ALICE Forward Calorimeter upgrade (FoCal):
Physics program and performance

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National University Corporation for the hearing impaired and visually impaired in Japan.

Outline

- A new ALICE forward calorimeter (FoCal)
- Physics programs
- Detector R&D and designs
- Beam test results
- Summary

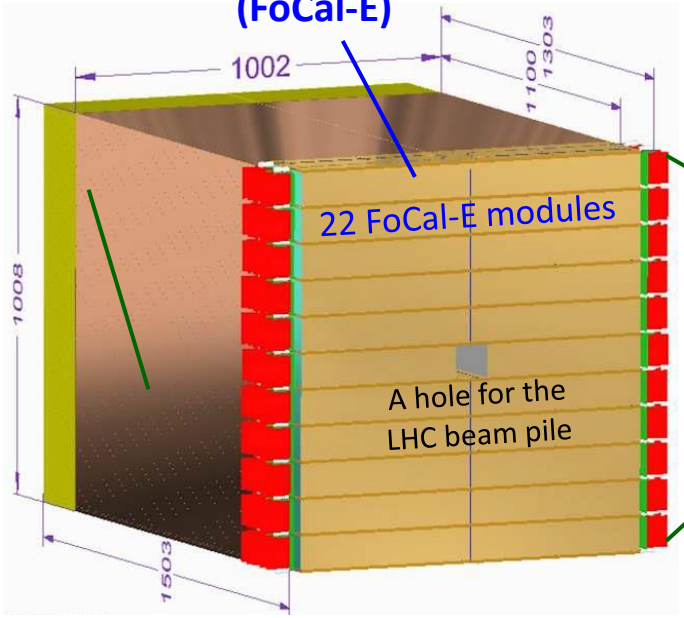
References:

[1] Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment (2020).
[2] Physics of the ALICE Forward Calorimeter upgrade (2023).
[3] Physics performance of the ALICE Forward Calorimeter upgrade (2023).
[4] Prototype electronics for the silicon pad layers of the future Forward Calorimeter (FoCal) of the ALICE experiment at the LHC (2023).
[5] Performance of the electromagnetic and hadronic prototype segments of the ALICE Forward Calorimeter (2023) - Result of beam tests.
[6] Technical Design Report of the ALICE Forward Calorimeter (FoCal) (2024) - Approved by LHCC.

A new ALICE forward calorimeter (FoCal)

Unique capabilities to measure the direct photon production at forward rapidity for $p_T \gtrsim 4$ GeV/c, as well as neutral hadrons, vector mesons, and jets.

The Si+W electromagnetic calorimeter (FoCal-E)



