Development and Experimental Study of the High Spatial Resolution Muography System with Micromegas Detectors

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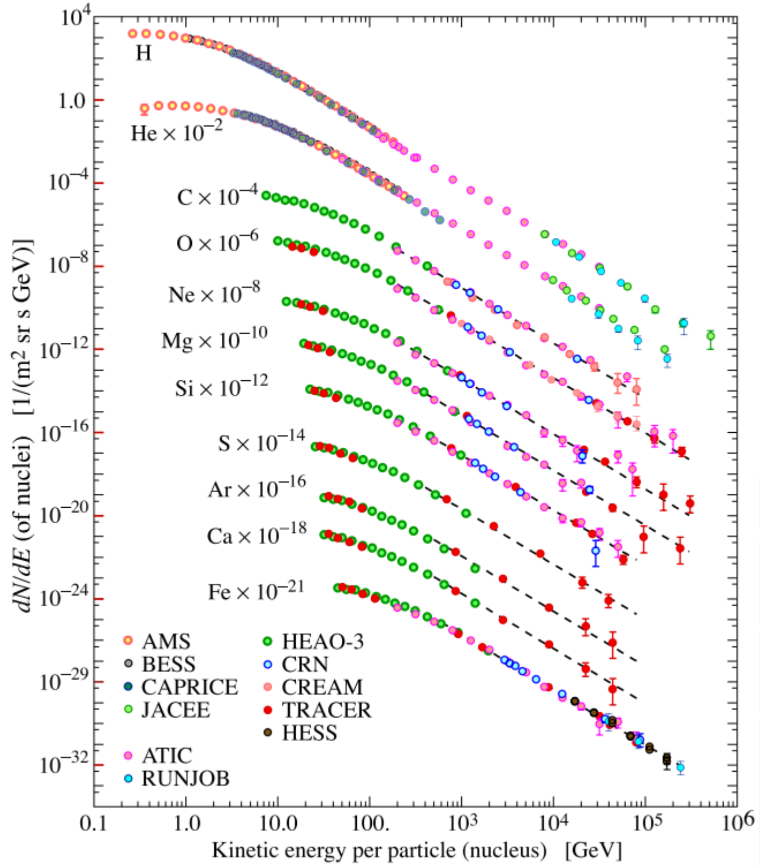
Outline

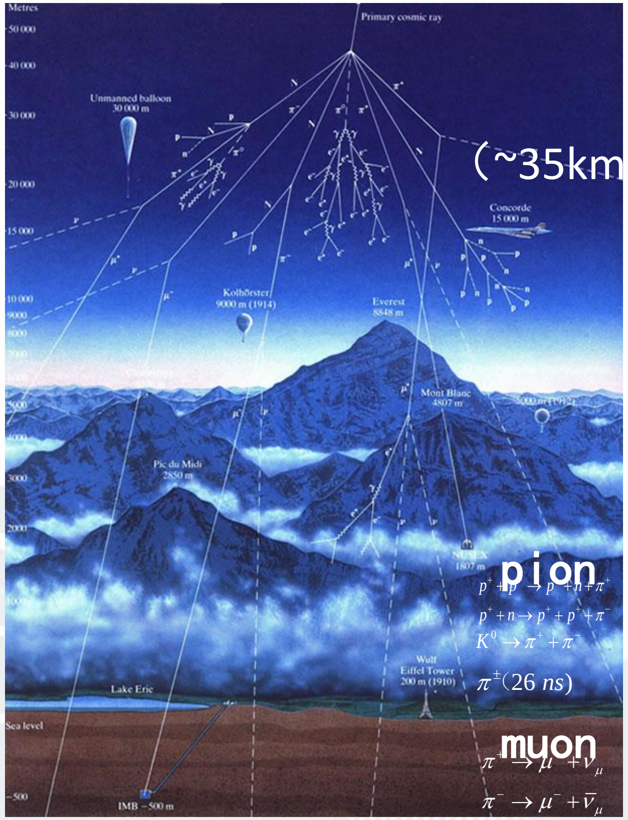
- Introduction
- Structure of the facility
- High spatial resolution Micromegas detectors
  - The thermal bonding Micromegas
  - Fabrication and applications
- Readout electronics
  - Channel multiplexing methods
  - Extensible module design
- Prototype construction and muography experiments
- Summary

Cosmic-rays: constituents

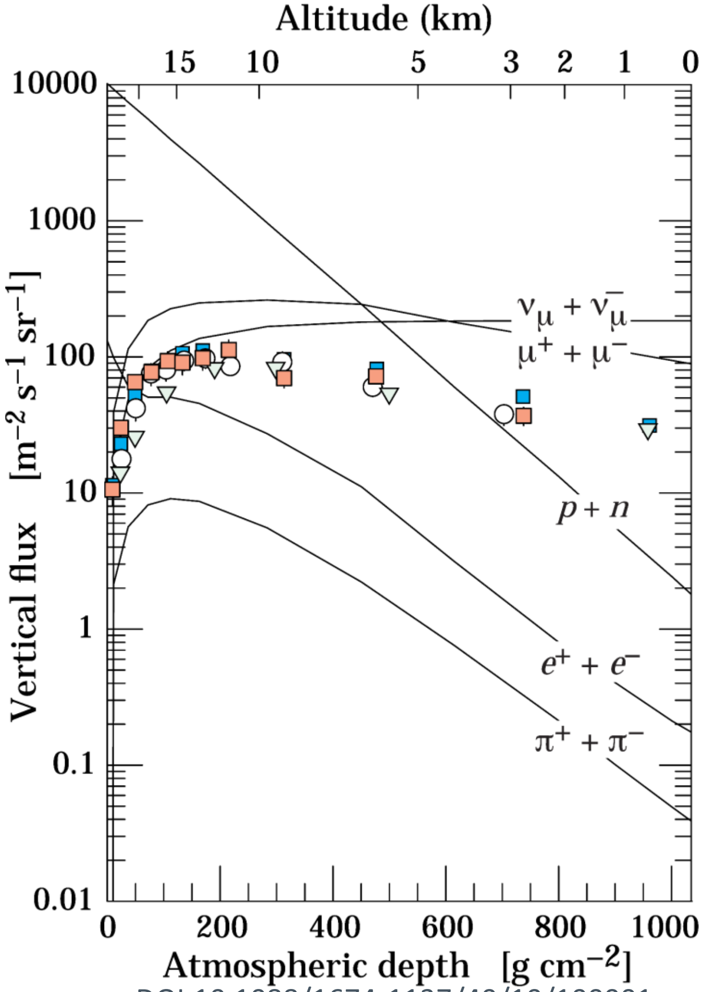
- Cosmic muons are produced by cascade of reactions induced by primary cosmic-ray accelerated at astrophysical sources
  - Natural, free and harmless radiation
  - Flux: ~150/m²/s $\propto \cos^2\theta$ (Maximum in zenith direction $\theta = 0$)



DOI:10.1093/ptep/ptac097

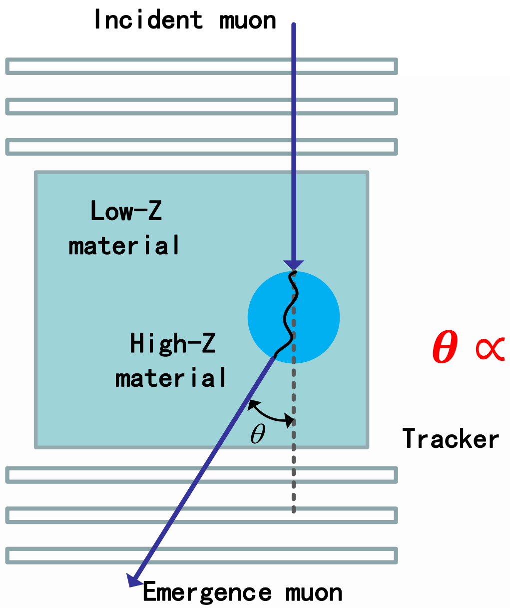


http://fafnir.phyast.pitt.edu/particles/conuni5.html

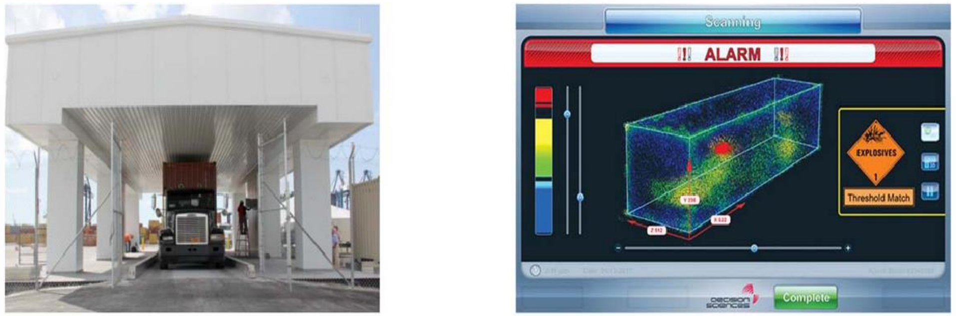


DOI:10.1088/1674-1137/40/10/100001

Muon Tomography

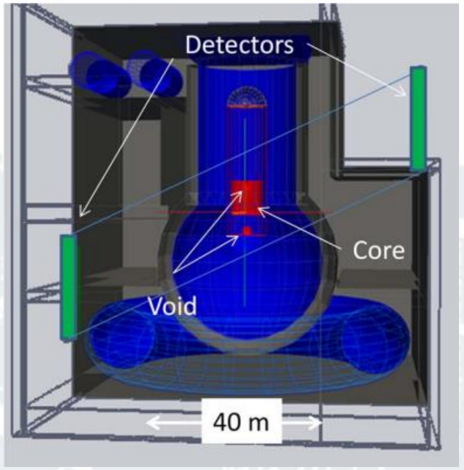


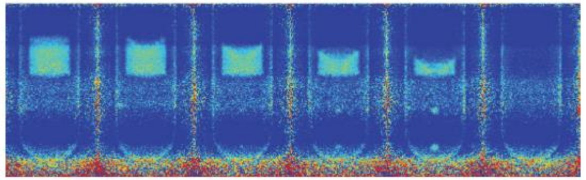
$\theta \propto Z$



(a) (b)

A Multi-Mode Passive Detection System by LANL & the DSC, for detecting trucks and large shipping containers at borders, customs, and ports.





Accident response: Simulations and imaging experiments of the Fukushima reactor core.

