INFN
Istituto Nazionale di Fisica Nucleare

Resistive Pixelized Micromegas for Applications at Future Colliders

Kacper Chmiel – On behalf of the RHUM Project*

*Resistive High granUlarity Micromegas for Future Detectors:

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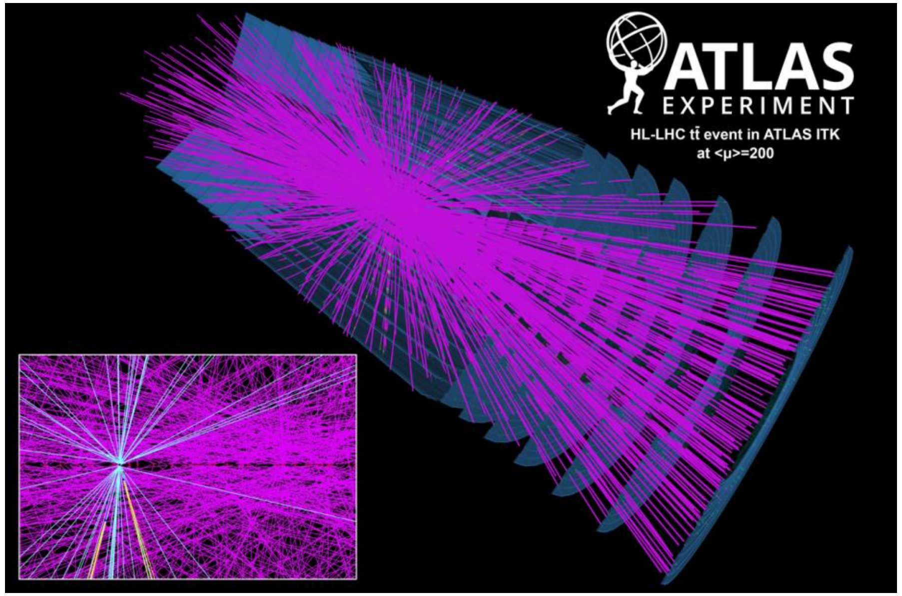
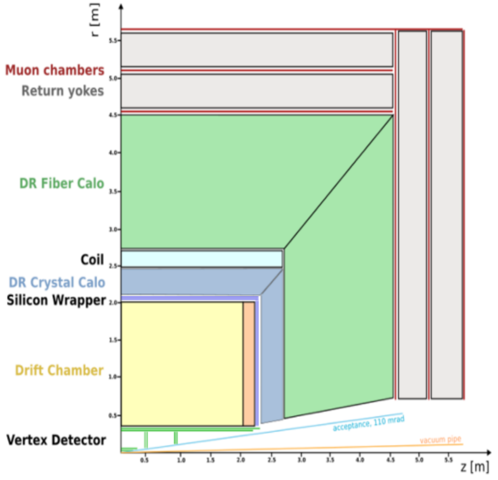
The two regimes of operation

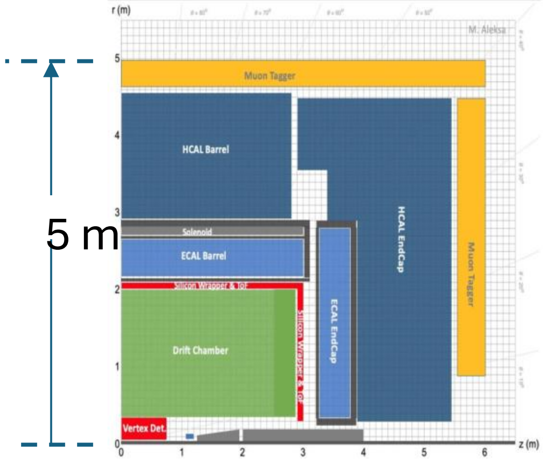
- Future detectors pose **new challenges** that the RHUM project is tackling at once.
- With the LS2 of LHC next-door, the HL-LHC phase is closer then ever. **Extreme particle rates** are to be expected in the very forward region, with **tracking detectors** that need both to be **fast and precise** (Large-eta-tagger option for Run 5, after LS3).
- **Enormous surfaces** (e.g., $\sim 500\ \mathrm{m}^2$ as educated guess for the IDEA or ALLEGRO muons systems at FCC-ee), needing **cost-effectiveness with low-rate capabilities** ($< 1\ \mathrm{kHz\ cm}^{-2}$)
- Finally, **extreme particles rates** are to be expected again with new hadronic collider (e.g., **FCC-hh**).



ATLAS HL-LHC



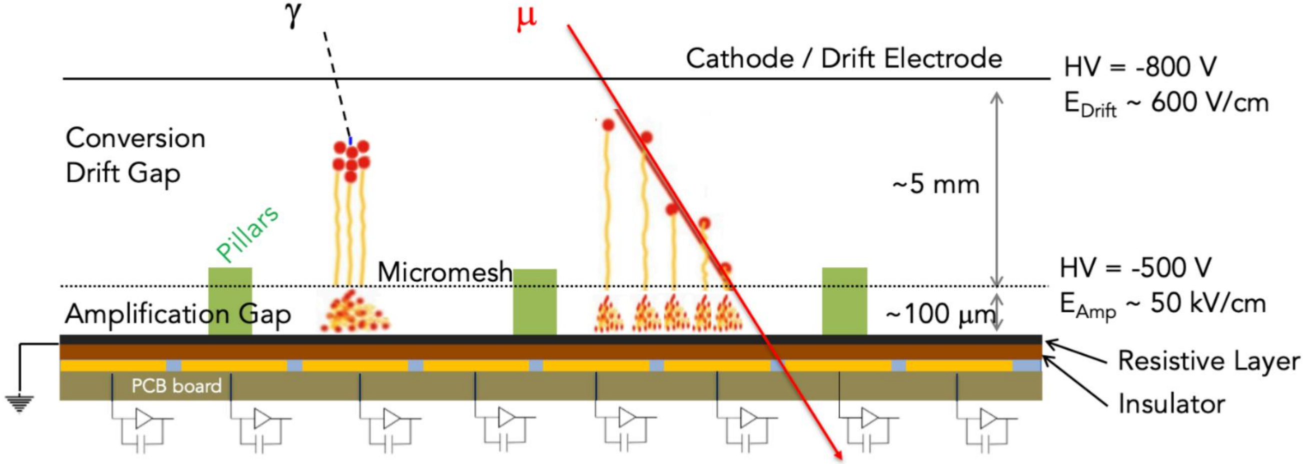
IDEA

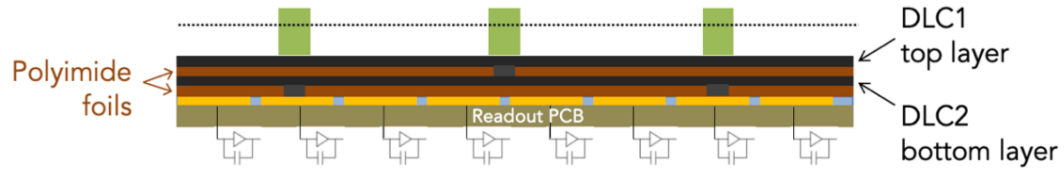


Allegro

The core solution: Resistive layout

- Resistive Micromegas (MM) are a single stage gaseous detectors:
  - The active volume is divided into two, by means of a metallic mesh: a conversion gap and an amplification gap.
- The **drift region** is of ~ 5 mm while the **amplification region** is of ~ 120 µm.





Double-layer DLC layout

- **Different resistive configuration** have been tested over the years, to maximize stability and performance.
- A single DLC layer is sufficient for low to medium rates, **provided the detector dimensions are optimized**.
- On the other hand, if one wants to achieved the most extreme particle rates, the double-layer DLC layout comes king.
- Grounding vias layout (every ~ 8 mm) is crucial for fast charge evacuation, enabling those high rates.
- **Tested resistivity** goes from $5\ \text{M}\Omega/\square$ to $50\ \text{M}\Omega/\square$.

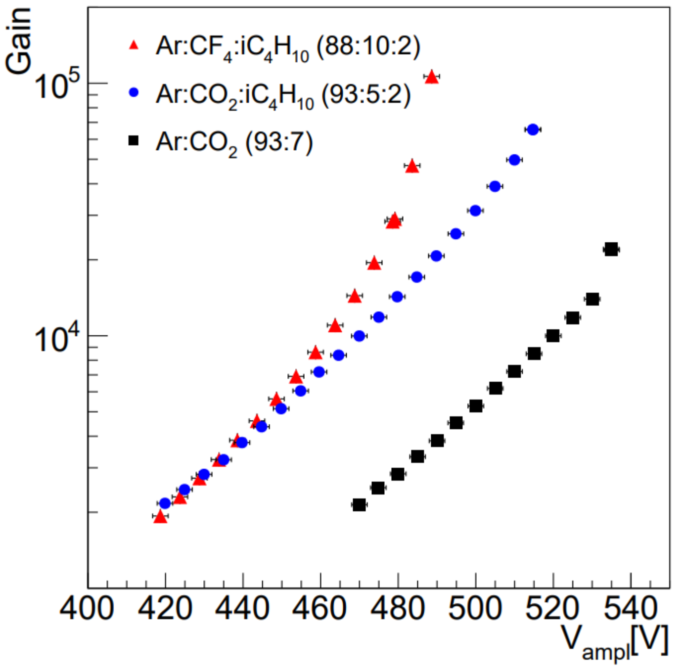
Proven high-rate capability

DLC-20: $4.8 \times 4.8\ \mathrm{cm}^2$ area, $1 \times 3\ \mathrm{mm}^2$ pad size.

