The 2024 International Workshop on the High Energy Circular Electron Positron Collider

Hangzhou, October $22^{\text{nd}} - 27^{\text{th}}$ 2024

# R&D on Noble Liquid Calorimeter for Future Collider Experiments

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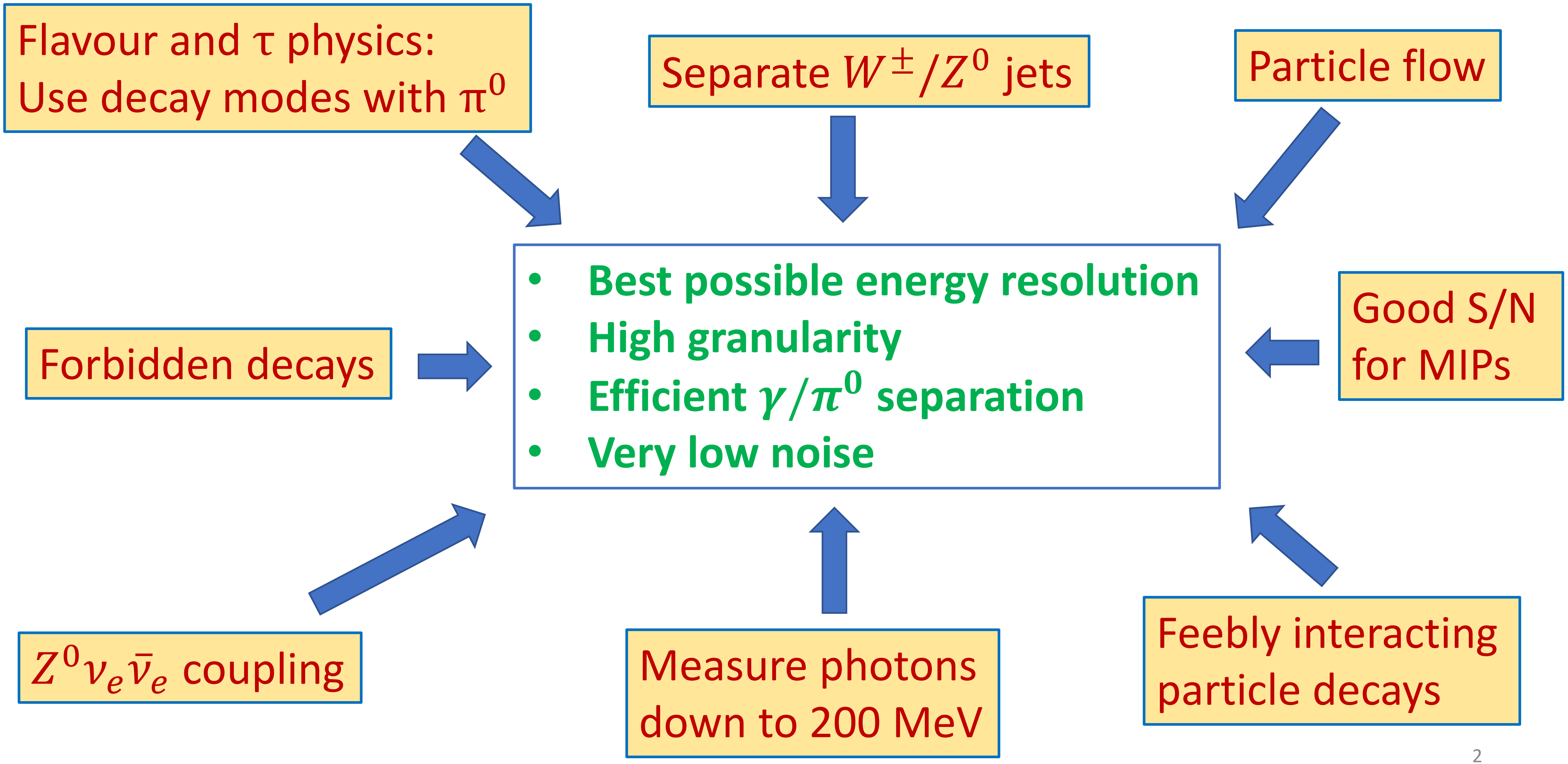
On behalf of DRD6—WP2

ALLEGRO

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE

CPPM

# Requirements on Electromagnetic Calorimetry at FCC-ee

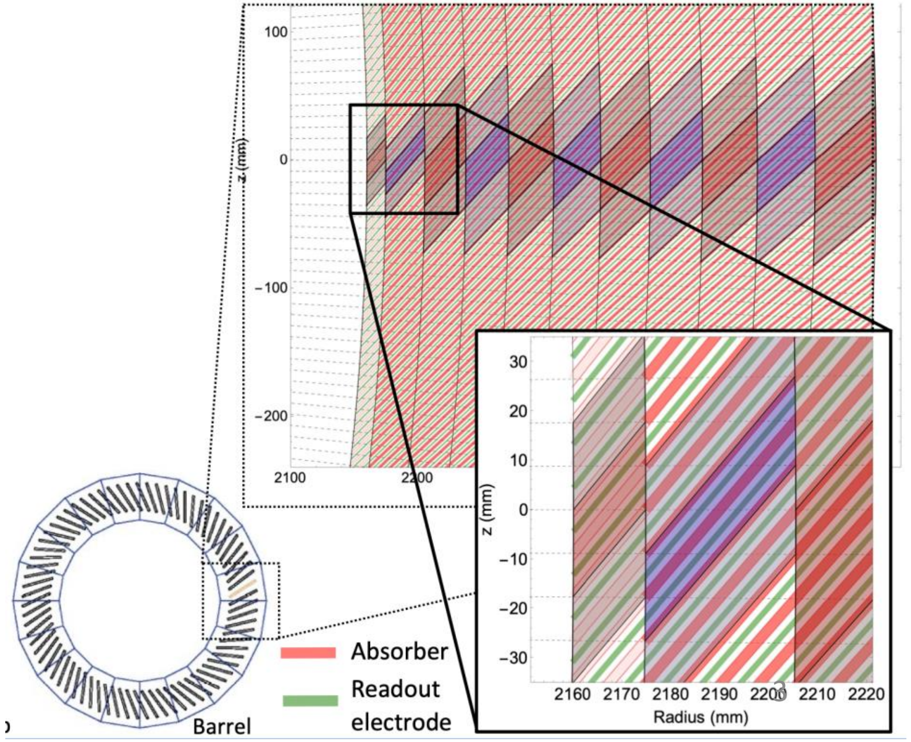


# Allegro Proposal: A Sampling Metal/Noble Liquid Calorimeter

- This technique has been used since 50 years at accelerators. It has demonstrated:
  - Easy implementation of granularity
  - Easy to calibrate
  - Good energy resolution
  - Hermetic, Linear, uniform, stable

- **Challenges at FCC-ee:**
  - **Finer granularity**
  - **Very low noise**
  - **Light cryostat**

- Alternate absorbers and electrodes to make a complete cylinder.
- To achieve uniform sampling, absorbers and electrodes are rotated with respect to the radial direction by 50°.
- Gaps between absorbers and electrodes maintained by spacers.
- $R_{inner} = 2160$ mm, $R_{outer} = 2560$ mm, thickness of 22 $X_0$.
- Absorbers are $\sim 2$ mm thick.
- Gaps go from 1.2 to 2.4 mm.
- Sampling fraction around 20 %.
- 1536 double-gap, $\Delta\varphi = 8$ mrad (2 electrodes).
- Granularity in polar angle: drawn on electrode, $\Delta\theta = 10$ mrad.

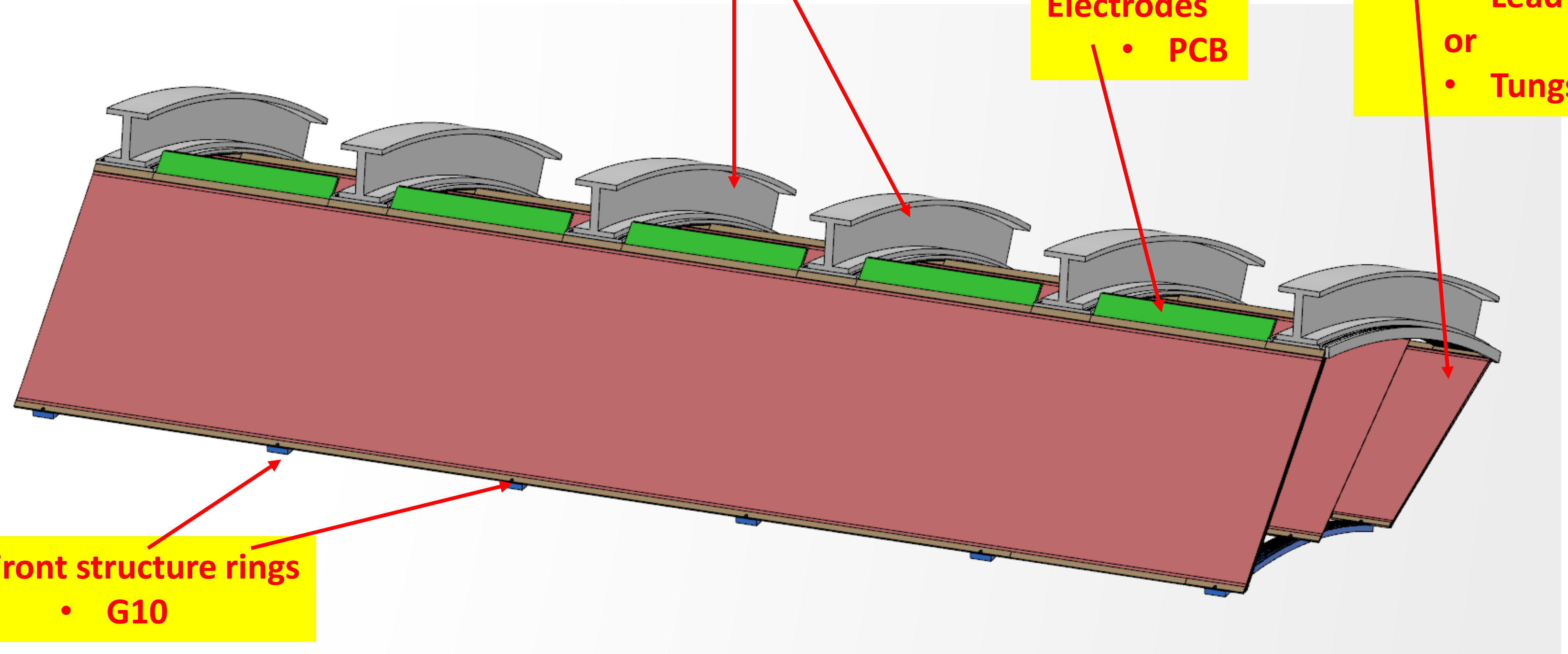


# A module of the Electromagnetic Calorimeter Barrel

- $\Delta\Phi = 15°$
- Length = 3 m of active area (half barrel length)

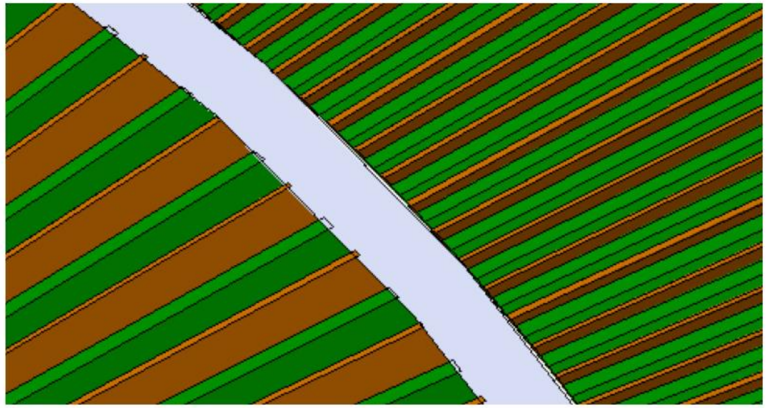
Active gap:
- Liquid Argon

or
- Liquid Krypton

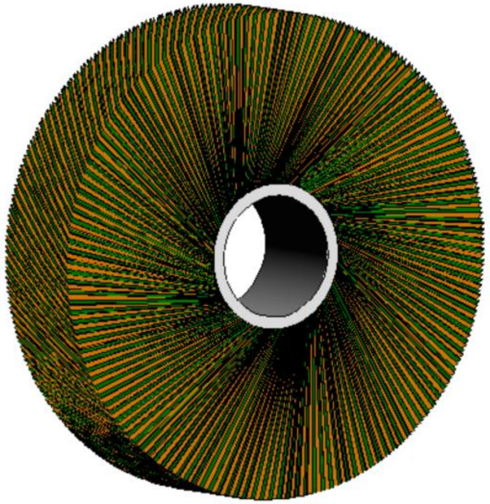


# Adaptation for Endcap

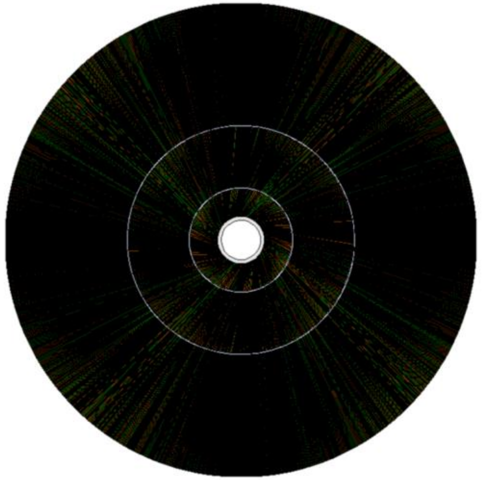
- 420 mm < R < 2750 mm
- Turbine implementation of the technique on the endcap: hermeticity, homogenous in ϕ, readout from the rear.
- But it has a major issue: Gap widening range is too large.
- Mitigation is being worked out:
  - 3 nested wheels.
  - But still sampling fraction varying a lot.
  - Solution to be evaluated: Variable absorber thickness.