DOI: 10.1103/PhysRevLett.109.152501
DOI: 10.1088/1748-0221/11/09/P09008

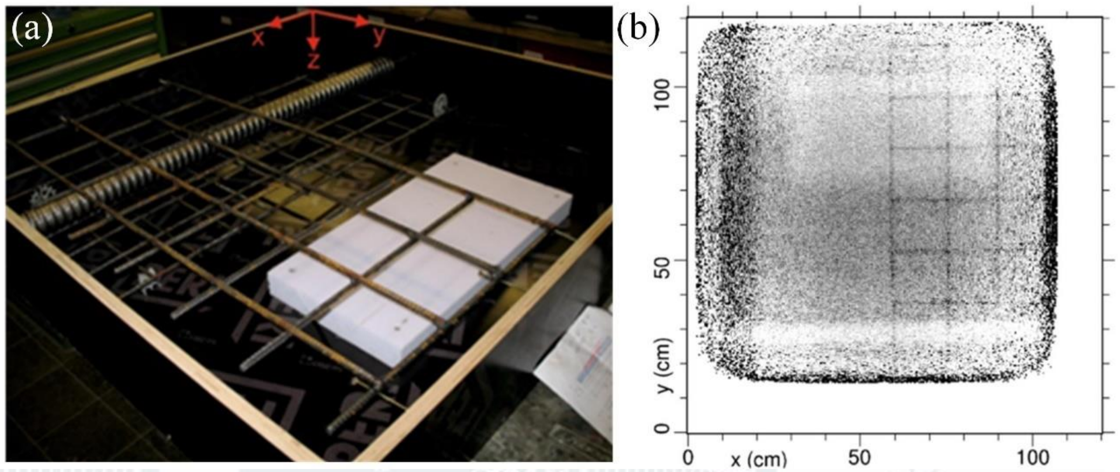
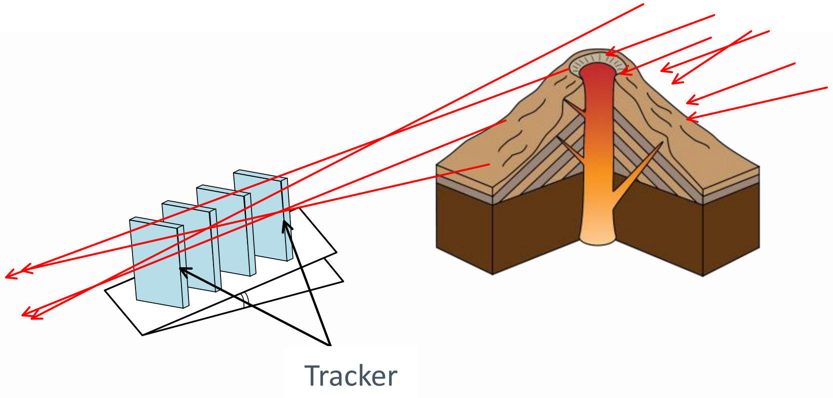


Image of the reinforced concrete (cost 43days)

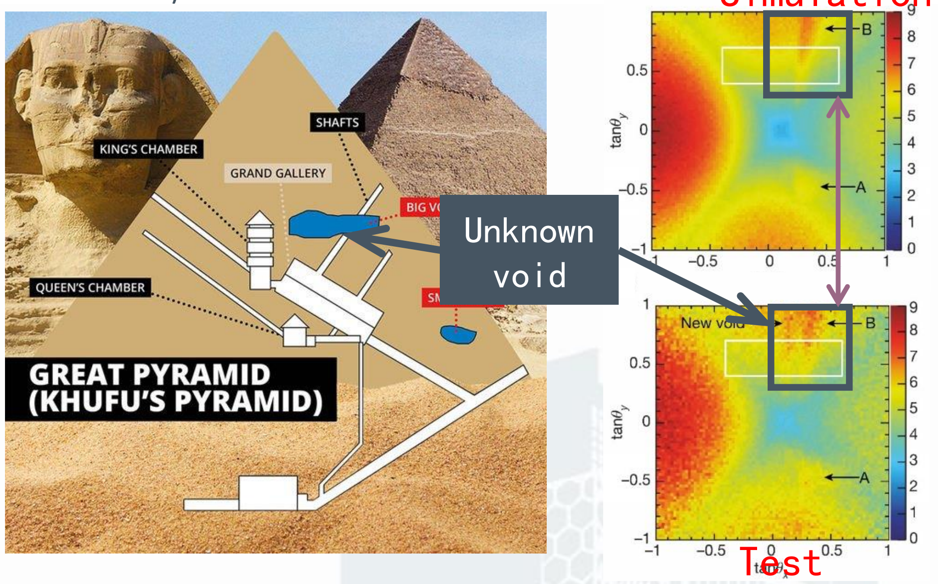
DOI:10.1088/1674-1137/40/10/100001

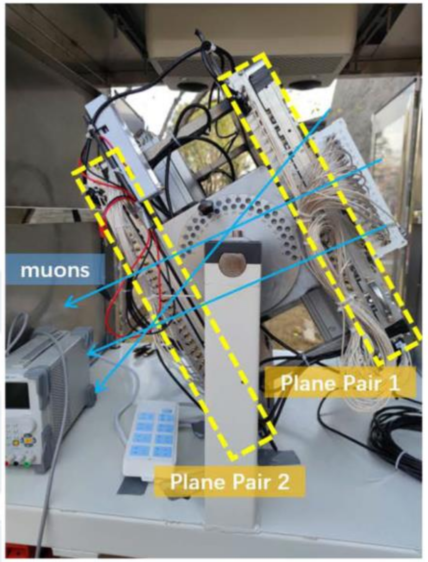
Nuclear Safety Inspection/Nuclear material Monitoring

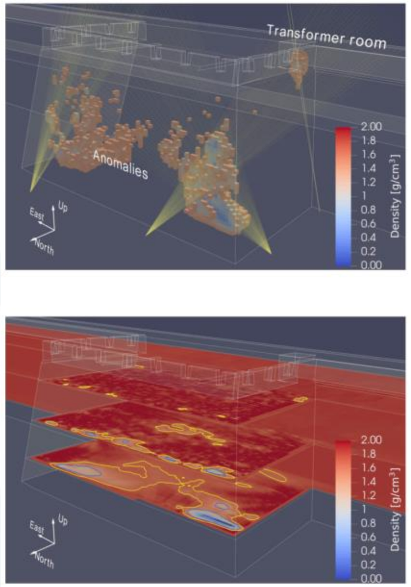
Muon Radiography



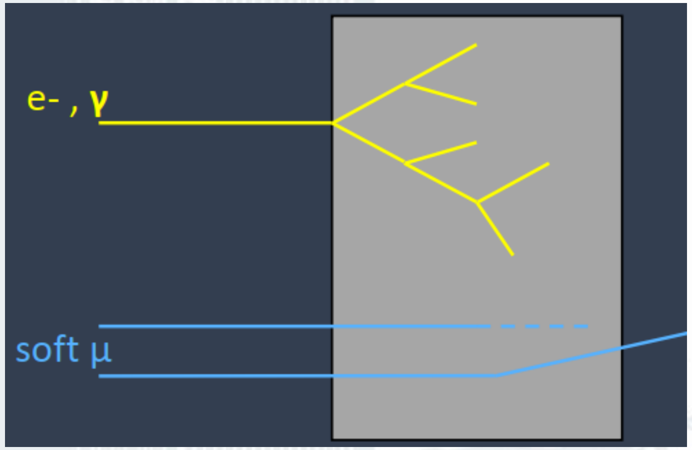
DOI:10.1038/nature24647







DOI:10.1063/5.0123337



(M. D'Errico et., al, 2023)

Geological investigation/ Archaeological site detection

Requirements for muon image

- The requirements for the detector and the available options
  - Large area
  - Fine spatial resolution：
    - Tomography： ~200 μm
    - Radiography: serval mm
  - Stable performance
  - High detection efficiency
  - Low cost

Type of Detectors	Implementation for Large Area Detection	Spatial resolution	Cost
MPGD	**Single unit**	**~100 μm**	Low
Scintillator	**Array**	1-10 mm	Moderate
Drift chamber	**Array**	**~400 μm**	Moderate
Nuclear emulsions	**Sheet or Stack**	**~1μm**	**High**
CCD (Cherenkov detector)	**NA**	**NA**	**Extremely high**

Large-area, high resolution MPGD is a competitive option

Schematic design

› μSTC： μ(muon) Scattering tomography & Transmission radiography imaging faCility

μSTC-T for tomography

μSTC-R for radiography

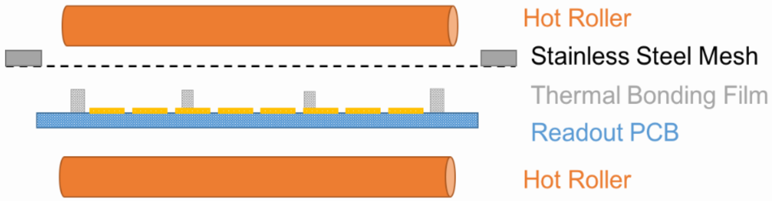
Design goals:

- Up to 60 ×60 cm^2 active area;
- < 200 μm spatial resolution for single detector layer;
- Rotatable horizontally and vertically for μSTC-R.

The thermal bonding method

› A novel thermal bonding method for the efficient fabrication of Micromegas detectors has been deleloped

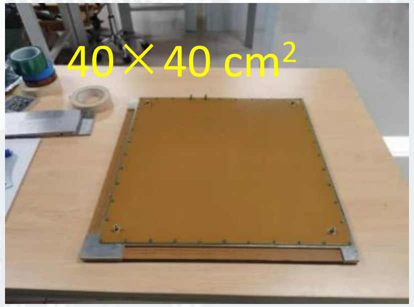
Thermal bonding processing

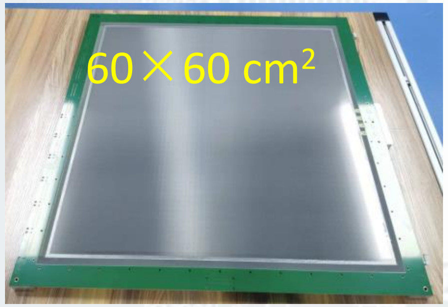


- No etching, no pollution
- Easy to handle at lab
- Easy to make new structures
- Φ0.5mm- Φ1mm spacers, ~1cm pitch