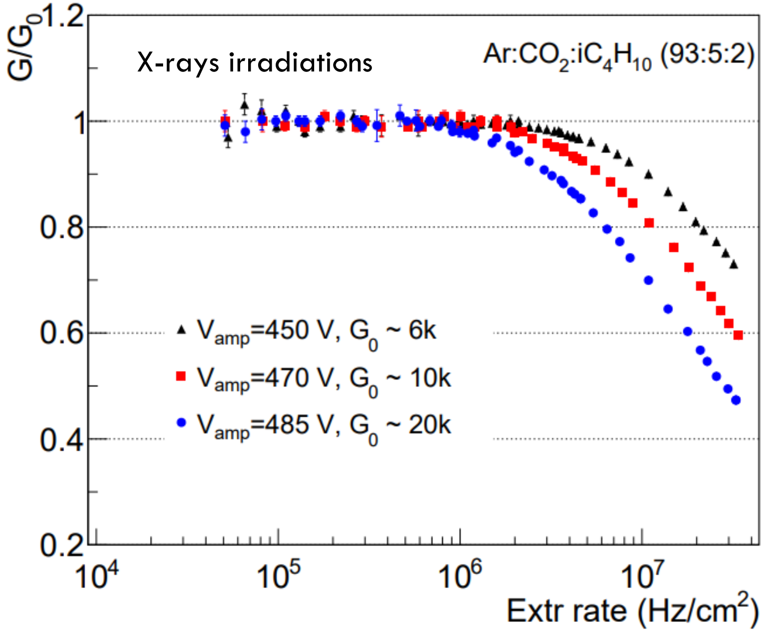
Paddy-400: $20 \times 20\ \mathrm{cm}^2$ area, $1 \times 8\ \mathrm{mm}^2$ pad size

$R = 20 - 20\ \mathrm{M\Omega}/\square$ (top –bottom)

$R = 25 - 35\ \mathrm{M\Omega}/\square$



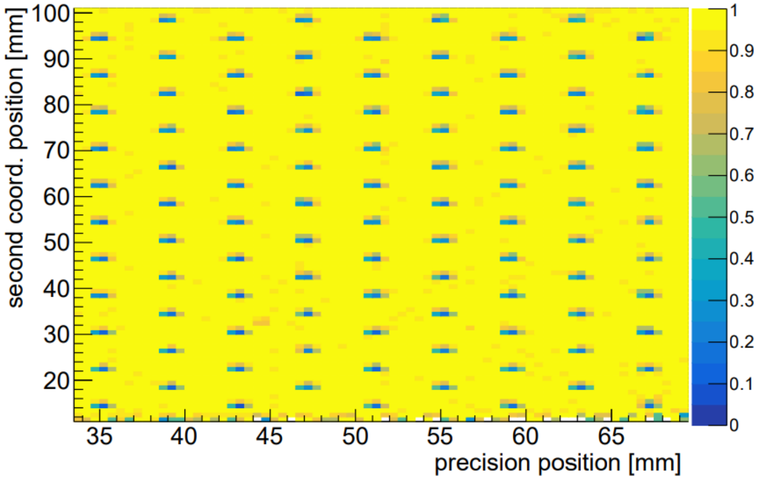
The double DLC layout proves **excellent stability** reaching **gains** as high as $\mathbf{10^5}$ adding only 2% of iC_4H_{10}.



Gain drop at $10\ \mathrm{MHz\ cm^{-2}}$ limited to:

- 10% at G_0=6k;
- 20% at G_0=10k;
- 30% at G_0=20k;

CERN SPS perpendicular muon beam



The detectors **reaches** nearly **100% efficiency** in the active areas. The supporting mesh **pillars** can be identified as the **inefficiency spots**. This effect is mitigated with inclined tracks.

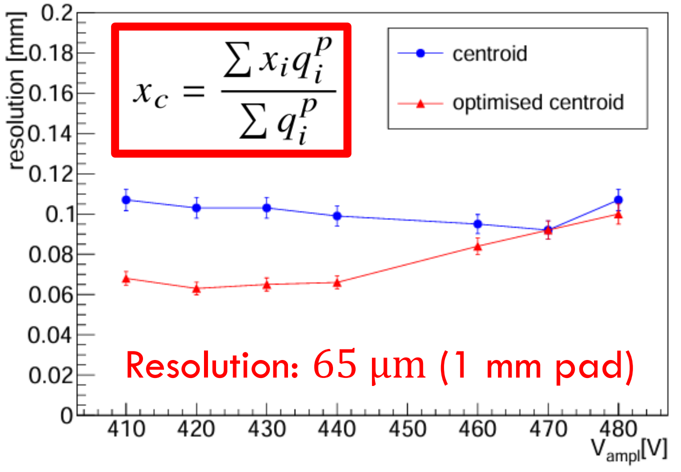
M. Alviggi et al 2025 JINST 20 P01012

Precision tracking in space and time

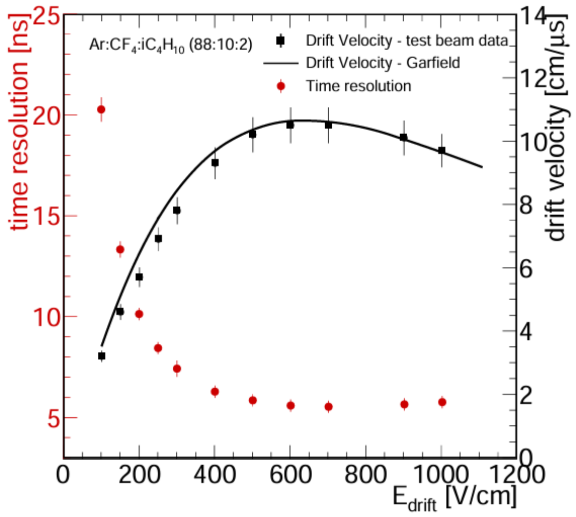
Paddy-400: $20 \times 20\ \mathrm{cm}^2$ area, $1 \times 8\ \mathrm{mm}^2$ pad size

$R = 25 - 35\ \mathrm{M}\Omega/\square$

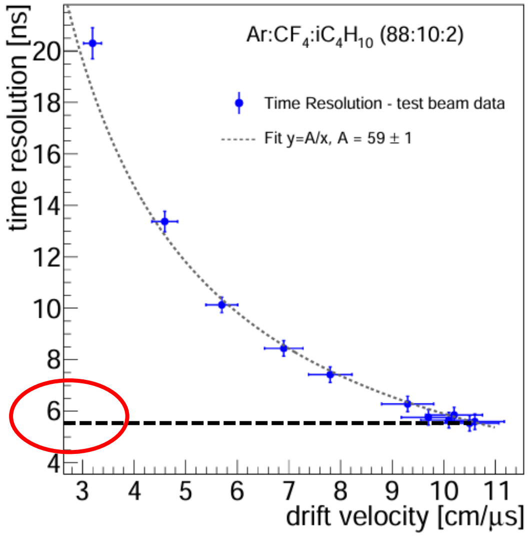
CERN SPS perpendicular muon beam



- Resolution of $< 100\ \mu\mathrm{m}$ is reached with the **standard centroid**.
- Best resolution: $< 70\ \mu\mathrm{m}$ reached with **optimized centroid** (p=0.65).

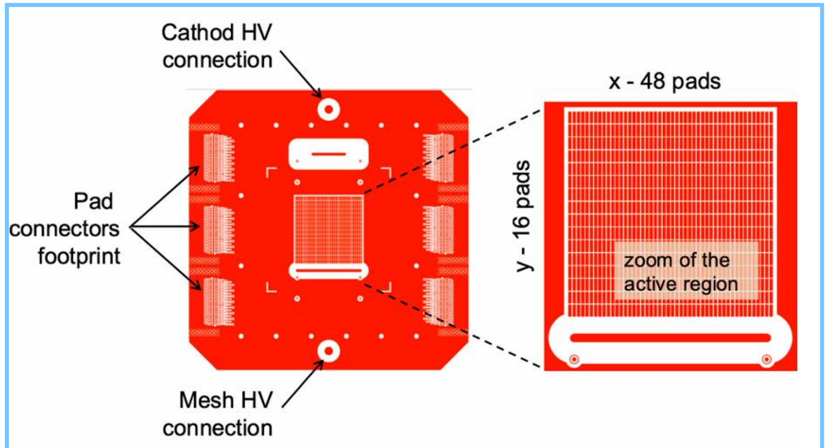


- Time resolution and drift velocity as a function of the drift electric field.
- The drift velocity is obtained from the width of the time distribution of all hits in reconstructed cluster.

