R&D on Noble Liquid Calorimeter for Future Collider Experiments

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On behalf of DRD6—WP2

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE

CPPM

Requirements on Electromagnetic Calorimetry at FCC-ee

Flavour and τ physics:
Use decay modes with π^0

Separate $W^{\pm}/Z^0$ jets

Particle flow

Forbidden decays

- **Best possible energy resolution**
- **High granularity**
- **Efficient γ/π^0 separation**
- **Very low noise**

Good S/N
for MIPs

$Z^0\nu_e\bar{\nu}_e$ coupling

Measure photons
down to 200 MeV

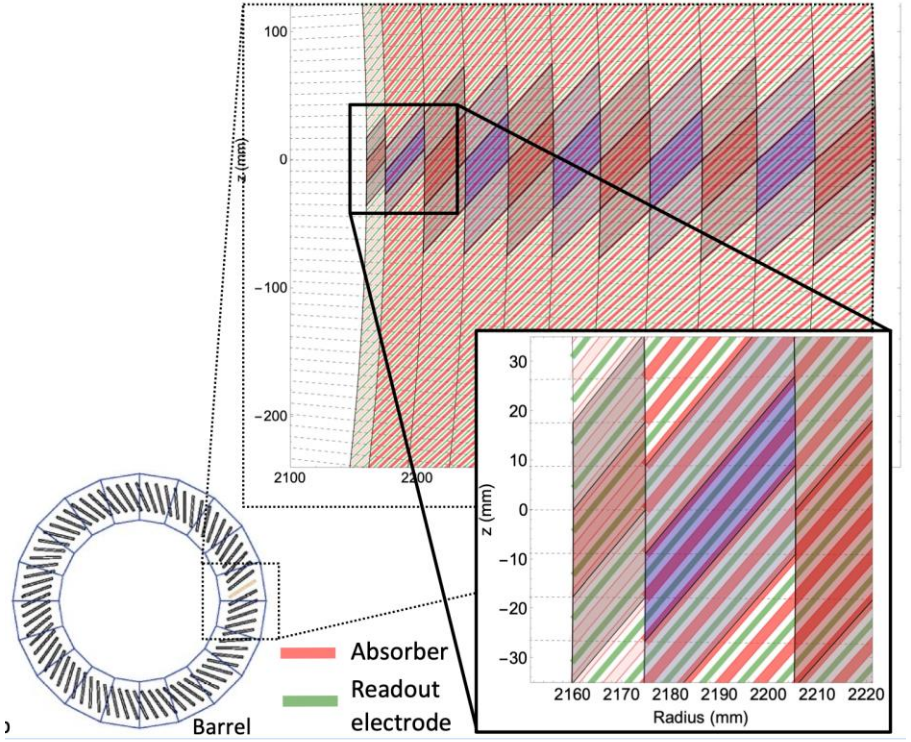
Feebly interacting
particle decays

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.
- $\mathrm{R_{inner}} = 2160\ \mathrm{mm}, \mathrm{R_{outer}} = 2560\ \mathrm{mm}$, thickness of 22 X_0.
- Absorbers are $\sim 2\ \mathrm{mm}$ thick.
- Gaps go from 1.2 to 2.4 mm.
- Sampling fraction around 20 %.
- 1536 double-gap, $\Delta\varphi = 8\ \mathrm{mrad}$ (2 electrodes).
- Granularity in polar angle: drawn on electrode, $\Delta\theta = 10\ \mathrm{mrad}$.

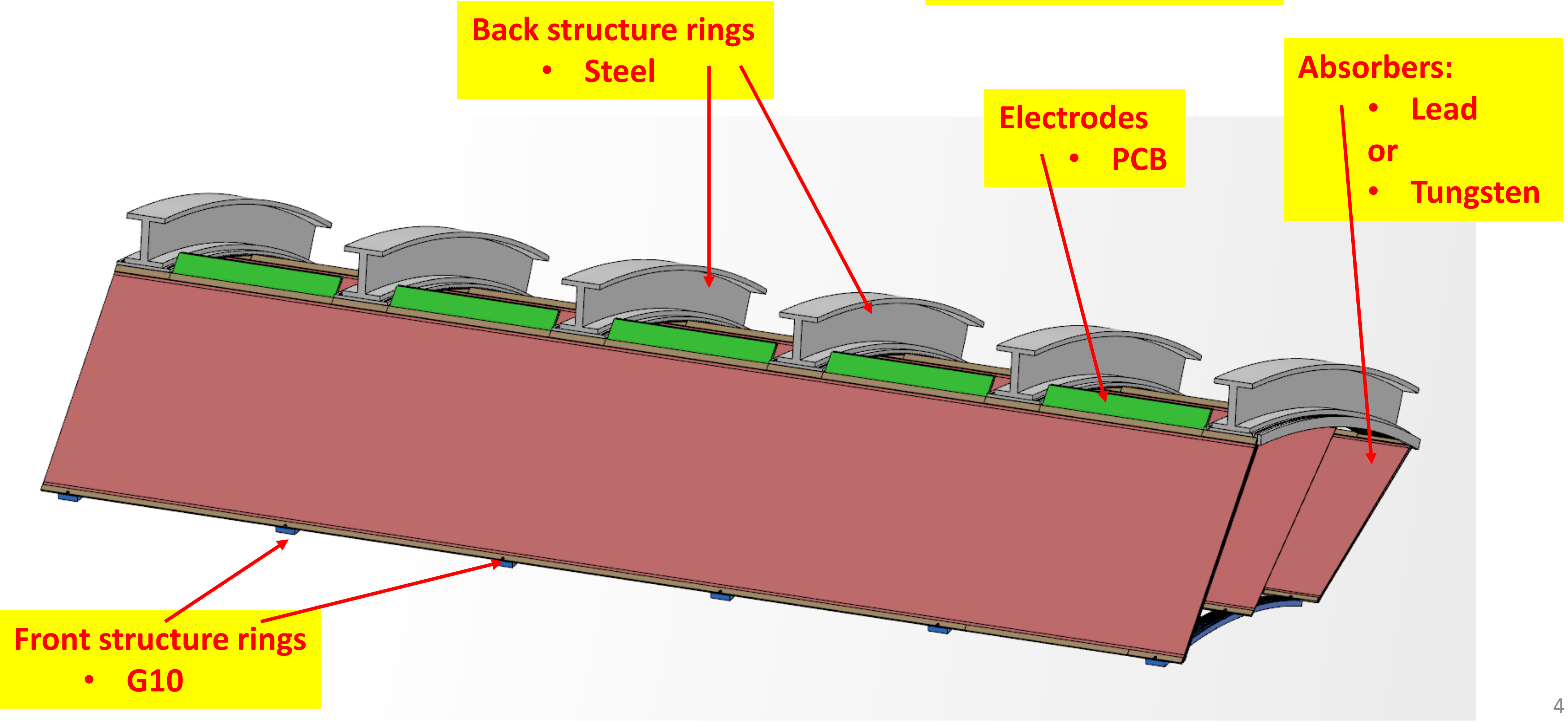


A module of the Electromagnetic Calorimeter Barrel

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

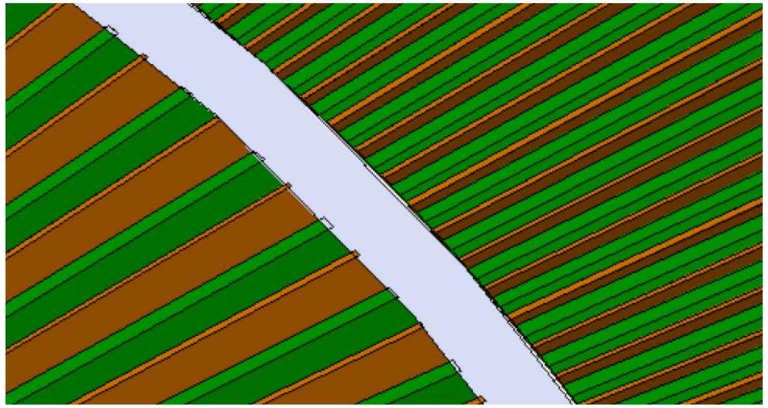
Active gap:
- Liquid Argon

or
- Liquid Krypton

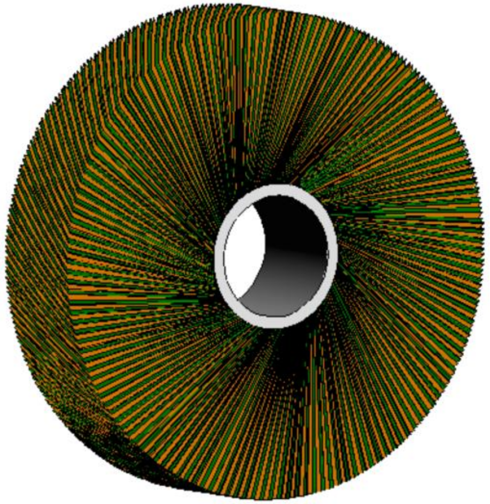


Adaptation for Endcap

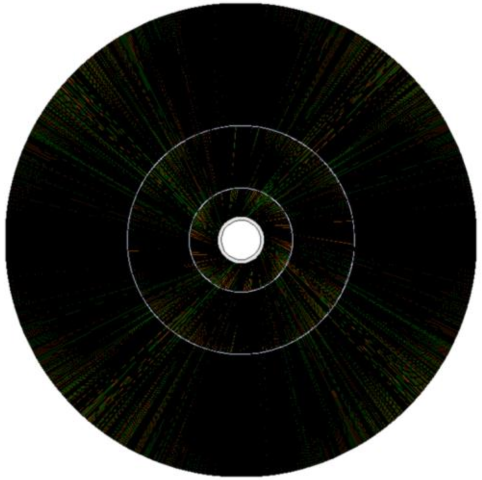
- 420 mm < R < 2750 mm
- Turbine implementation of the technique on the endcap: hermeticity, homogenous in ϕ, readout from the rear.
- But it has a major issue: Gap widening range is too large.
- Mitigation is being worked out:
  - 3 nested wheels.
  - But still sampling fraction varying a lot.
  - Solution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