  ➔easy to clean, especially for large area

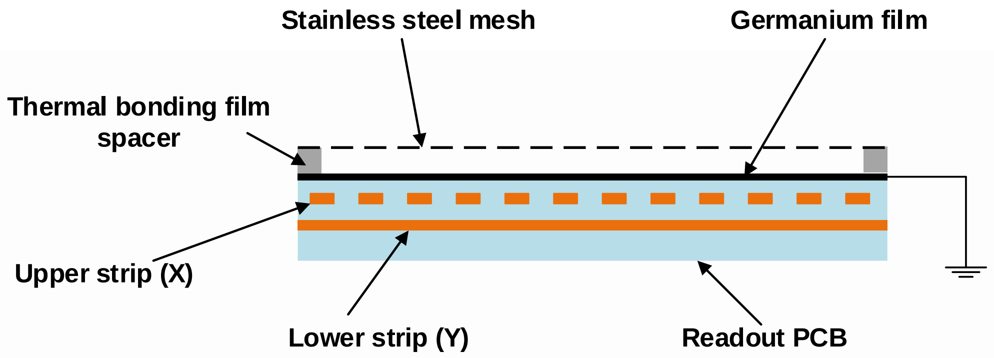
  ➔less than 1% spacer area





Large size Micromegas detectors

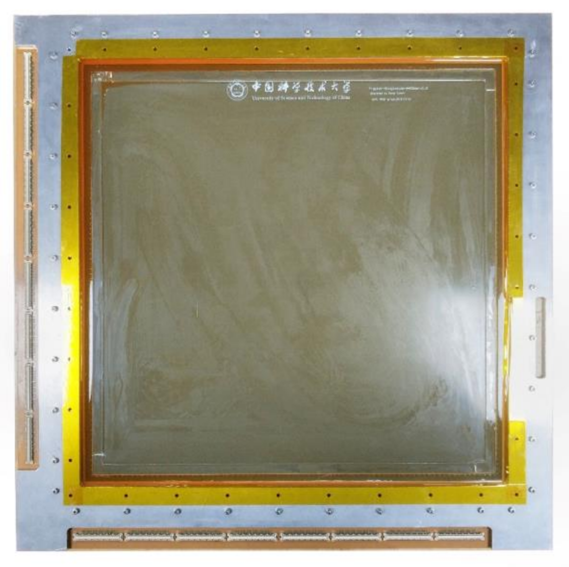
› Structure
- Stainless steel mesh
- Germanium film
- Embedded readout strips



15 cm × 15 cm

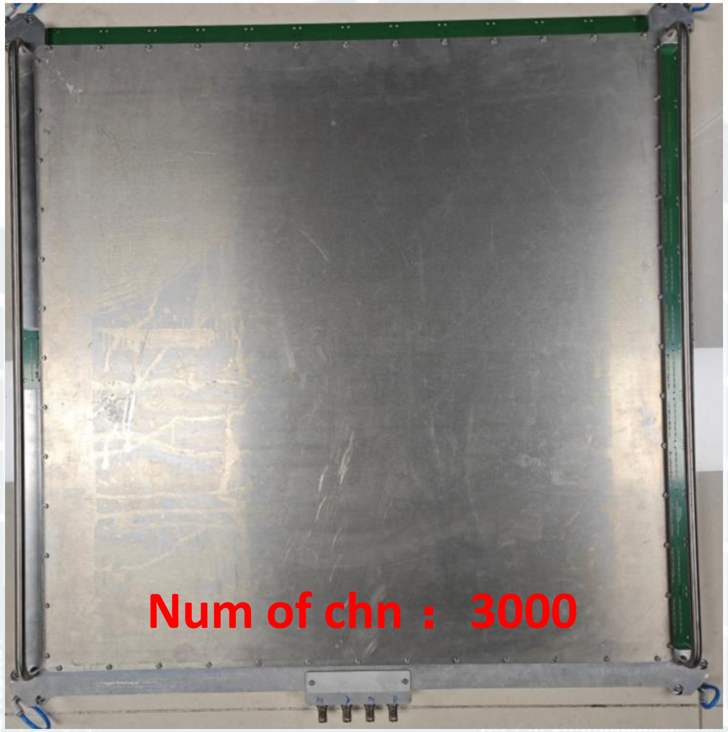
Num of chn： 768

40 cm × 40 cm



Num of chn ： 2000

60 cm × 60 cm



Num of chn ： 3000

Larger areas

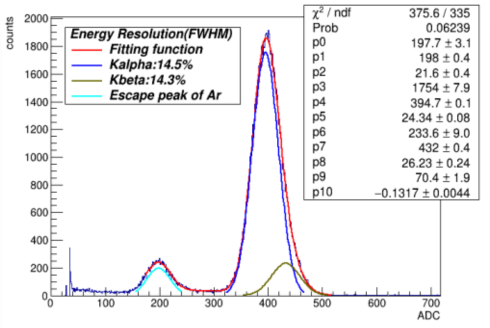
Performance of the Thermal bonding Micromegas

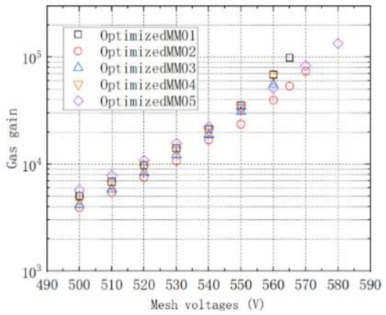
5.9 keV X-ray test

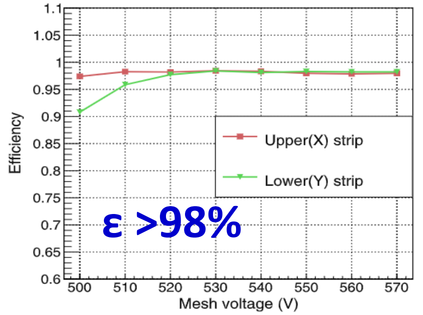
- Gas gain： ~10^5 (Ar+7%CO_2)
- Energy resolution： < 15% (FWHM)

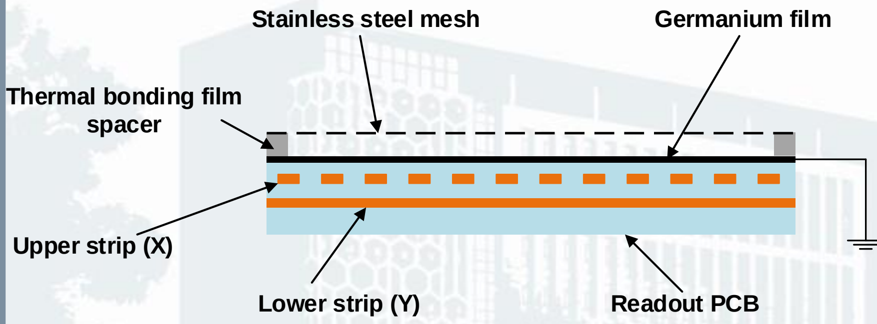
Electron beams test

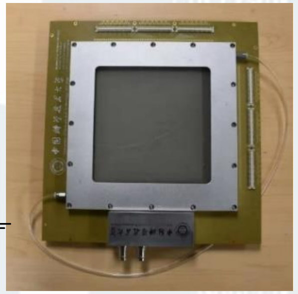
- X-Y 2D readout
- Efficiency： >98%
- Resolution： <100 μm

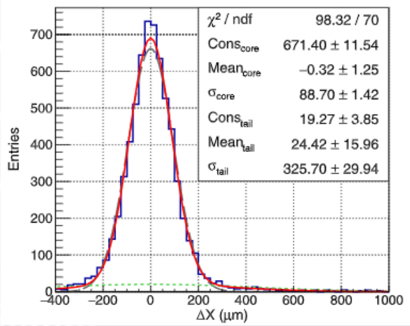


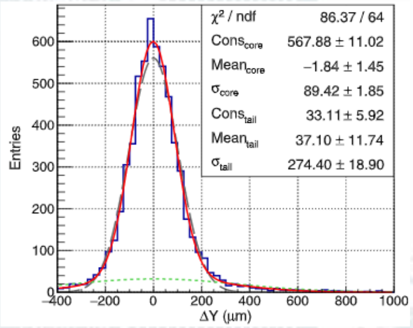












Jianxin Feng, Zhiyong Zhang, Jianbei Liu et al., NIM-A 989 (2021) 164958.

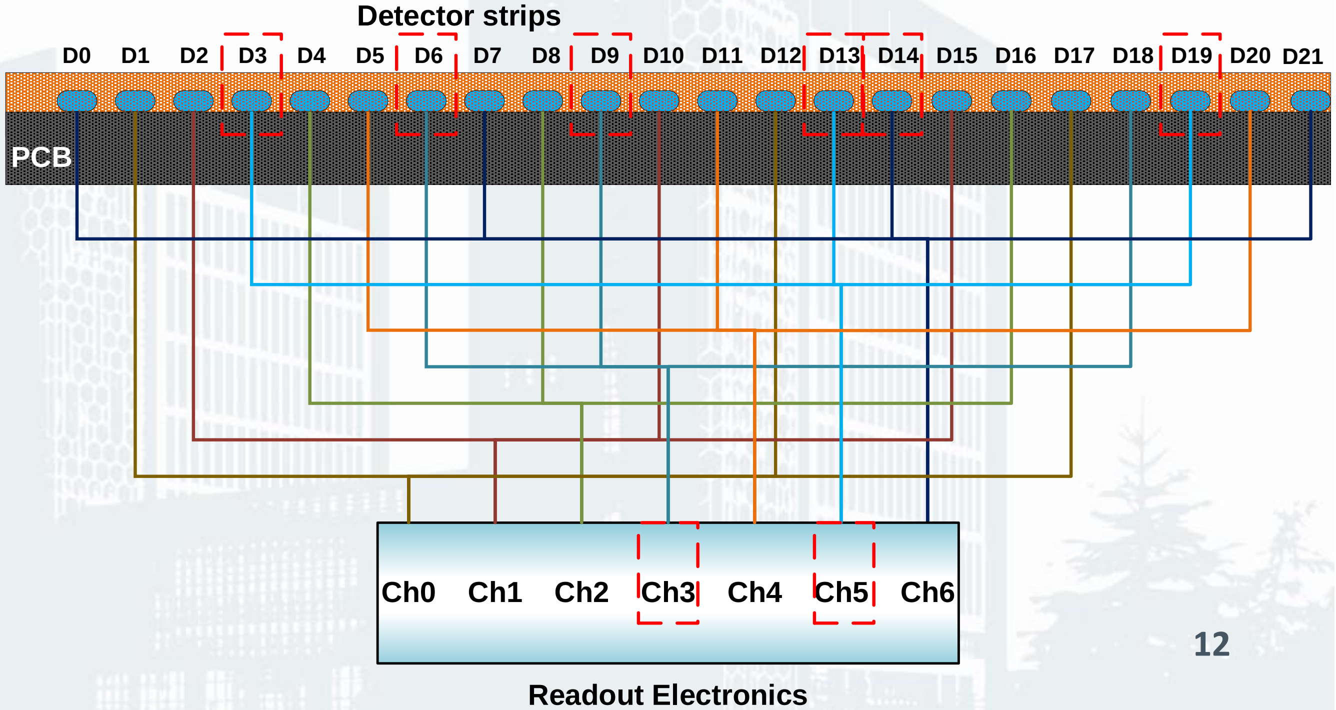
Readout Electronics

- Challenges
  - Large number of readout channels
    - Eg: The detector, with a size of $60\ \mathrm{cm} \times 60\ \mathrm{cm}$, has 3000 readout channels.
    - For a Tomography facility device, composed of 8 layers of detectors, will have up to 24,000 readout channels
  - High precision, low noise measurement of MIPs signals
  - May operate in diverse environments and may need to be configured for varying scales
- Our solution
  - Channel encoding multiplexing method to minimum the readout channels
  - Develop low noise front-end electronics with ASICs
  - Modular design to ensure the extensibility of the system