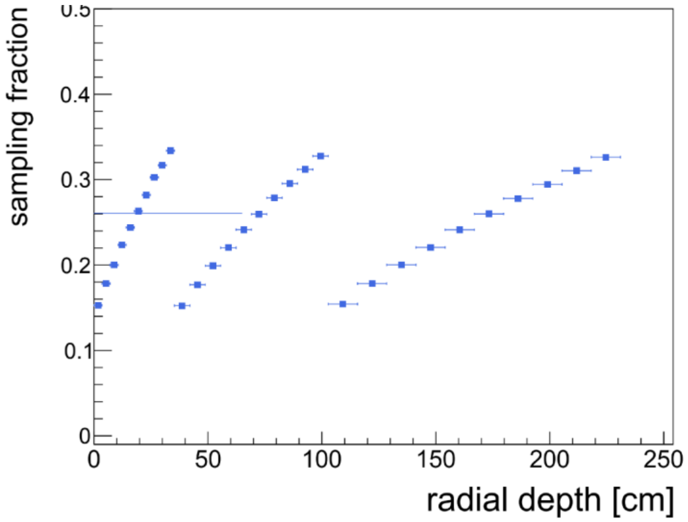
Zoom between 2 nested wheels



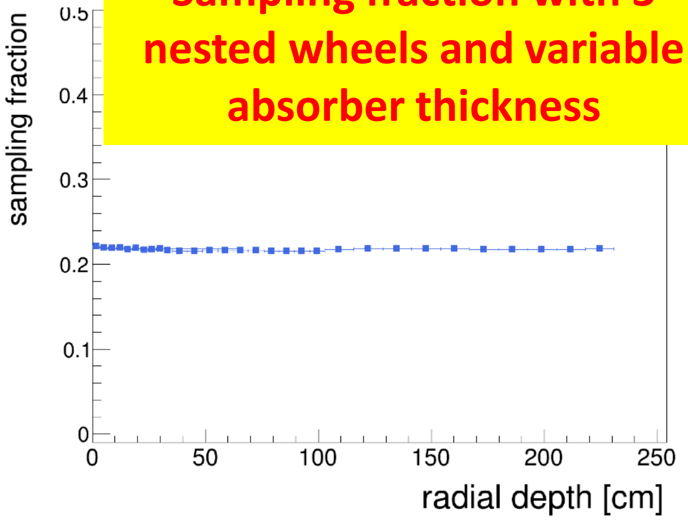
Simple turbine



3 nested wheels



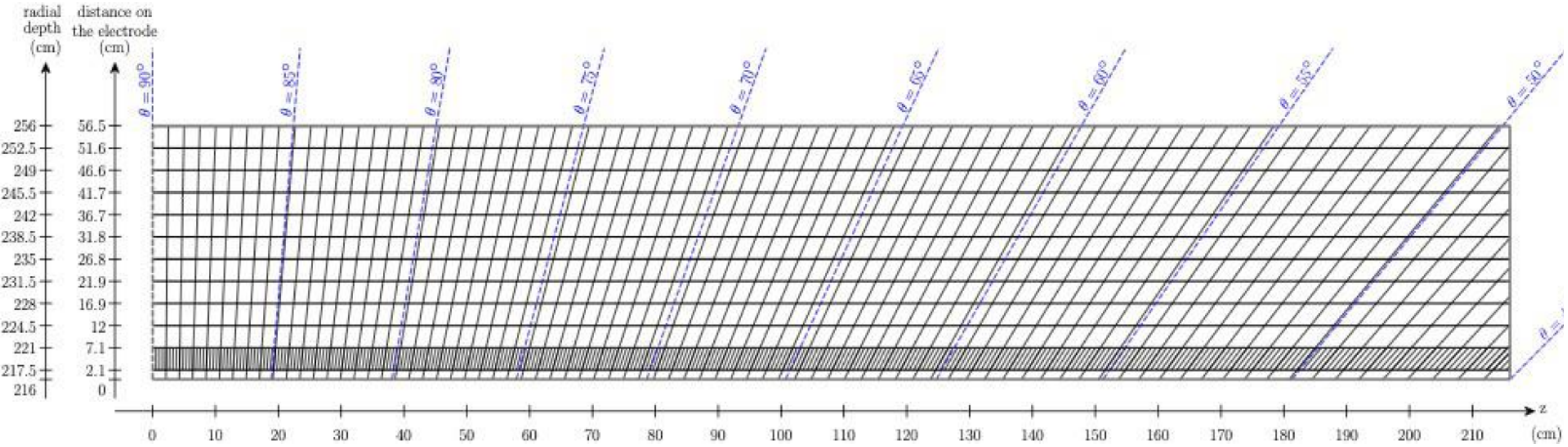

Sampling fraction with 3 nested wheels

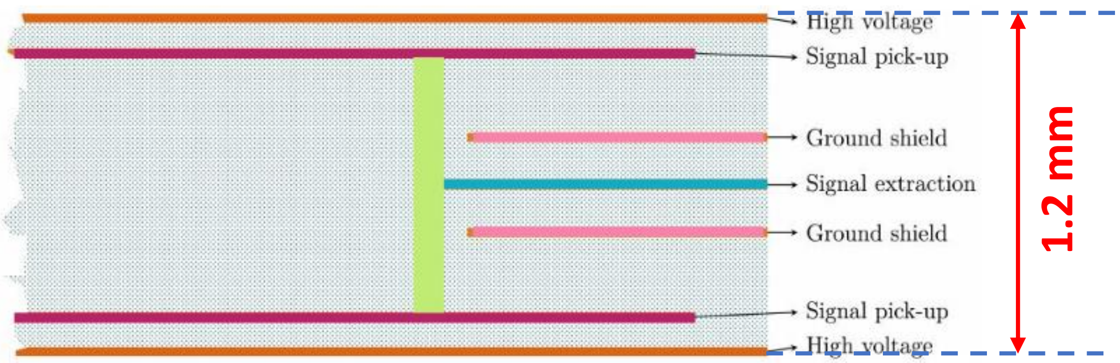


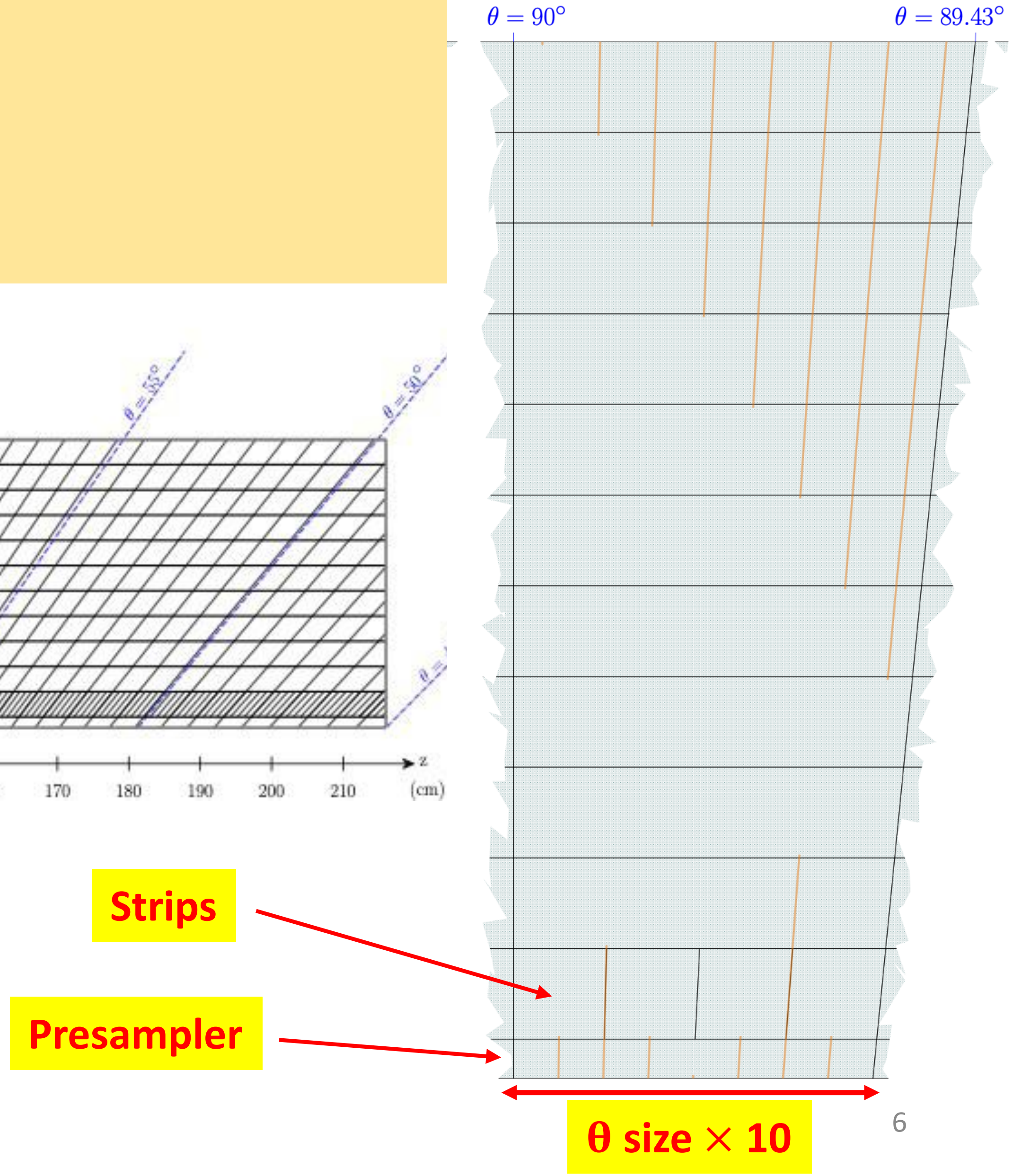

Sampling fraction with 3 nested wheels and variable absorber thickness

# Electrodes

- Exploit the progress made on Printed Circuit Boards (PCB): thinner PCB and vias.
- Basic configuration: 7 conductive layers.
- Polar granularity drawn on the electrodes like scale on a ruler.
- Longitudinal granularity also drawn.
- Base line: $\Delta\theta = 10$ mrad (4 times less for strips)

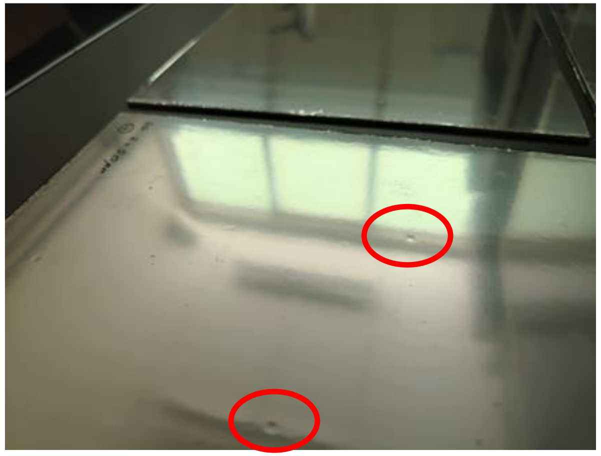


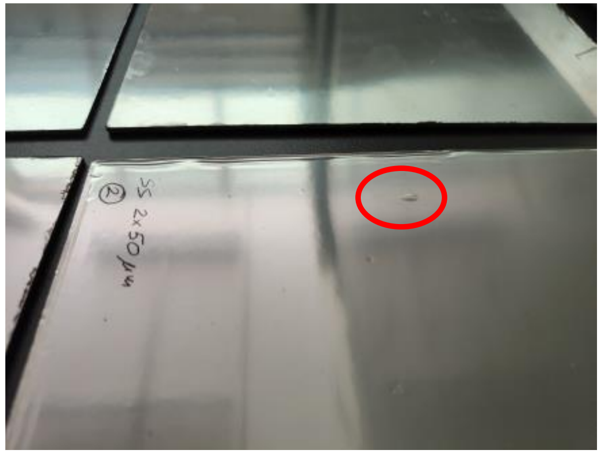



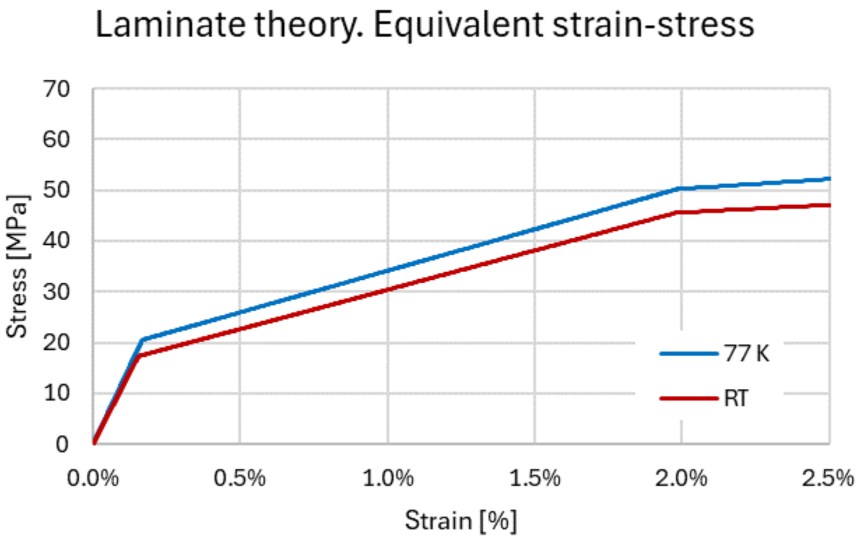
# Absorbers

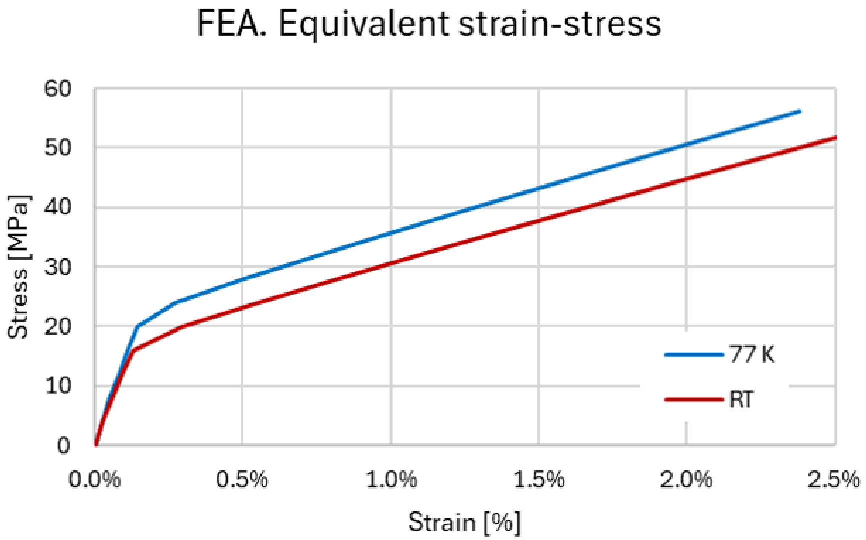
- Prototypes of absorbers have been manufactured.
- Stainless steel – glass fiber – lead – glass fiber – stainless steel assembly.
- Base line was 0.050 mm of steel and glass fiber, and 1.8 mm of lead.
- But deformations were observed.
- No deformation for prototypes with a thicker steel (0.100 mm).





| Yielding point | $\sigma y$ at RT [MPa] | $\sigma y$ at 77 K [MPa] | CTE at 77 K [$10^{-6}$ $K^{-1}$] |
|---|---|---|---|
| Test | 16.0 | 38.0 | 15.6 |
| Laminate theory | 17.3 | 20.5 | 13.7 |
| FEA | 16.0 | 20.0 | 14.5 |

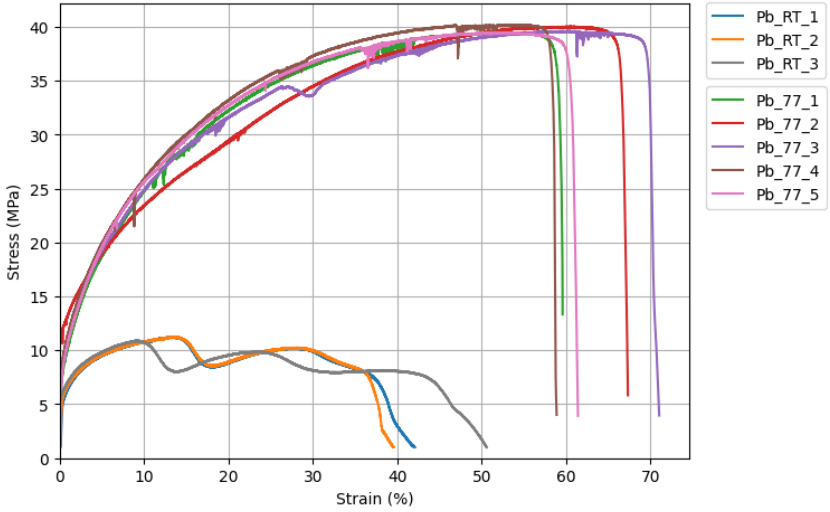


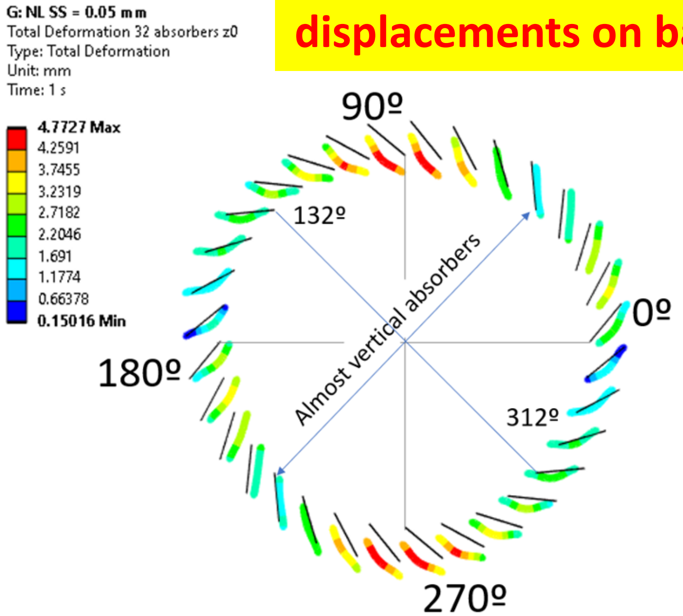

- Room temperature: Measurements in agreement with Laminate Theory and Finite Element Method.
- At 77° K : LT and FEM underestimate measurements.