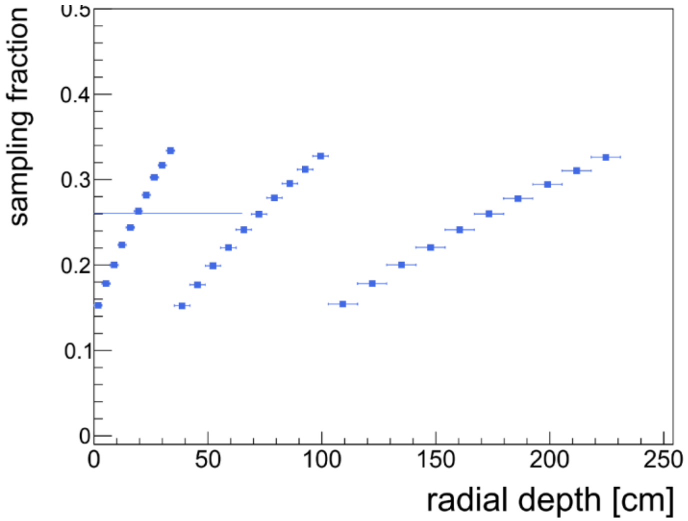
Zoom between 2 nested wheels



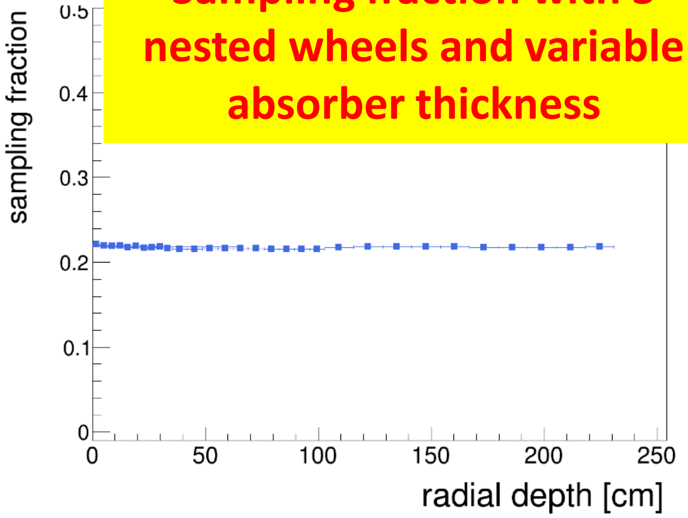
Simple turbine



3 nested wheels



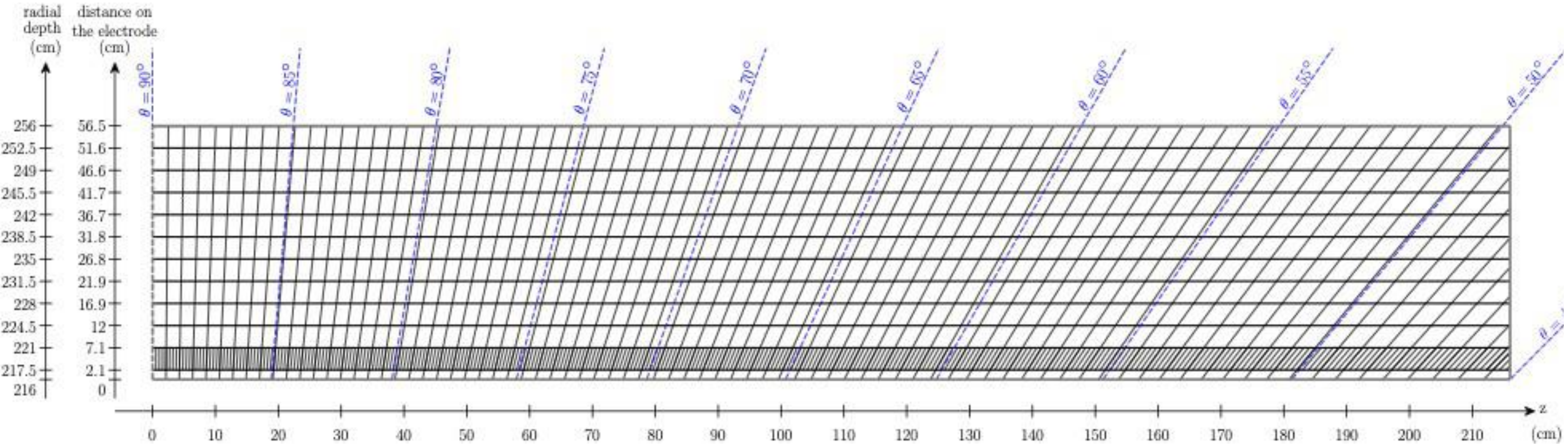
Sampling fraction with 3 nested wheels

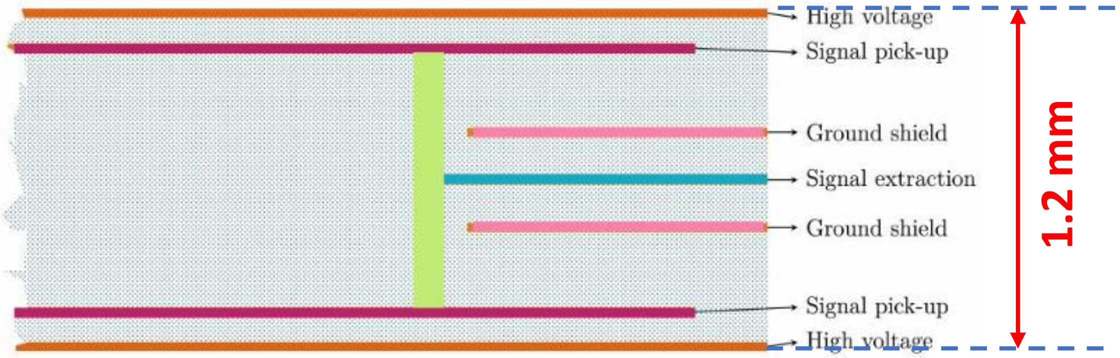


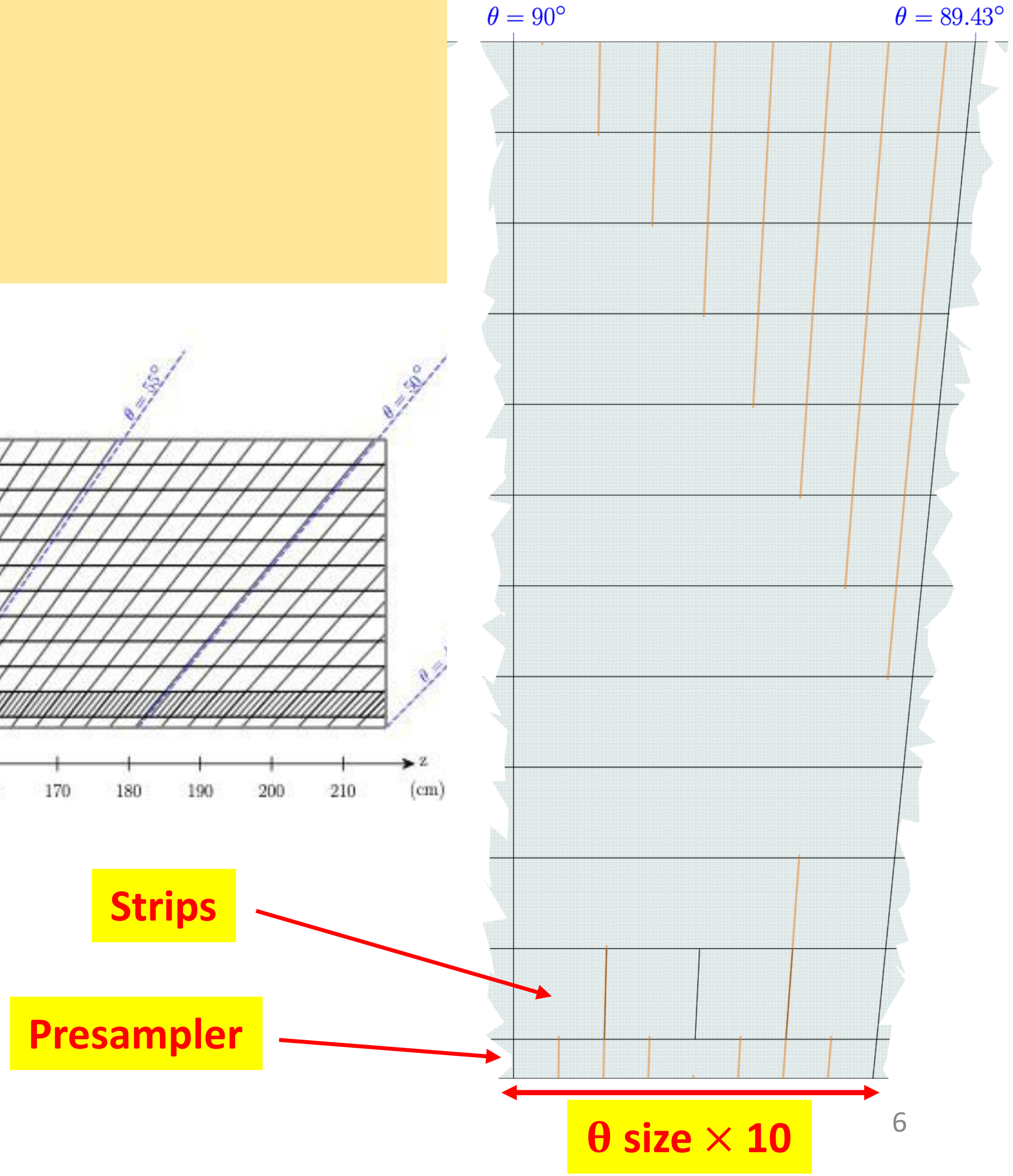
Sampling fraction with 3 nested wheels and variable absorber thickness

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)

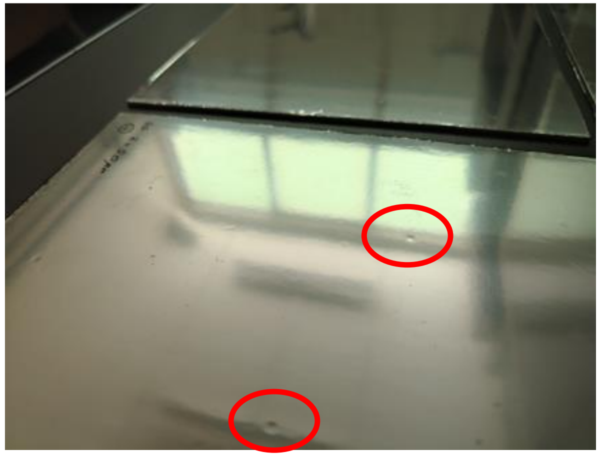


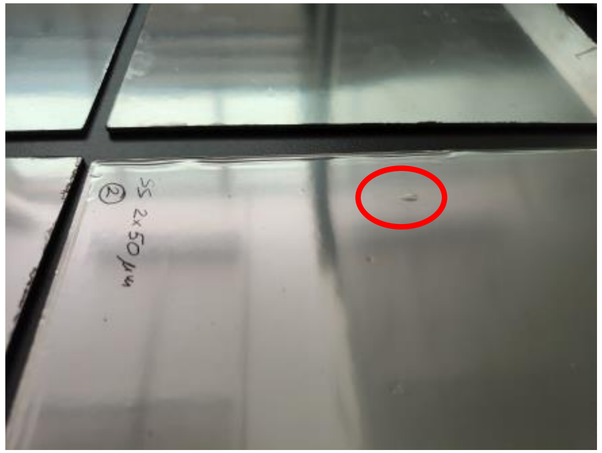




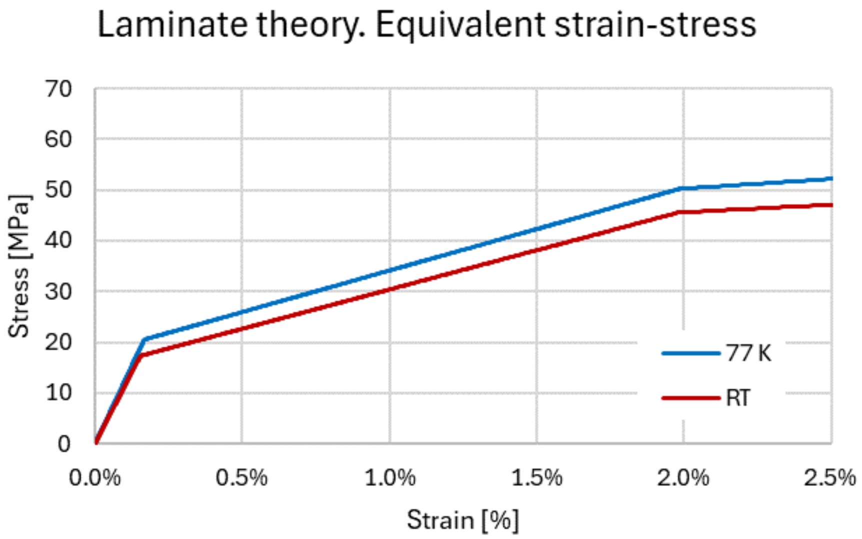
Absorbers

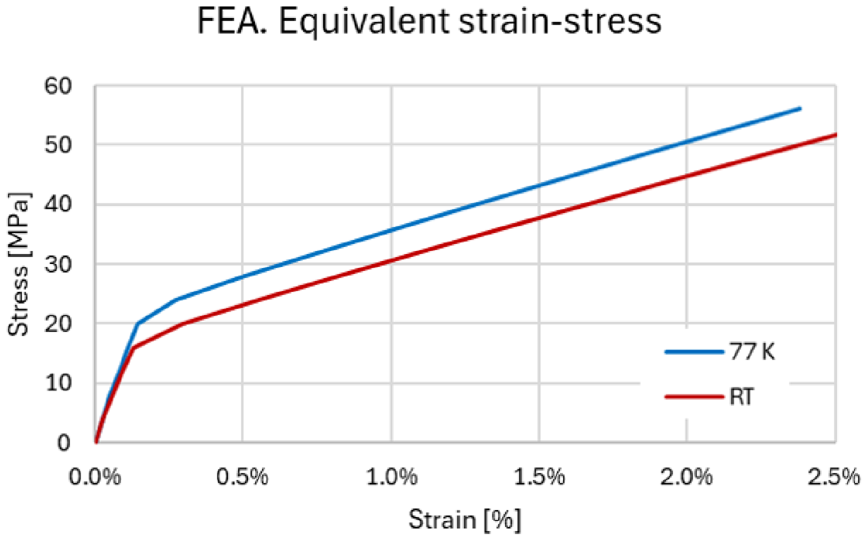
- Prototypes of absorbers have been manufactured.
- Stainless steel – glass fiber – lead – glass fiber – stainless steel assembly.
- Base line was 0.050 mm of steel and glass fiber, and 1.8 mm of lead.
- But deformations were observed.
- No deformation for prototypes with a thicker steel (0.100 mm).