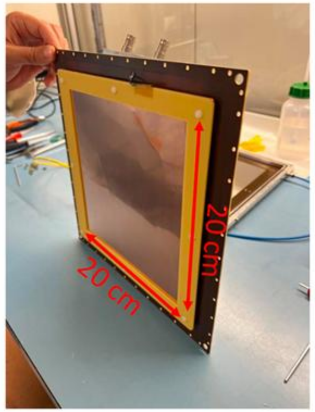


- A time resolution of ~ 5.5 ns is reached using a fast gas mixture with CF_4.
- We achieve excellent timing and spatial resolution.

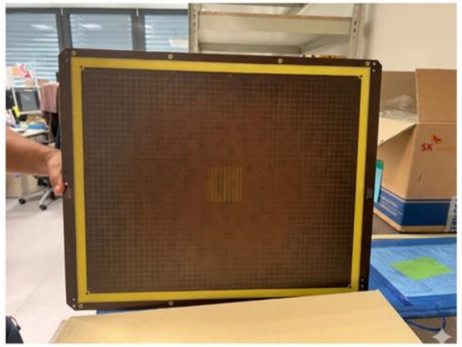
Scalability: From small to big chambers



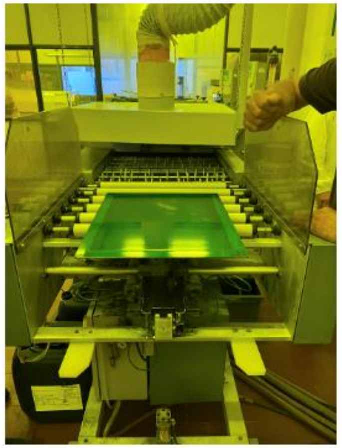
$4.8 \times 4.8 \text{ cm}^2$ area



$20 \times 20 \text{ cm}^2$ area

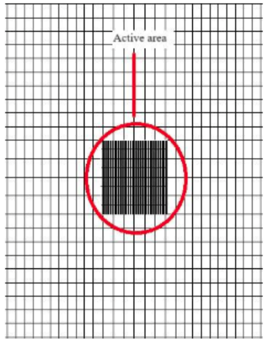


$50 \times 40 \text{ cm}^2$ area

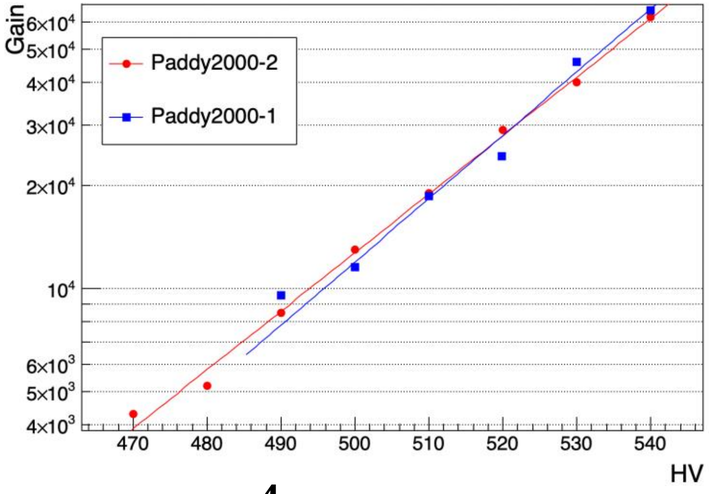


- To improve and further consolidate the construction process we are actively partnering with industries.
- Here illustrated is the production effort with the Italian ELTOS.

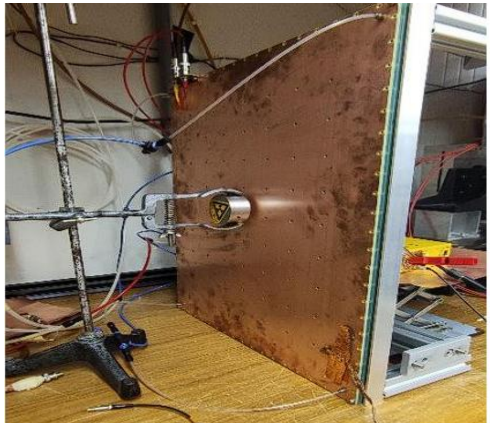
Performance of Large Area Resistive Micromegas

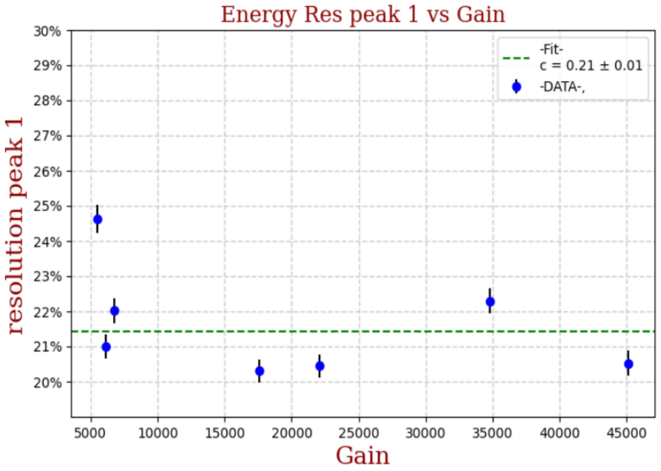


Readout $6.4 \times 6.4\ \text{cm}^2$
1x8 mm^2 pads.



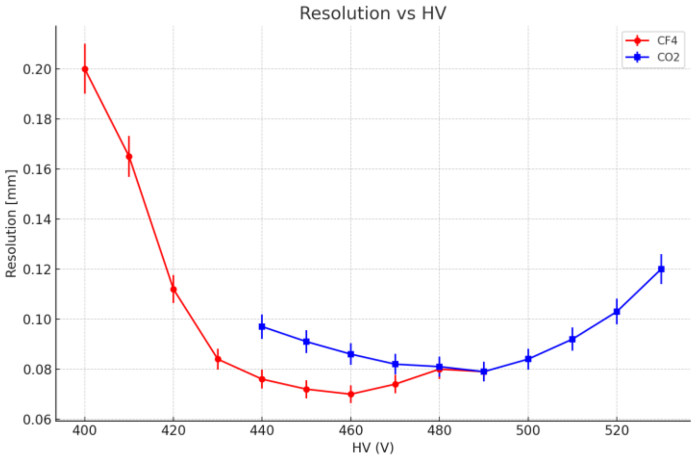
Stability to gains up to $\mathbf{6 \times 10^4}$.

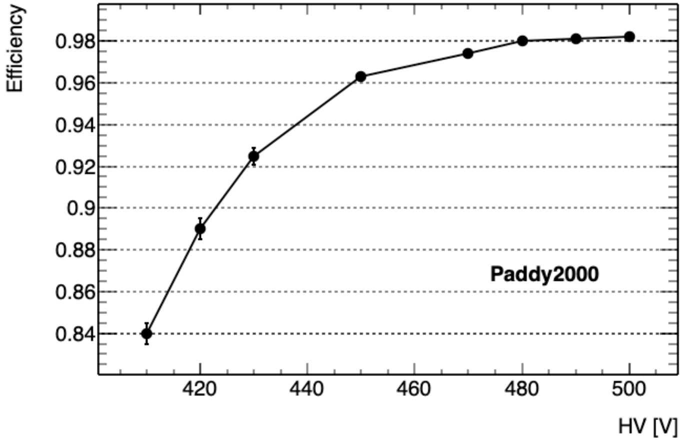


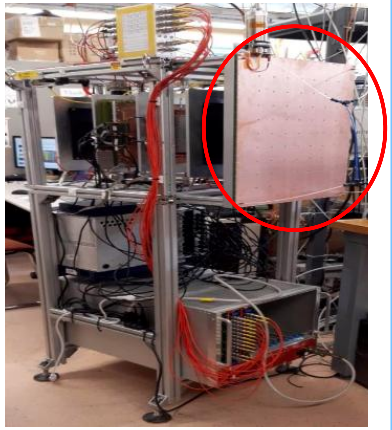


Mean energy resolution of 21% at 5.9 keV peak of ^{55}Fe.