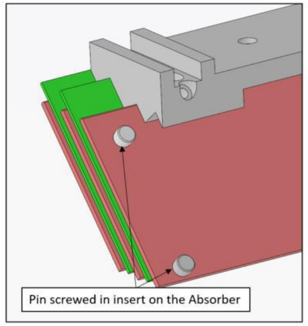
# Barrel Structure

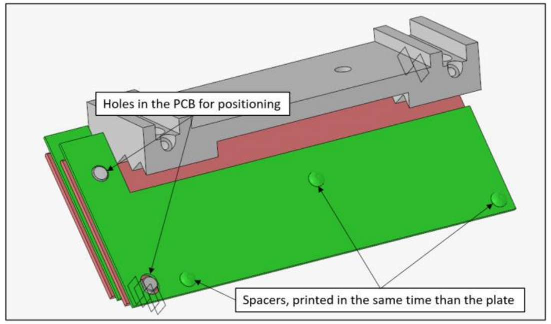
## Lead strength test

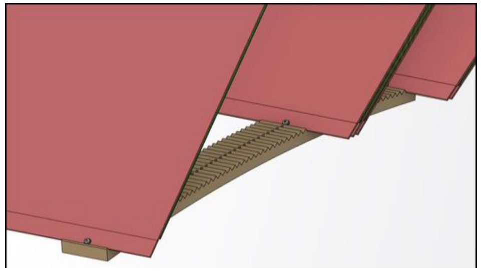


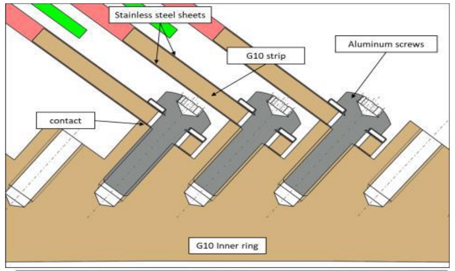

## Simulation of absorber displacements on barrel



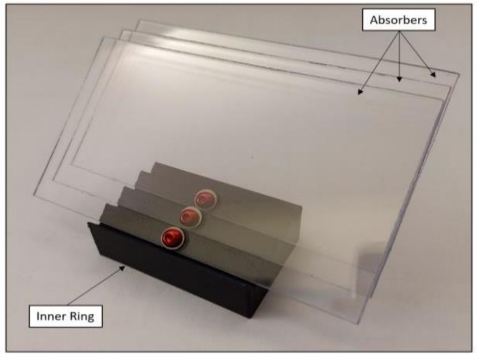



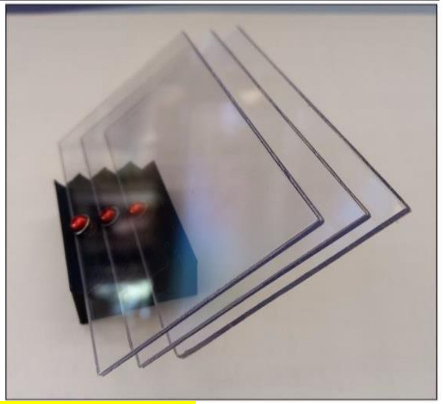






**Full scale 3D printed samples**



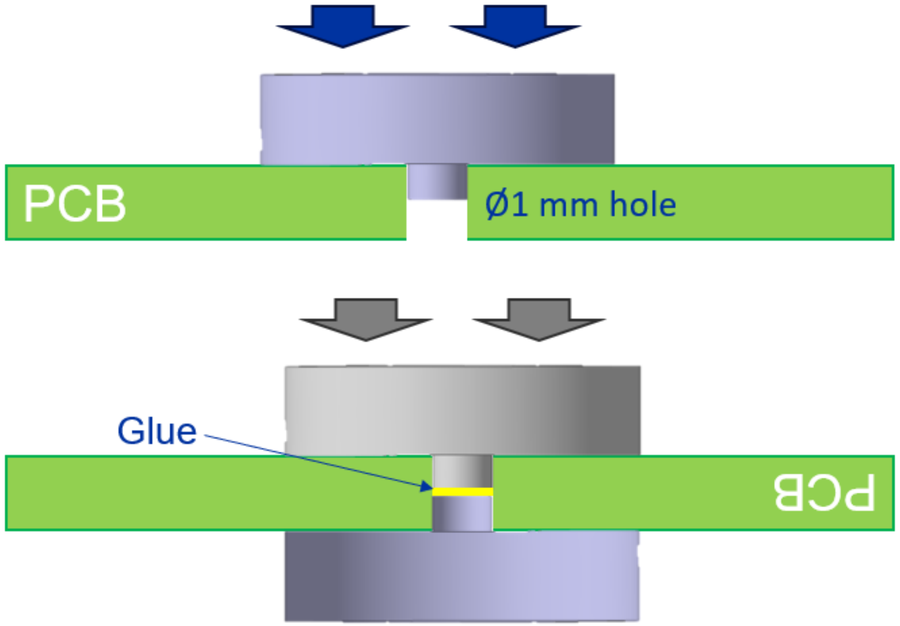
**Fixation on outer rings**

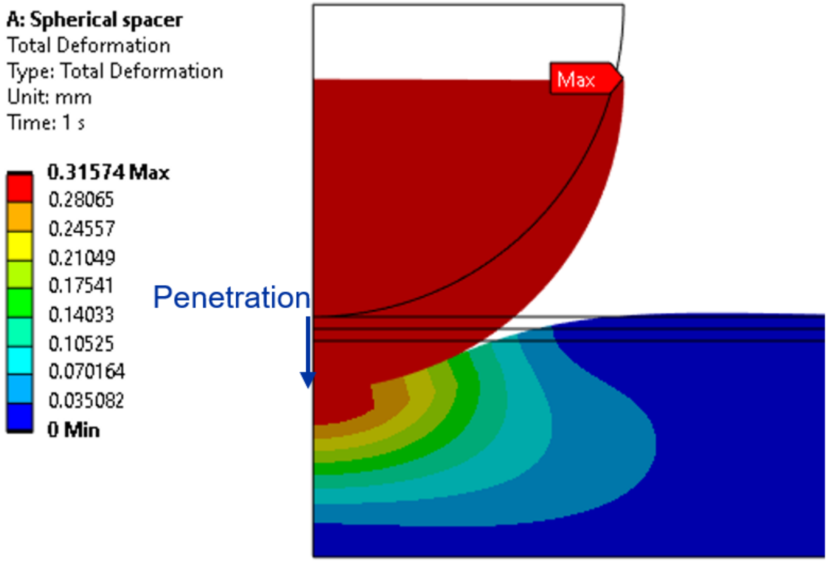
**Fixation on inner rings**

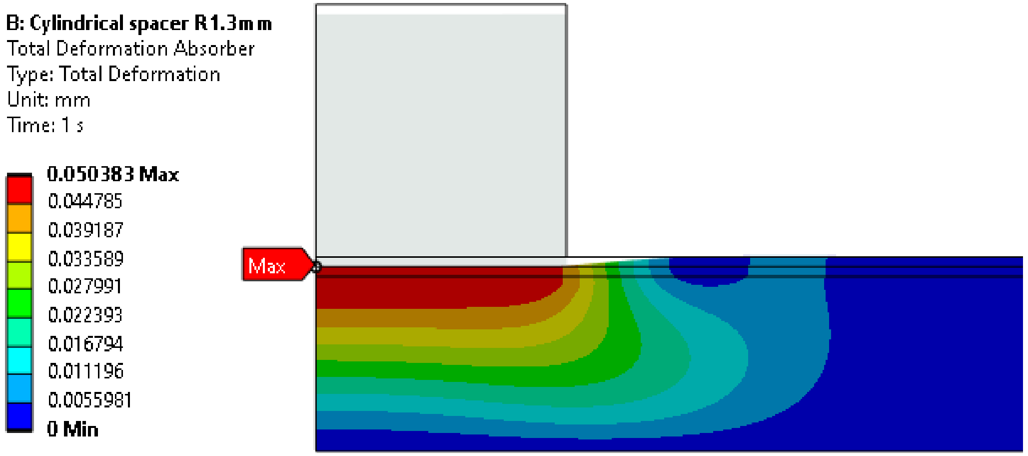
# Spacers

- Tests showed that spherical spacers induce high pressure on absorbers and electrodes.
- 6 mm diameter cylindrical spacers gave better results.
- Simulation and tests: A spacer needed each 200 mm: 20 spacers for module length.
- 5 different heights because of radial gap variation.
- A total of 20 × 5 = 100 spacers per gap.
- Equivalent to 0.15 % of total liquid argon volume. Signal loss to be evaluated.

**Spacer assembly on PCB**



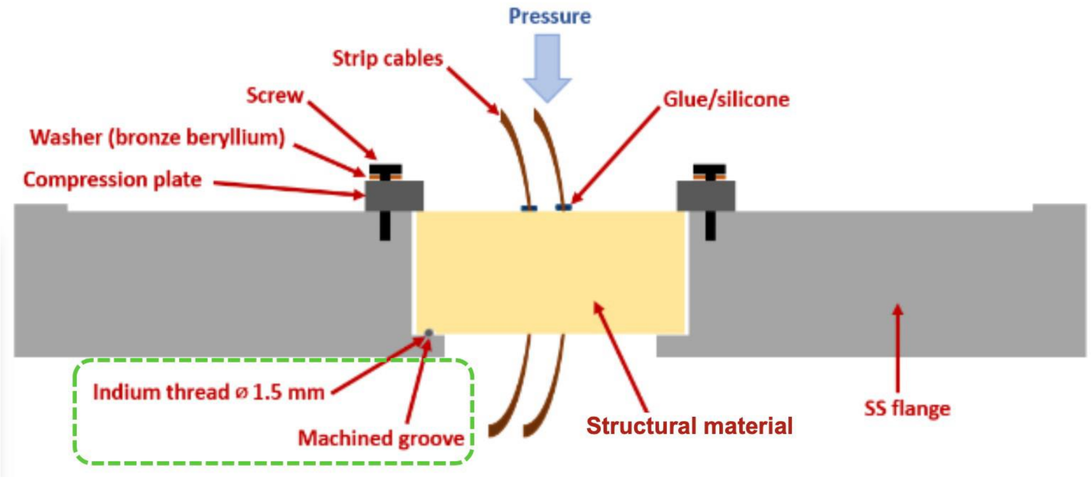



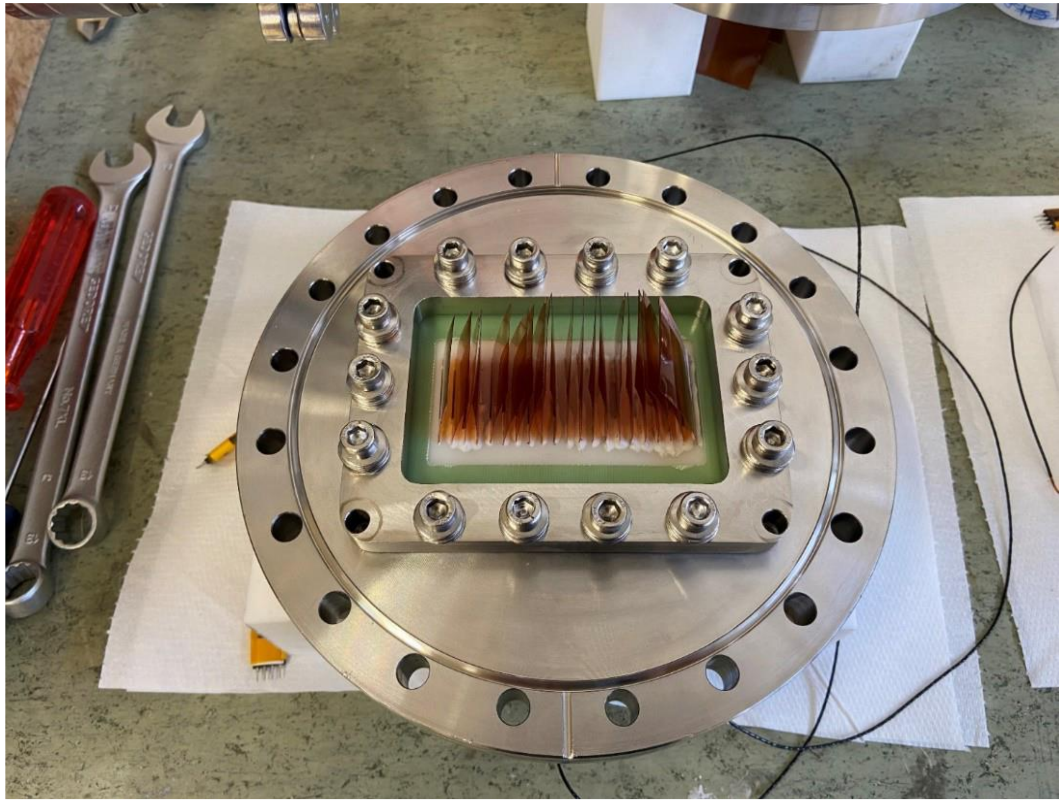




**Simulation of absorber deformation with spherical and cylindrical spacers**

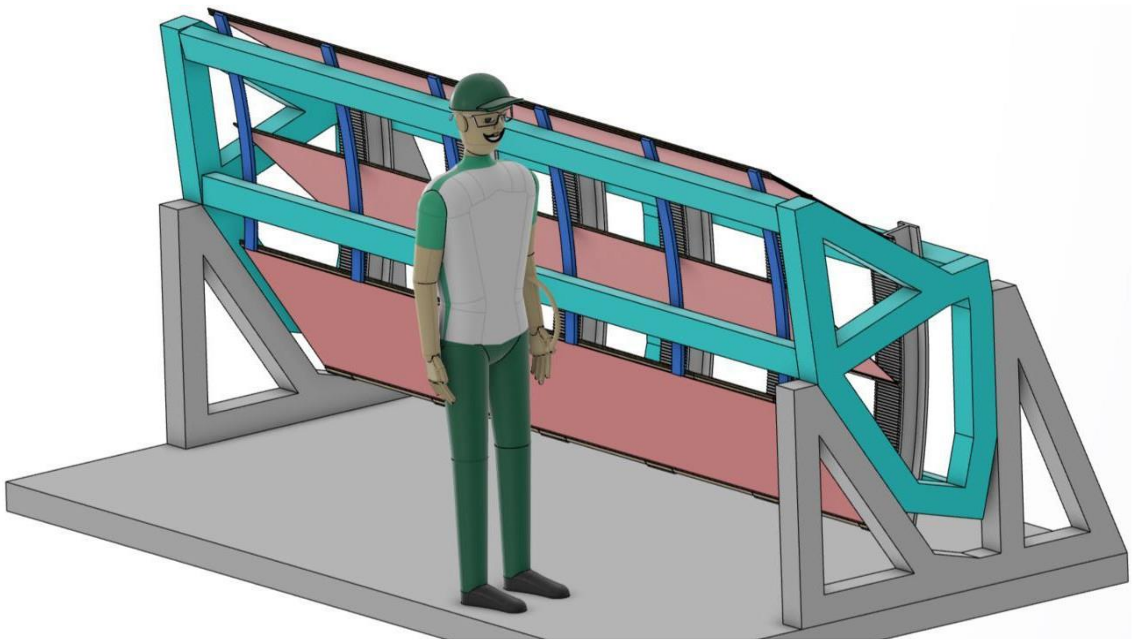
# Cryostat and Feedthroughs

- Developping a very light cryostat made with carbon fiber including a full carbon composite honeycomb.
- Channel density in the feedthroughs will be 5 time larger than in ATLAS.
- Developping a connectorless feedthrough:
  - 3D printed epoxy resine structure with slits for strip cables, glued to the flange.
  - Passed leak and pressure tests at room and liquid nitrogene temperatures.