Yielding point	σy at RT [MPa]	σy 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

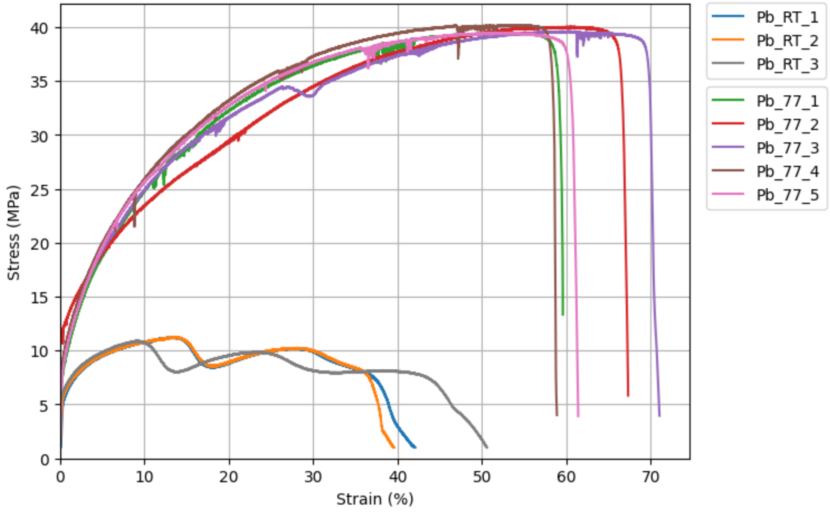




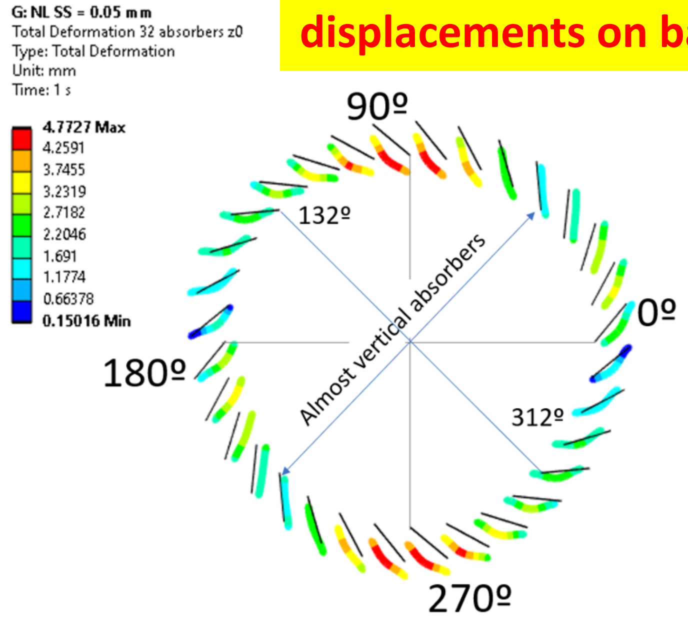
- Room temperature: Measurements in agreement with Laminate Theory and Finite Element Method.
- At 77° K : LT and FEM underestimate measurements.