CERN SPS perpendicular muon beam







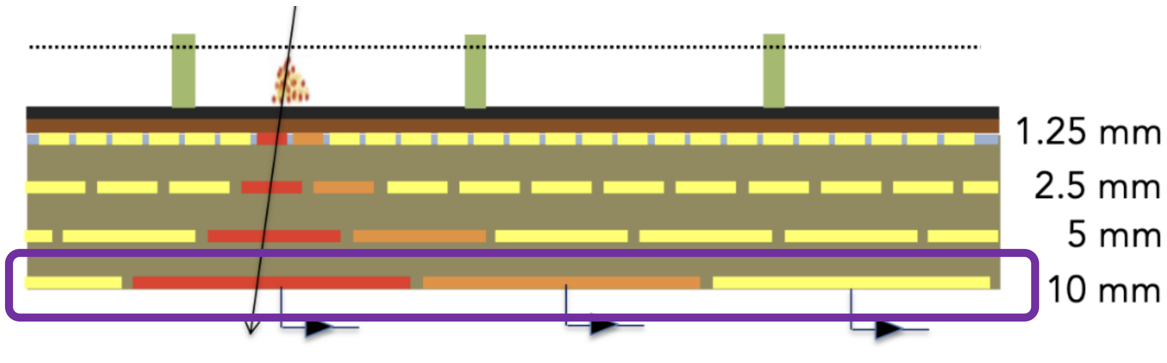
Spatial **resolution** of $< \mathbf{80\ \mu m}$ with $\sim \mathbf{98\%}$ **efficiency** include pillars dead area.

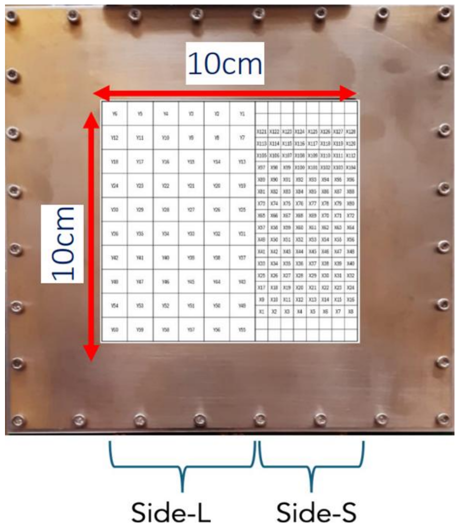
The large size prototype (Paddy-2000) proves excellent stability and performance confirming its potential scalability.

Reducing channels for large areas

- For very large areas, reading out every pad becomes demanding in terms of cost and complexity. We need to reduce channels without losing precision.
- The capacitive-sharing layout enables the use of a coarser pad geometry, **reducing the readout electronic channels**, while **preserving spatial resolution**.

(Idea from: K. Gnanvo et al., Nucl. Instrum. Meth. A 1047 (2023) 167782)





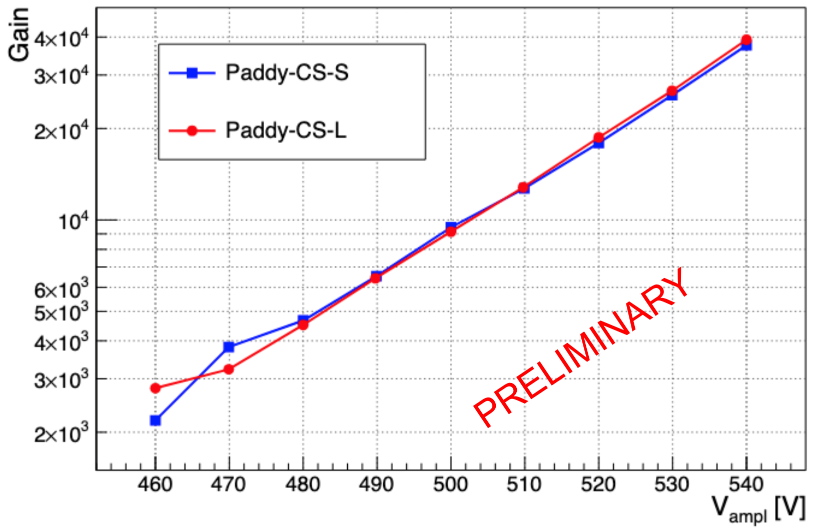
- Our **first capacitive-sharing prototype** (Paddy-CS) was realized with a **dual geometry**, to enable to simultaneous study of two different geometries.

- Both the sides have **four layers** with the following geometry:
- Side L: $1.25 \times 1.25\ \mathrm{mm}^2 \rightarrow 2.5 \times 2.5\ \mathrm{mm}^2 \rightarrow 5 \times 5\ \mathrm{mm}^2 \rightarrow \mathbf{10 \times 10\ mm^2}$
- Side S: $1.25 \times 1.25\ \mathrm{mm}^2 \rightarrow 2.5 \times 2.5\ \mathrm{mm}^2 \rightarrow 5 \times 5\ \mathrm{mm}^2 \rightarrow \mathbf{5 \times 5\ mm^2}$

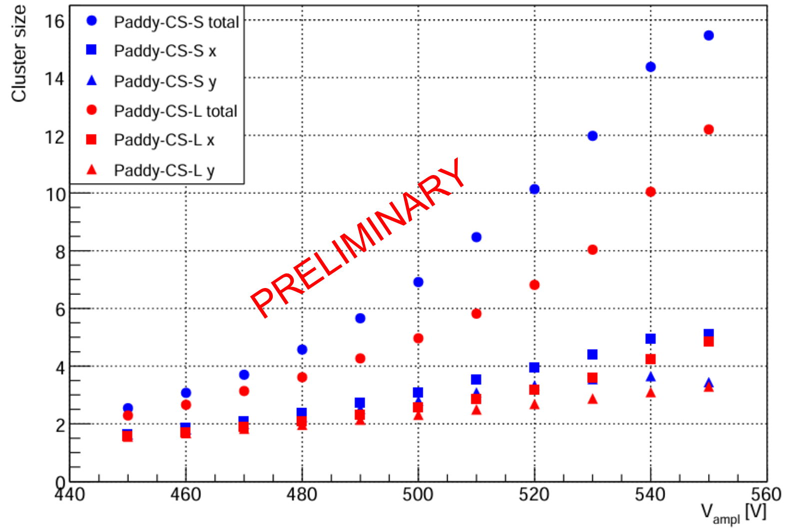
- Since **larger readout** pads **increase occupancy,** this design is only **suitable** from **low** to **medium rate particle fluxes**.

CS performance: Precision with Macro-Pads

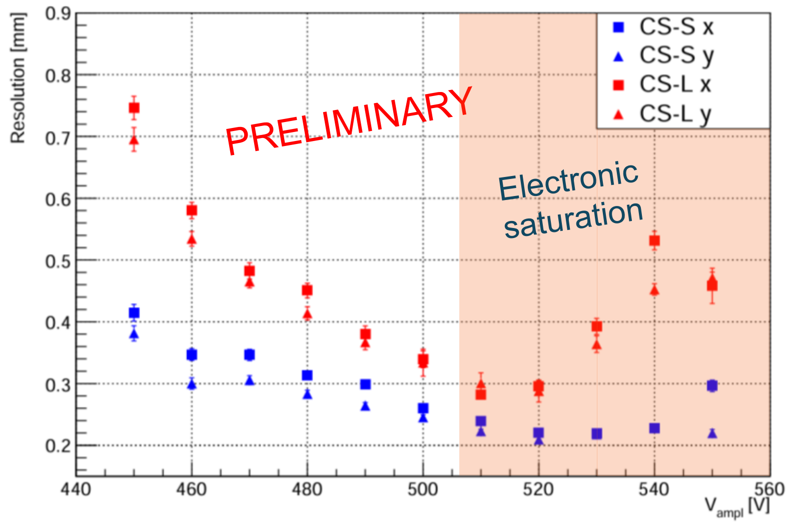
CERN SPS perpendicular muon beam



- Gain vs amplification voltage.
- Gains up to 4×10^4, with excellent stability.



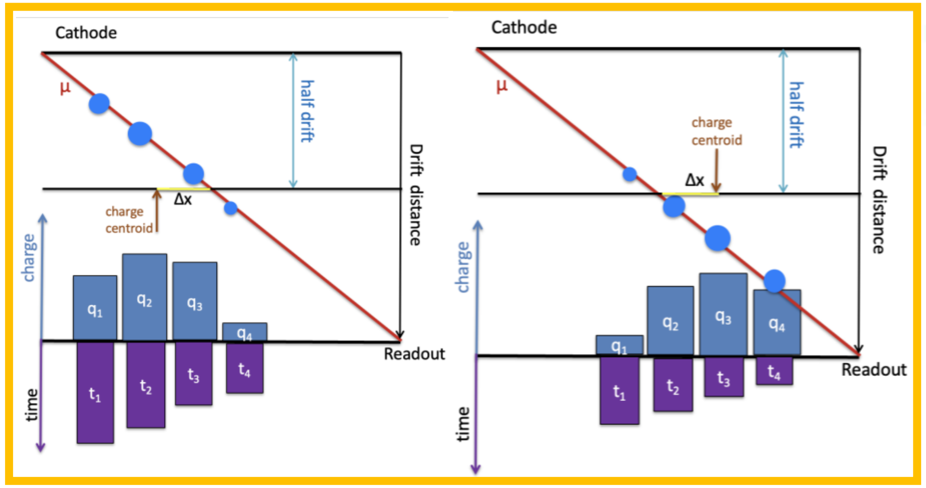
- Cluster size vs amplification voltage for cluster on track.
- Large cluster size, proving the capacitive-sharing.