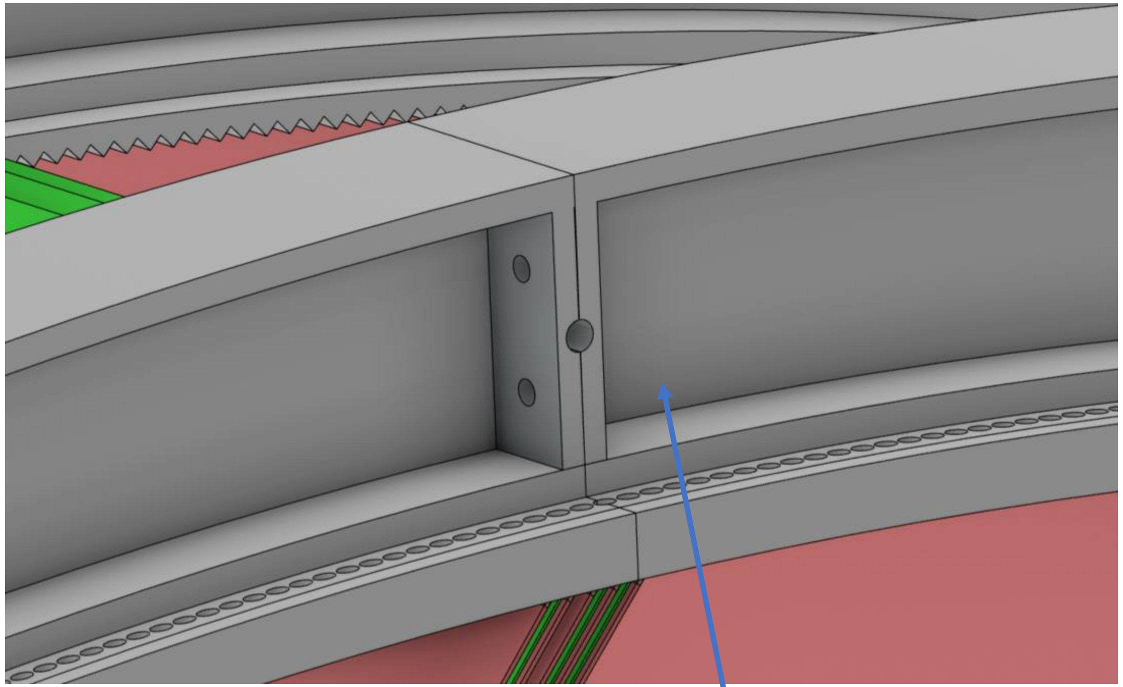


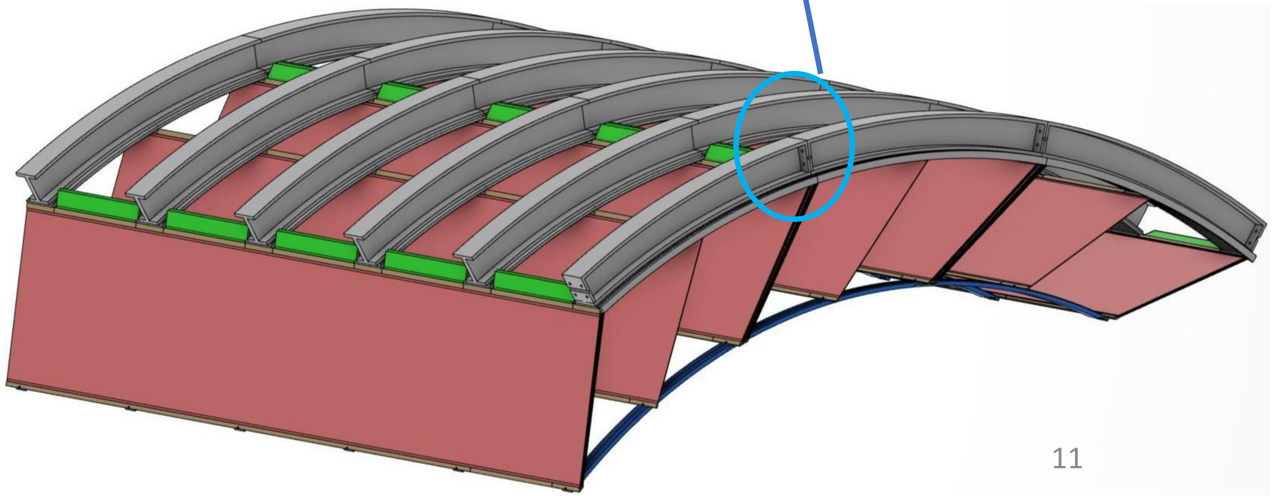
# Assembly Studies and Tools



Assembly structure of a barrel module



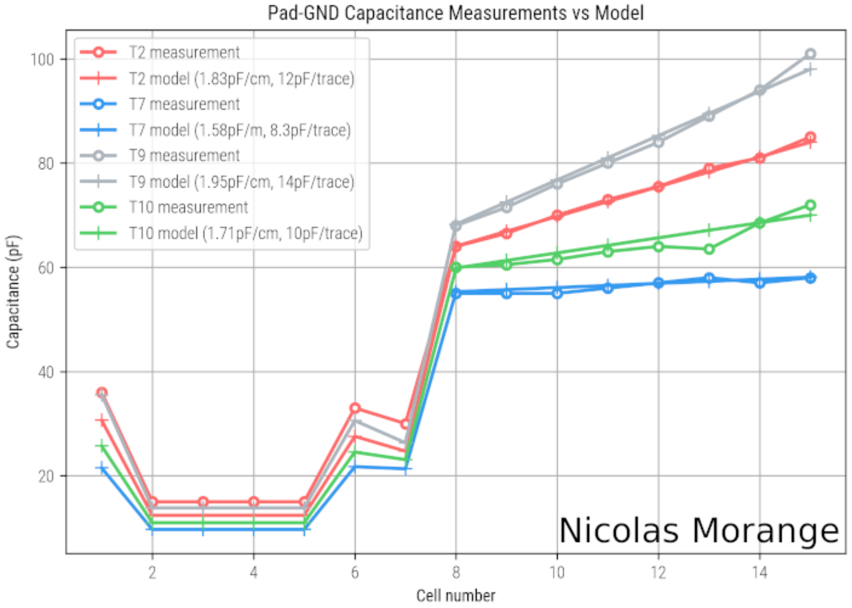
Outer ring junction between modules

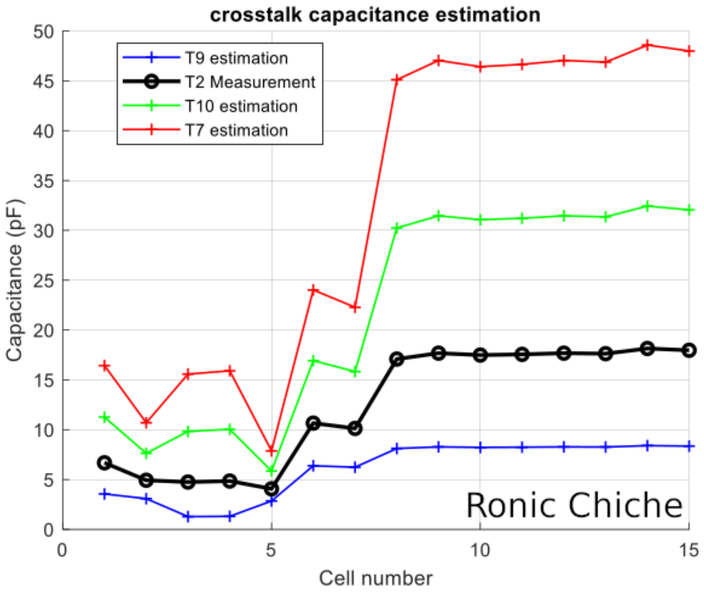


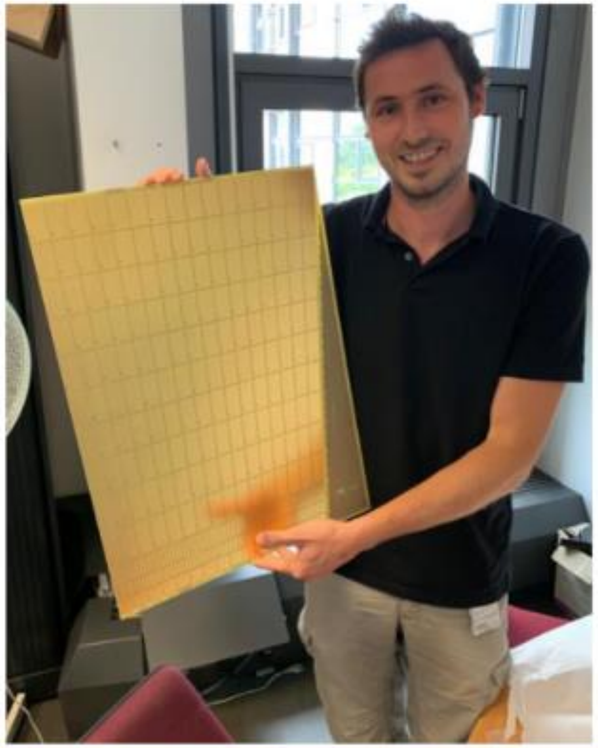
# CERN PCB Prototype V1

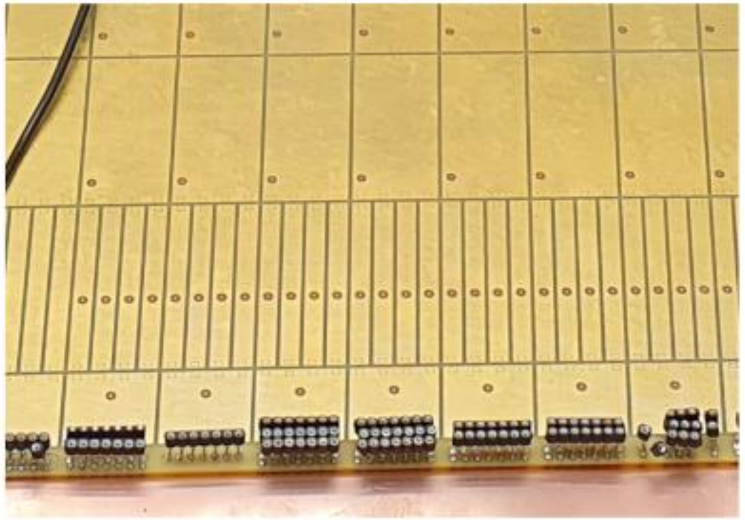
- First full depth prototype.
- 58 cm × 44 cm.
- 12 depth layers, 40 cm depth.
- Readout from 2 edges.
- 16 θ towers.
- First Layer L0 not covered by absorber: It will play the role of a presampler.
- Strips in L1.
- 240 cells.

**Estimated and measured cell and cross-talk capacitances**



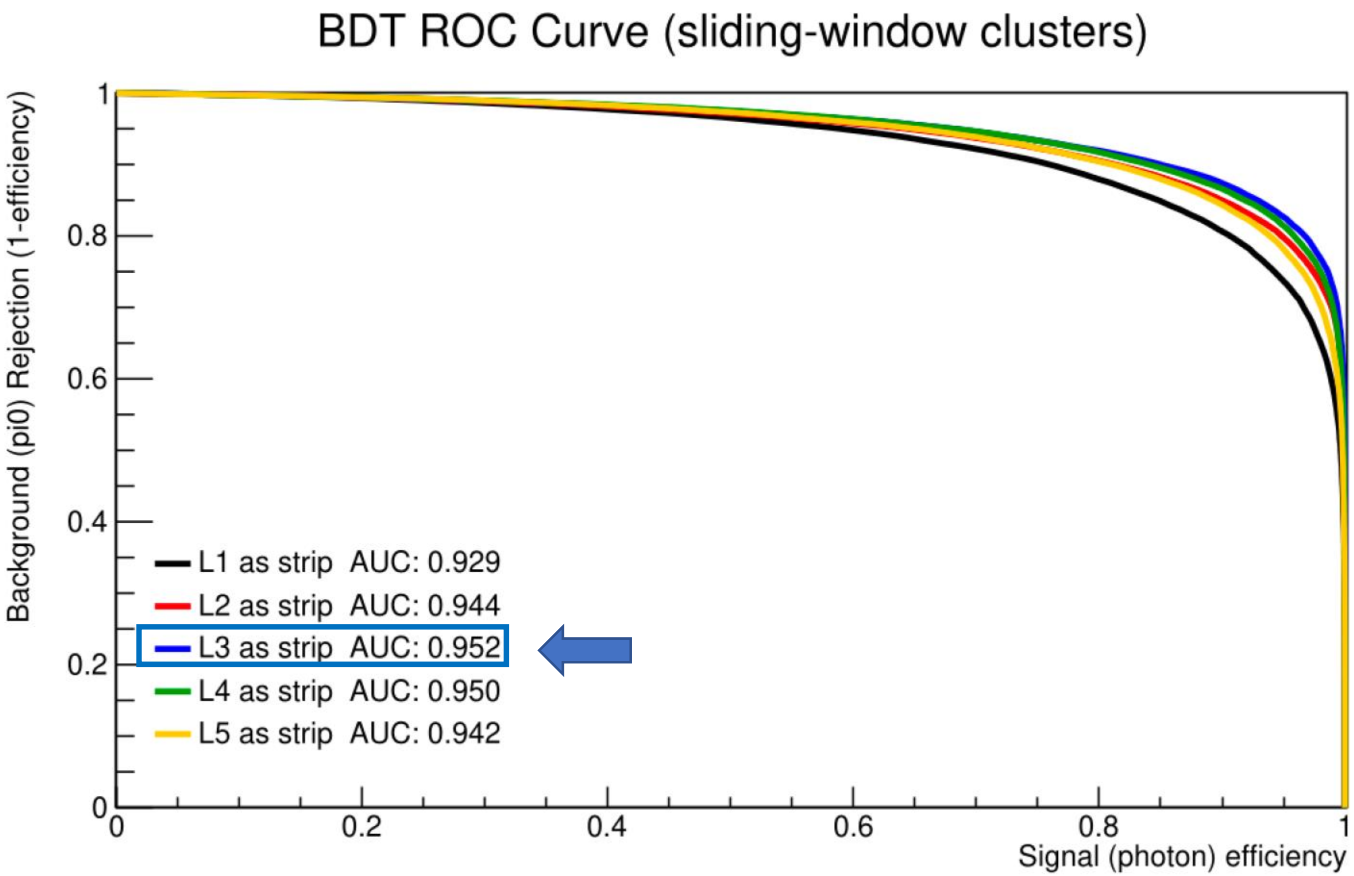





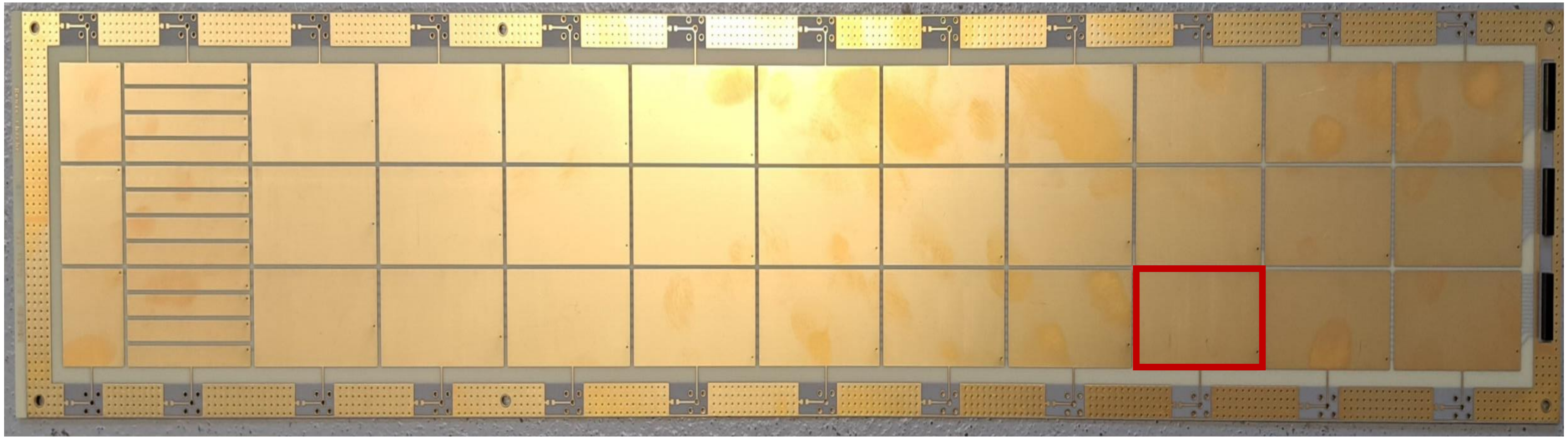
# CERN PCB Prototype V2

- It is being finalized by the light of measurements, tests and simulation.
- Readout from outer radius.
- Industrial connectors.
- Optimised trace ordering.
- Simulation: Better $\gamma/\pi^0$ separation with strips in third layer.

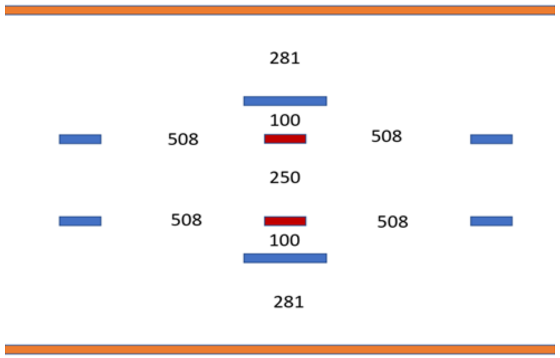


# Orsay PCB Prototype V3

- 6 conductive layers (2 signals, 2 shieldings, 2 readouts, no HV).
- 2 readout layers because it is easier to manufacture an even number of conductive layers.
- Tower 1 and 2 have also lateral shielding.
- 59 cm × 9 cm.



