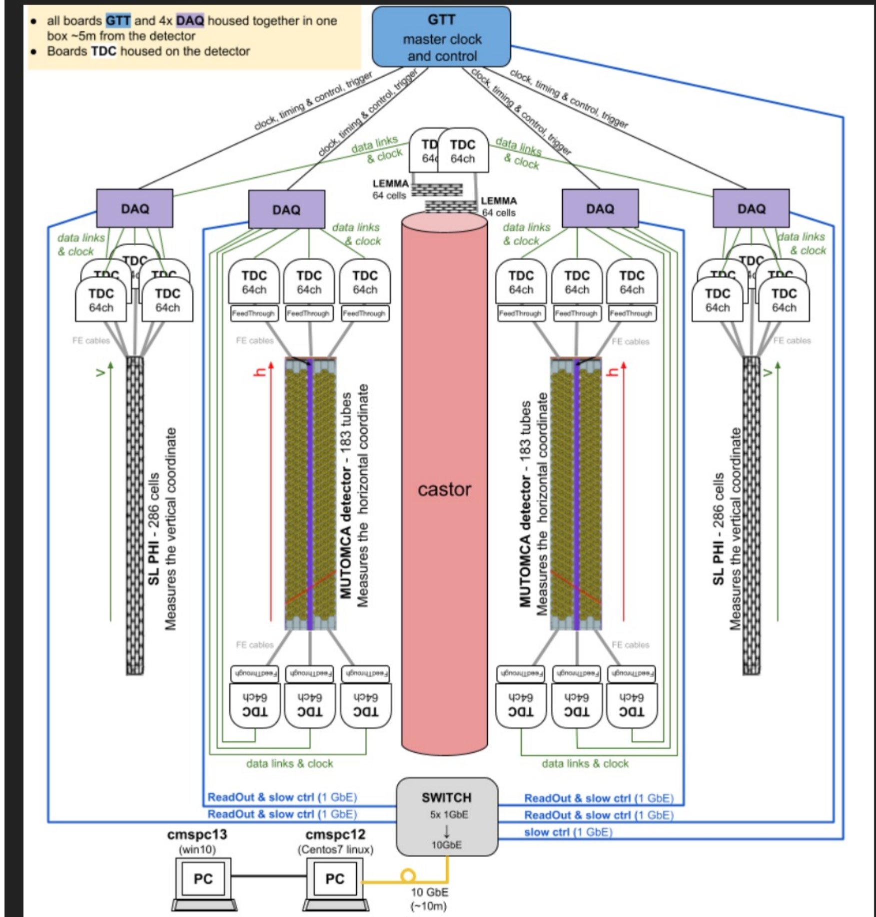


"GTT" card (Zynq UltraScale+ based)

- It is the top of the system.
- Responsible of the clock distribution, the synchronization among the various boards and the generation of the Global Trigger.
- Allows different detectors to be processed together.