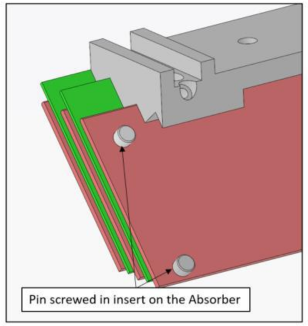
Barrel Structure

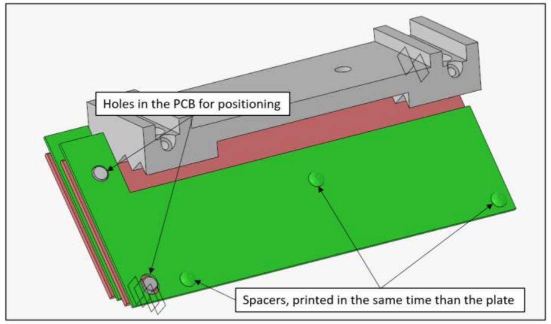
Lead strength test



Simulation of absorber displacements on barrel

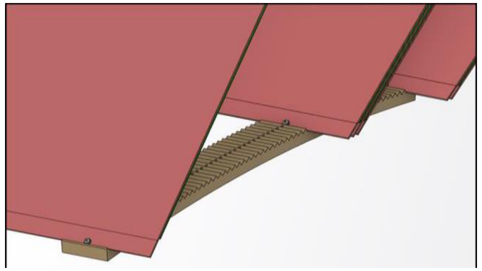


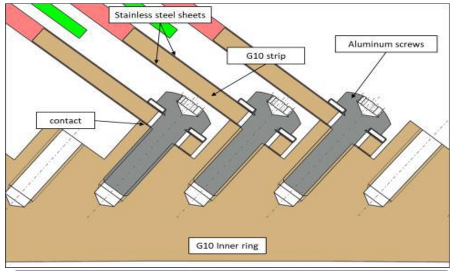


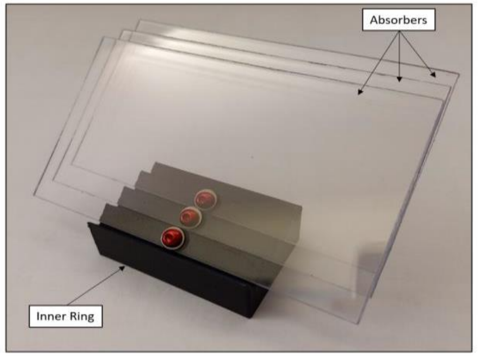


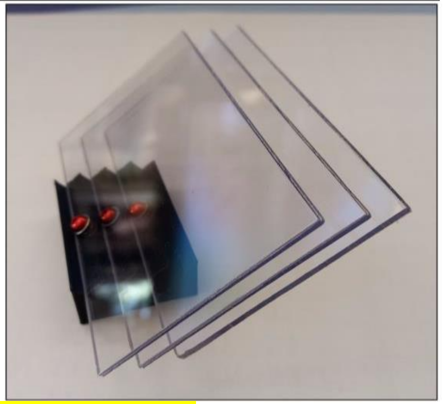
Full scale 3D printed samples

Fixation on outer rings







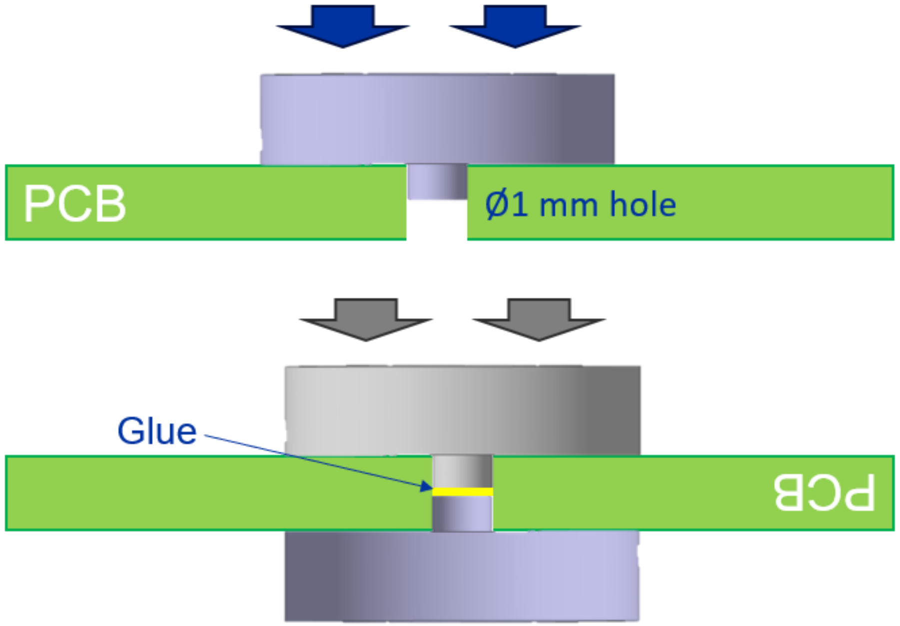


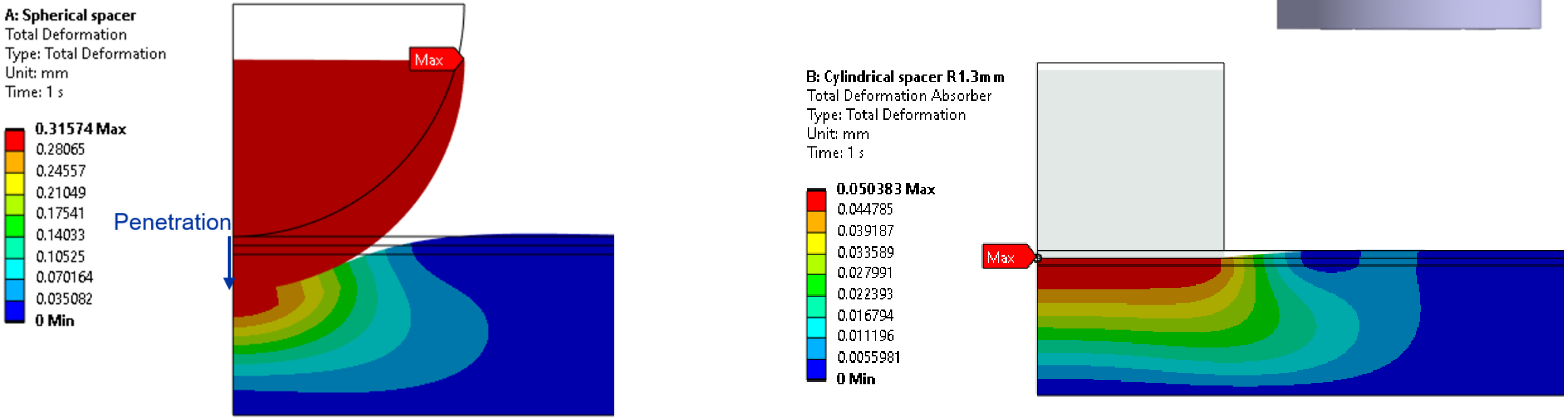
Fixation on inner rings

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

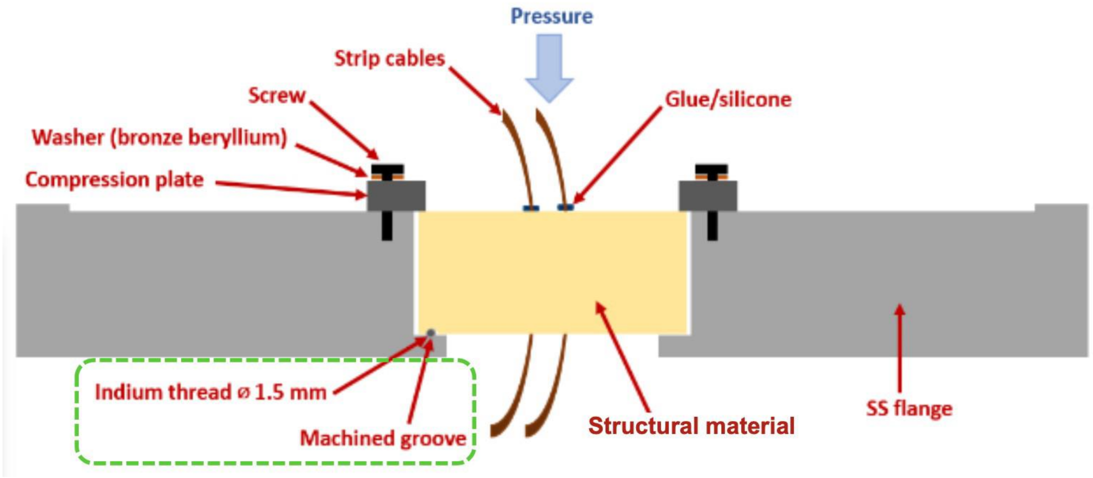


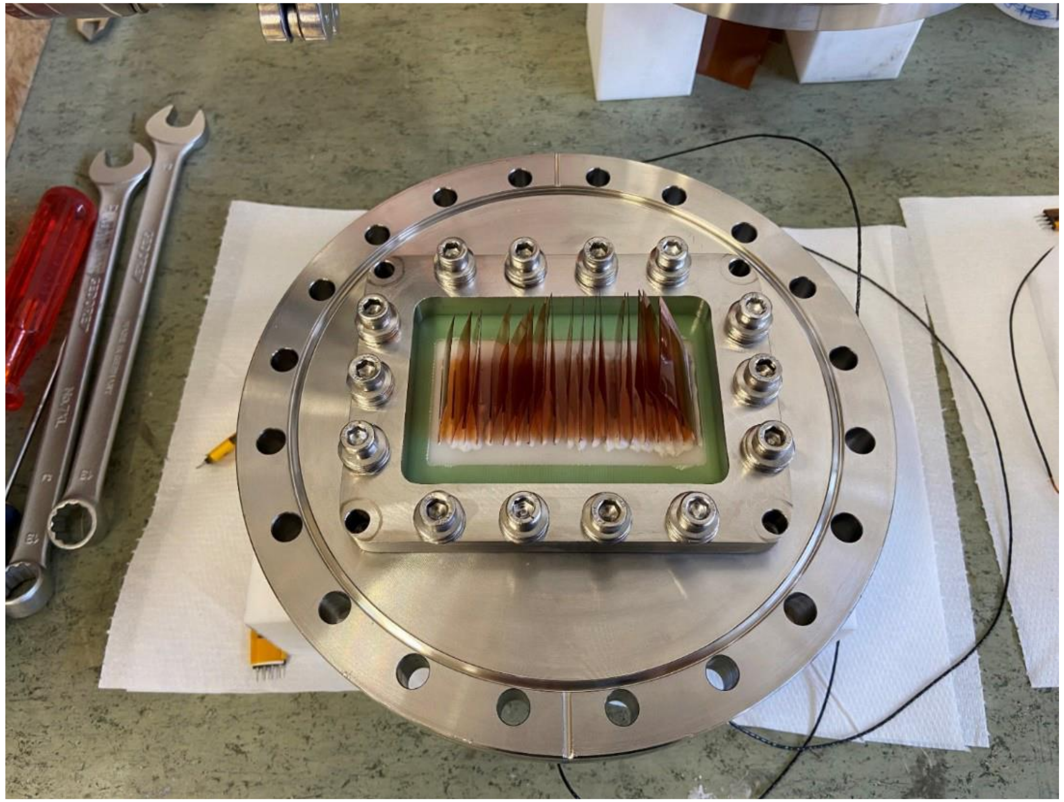


Simulation of absorber deformation with spherical and cylindrical spacers

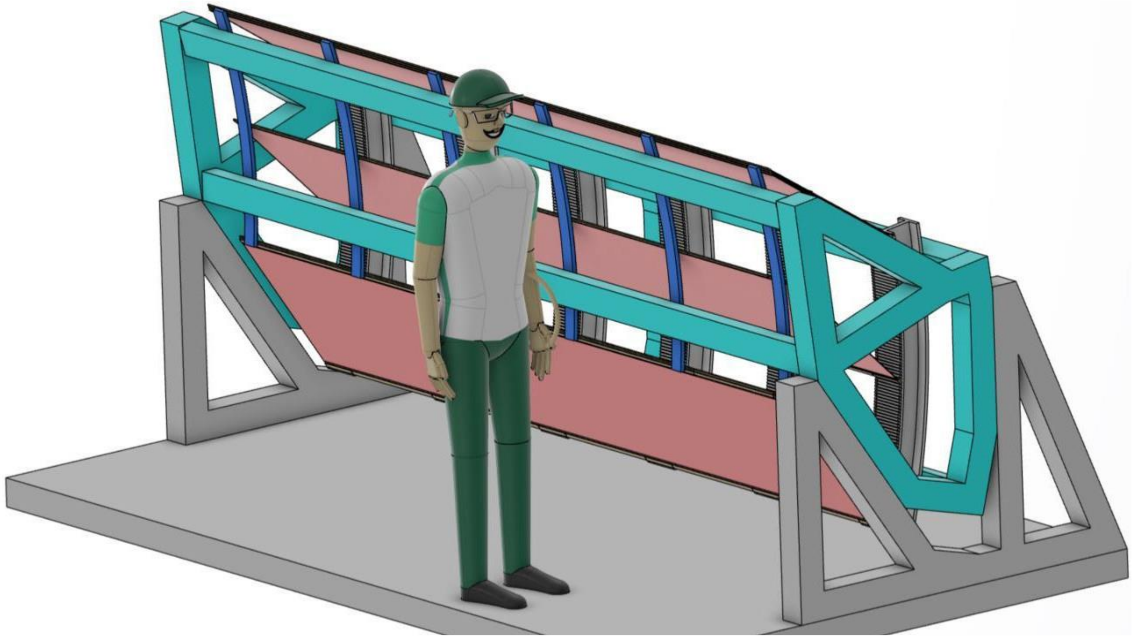
Cryostat and Feedthroughs

- 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.