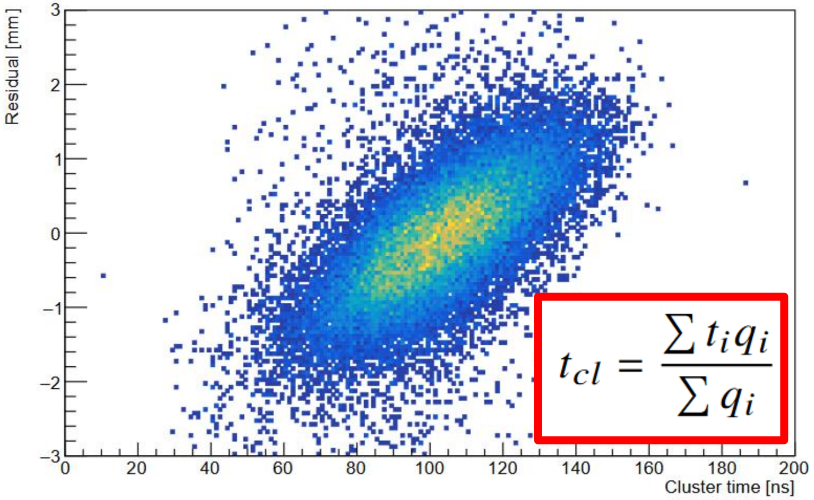


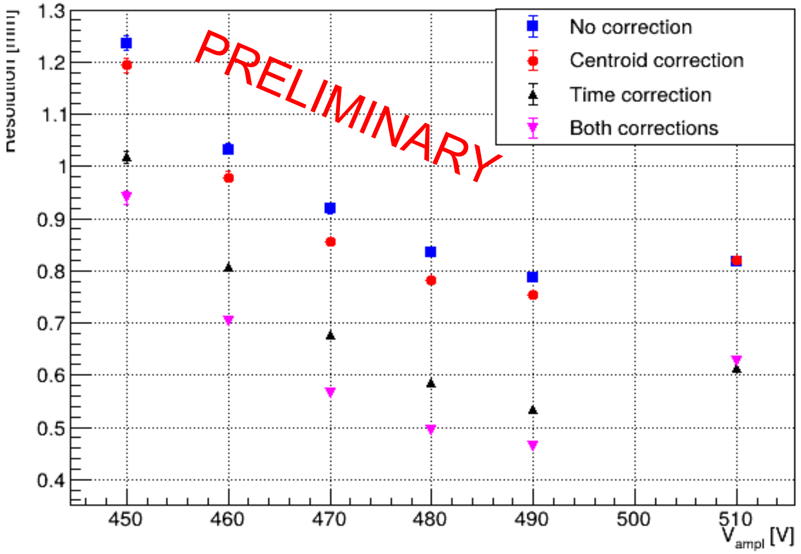
Resolution as low as $\mathbf{320\ \mu m}$ are achieved with the $\mathbf{10 \times 10\ mm^2}$ pads, and $\mathbf{250\ \mu m}$ with the $\mathbf{5 \times 5\ mm^2}$ pads.

CS performance: Precision with Macro-Pads

CERN SPS **inclined** muon beam

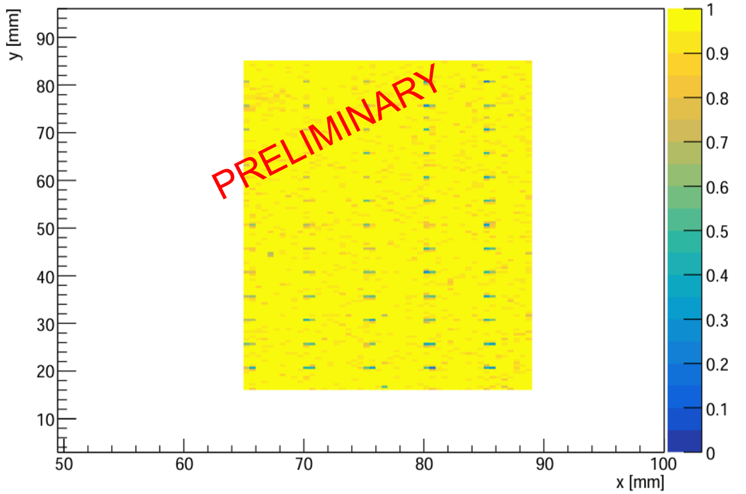






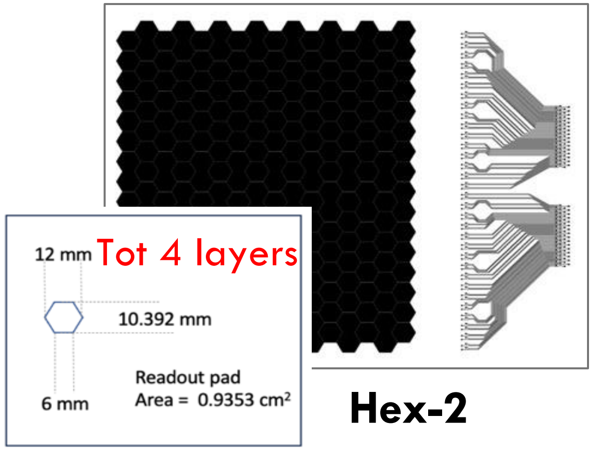
- For inclined tracks at **fixed angle**, a proportionality is observed between the cluster time and the residual.
- A resolution of 800 μm is obtained with ~ **38° inclined tracks** for $10 \times 10\ \mathrm{mm}^2$ pads.
- Using the **time information** and the **centroid optimization**, we obtain < **500 μm** for $10 \times 10\ \mathrm{mm}^2$ pads.

CERN SPS perpendicular muon beam

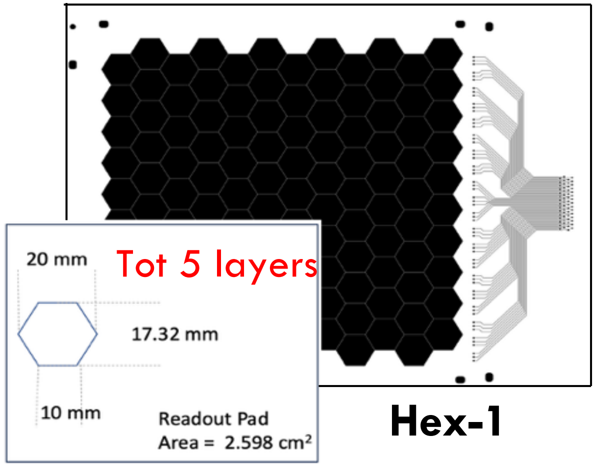


~ 100% efficiency away from the pillar's dead areas.

New geometries

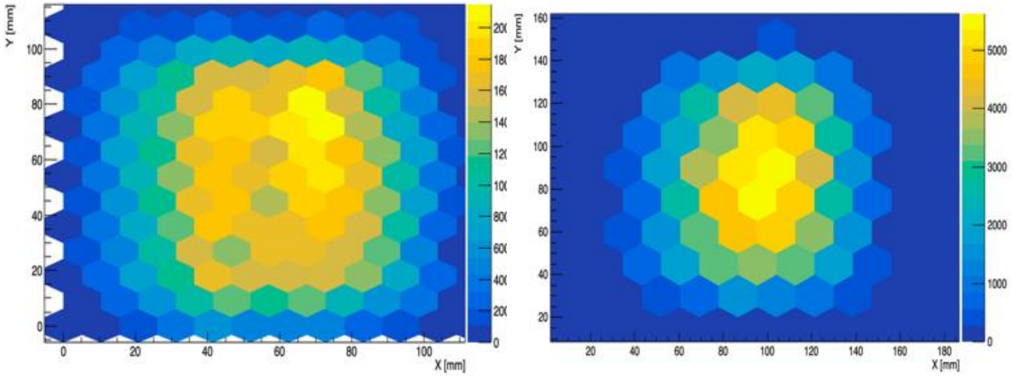


Hex-2



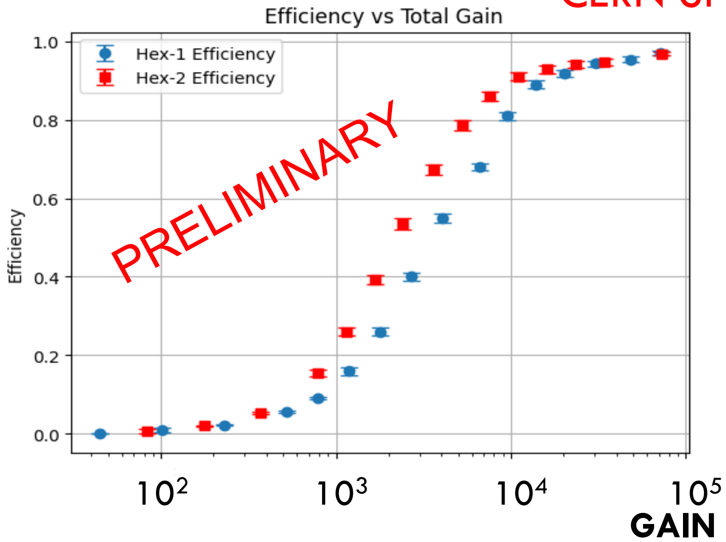
Hex-1

To further explore the CS potential and its limits, prototypes with more layers and hexagonal geometries were realized.