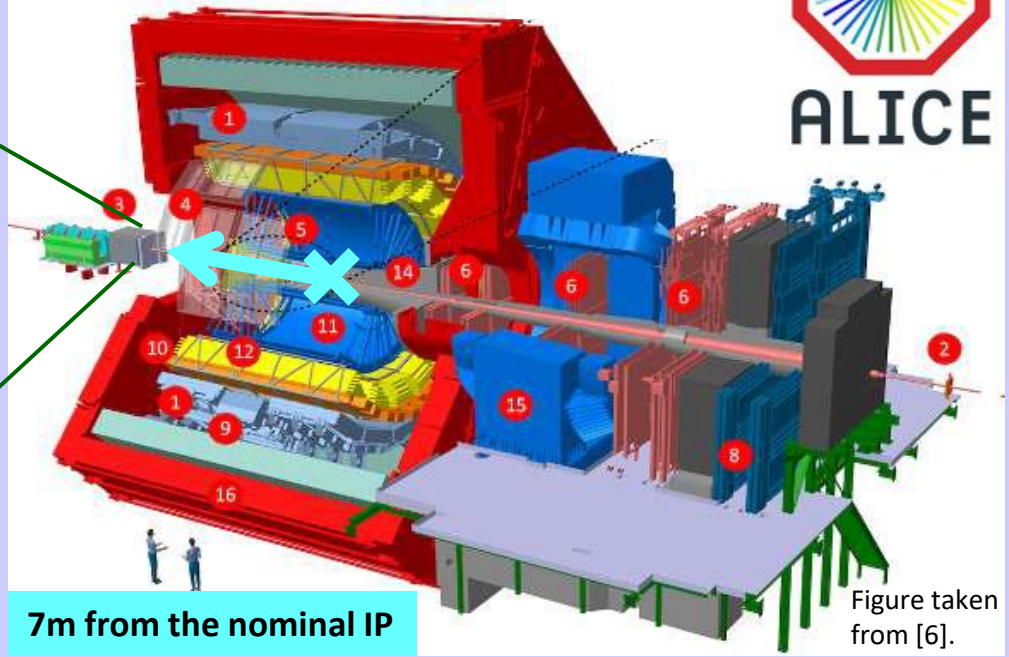
~ 1m^3

Cu+ Scintillation-fiber hadronic calorimeter (FoCal-H)

Figure taken from [6].

Installation during the LHC Long Shutdown 3 (2026-2028)

Pseudo-rapidity
$3.2 < \eta < 5.8$

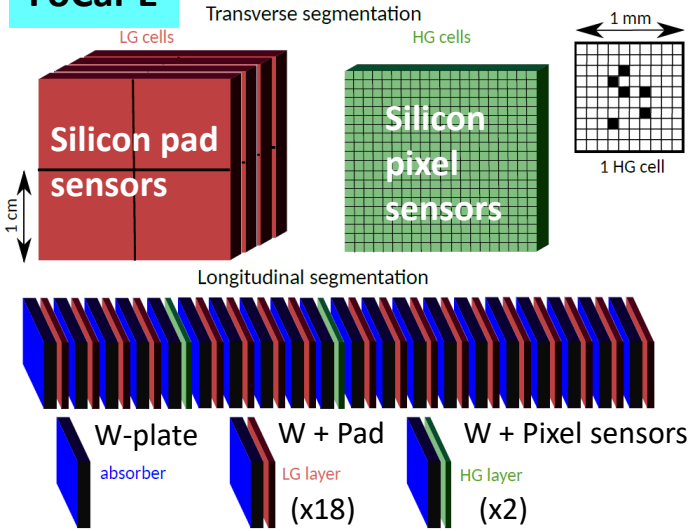


7m from the nominal IP

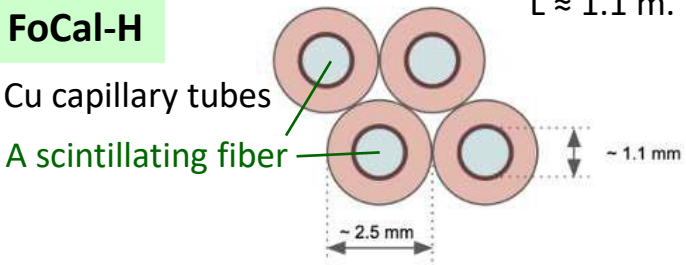
Figure taken from [6].

FoCal detecotor

FoCal-E



FoCal-H



Figures taken from [6].

[Silicon pad sensors]

A pad size ≈ 10 × 10 mm^2.
The sensor size ≈ 93 × 83 mm^2.

[Silicon pixel sensors (ALPIDE MAPS)**]**

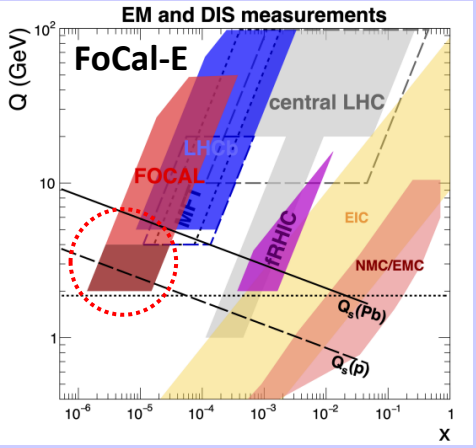
A pixel size ≈ 30 × 30 μm^2.
The sensor size ≈ 30 × 15 mm^2.