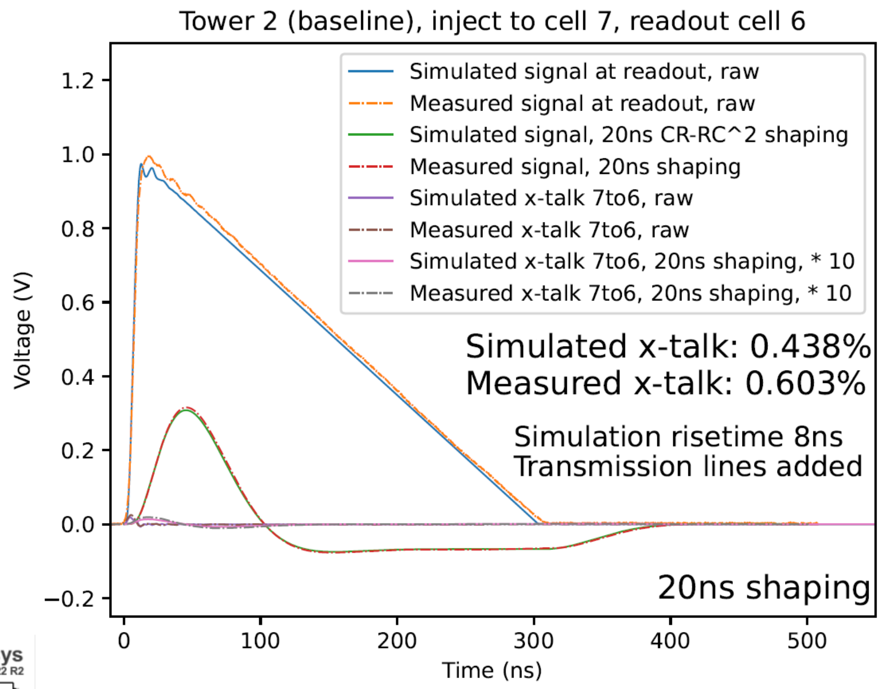
Front view with lateral shielding and distances in µm

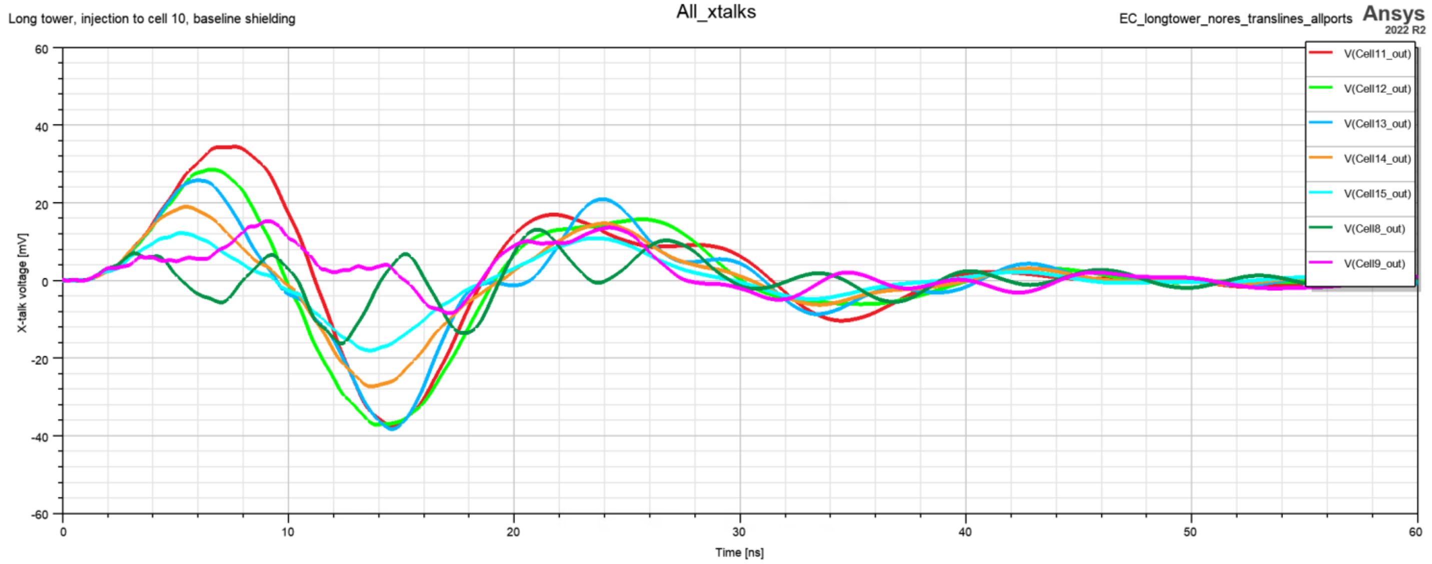


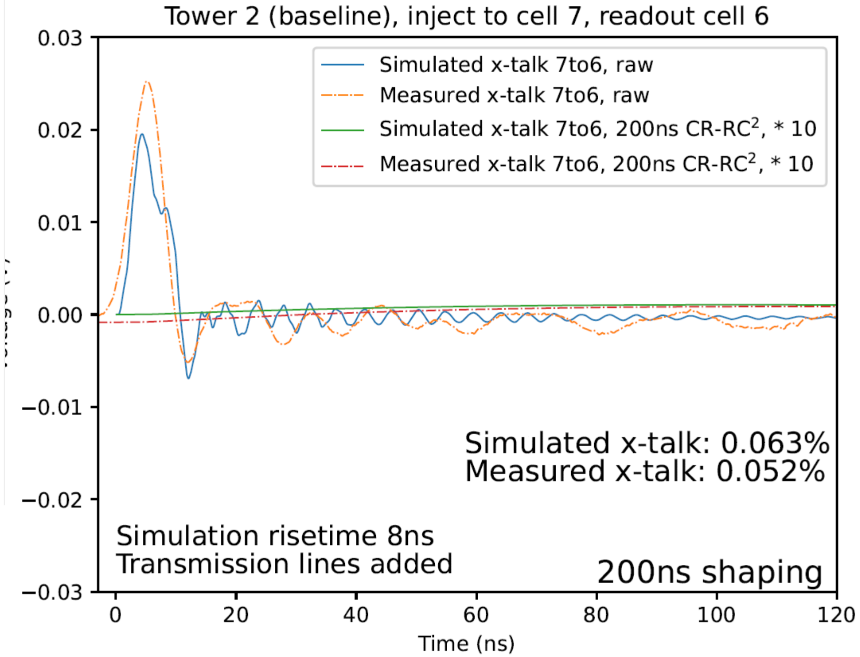

**Widths:**
**Signal: 127µm**
**Top/bottom shielding: 254µm**
**Lateral shielding: 127µm**

# A New Tool: Electrode Simulation

- Ansys HFSS Electronics Desktop.
- CERN prototype V1 design.
- Added 50 Ω transmission lines to injection and readout.
- Good agreement with cross-talk measurement, peak to peak and after shaping.
- Can use the simulation to understand fine effects.



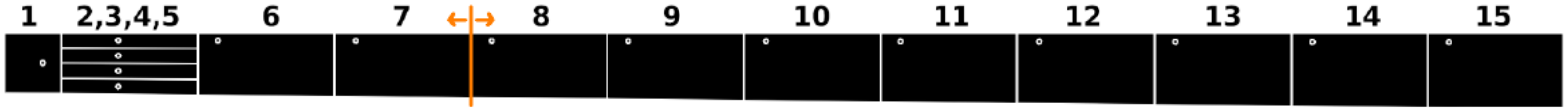




**Simulated cross-talk signal on neighbour cells of the same tower**

# Measurement of Cross-Talk Matrix for a Tower of PCB v1

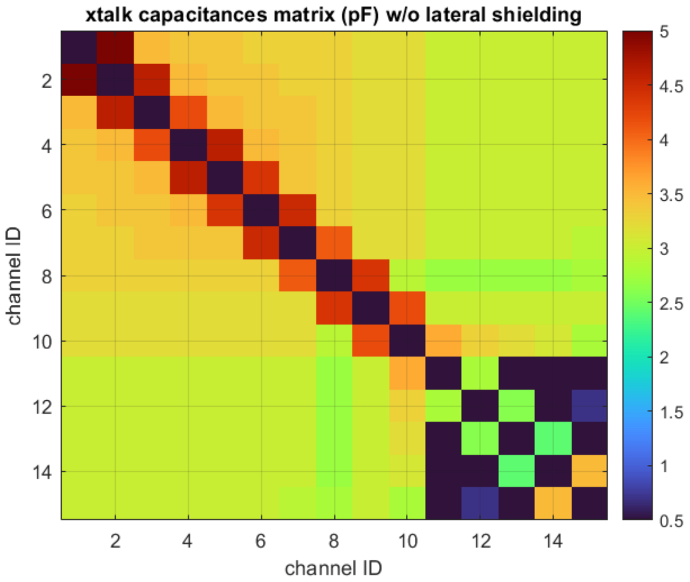
| Cell | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | 0.8 | 1.1 | 1 | 0.7 | 0.9 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.6 | - | 0.7 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0.9 | 0.7 | - | 2.3 | 0 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0.9 | 0 | 2.3 | - | 0.7 | 0.2 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.6 | 0 | 0 | 0.7 | - | 0.1 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0.7 | 1.1 | 0.7 | 0.2 | 0.1 | - | 2.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0.6 | 0 | 0 | 0.7 | 0.3 | 2.8 | - | 0.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | - | 2.8 | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 | 1.7 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.8 | - | 2.8 | 1.4 | 1.4 | 1.4 | 1.5 | 1.6 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 2.8 | - | 2.7 | 1.4 | 1.4 | 1.5 | 1.6 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 1.4 | 2.6 | - | 2.8 | 1.4 | 1.5 | 1.7 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 1.4 | 1.4 | 2.7 | - | 2.7 | 1.5 | 1.7 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 1.4 | 1.4 | 1.4 | 2.7 | - | 2.9 | 1.7 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 2.8 | - | 3.1 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.7 | 1.6 | 1.6 | 1.7 | 1.7 | 1.7 | 3.1 | - |

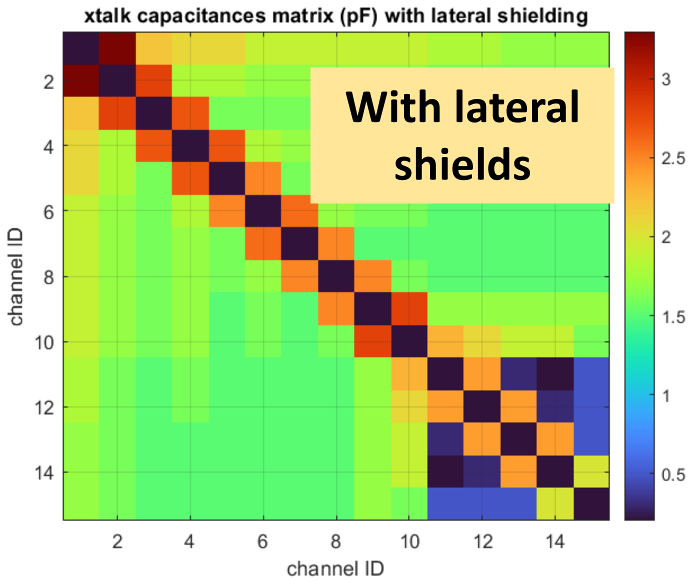
*X-talk capacitances in pF in Tower2, rounded to once decimal place. Digitized by Ronic Chiche at IJCLab.*