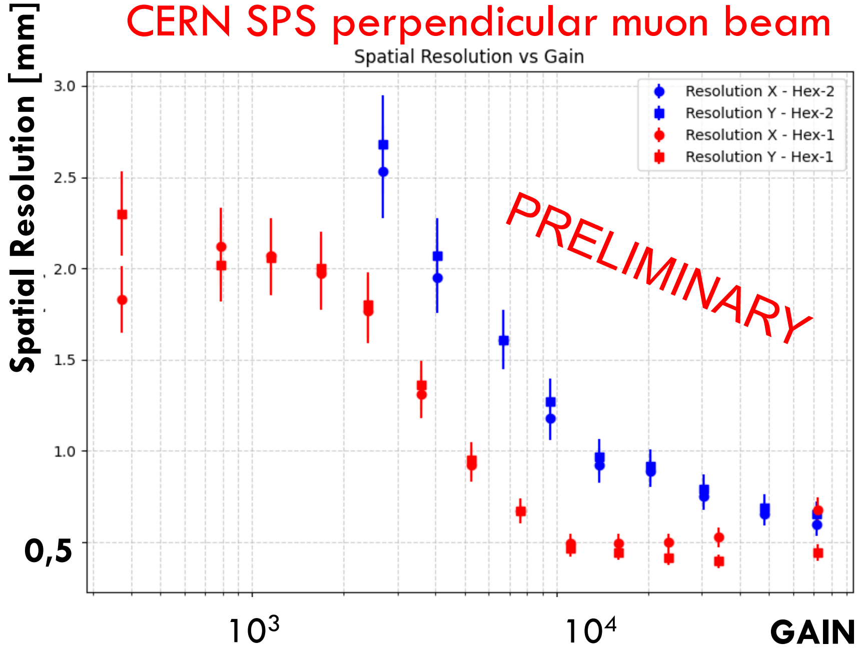
Beam spot seen from the two hexagonal prototypes.

CERN SPS perpendicular muon beam



- Both prototypes prove to be fully efficient.
- The prototype with one additional CS layer, lags a bit behind
- Cuts in charge are still not optimized and studies are ongoing.

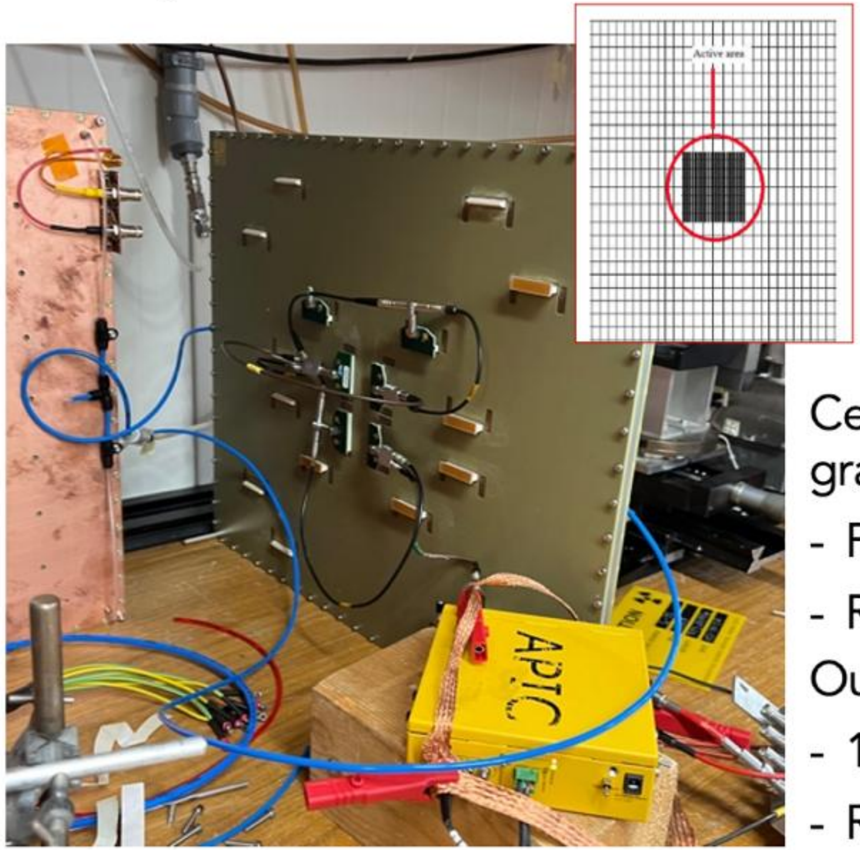
CERN SPS perpendicular muon beam



Both prototypes reach ~ 500 μm resolution, but at sensibly different gains.

Large area capacitive-sharing

- Two NEW LARGE-SIZE Resistive Micromegas
  - double layer DLC
  - 3 layers CAPACITIVE SHARING

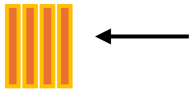


Active Area
50x40 cm^2

Central area with finer granularity:
- First layer 1x2 mm^2 pads
- Readout layer: 1x8 mm^2

Outer region:
- 1st layer: 2.5 x 2.5 mm^2
- Readout layer: 10 x 10 mm^2

Readout patterns in the $6.4 \times 6.4\ \mathrm{mm}^2$ **central** region

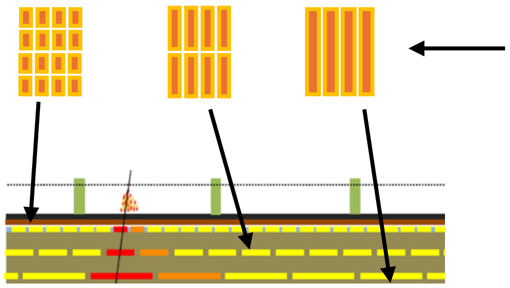


Pad pattern
Readout layer:
1x8 mm^2

Standard layout

1st layer:
1x2 mm^2

2nd layer:
1x4 mm^2



Pad pattern
Readout layer:
1x8 mm^2

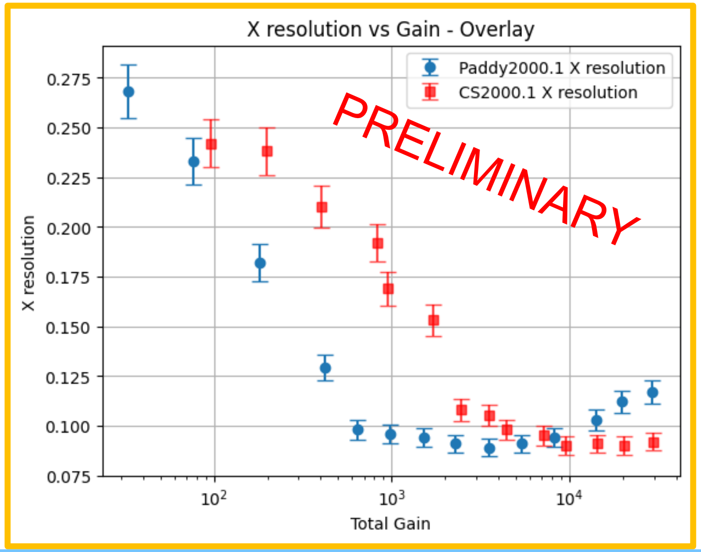
Capacitive-sharing layout

With **this CS layout** we aim to **improve** the resolution on the **y-coordinate, while** leaving the **x-coordinate** resolution **unchanged compared to the standard** layout.