The channel encoding multiplexing method

- It is practical to encode the readout channel for very low rate of the cosmic muons
  - ⇛ According to reasonable connection rules, electronic channels can be multiplexed
    - The required number of readout channels can be reduced by an order of magnitude

Diagram of 7 Electronic channels Reading Out 22 Detector Channels



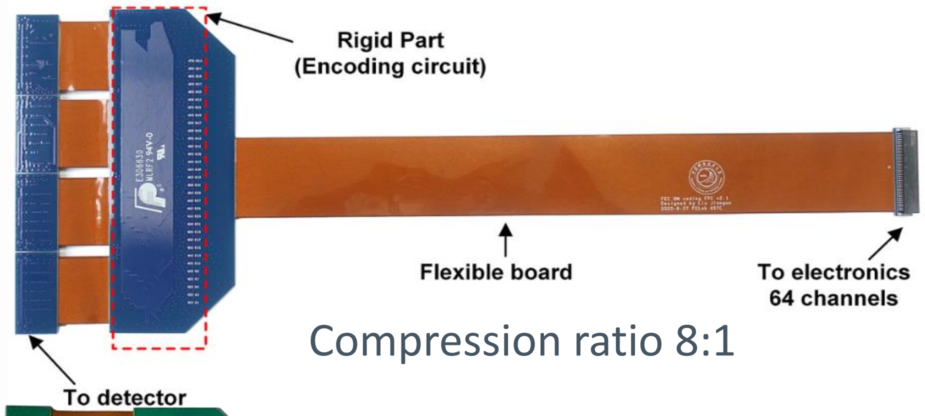
Eg：

1. At readout side:ch3 and ch5 are fired
2. The possible hit strips are

   3, 6, 9, 13, 14, 19
3. As the hit strips must be continuous, the real results is 13 and 14

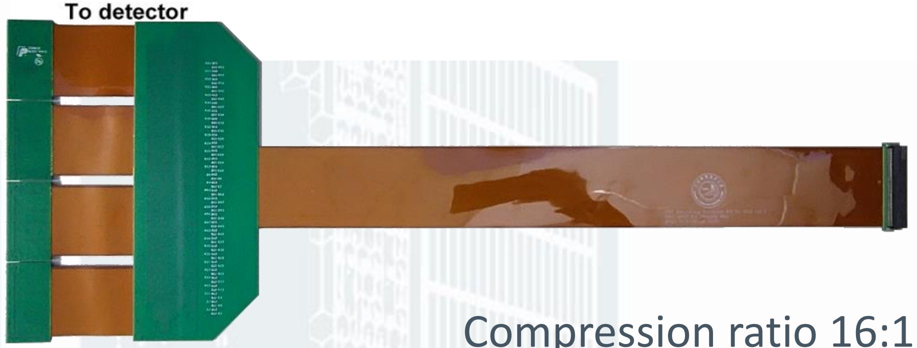
The channel encoding multiplexing method

- We have established a mathematical model using graph theory, specifically Eulerian graph theory, to describe the scheme of electronic channel multiplexing
- Two different schemes
  - Interleaved Coding Readout Scheme
  - Hamilton Circuit Coding Readout Scheme
    - For Complete Graphs
    - For bipartite graph



Compression ratio 8:1

Number of chn： 512



Compression ratio 16:1

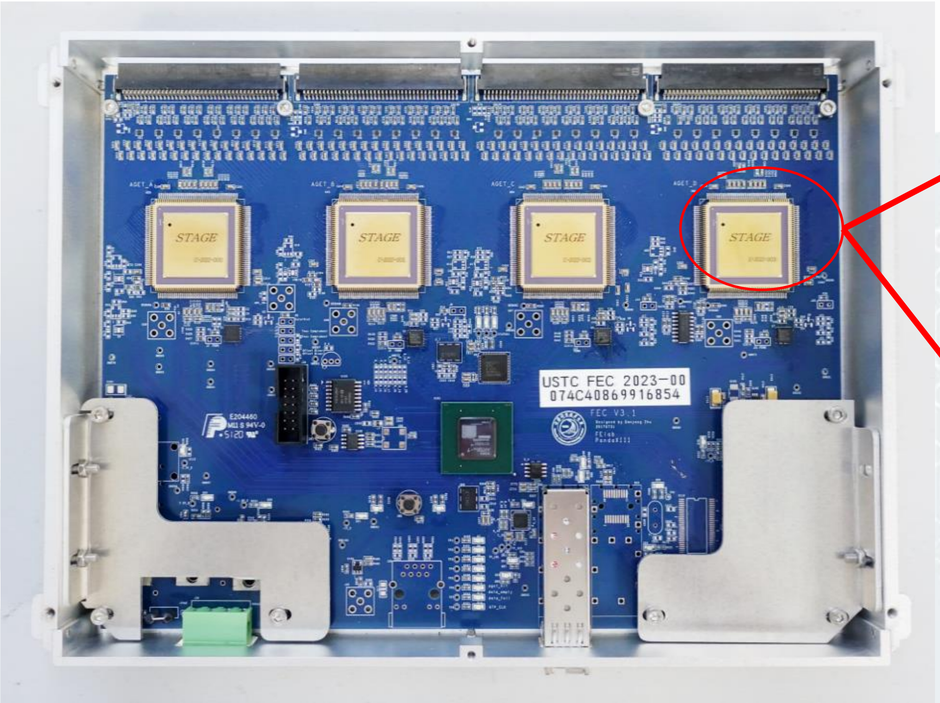
Number of chn： 1024

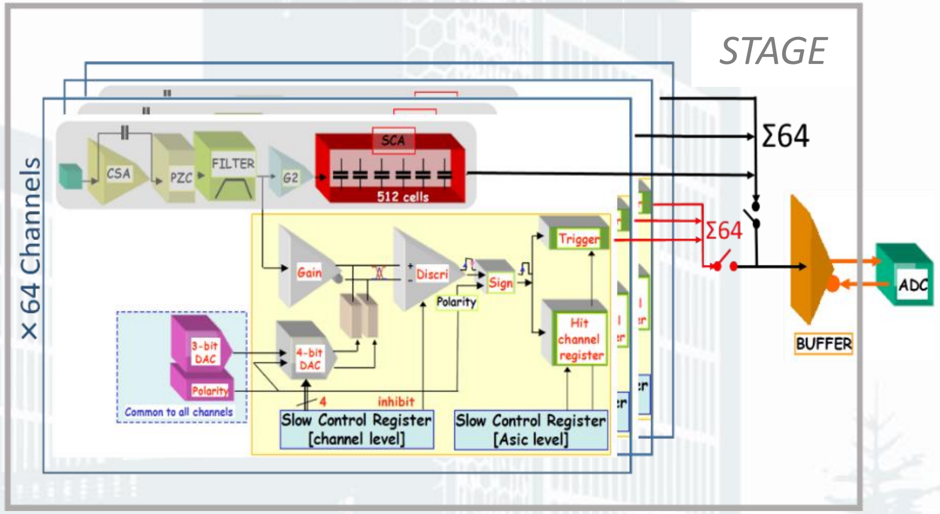
Number of chn： 386

Compression ratio 6:1

Front-end Electronics Card – Type I

- Front-end Card with waveform digitization
  - Each board integrate 4 chips for readout 256 channels
  - Sample rate from 1MHz to 100MHz
  - The noise for single channel is better than 0.2fC

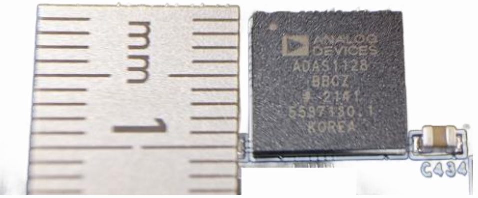




This chip is provided by IRFU/CEA Saclay

Front-end Electronics Card – Type II

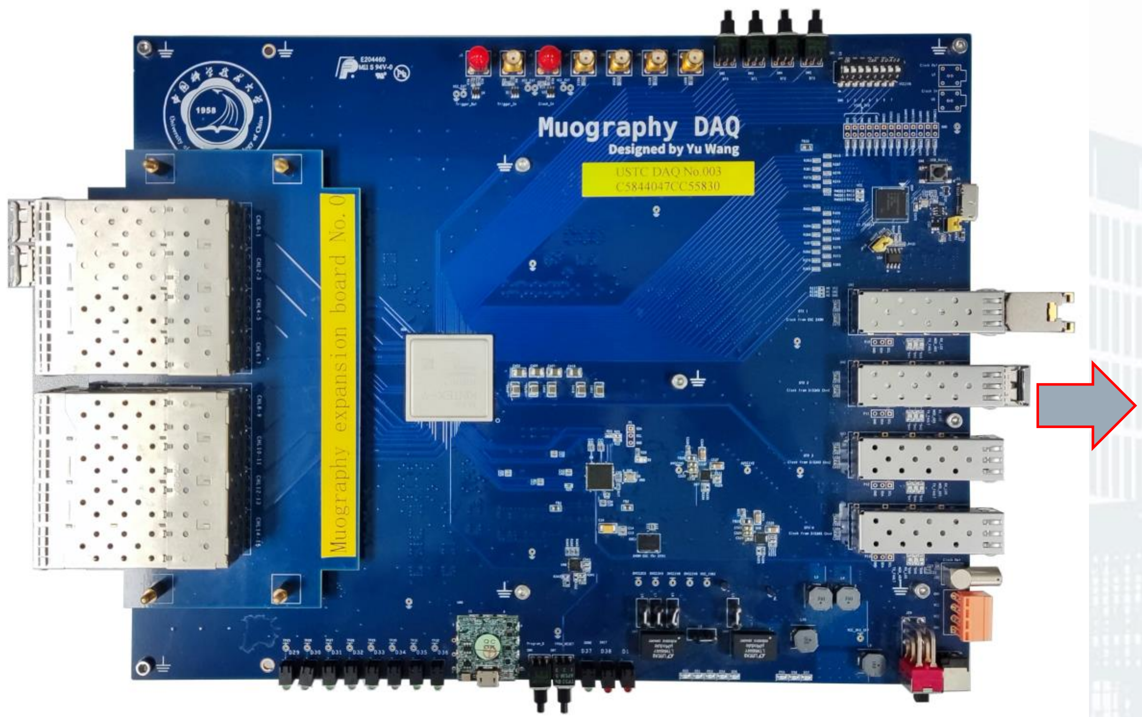
- FEC with only aptitudes readout
  - Using compact commercial current readout chip
  - 128 channels with size $1 \times 1\ \mathrm{cm}^2$
  - RMS noise 1.6 fC