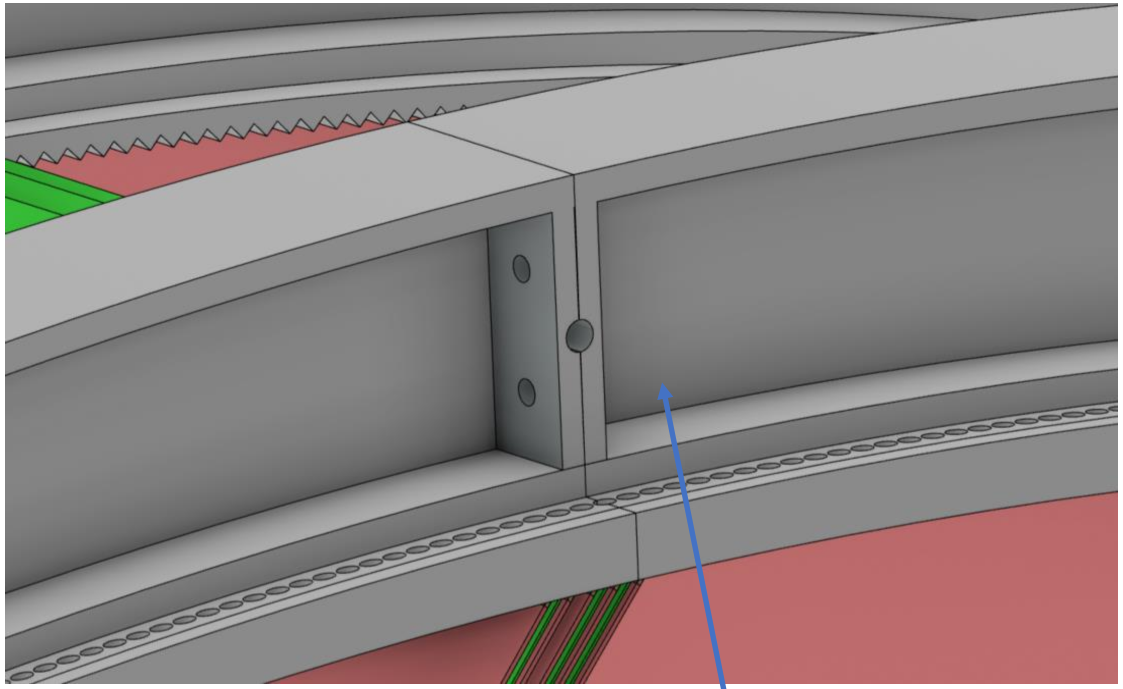




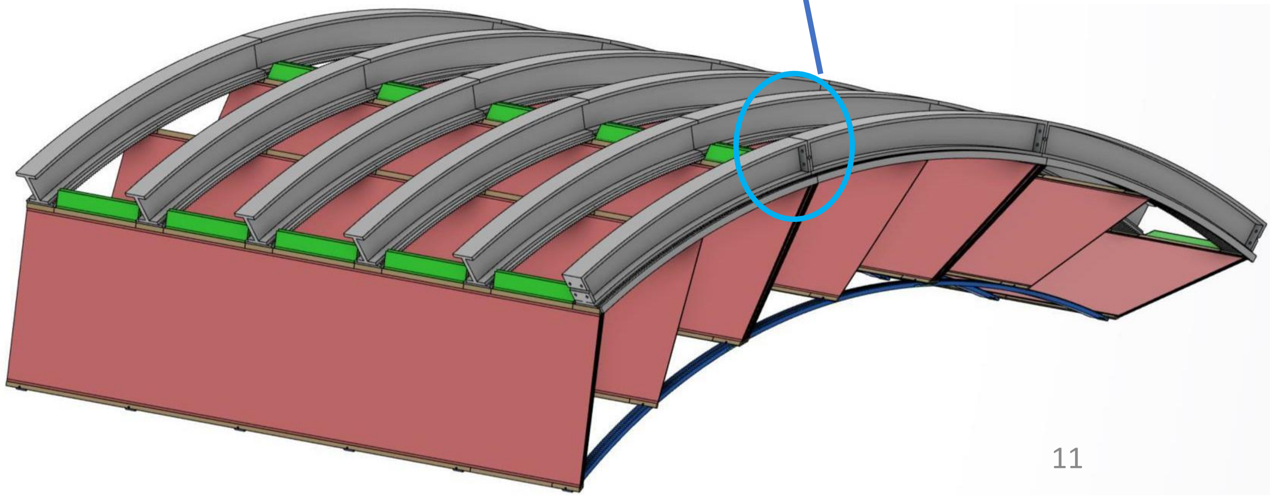
Assembly Studies and Tools



Assembly structure of a barrel module

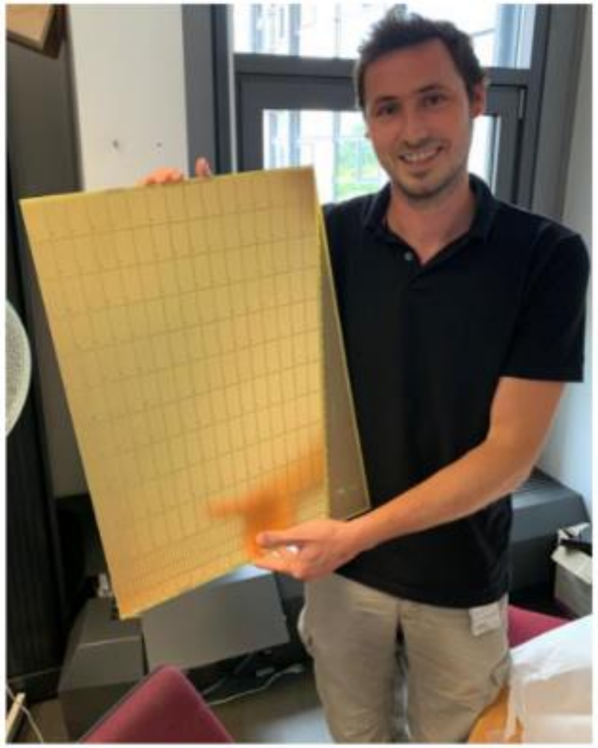


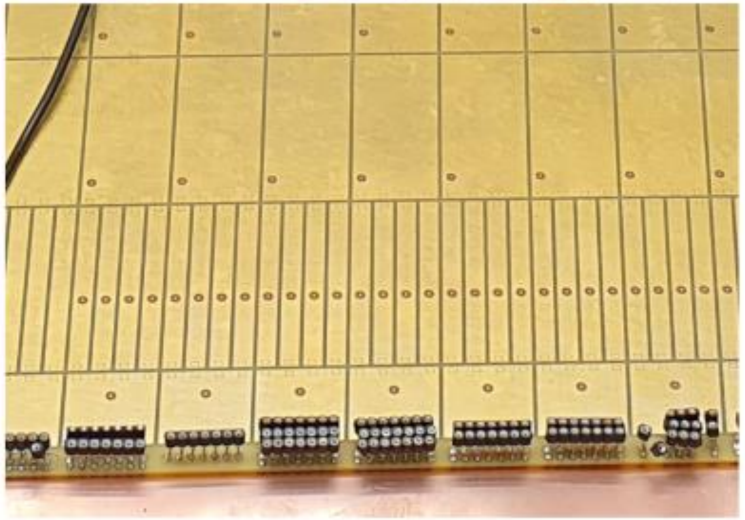
Outer ring junction between modules



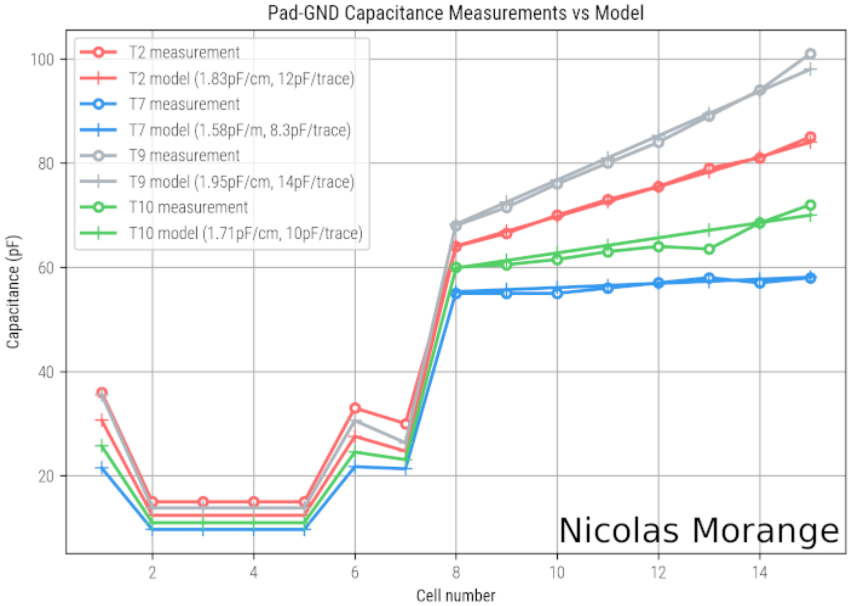
CERN PCB Prototype V1

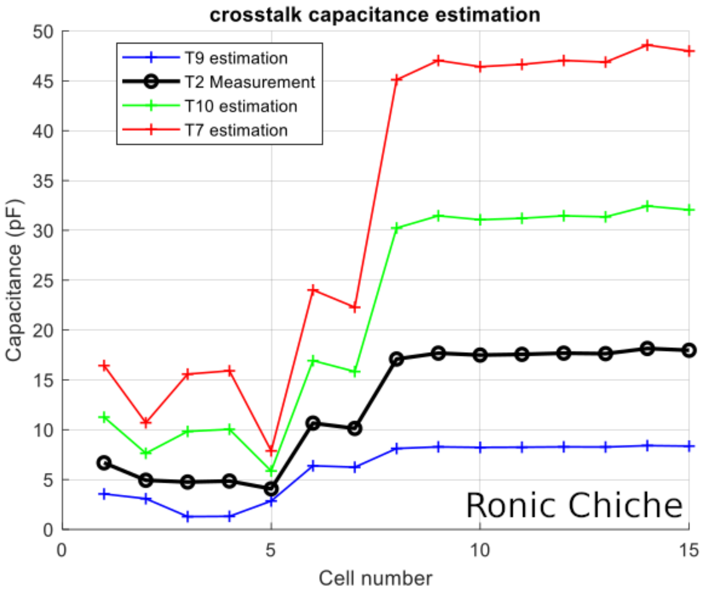
- First full depth prototype. Already shown at Paestum.
- 58 cm × 44 cm.
- 12 depth layers, 40 cm depth.
- Readout from 2 edges.
- 16 θ towers.
- First Layer L0 not covered by absorber: It will play the role of a presampler.
- Strips in L1.
- 240 cells.





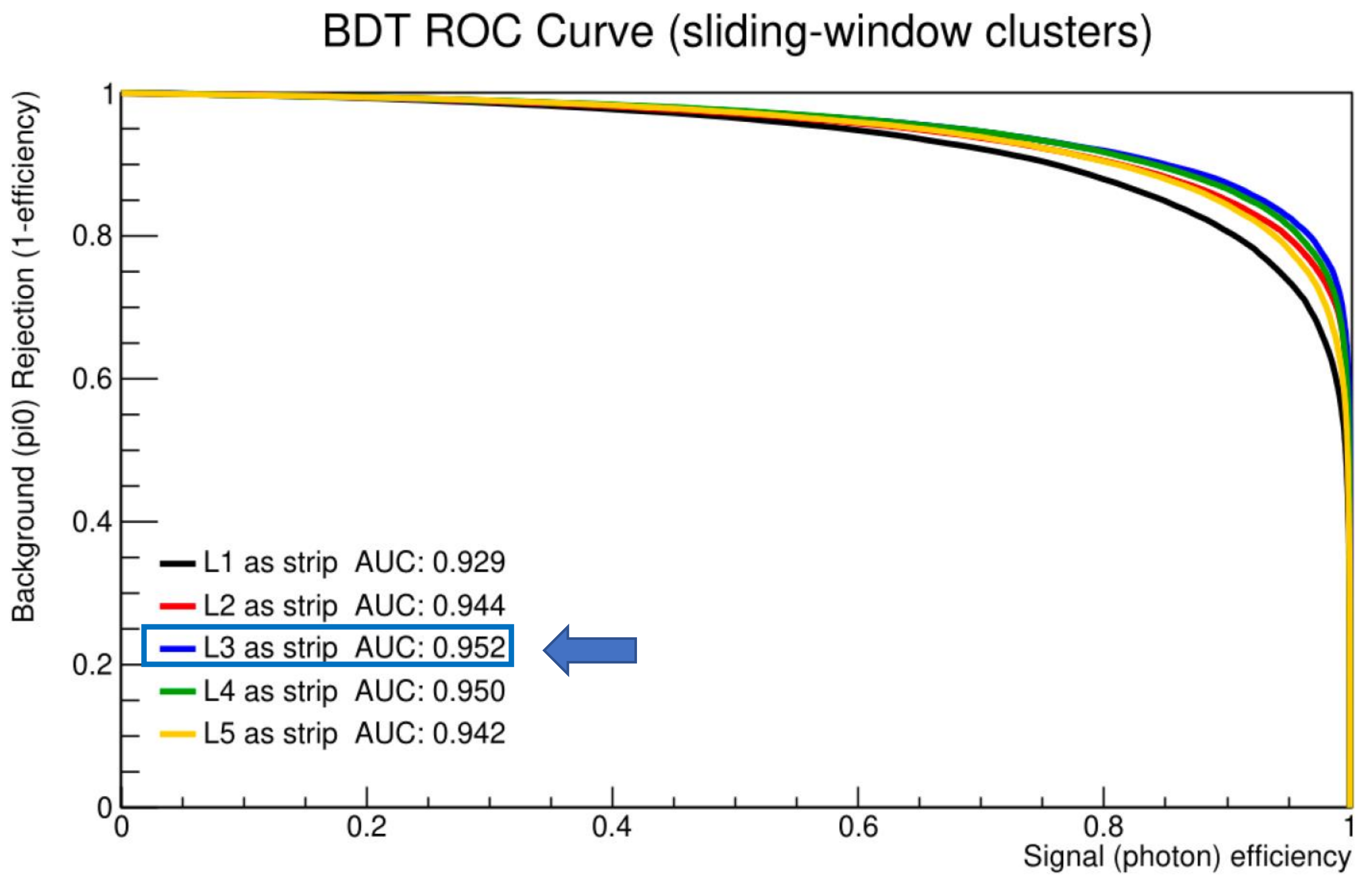
Estimated and measured cell and cross-talk capacitances





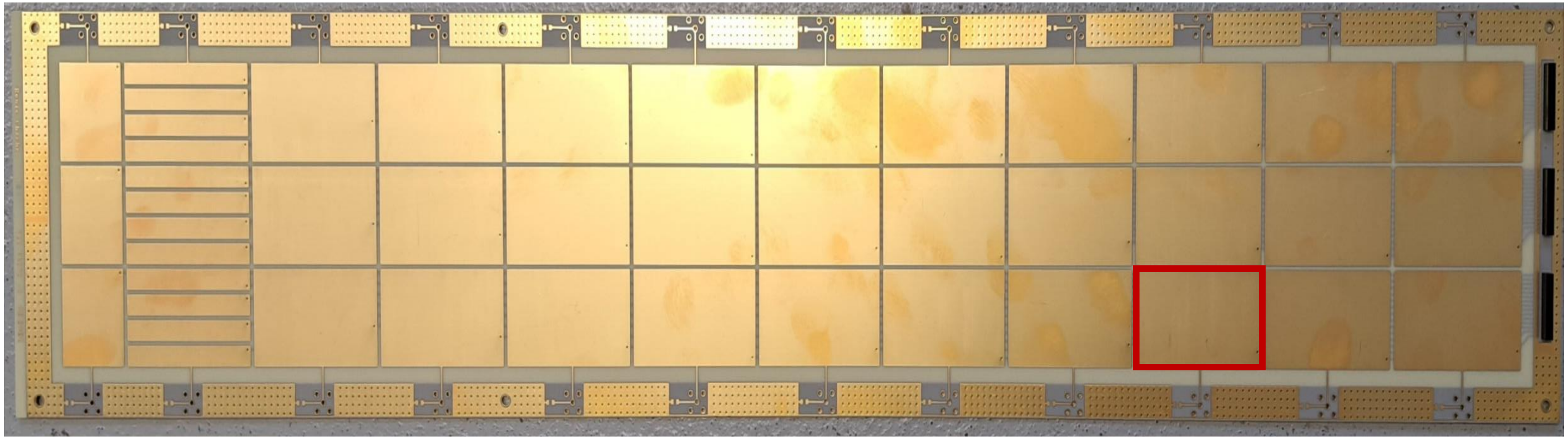
CERN PCB Prototype V2

- It is being finalized by the light of measurements, tests and simulation.
- Readout from outer radius.
- Industrial connectors.
- Optimised trace ordering.
- Simulation: Better γ/π^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:

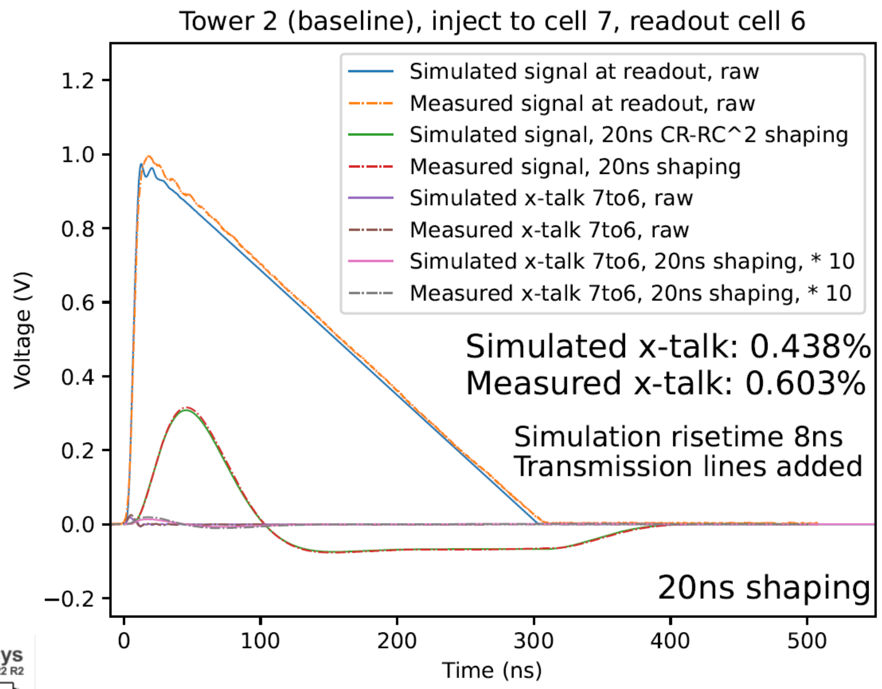
Signal: 127µm

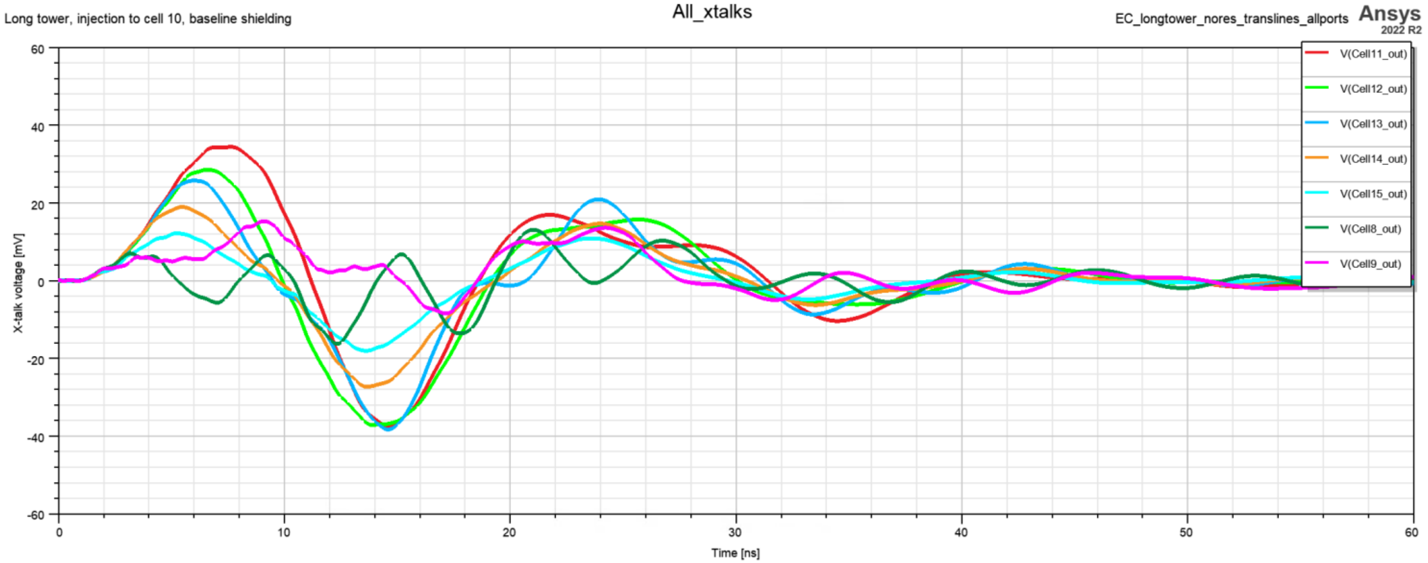
Top/bottom shielding: 254µm

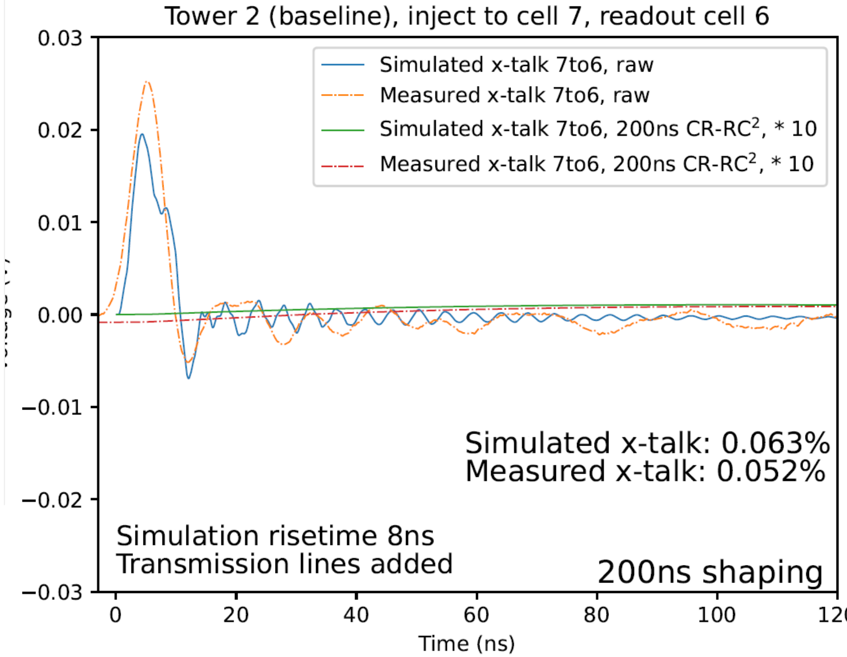
Lateral shielding: 127µm

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.





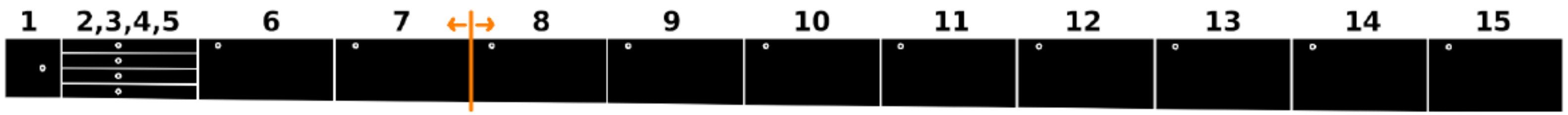


Simulated cross-talk signal on neighbour cells of the same tower

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

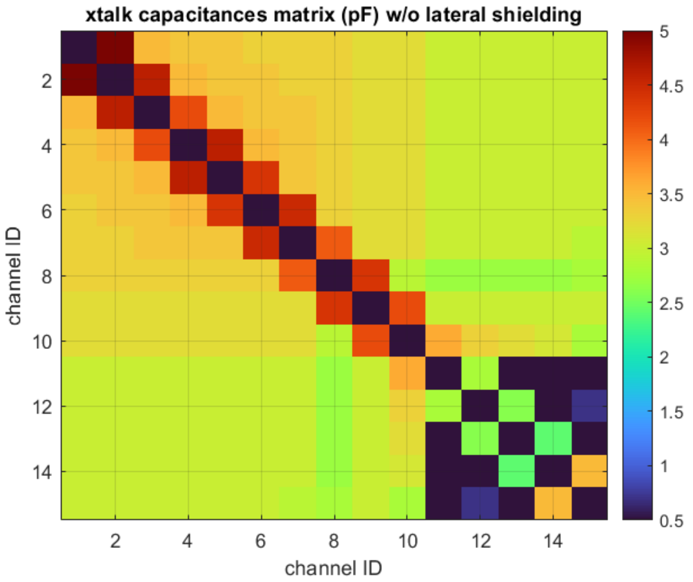
Cell	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-	0.8	1.1	1	0.7	0.9	0.7	0	0	0	0	0	0	0	0
2	0.6	-	0.7	0	0	1.2	0	0	0	0	0	0	0	0	0
3	0.9	0.7	-	2.3	0	0.7	0	0	0	0	0	0	0	0	0
4	0.9	0	2.3	-	0.7	0.2	0.7	0	0	0	0	0	0	0	0
5	0.6	0	0	0.7	-	0.1	0.3	0	0	0	0	0	0	0	0
6	0.7	1.1	0.7	0.2	0.1	-	2.8	0	0	0	0	0	0	0	0
7	0.6	0	0	0.7	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	-

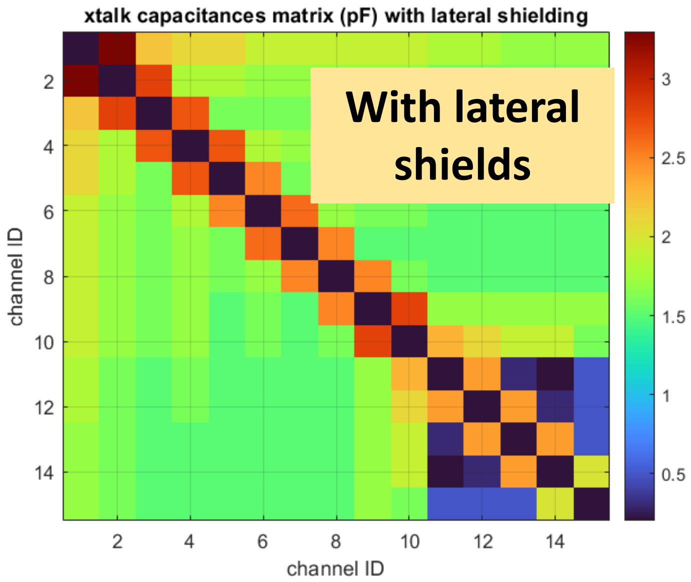
X-talk capacitances in pF in Tower2, rounded to once decimal place. Digitized by Ronic Chiche at IJCLab.



Effect of Lateral Shields (PCB v3)

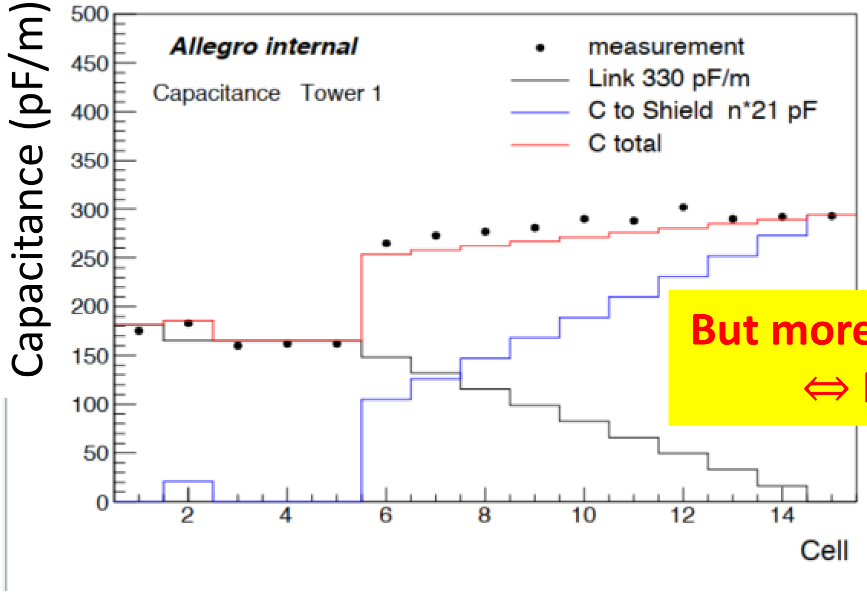
Less cross-talk:



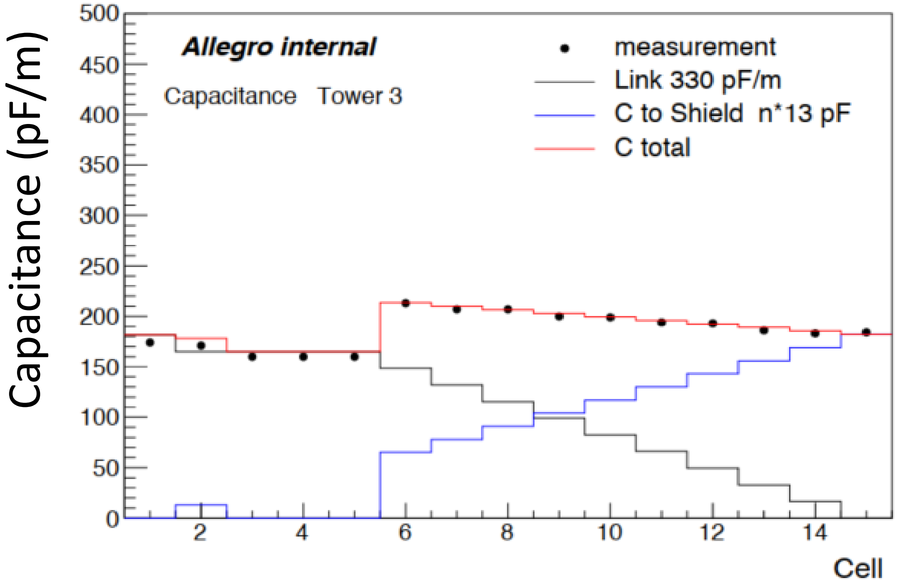


With lateral shields

With lateral shields



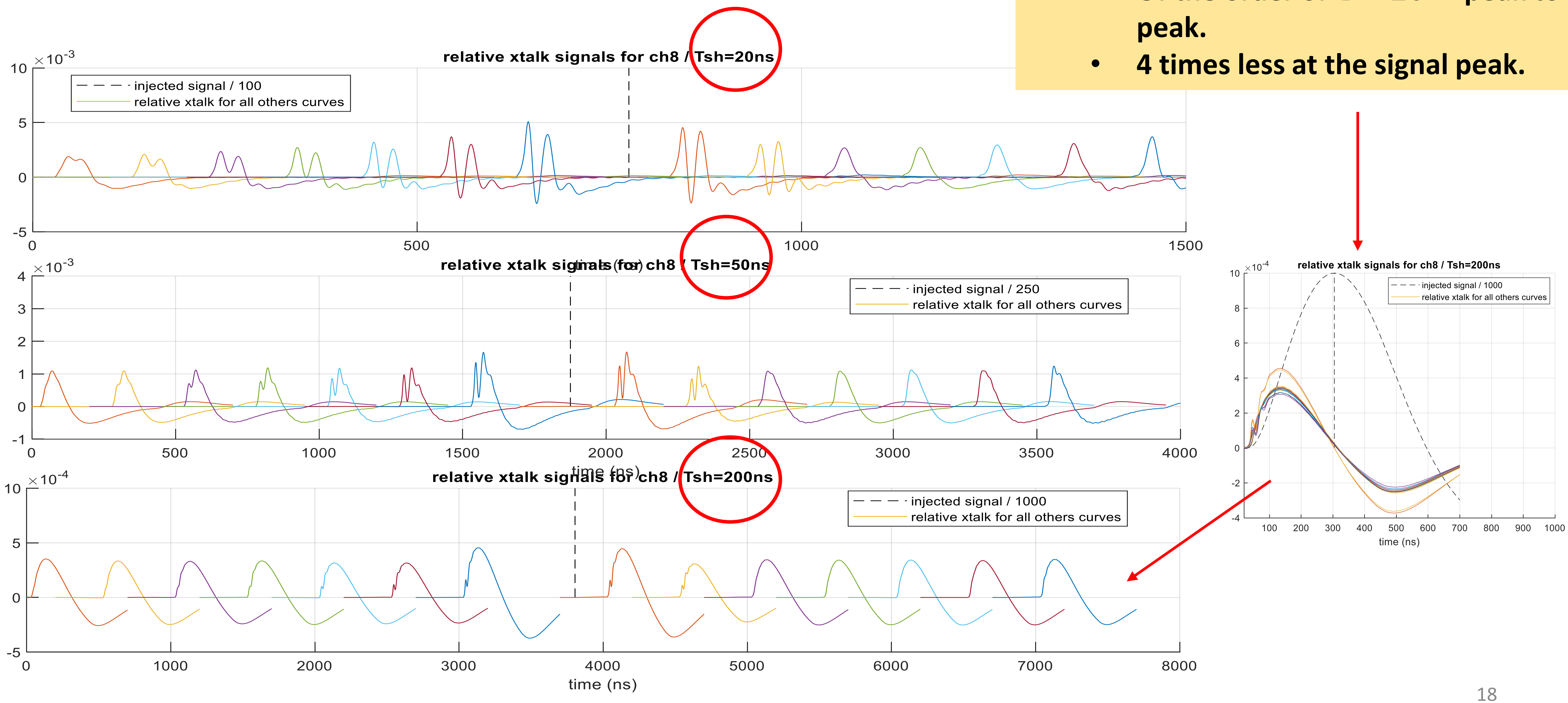
But more cell capacitance ⇔ More noise



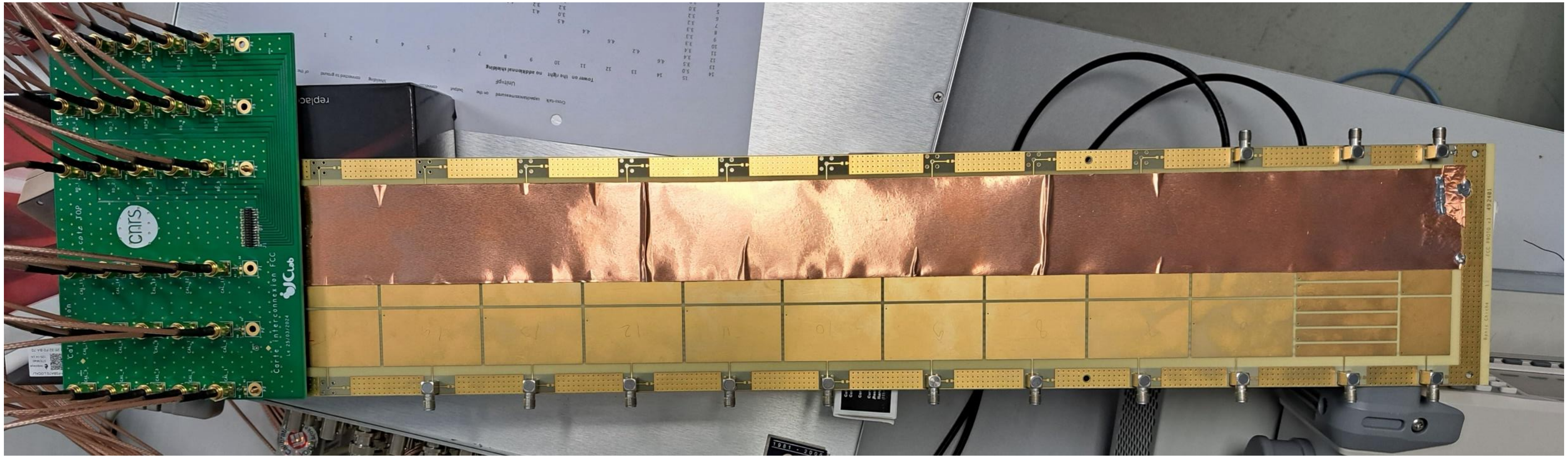
Effect of Shaping Time on Cross-Talk (PCB v3)

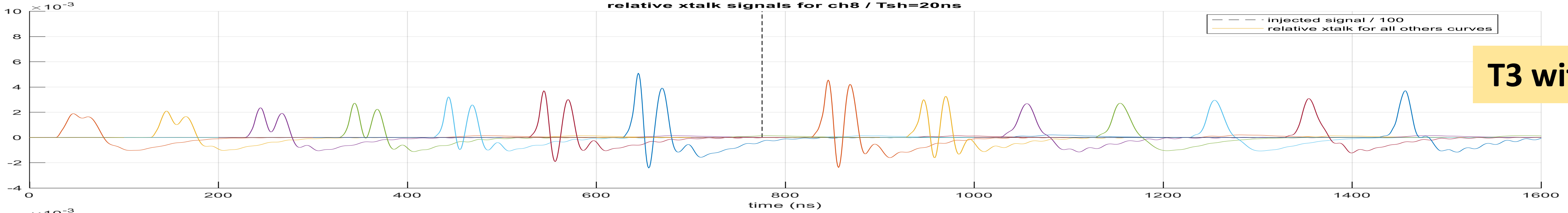
With a shaping of 200 ns, the cross-talk is:

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

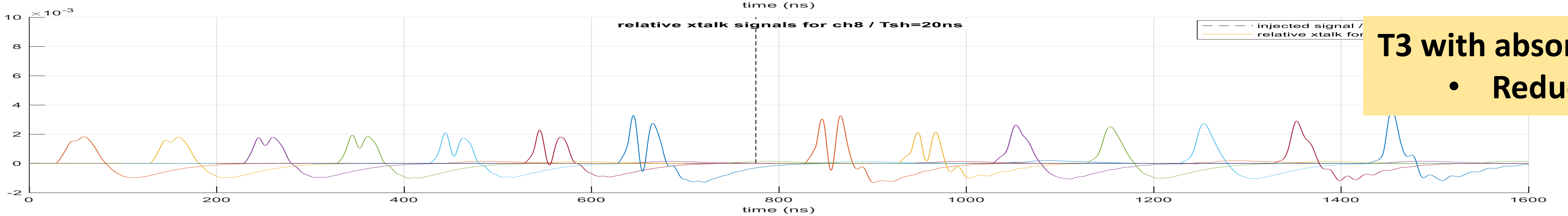


Effect of Adding an Absorber on One Side of PCB (PCB v3)