Large area CS performance

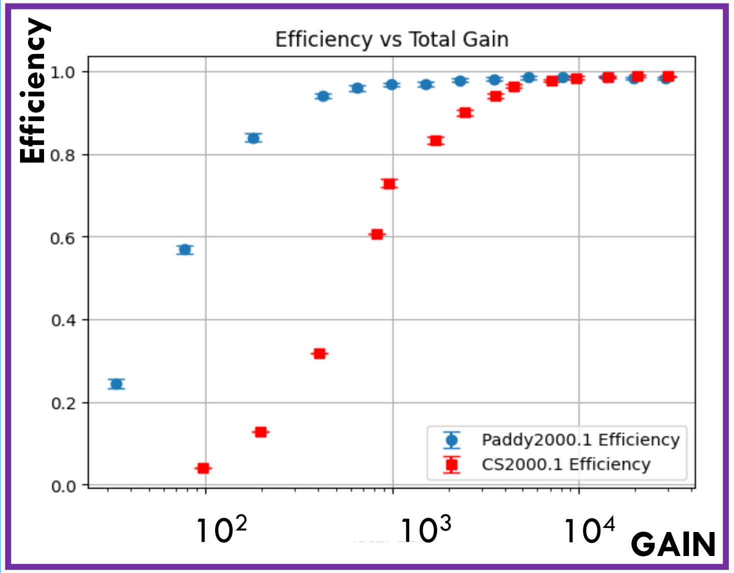
CERN SPS perpendicular muon beam

X-coordinate
1 mm pad size
Non-CS direction
Resolution



- **Comparable** spatial resolution ~ 80 µm.
- **Larger gains needed** for the **CS layout.**

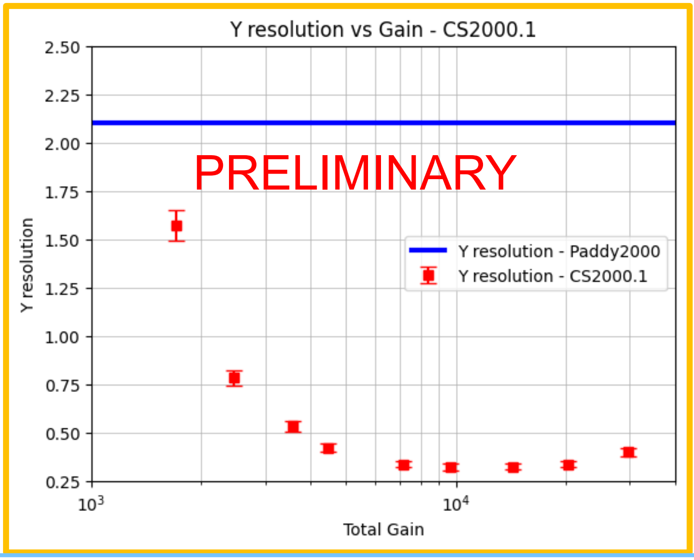
Overall **efficiency** comparison.



- The CS layers do not penalize the efficiency.
- Still, the CS prototype needs higher gains to reach same efficiency.

CERN SPS perpendicular muon beam

Y-coordinate
8 mm pad size
CS direction
Resolution



- Non-CS layout resolution: ~ 2 mm.
- **CS layout resolution: ~ 300 µm**
- Greatly improved resolution.

Summary

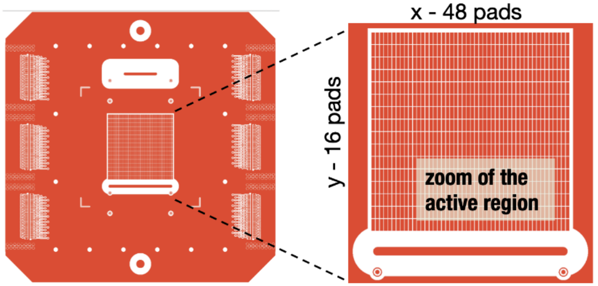
1. **High-rate performance**
   - **Extreme Rate Capability**: Validated stable operation up to 10 MHz/cm^2 with gain $>10^4$.
   - **Precision**: Achieved spatial resolution **< 70 μm** (with 1 mm pads) and time resolution of **~5–6 ns**.
   - **Robustness**: Double-DLC resistive scheme effectively prevents sparking, and voltage drops even at high flux.
2. **Scalability & Industrialization**
   - **Large Area Prototyping:** Successfully scaled from small R&D sensors to the **Paddy-2000 (50×40 cm^2)** module.
   - **Uniformity:** Beam tests confirm that large-area performance matches that of small prototypes (efficiency > 98%).
   - **Manufacturing:** Technology transfer with industry partners (ELTOS) is established with promising results.
3. **Capacitive Sharing**
   - **Channel Reduction**: Demonstrated a channel count reduction of factor >20 by using large readout pads (1-2 cm^2).
   - **Resolution:** Maintained tracking precision of **~300–400 μm** despite the large pad size.
   - **Validation:** New **CS-2000** prototype confirms the technique works on large-scale modules with efficiency comparable to standard readout.

Thank you for the attention!

Backup

Scalability : Towards Large Size Pixelised Micromegas

small size prototypes

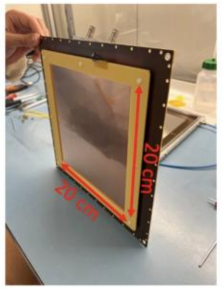


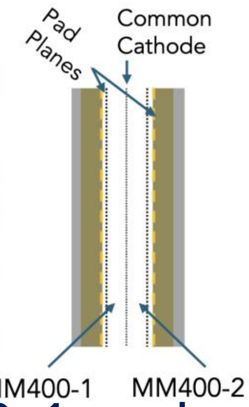
active area : 4.8cm x 4.8 cm

segmented in 48 x 16 readout pads

pad size: 1 x 3 mm^2

medium size prototypes





Two detectors Paddy400-1 and Paddy400-2

active area : 20 cm x 20 cm (40% readout in central part)

Anode plane pad size: 1 x 8 mm^2

also tested successfully in sandwich config sharing the same cathode

large size prototype

“The Big one”
Paddy-2000: 50 x 40 cm^2
Readout central region 6.4x6.4 cm^2 with 1x8 mm^2 pads

Surrounding area – 2048 pads, 10x10 mm^2

SPS-H4 November 2025 – detector setup

All Resistive Micromegas

- 3 trackers
- 6 Detectors under test

Gas Mixtures:

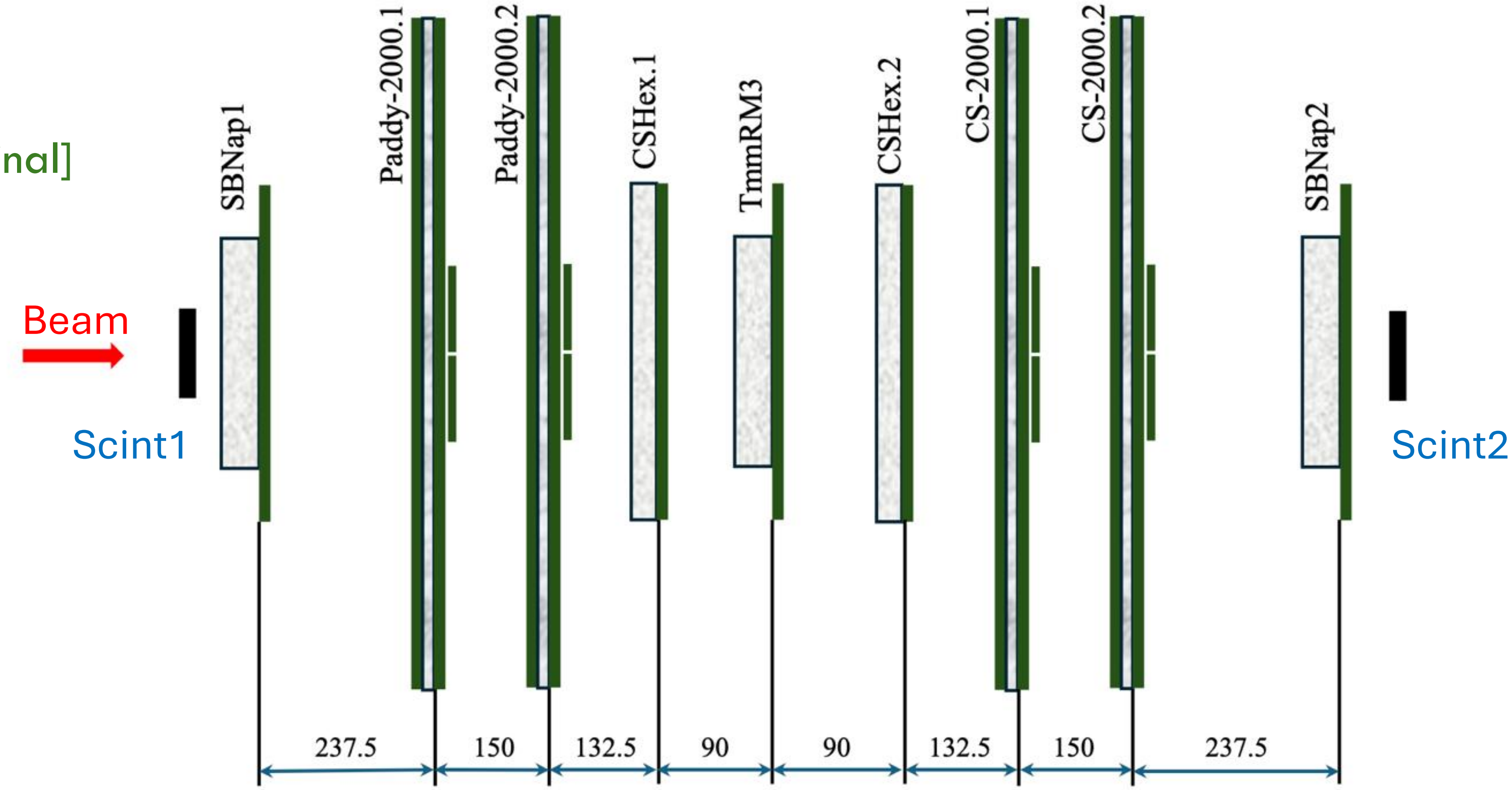
- Ar-CO2-iC4H10 (93-5-2) [Nominal]
- Ar-CF4-iC4H10 (88-10-2)
- Ar-iC4H10 (98-2)