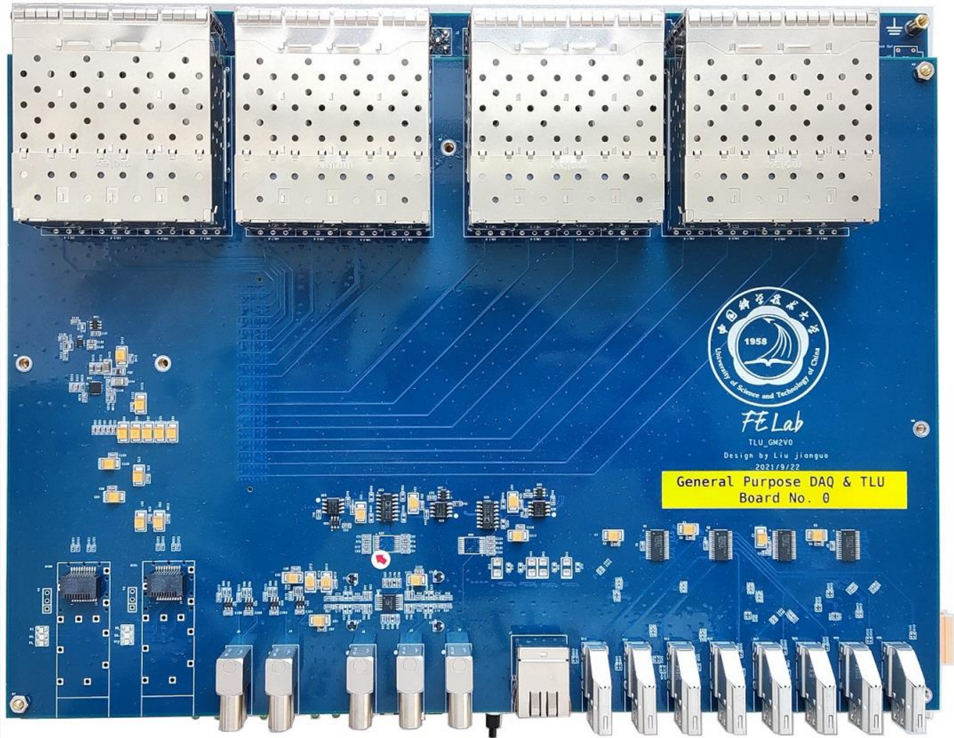


Detail can be seen in Ting Wang's Poster: Design of A Highly Integrated Readout Electronics for Micromegas Detector Used in Muon Imaging

Data Collection Module

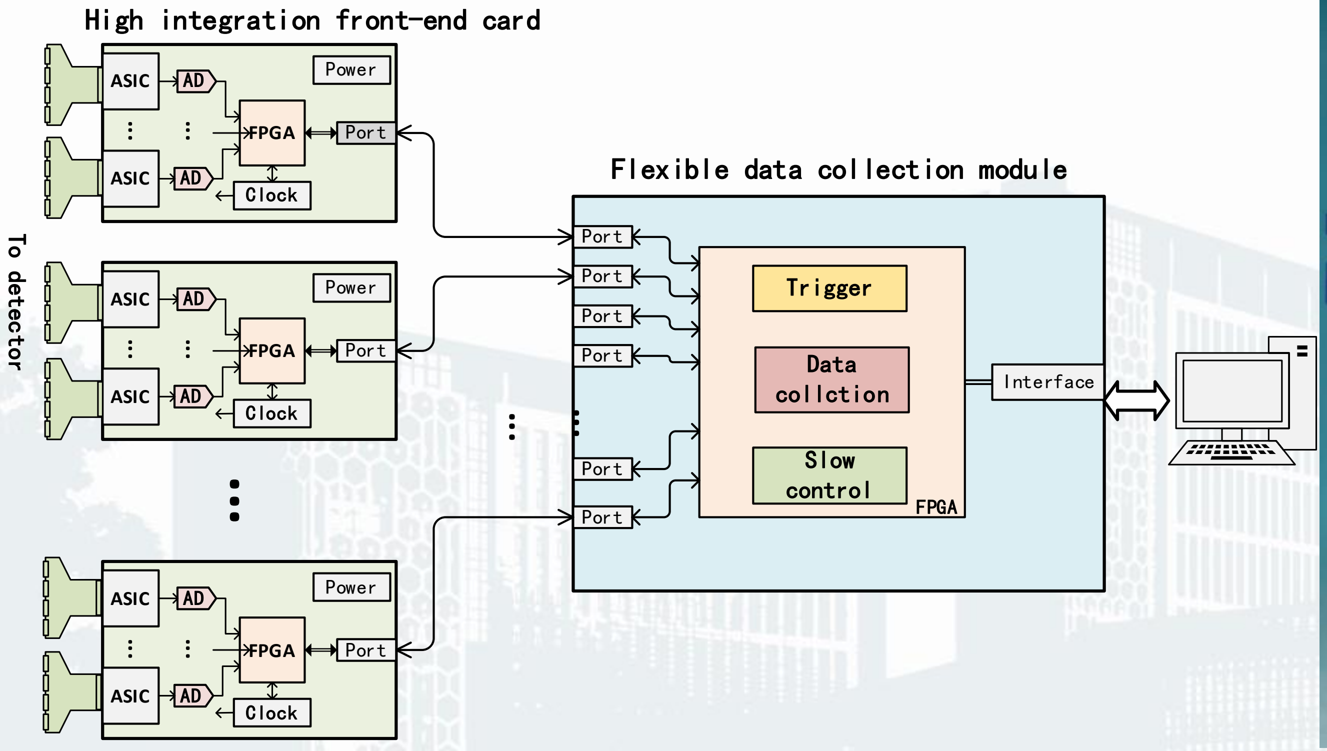
› DCM
  - Adapt to various scales and types of front ends
  - Interconnected with front-end electronics via optical fibers, a maximum of 32 FECs can be readout
  - Supports trigger input, output, and distribution functions

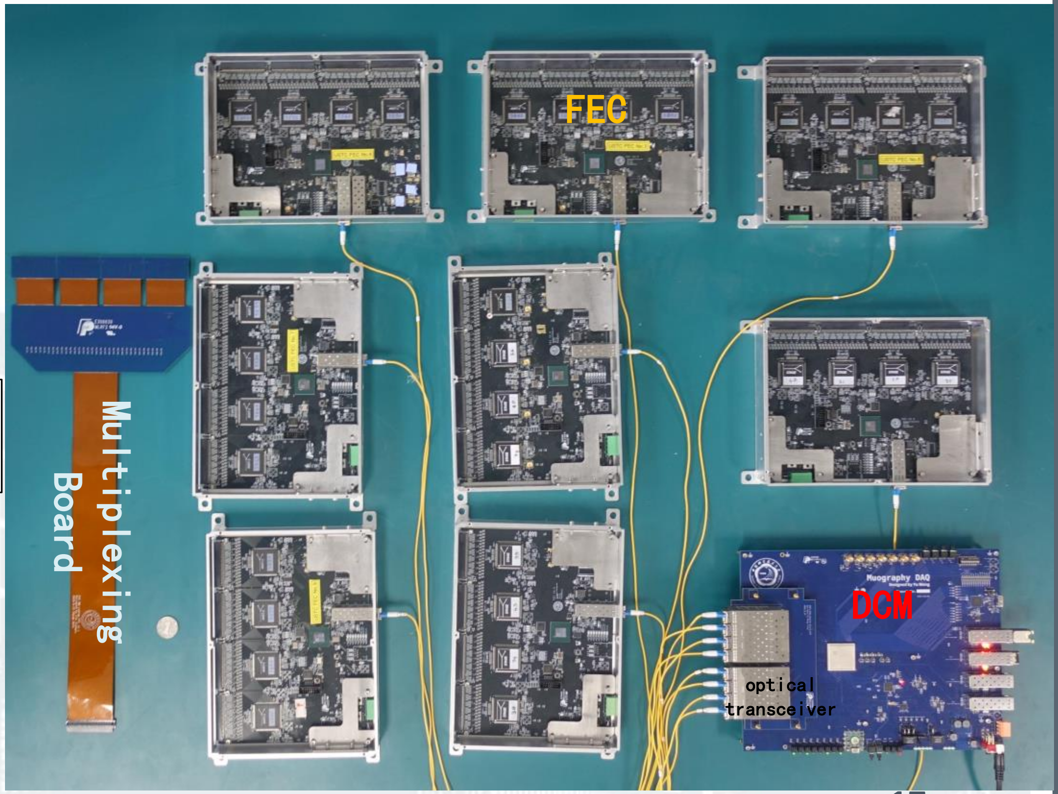




Extensible module design

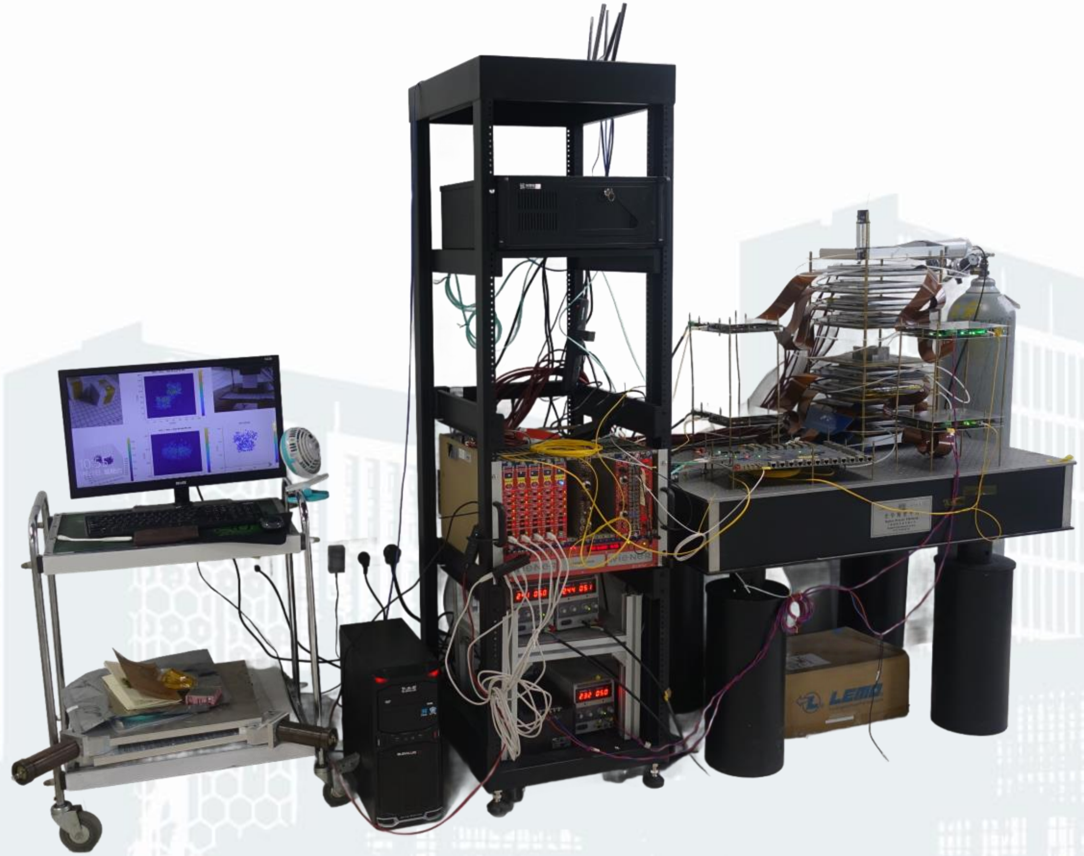
- A versatile readout system
  - High integration front-end card (FEC)
  - Flexible data collection module (DCM)