# Effect of Lateral Shields (PCB v3)

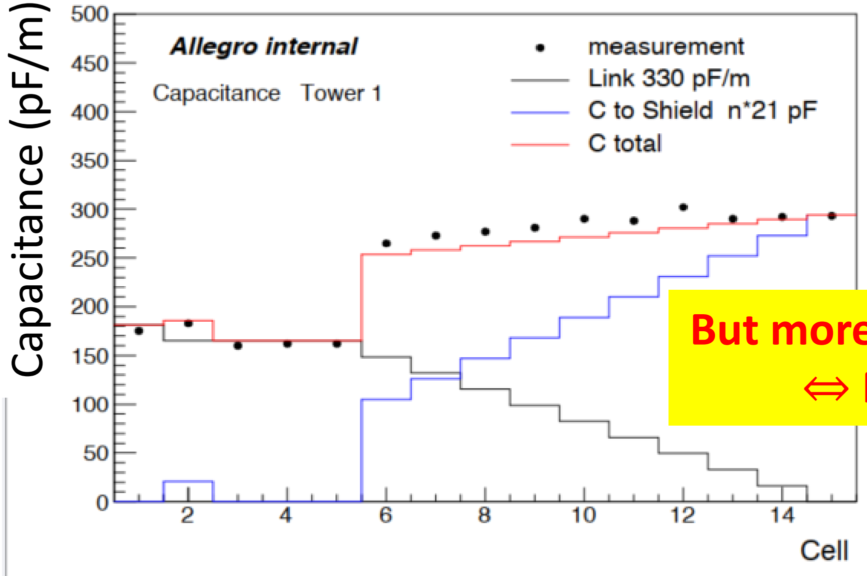
**Less cross-talk:**



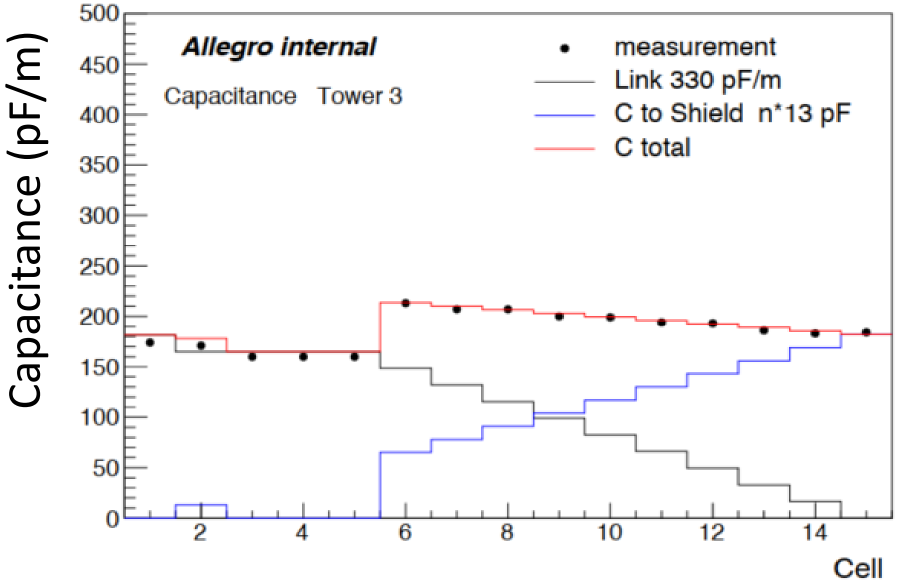




**With lateral shields**

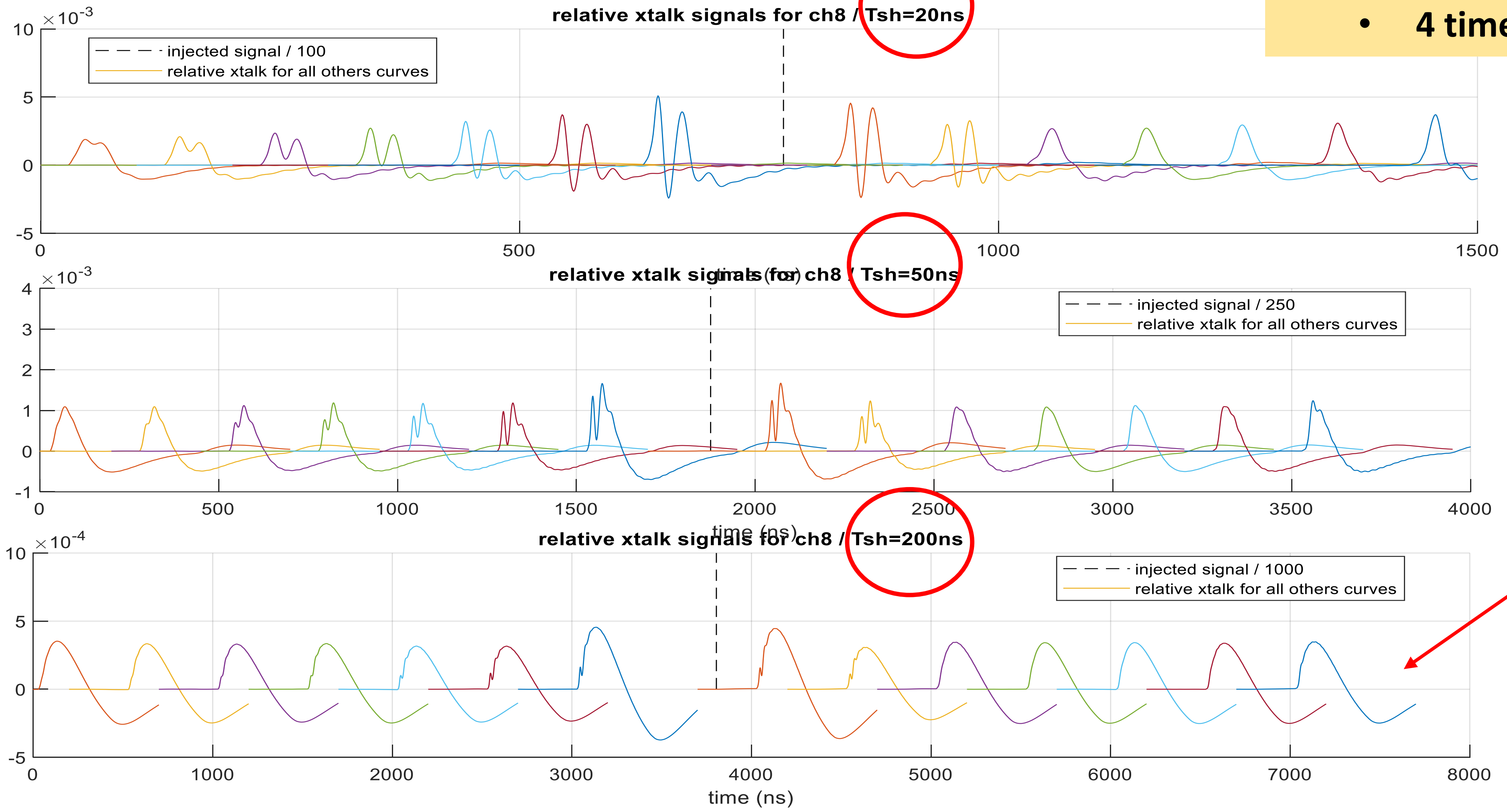
**With lateral shields**




**But more cell capacitance ⇔ More noise**

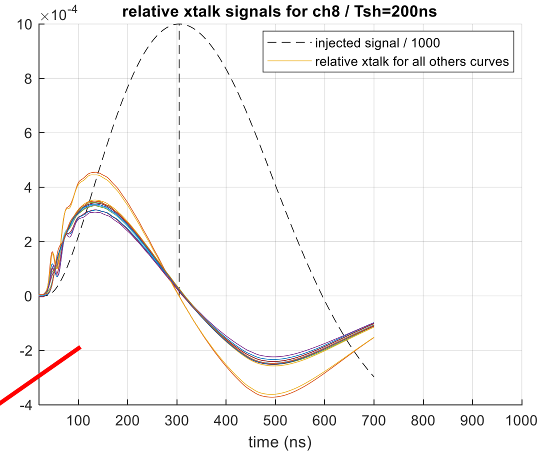


# Effect of Shaping Time on Cross-Talk (PCB v3)

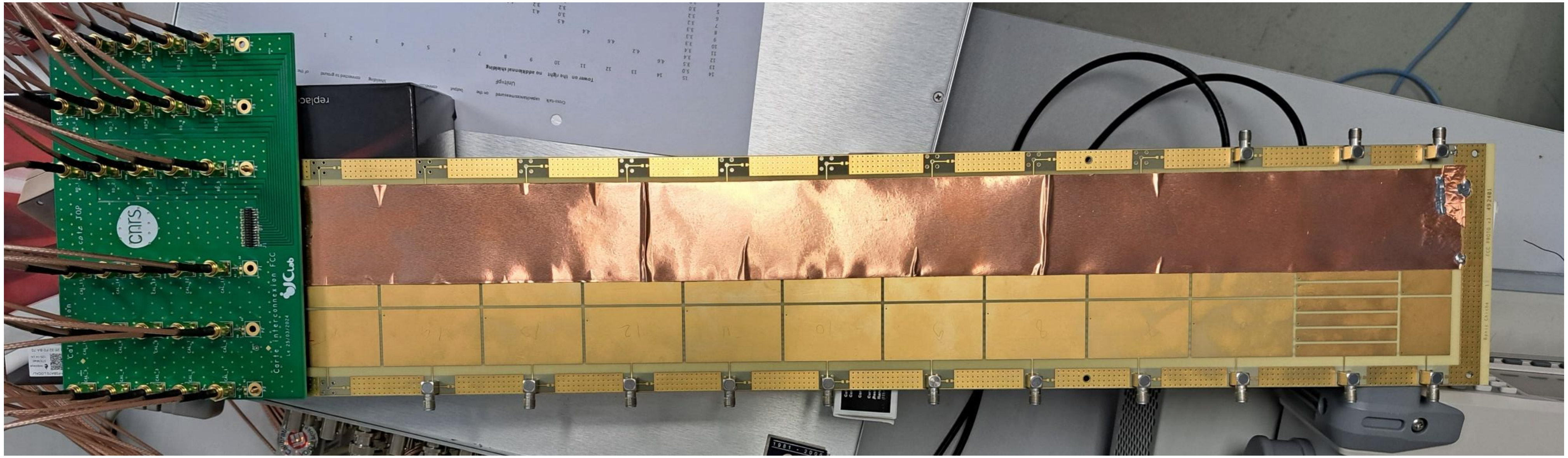


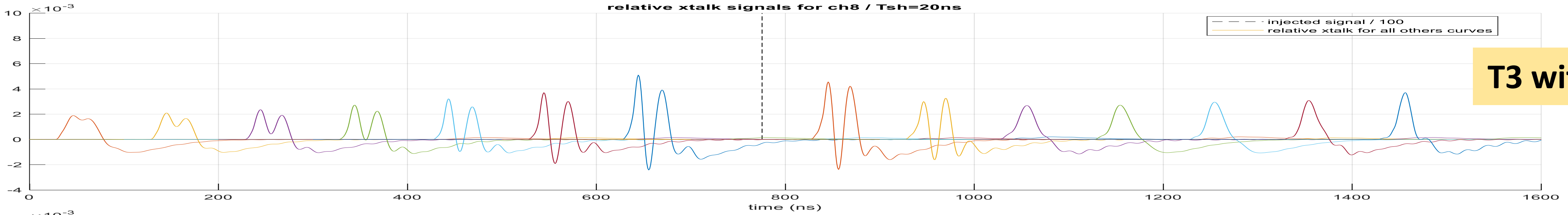

With a shaping of 200 ns, the cross-talk is:

- Of the order of $4 \times 10^{-4}$ peak to peak.
- 4 times less at the signal peak.

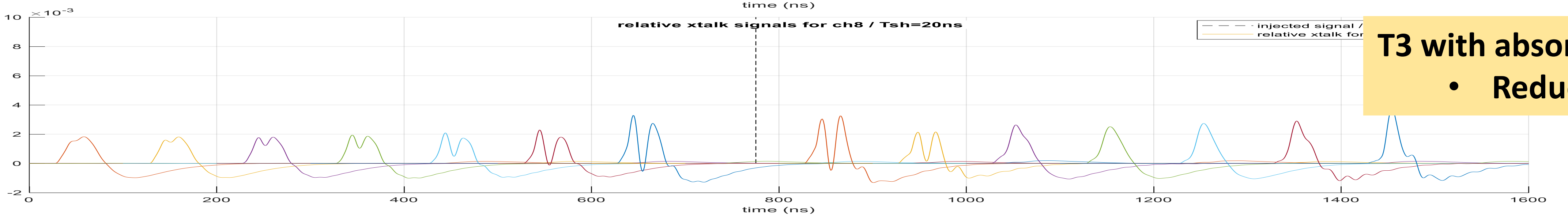


# Effect of Adding an Absorber on One Side of PCB (PCB v3)





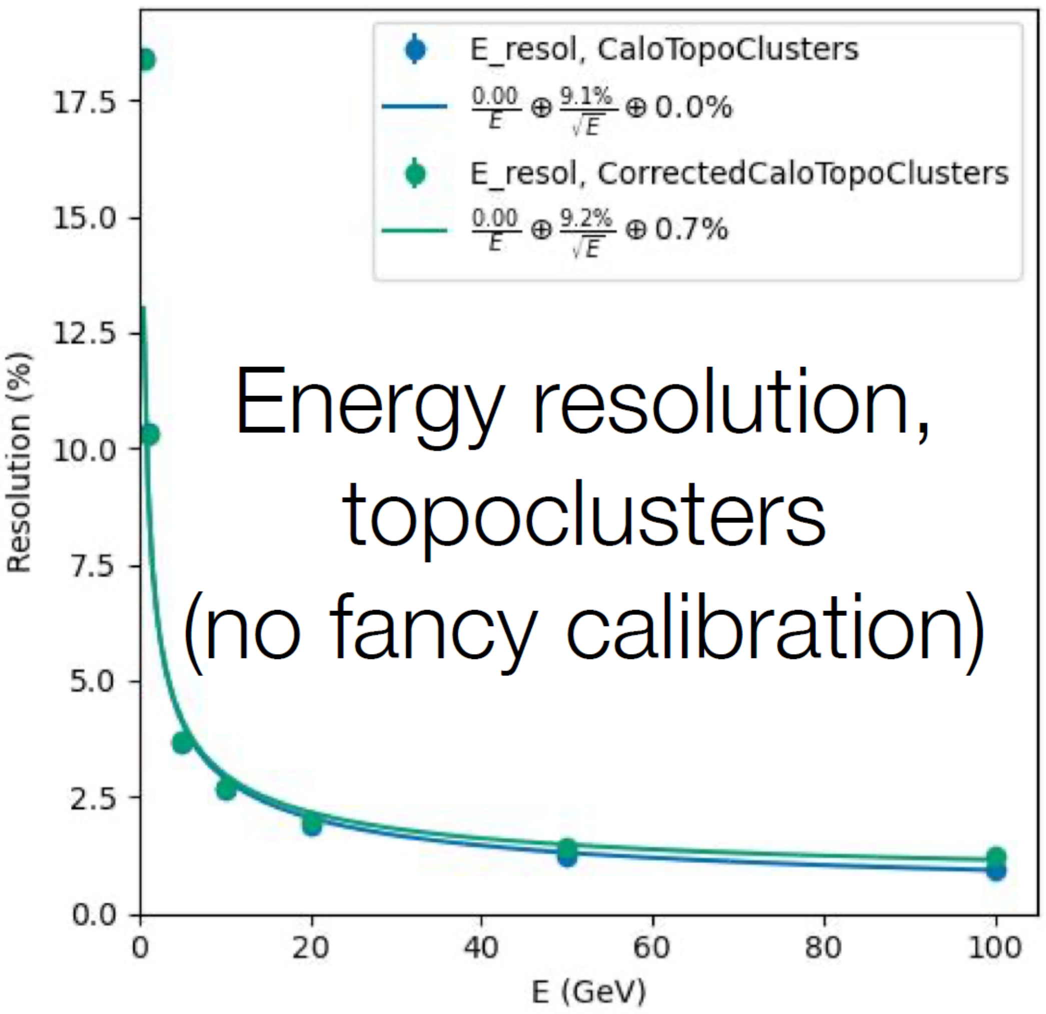

T3 without absorber



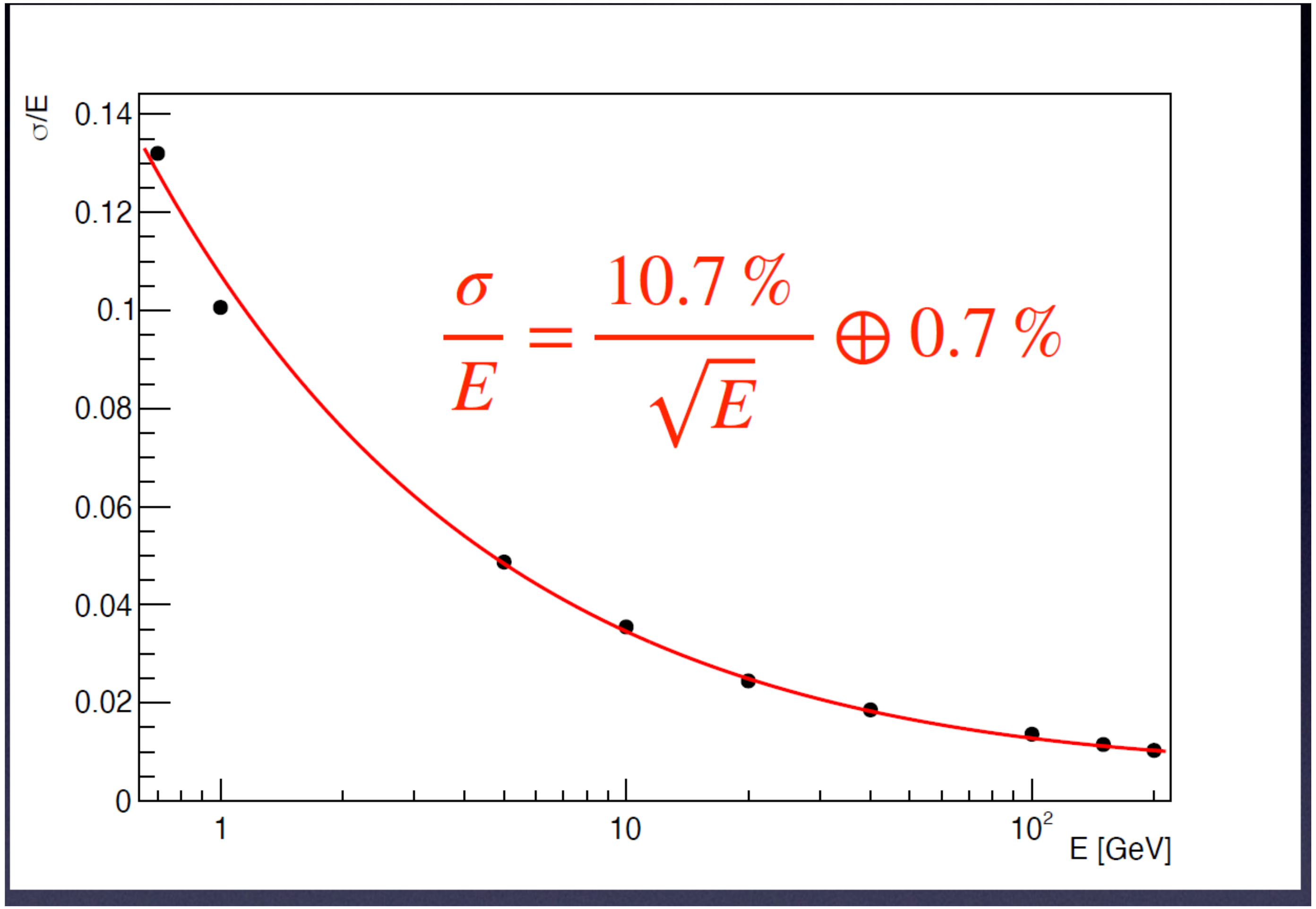

T3 with absorber:

- Reduce inductive effect

# Preliminary Resolution

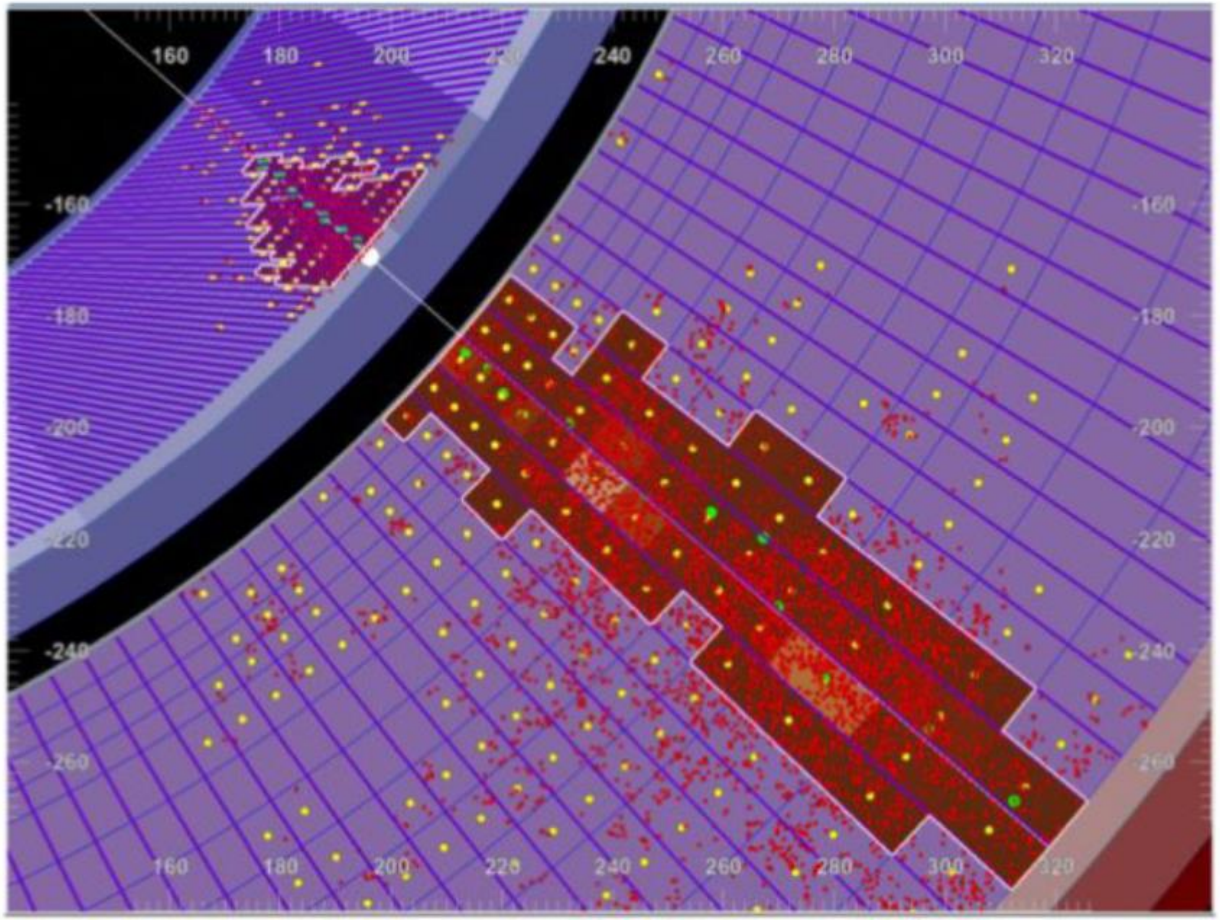


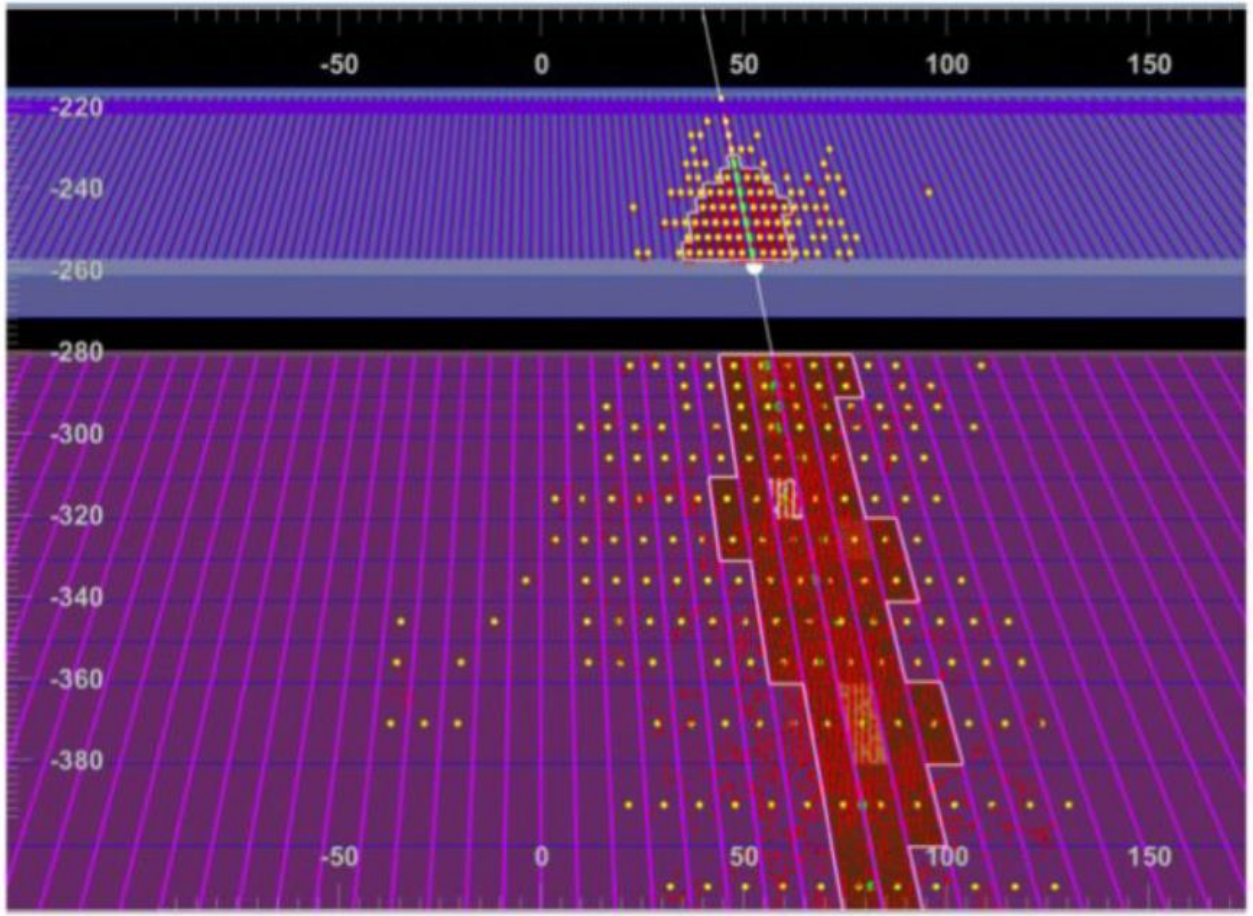

**Barrel**



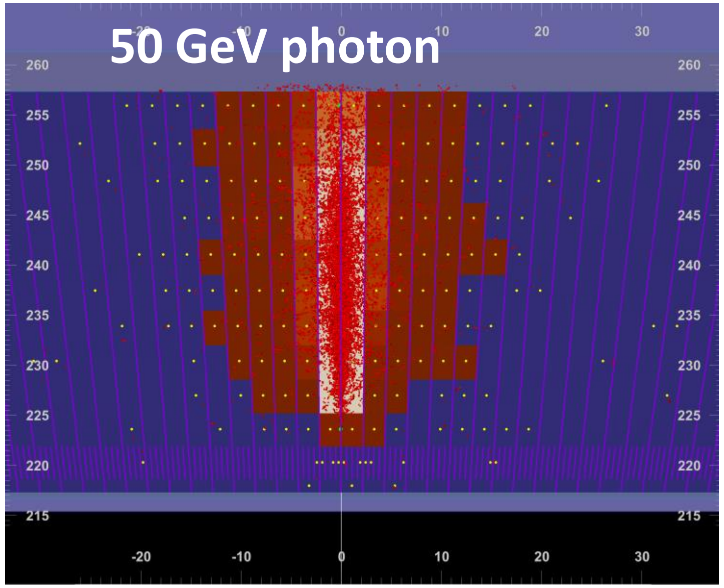

**New Endcap:**
- **Three nested wheels**
- **Tapered absorbers**

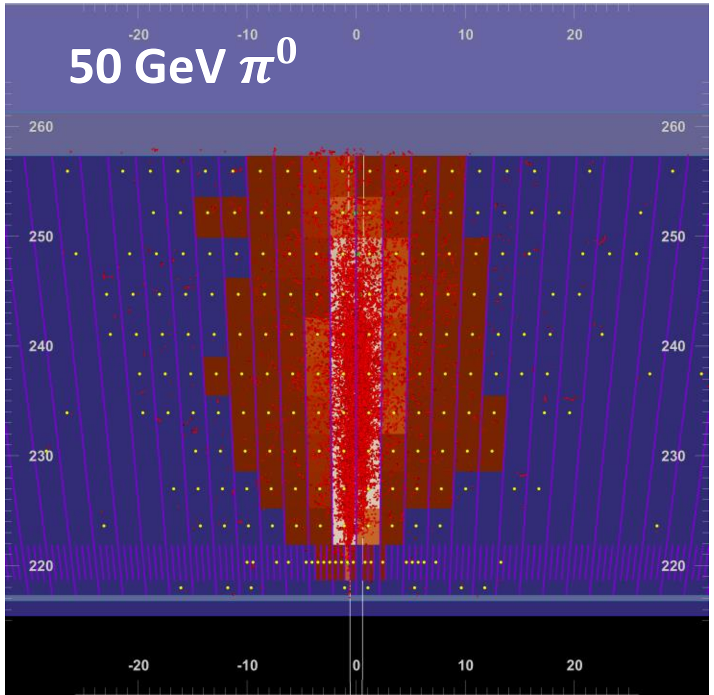
# 50 GeV pion in ALLEGRO (Lead/LAr  + Tile)



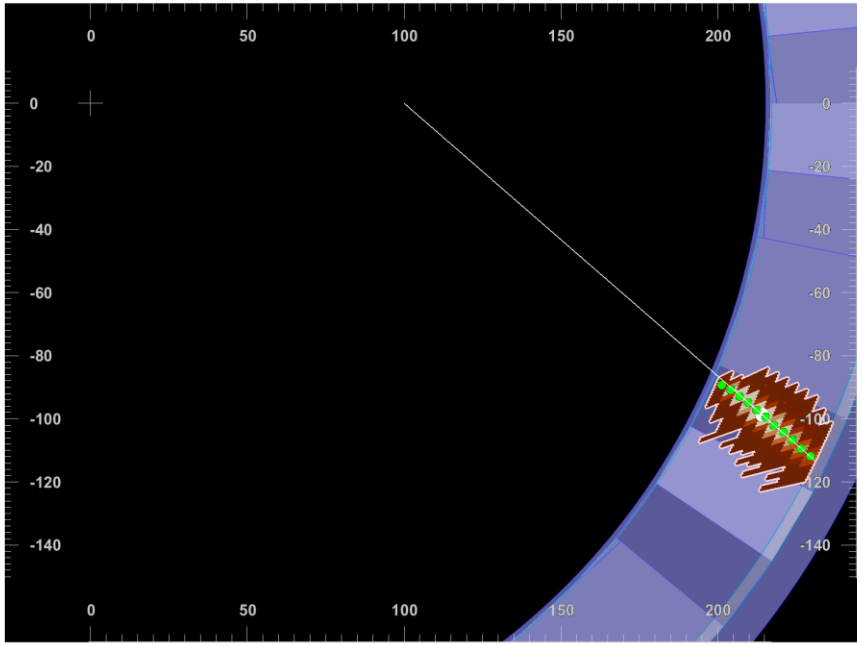



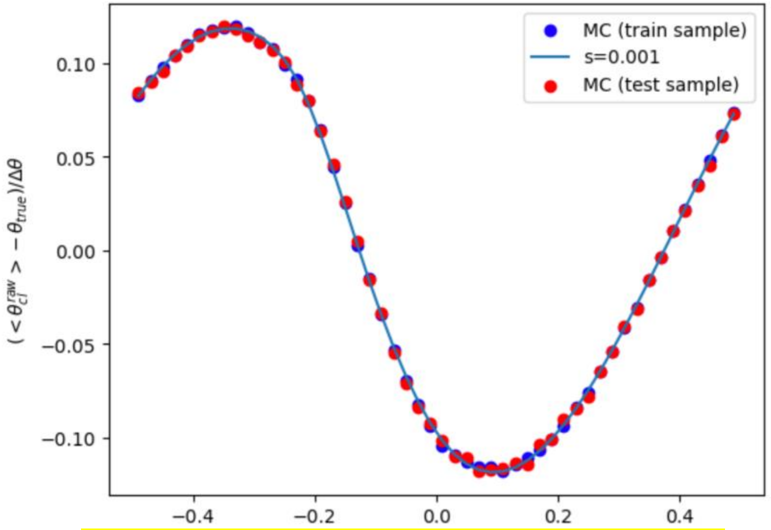
# $\pi^0/\gamma$ Separation, non-Pointing Electrons, Polar Position