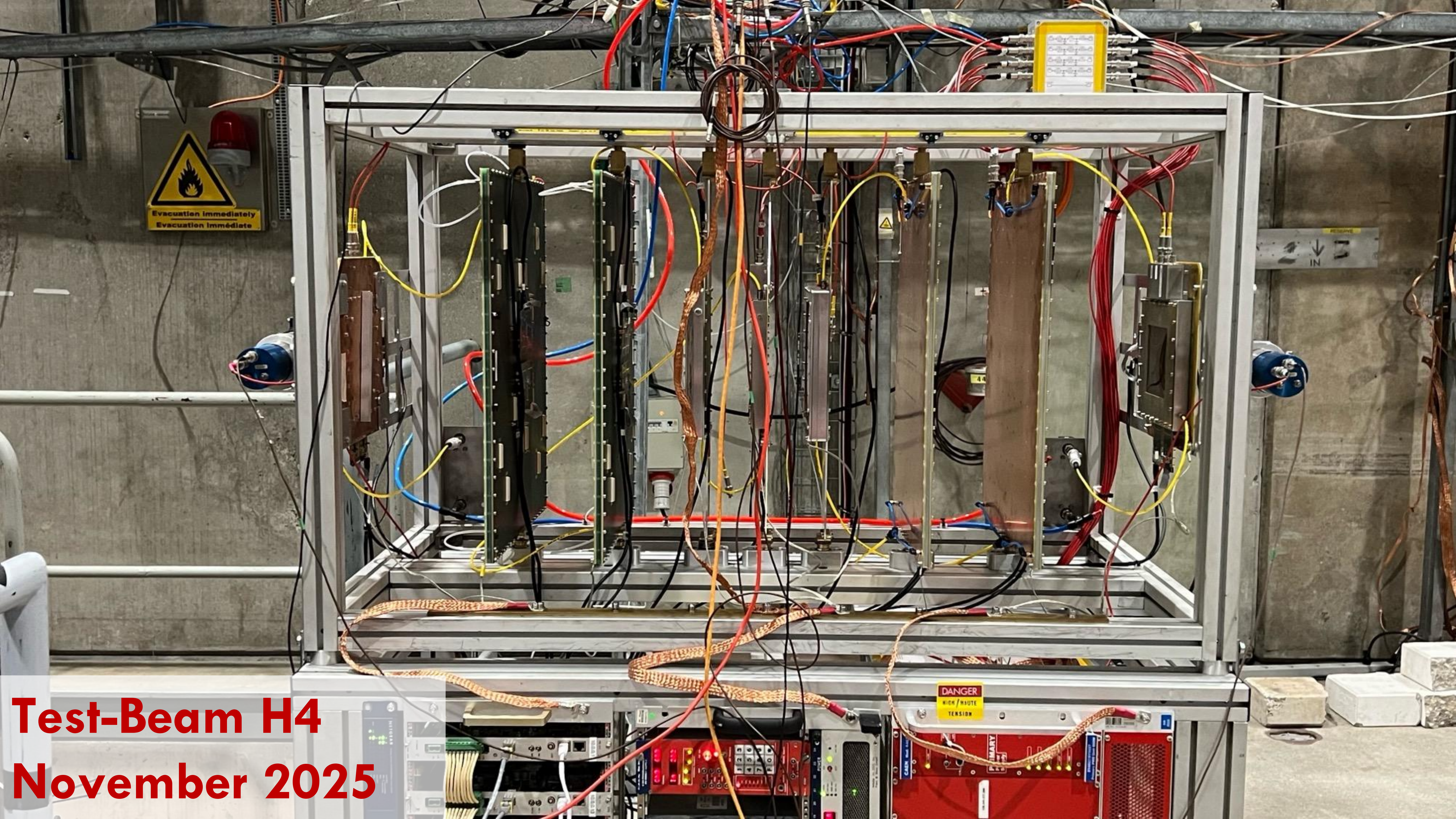
Front-end/DAQ:

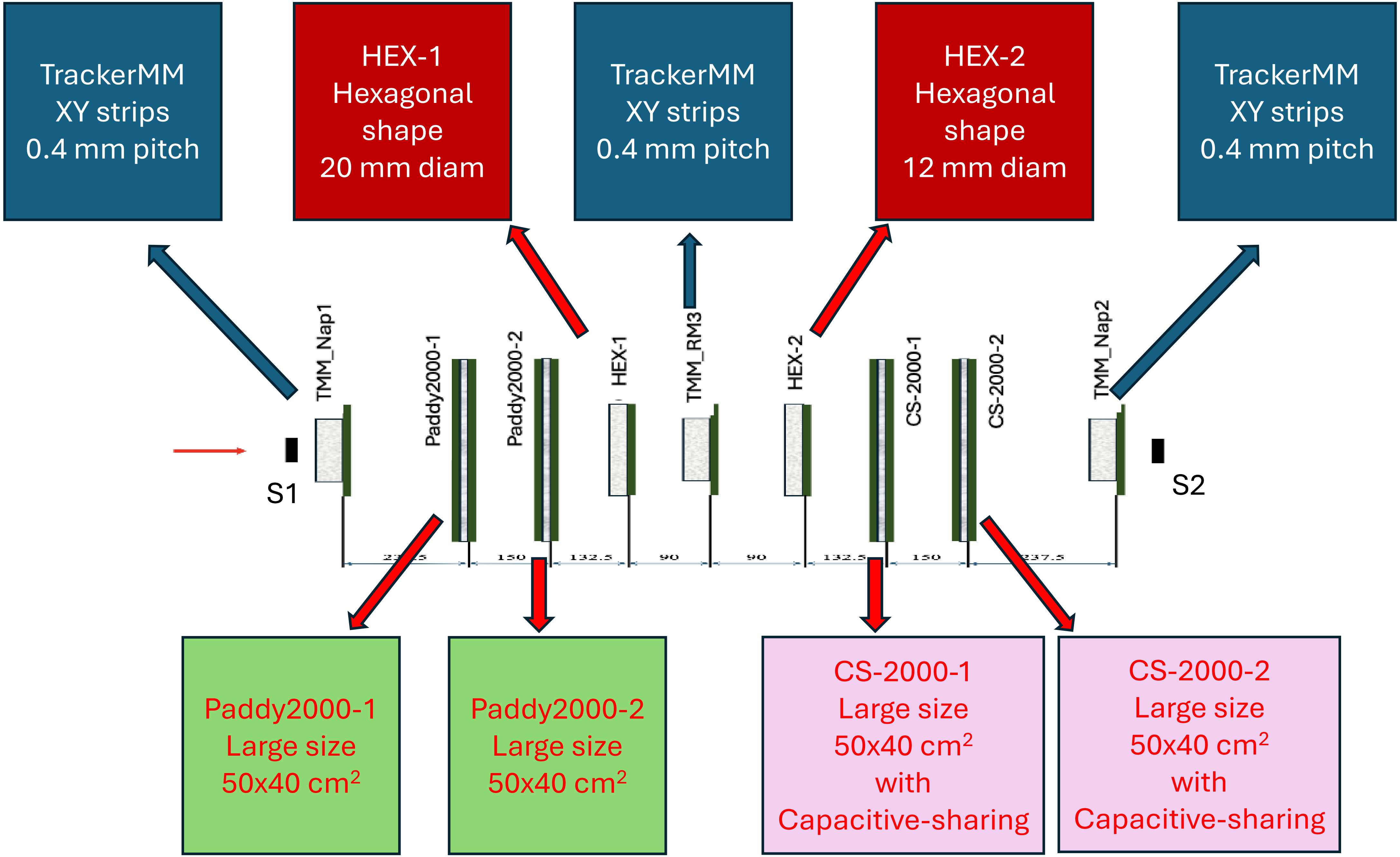
- APV25 / SRS

Trigger:

- Two scintillators 10x10 cm^2




Test-Beam H4
November 2025
Evacuation immediately
Evacuation immédiate
DANGER
HIGH / HAUTE
TENSION



TrackerMM
XY strips
0.4 mm pitch
HEX-1
Hexagonal
shape
20 mm diam
TrackerMM
XY strips
0.4 mm pitch
HEX-2
Hexagonal
shape
12 mm diam
TrackerMM
XY strips
0.4 mm pitch
TMM_Nap1
Paddy2000-1
Paddy2000-2
HEX-1
TMM_RM3
HEX-2
CS-2000-1
CS-2000-2
TMM_Nap2
S1
S2
150
132.5
90
90
132.5
150
237.5
Paddy2000-1
Large size
50x40 cm²
Paddy2000-2
Large size
50x40 cm²
CS-2000-1
Large size
50x40 cm²
with
Capacitive-sharing
CS-2000-2
Large size
50x40 cm²
with
Capacitive-sharing