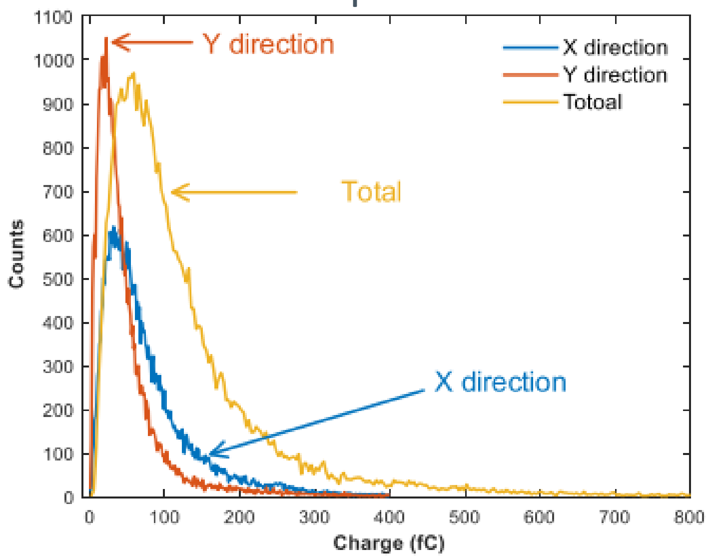


Small size prototype for tomography

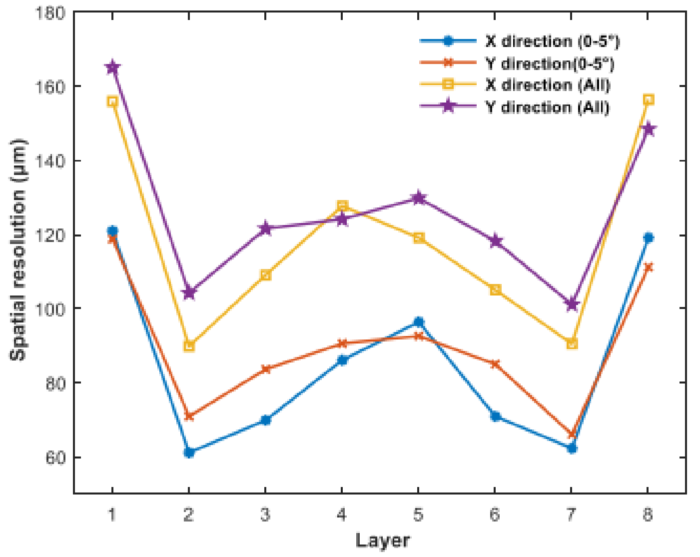
- First μSTC-T prototype: (2019.12-2021.05)
  - 8 layers of 15 cm×15 cm Micromegas
  - ~100 μm resolution
  - Compression ratio 6:1