T3 without absorber

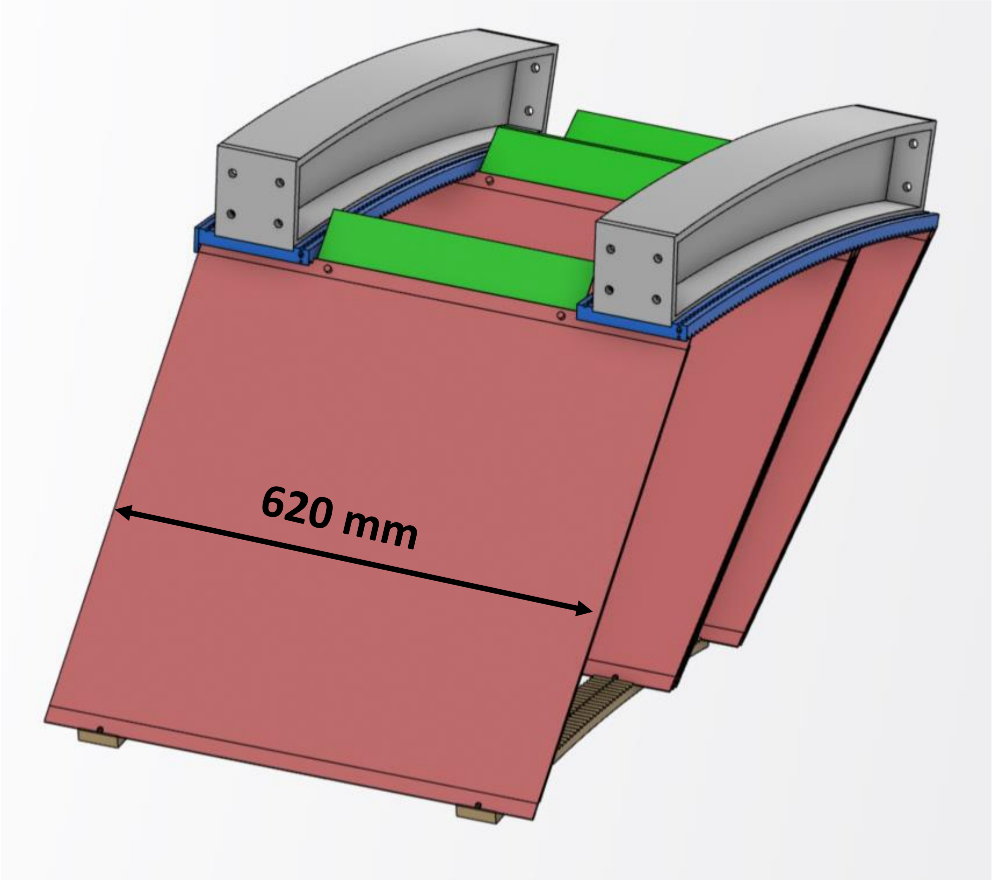


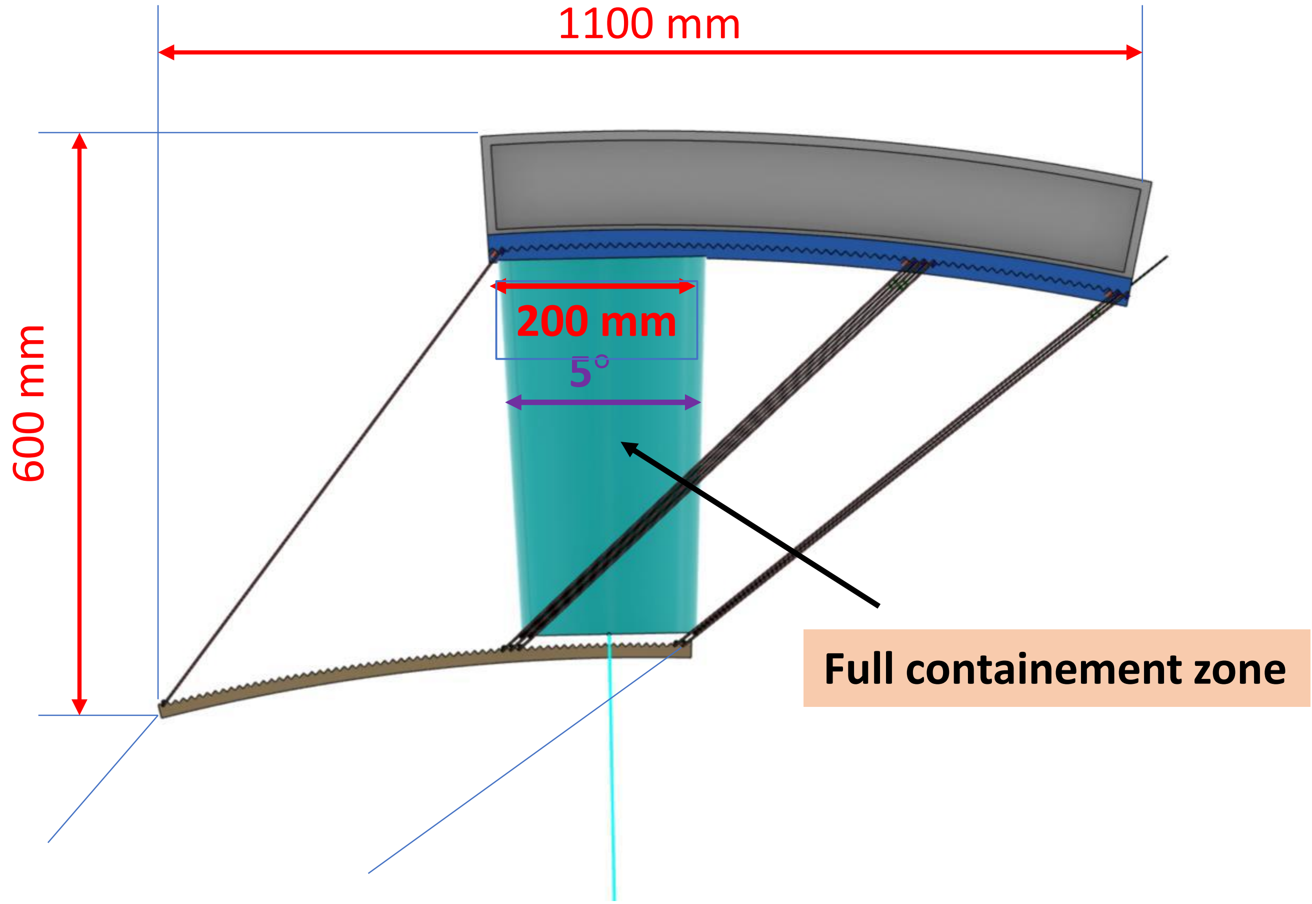
T3 with absorber:

- **Reduce inductive effect**

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

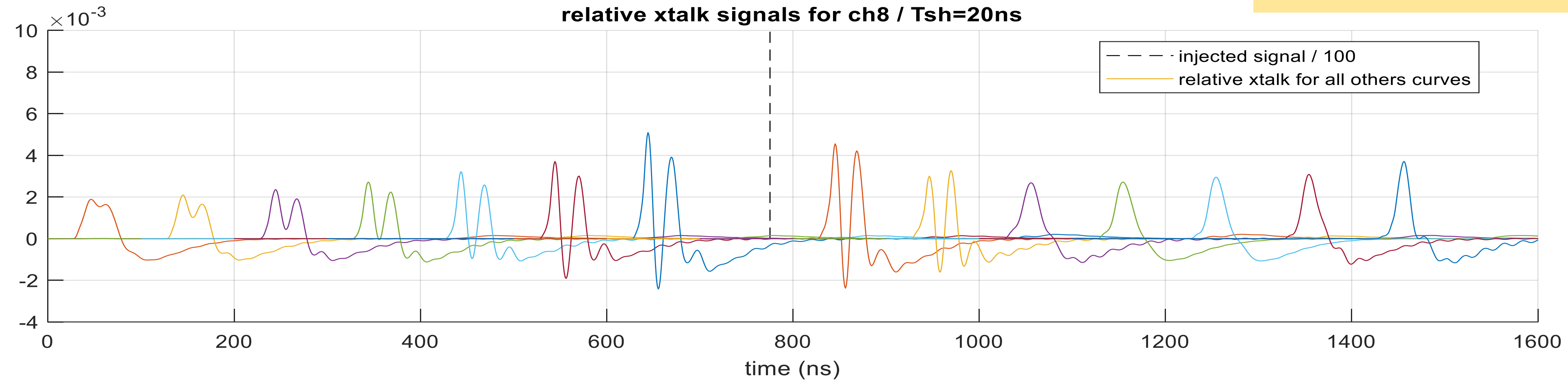
- Significant progress has been made during 2024.
- The concept is being adapted for the endcap.
- Solutions are being investigated for mechanics: Structure conception and simulation, fixing and indexing, module and barrel mounting, spacers.
- Tests of absorber prototypes: Rigidity, yielding point, behaviour 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.
- Mechanics of our first test beam prototype is making good progress.
- Simulated performance will now be shown by Michaela.

Backup

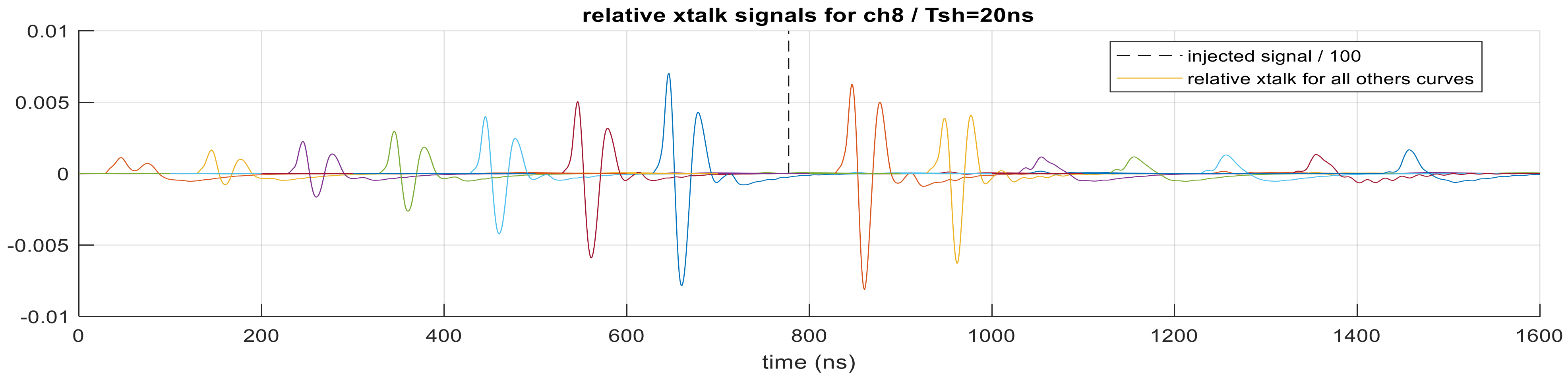
Effect of Lateral Shields on Cross-Talk (PCB v3)

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

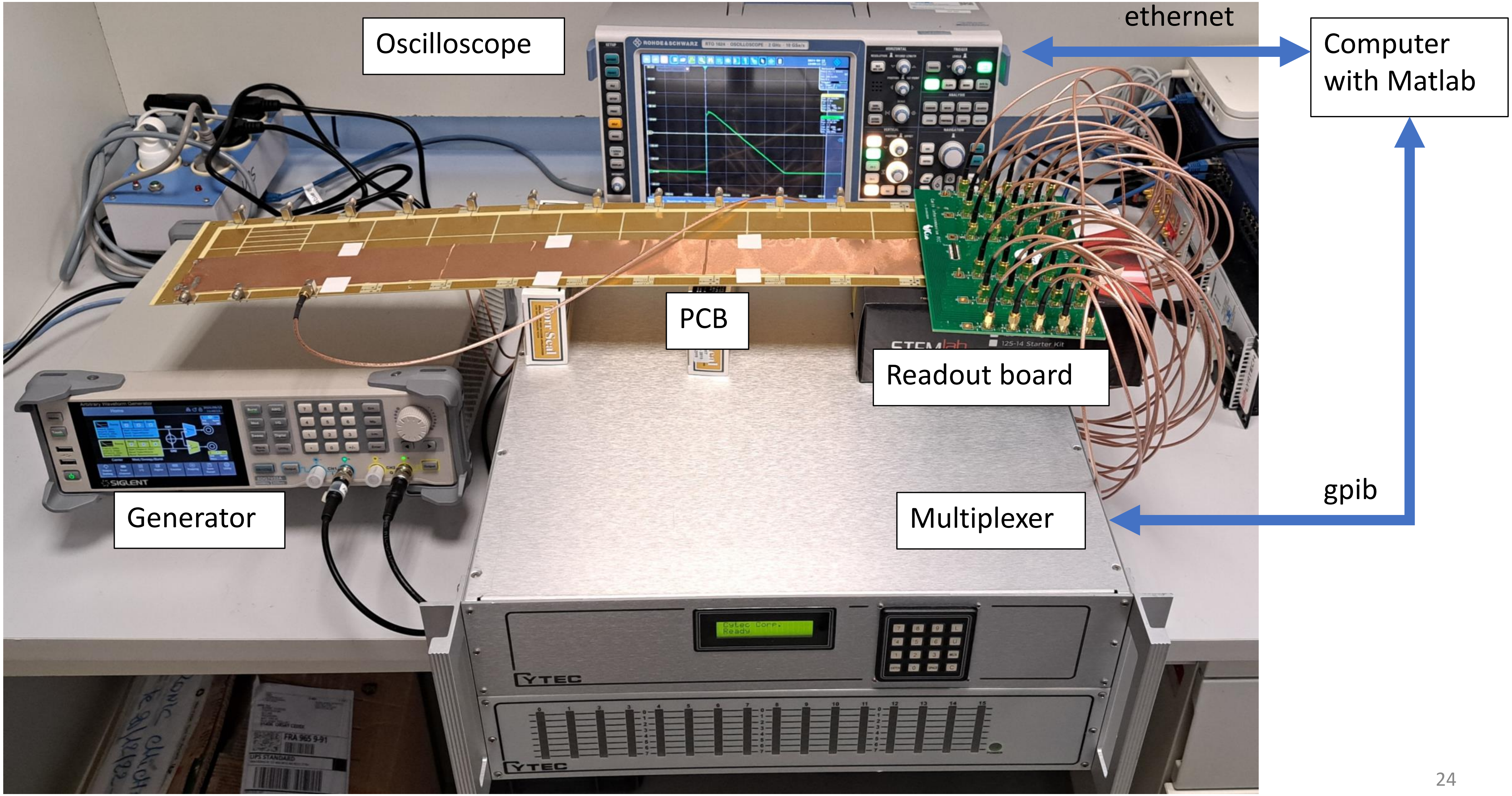
(w/o lateral shielding)



(with lateral shielding)



Automatized Measurement Bench at Orsay



Simulation of Trapezoidal Absorbers and Alternative Components