ELECTRONICS

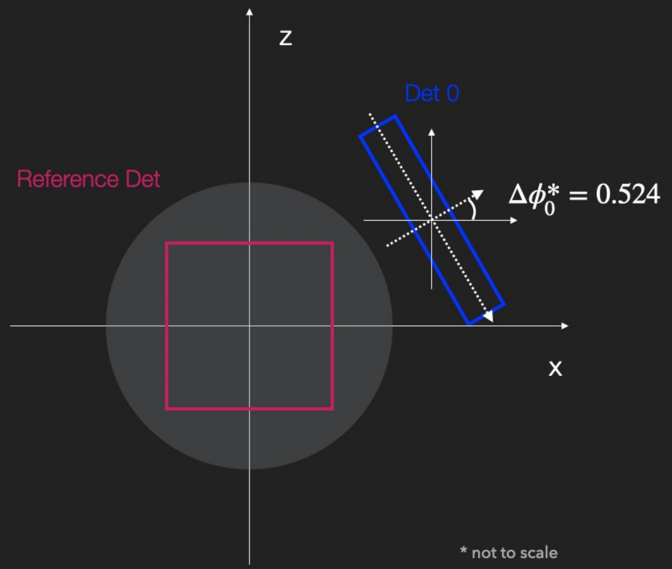


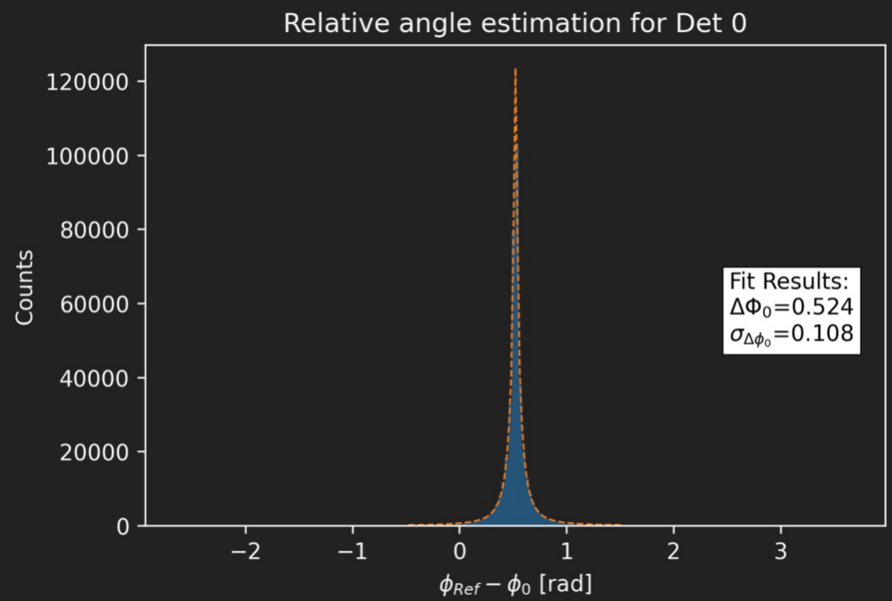
- **2 MUTOMCA detectors** and **2 SL PHI detectors** controlled and read out by a single unified system providing both 'ReadOut of TDC' and 'Trigger on event' functionalities.
- System composed by:
  - **24 TDC cards** instrument about 1000 channels with Time-to-Digital Converters.
  - **4 DAQ cards** each elaborate a trigger signal and enable the TDC read out.
  - **1 GTT** processes the global trigger by composing those coming from DAQ boards. It is responsible for clock distribution and control of the system.
  - **12 FeedThrough**: simple interface boards between MUTOMCA detector and daq electronics.
  - Clock and trigger distributed through CAT6A cables.
  - Detectors read out and slow control via standard 1 Gb Ethernet connection to a local PC.

BACKUP

POSITIONING AND SELF-ALIGNMENT

- Additionally, we will exploit cosmic ray muons to perform a self-alignment and check the position of the two detectors around the cask.
- For this purpose, a couple of smaller drift chambers could be placed in a fixed position above the cask for the whole data-taking period.

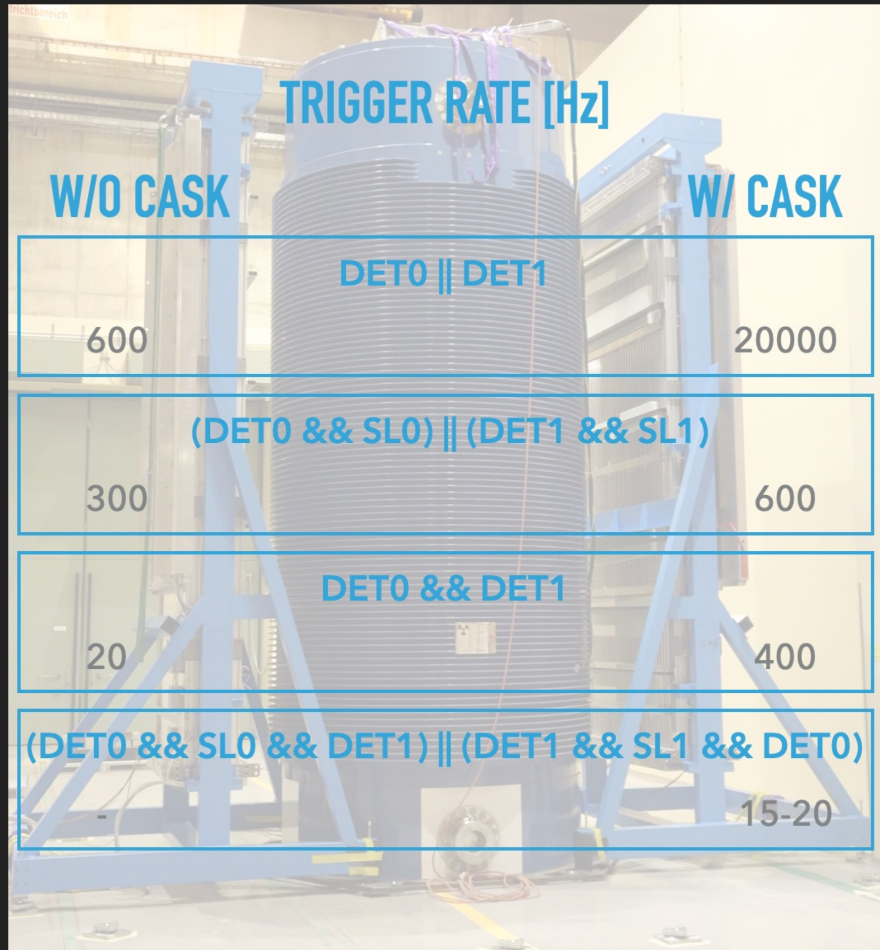




BACKUP

THE FIELD TEST: NOISE REDUCTION

- The main difficulty of this measurement is the radioactivity emitted by the cask (mainly neutrons and gammas), that leave random signals (a.k.a. "hits") in the detector during the time window of the muon track acquisition.
- Trigger architecture is highly configurable, some tuning was possible before the actual data taking, to minimise the number of noise-only events.



TRIGGER RATE [Hz]

	W/O CASK	W/ CASK
DET0 || DET1	600	20000
(DET0 && SL0) || (DET1 && SL1)	300	600
DET0 && DET1	20	400
(DET0 && SL0 && DET1) || (DET1 && SL1 && DET0)	-	15-20