MIP spectrum

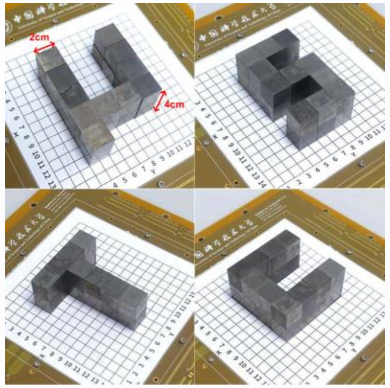


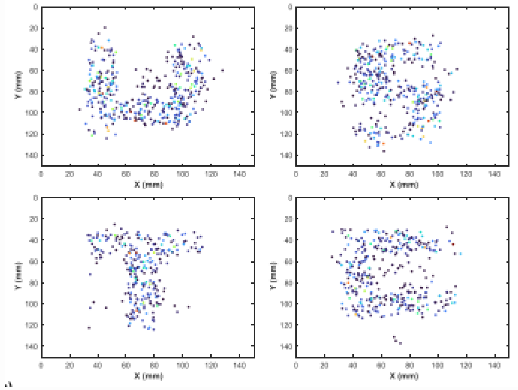
Position resolution



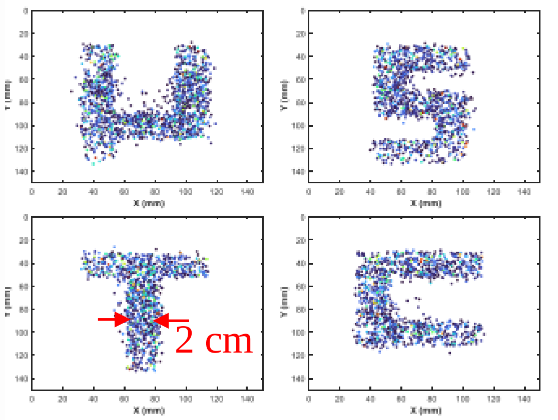
Small size prototype for tomography

› First μSTC-T prototype: tomography with small size objects

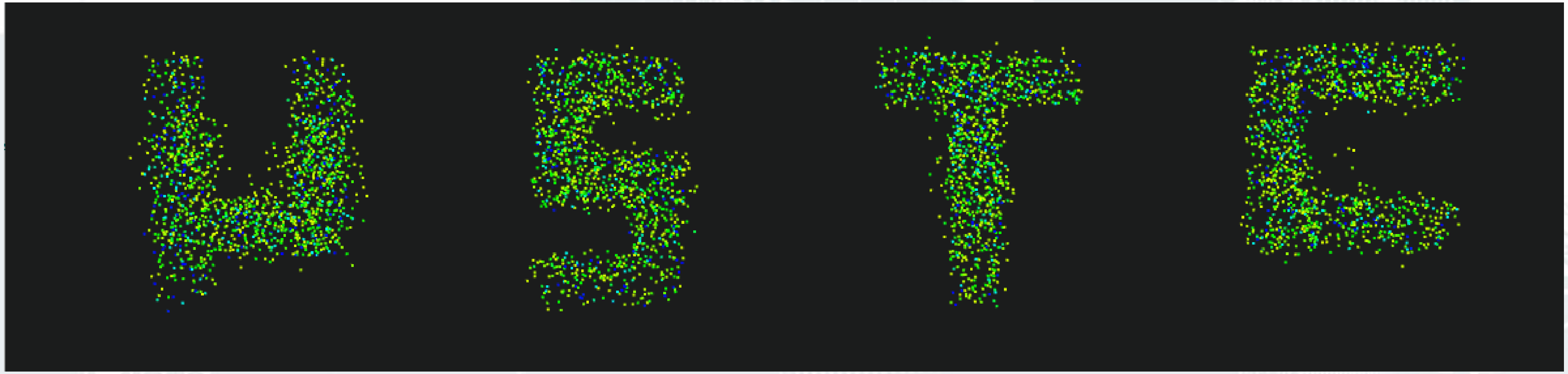




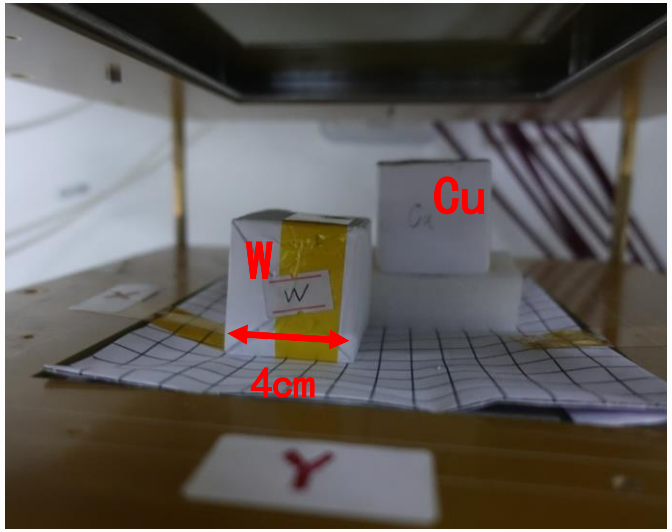
4-hour exposure

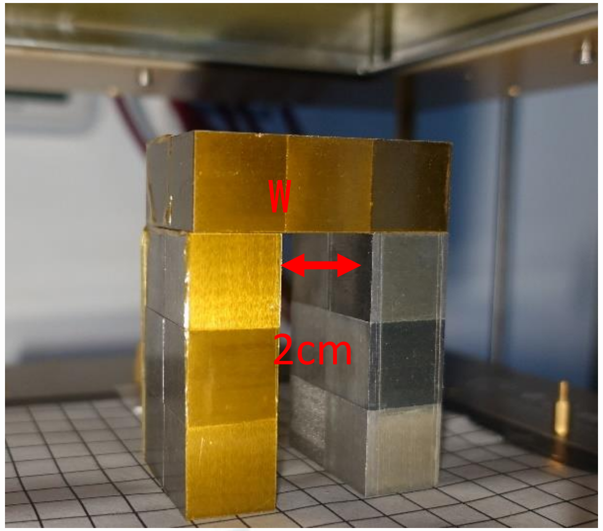


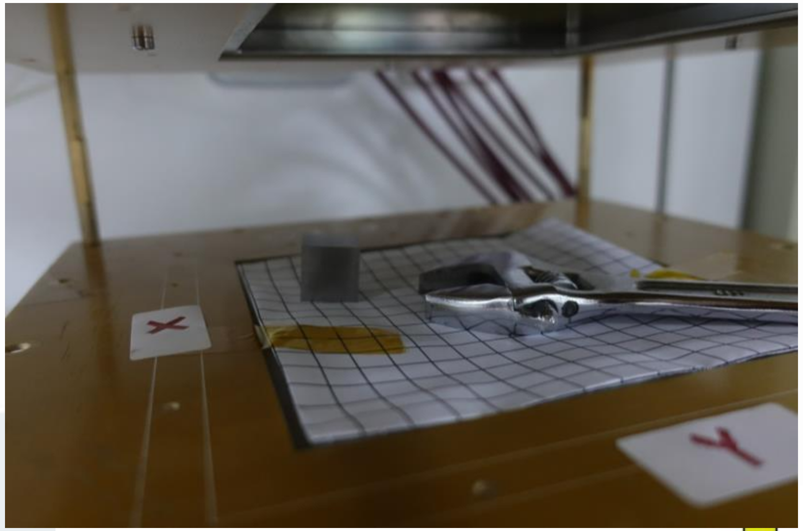
24-hour exposure

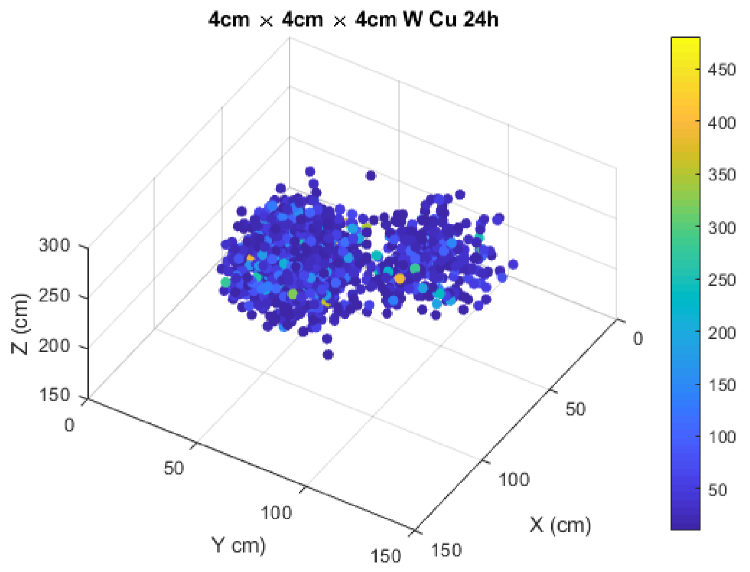


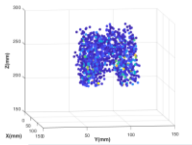
Small size prototype for tomography

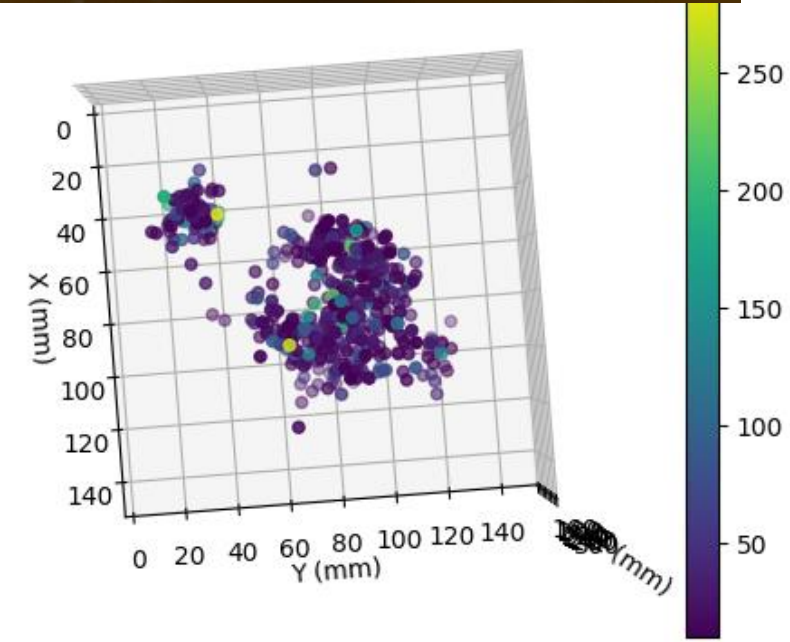








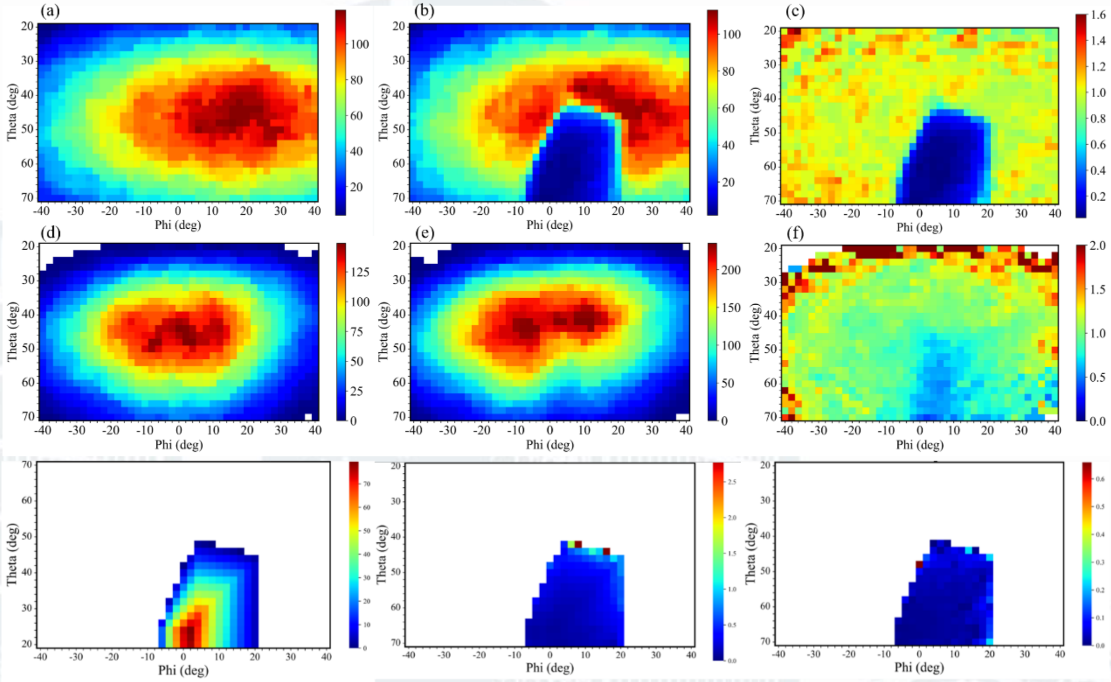




Small size prototype for radiography

- First μSTC-R prototype: (2021.01-2021.05)
  - 4 layers of 15 cm × 15 cm Micromegas
  - ~100 μm resolution

Radiography with a building for verification test



Middle size prototype

- Second generation of μSTC prototypes: (2021.01-now)
  - Upgrading with the larger detectors of 40 × 40 cm^2
  - Compression ratio 8:1

Tomography μSTC-T-G2
8layer, total number of channel: 16k

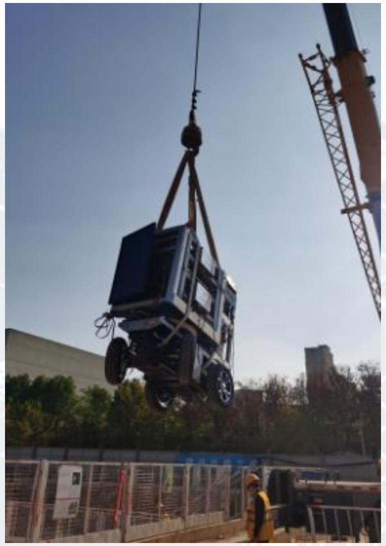
Radiography μSTC-R-G2
4layer, total number of channel: 8k

Radiography in subway tunnel

› A river flows over the tunnel

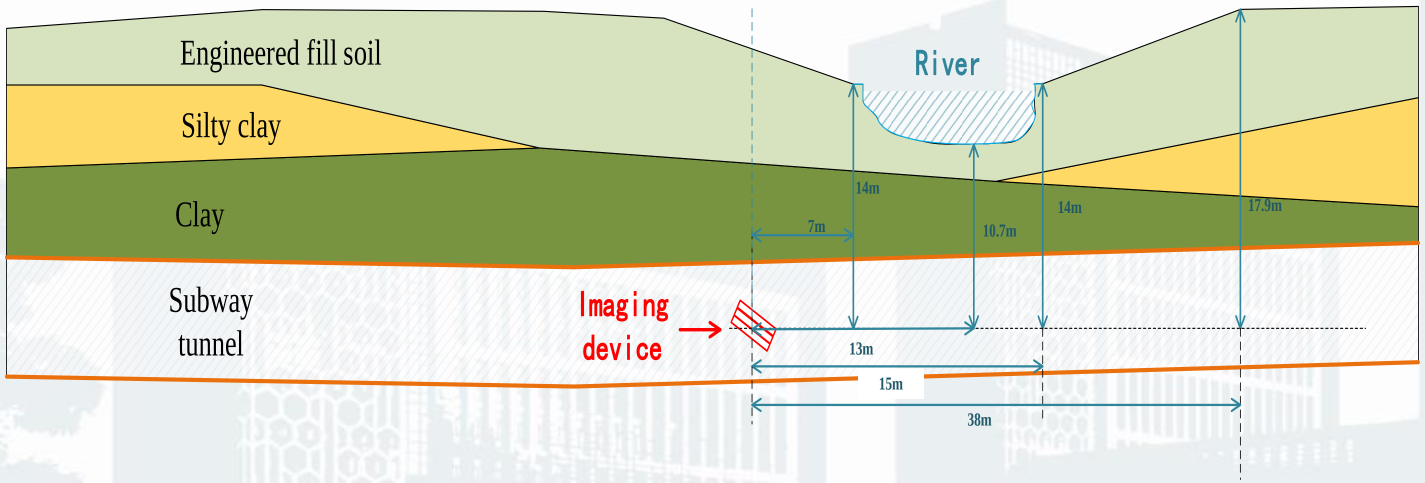
› Operating Environment: Construction site
  - Large amount of dust
  - Presence of water vapor
  - Strong vibrations

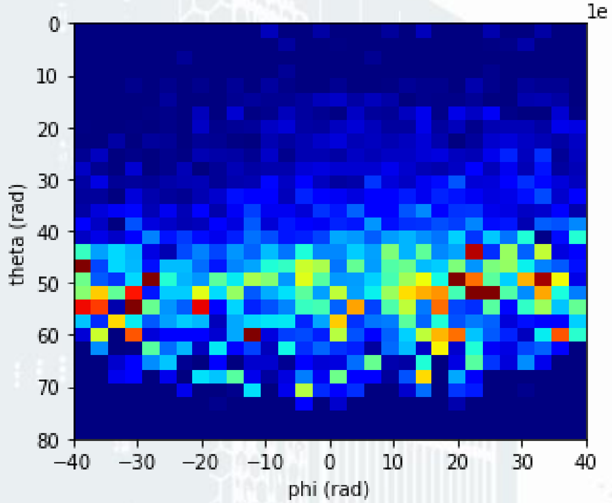
Adaptability to harsh environments confirmed
Device successfully operated in challenging conditions