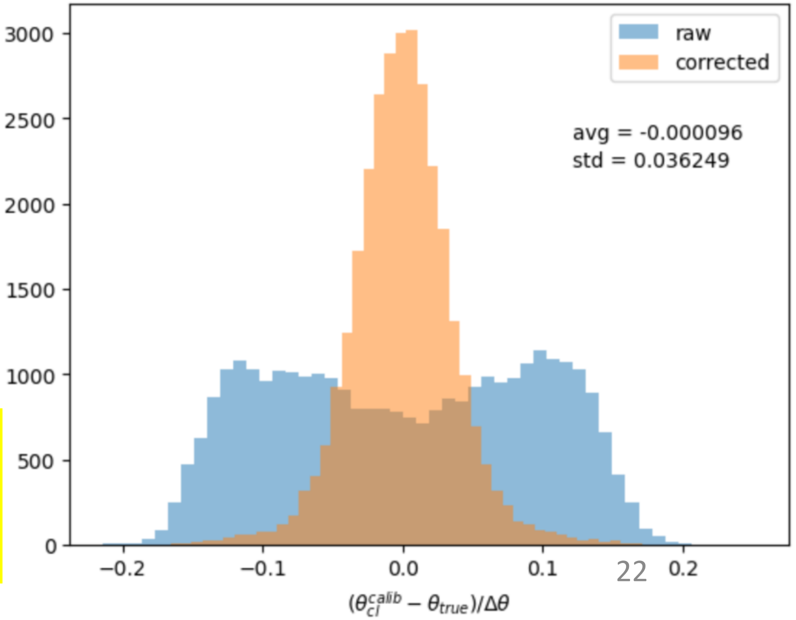




50 GeV non-pointing electron, B = 0



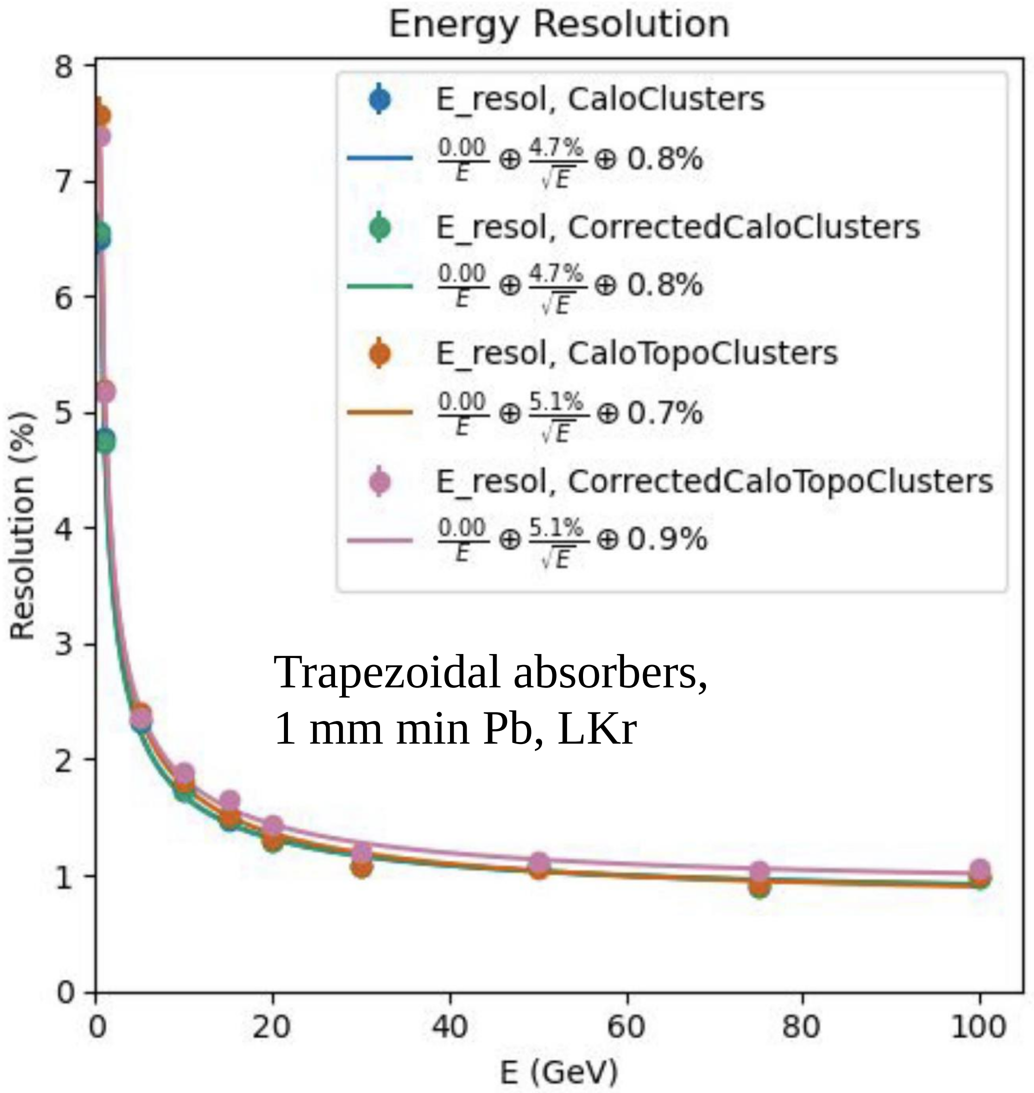


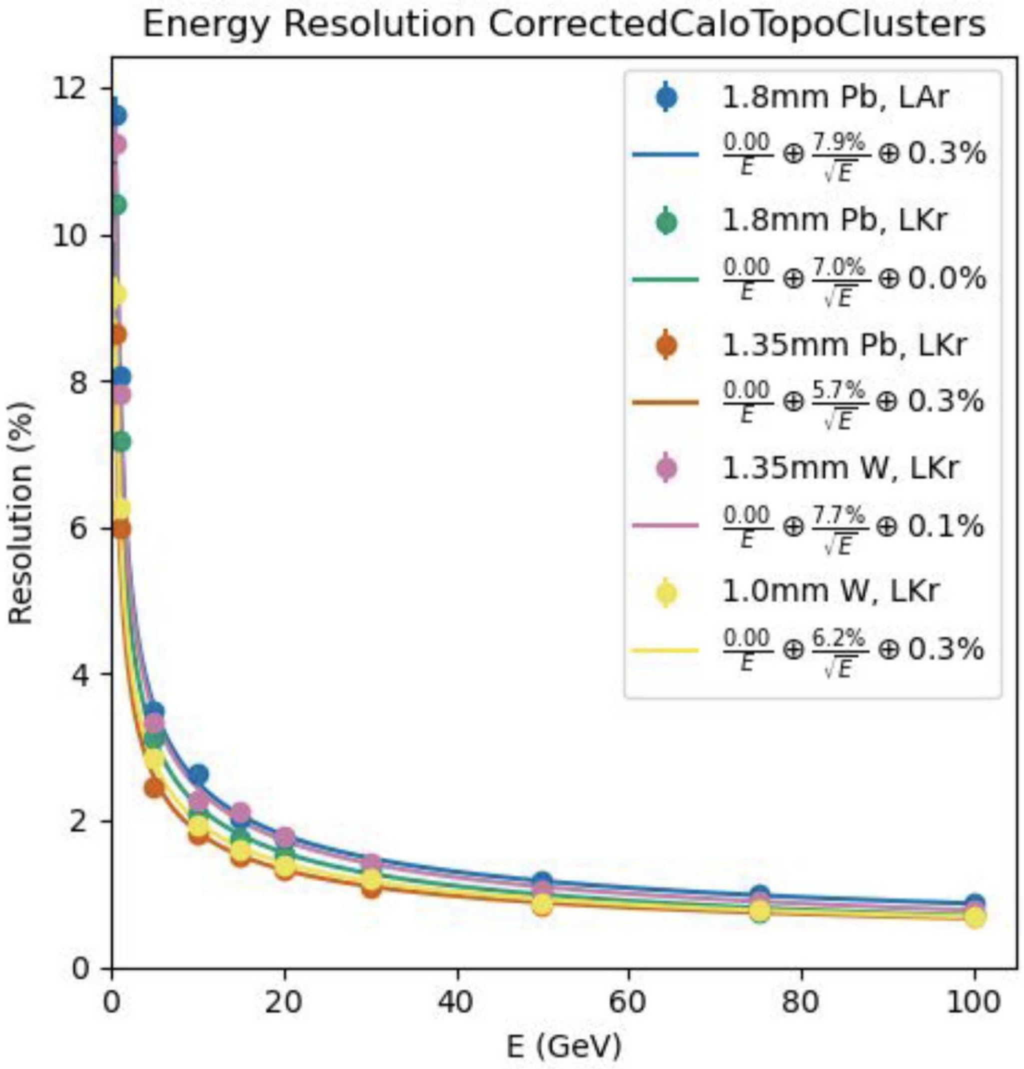

S-curve residual for polar position




Residual projection before and after s-curve correction

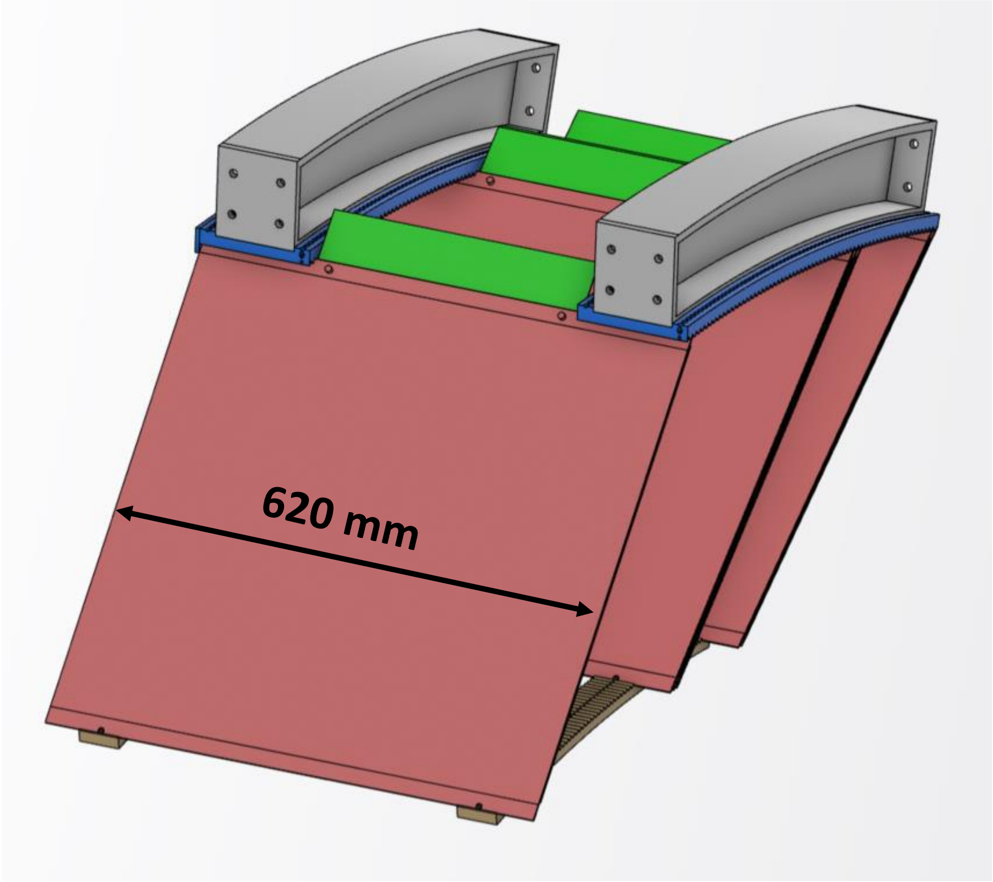
# Simulation of Trapezoidal Absorbers and Alternative Components

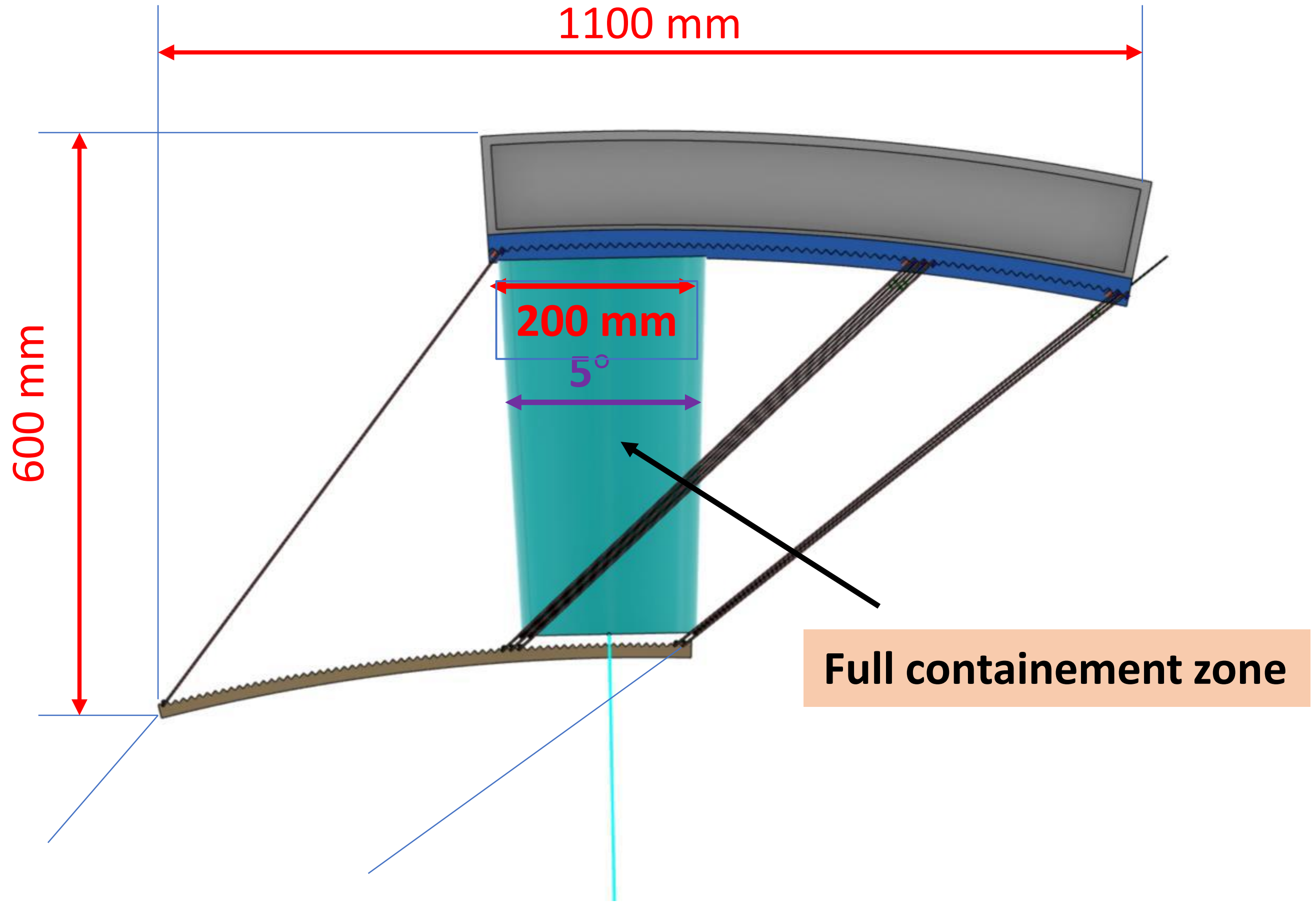


# Beam Test Prototype

- Forseen by 2028 – 2029.
- Azimuthal width: 15°, like an Allegro barrel module: 64 PCB, 65 absorbers.
- Length: 620 mm, about 20 % of an Allegro barrel module.



# Summary

- Significant progress has been made during 2024.
- The concept is being adapted for the endcap.
- Solutions are being investigated for mechanics: Structure conception and simulation, fixing and indexing, module and barrel mounting, spacers.
- Tests of absorber prototypes: Rigidity, yielding point, behaviour at cold.
- Many measurements of electrical properties on 2 prototype electrodes. Some fine effects understood. There are still measurements under investigation with help from electrical simulation.
- These measurements are used to better design next prototypes.
- Simulation is improving daily and will be helpful is detector optimisation.
- Mechanics of our first test beam prototype is making good progress.

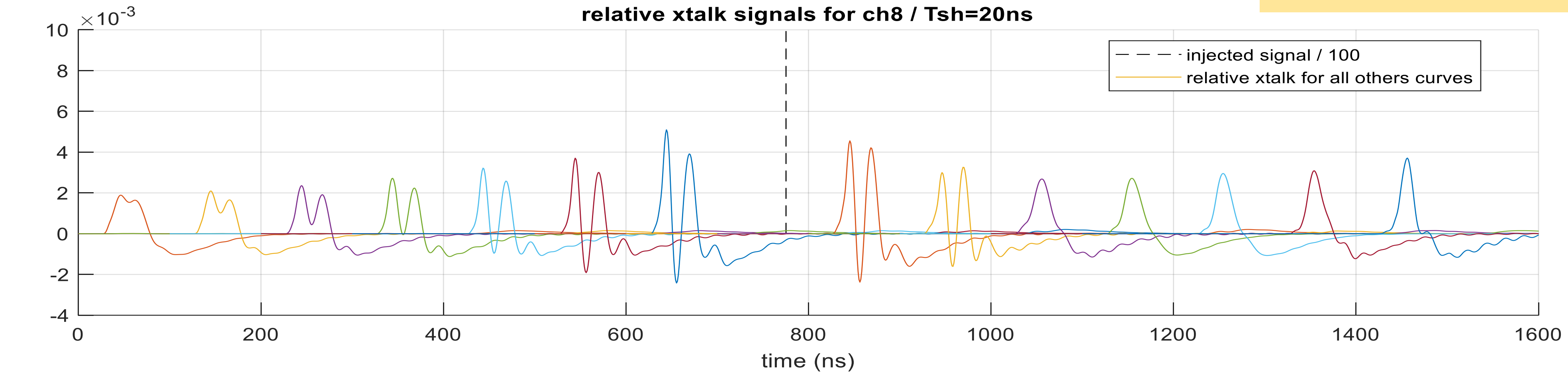
# Backup

# Effect of Lateral Shields on Cross-Talk (PCB v3)

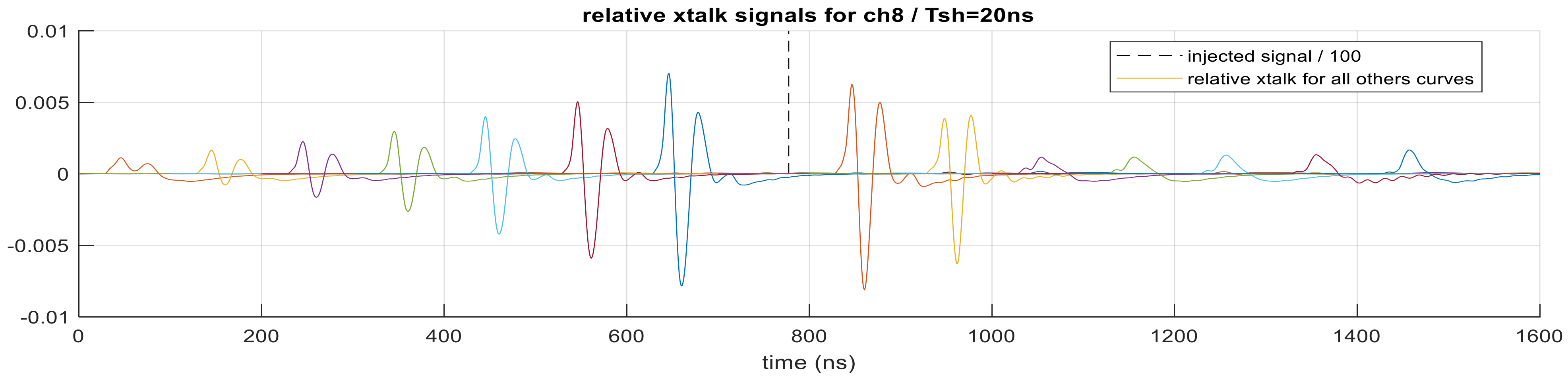
**Lateral shields:**

- **Reduces capacitive coupling.**
- **Increases inductive coupling. Because of the pad-ground capacitance increasing, involved in inductive cross-talk.**

(w/o lateral shielding)




(with lateral shielding)



# Automatized Measurement Bench at Orsay