› The device is placed inside the tunnel, aligned at a 30-degree angle to the river channel

  – Measure muon flux in both the 30° and -30° directions
  – Test for river data: 12 days
  – Test for reference data: 6 days



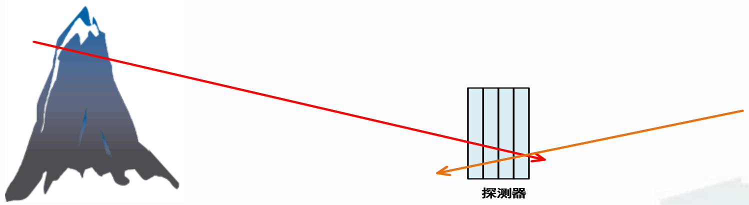


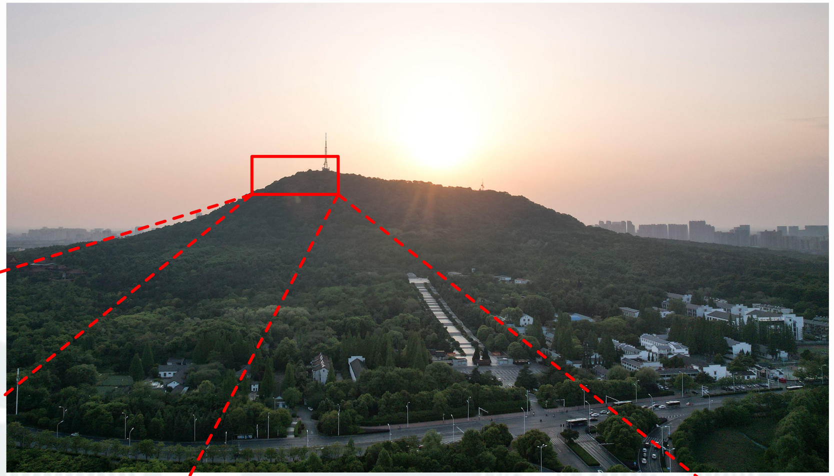
Radiography of Mt. Dashu

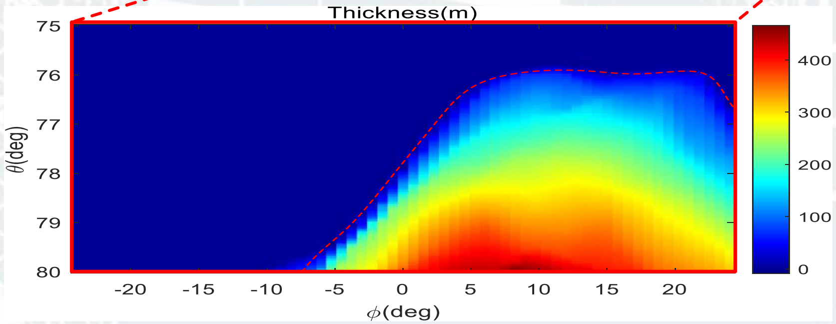
- An ancient volcano formed 65 million years ago
- Nearby the urban area of Hefei city
- Altitude of the mountain and facility （μSTC-R-G2） is 280m and 60 m respectively

Radiography of Mt. Dashu

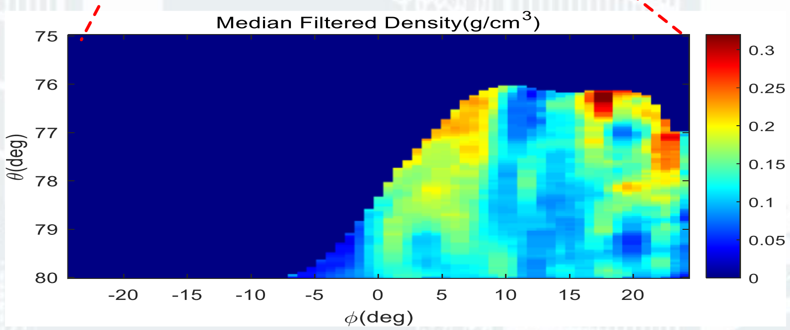
- The μSTC-R-G2 was set at horizontal angle
  - Recording muons from both mountain side and the other side (for reference)
- Test for duration more than 4 months
  - Winter -> Next Spring







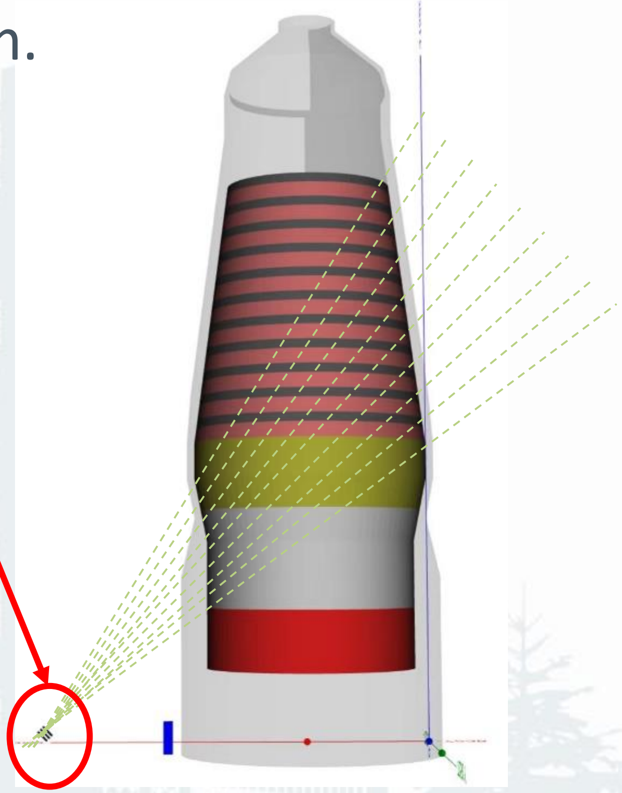
The path length of a muon through an object



The density distribution after median filtering

Radiography at Anyang Steel Plant

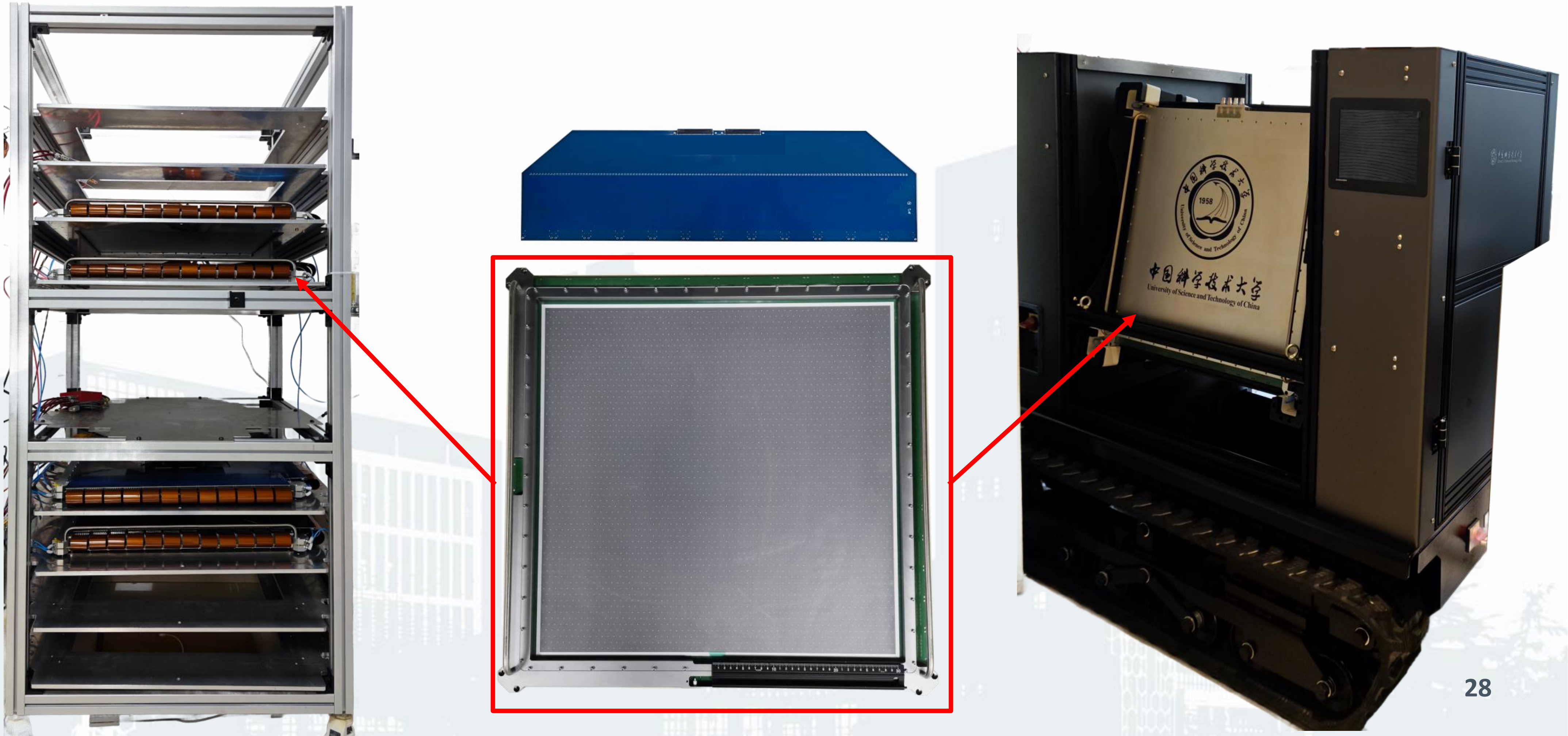
- Industrial application demonstrates the potential of high spatial resolution muography for imaging dense structures
  - Continuously running for 10 months (Still running)
  - The radiography was conducted in a challenging, dusty environment, demonstrating the robustness of our muography system.



Third generation of μSTC facilities

With 60 cm × 60 cm detectors and 12:1 compression circuits

You are welcome to visit our laboratory in room C1404



Summary

- We proposed and finally built high resolution facilities (μSTC) for muography study using Micromegas detector, low noise electronics and encoding readout method.
- The performance including high resolution, long-term stability and environmental adaptability were verified.
- Owning to the high resolution and modular design, it will be convenient to extend and fulfill other muography applications.

Outlook

- A larger detector device is under construction and will shorten the imaging time.
- More rapidly image algorithm will be developed.

Thank you for your attention！

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