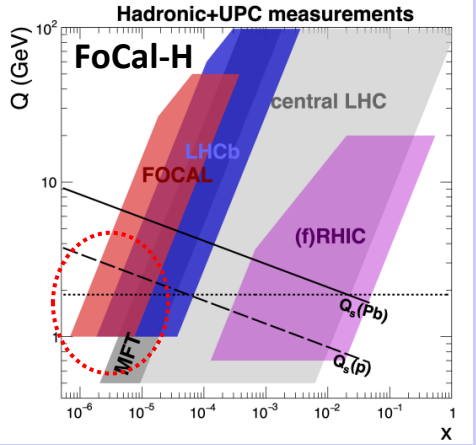
[Tungsten absorber]

A small Molière radius (0.9 cm) and one radiation length (X_0 = 3.5 mm).

→ Optimized to probe the partonic structure of hadronic matter and the nature of QCD evolution with unprecedented reach in momentum fraction Bjorken-*x*, down to $x \sim 10^{-6}$ for small and moderate momentum transfer Q^2.

→ Designed for photon isolation and jet measurements.





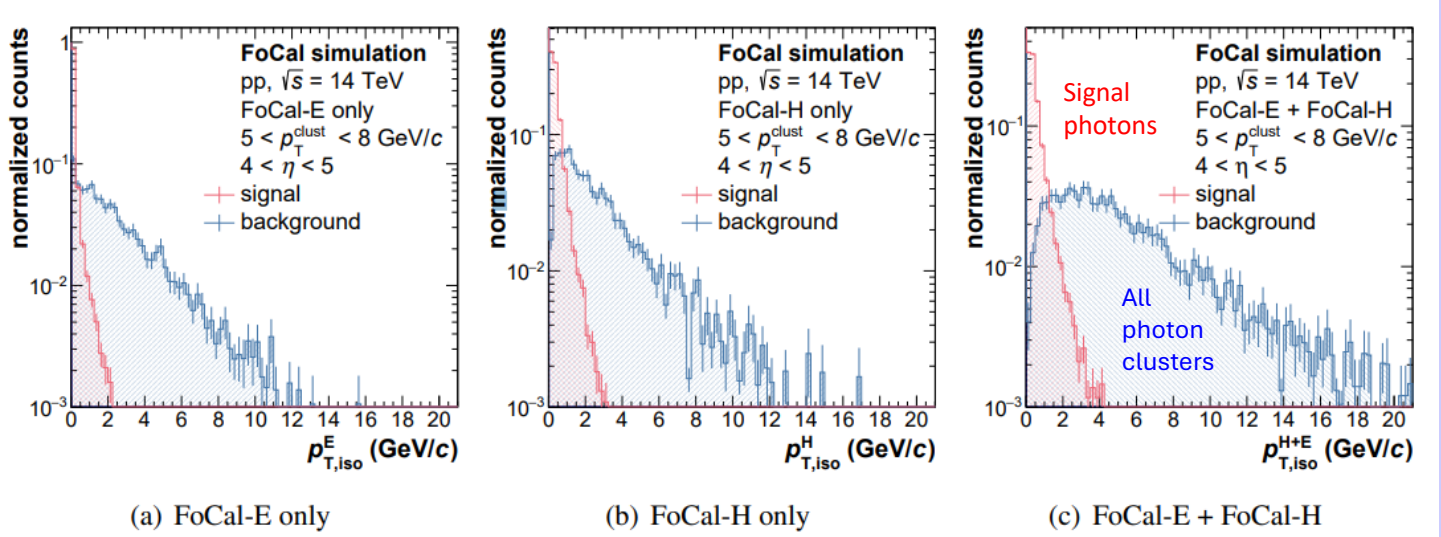
Figures taken from [2].

Key challenges

Three techniques for the measurement of prompt-photon production.

Isolation

→ Measurement of the isolation energy in FoCal-E and FoCal-H in a cone of given radius around the photon candidate.



Distribution of isolation energy of photon clusters [PYTHIA simulation]. Figures taken from [3].

Invariant mass

→ Rejection of photons originating from π^0 decays using the invariant mass of cluster pairs.

Shower shape

→ Rejection of elongated clusters originating from decay photons with small opening angle.

Physics programs

Isolated and prompt photon measurements at small x and Q^2.

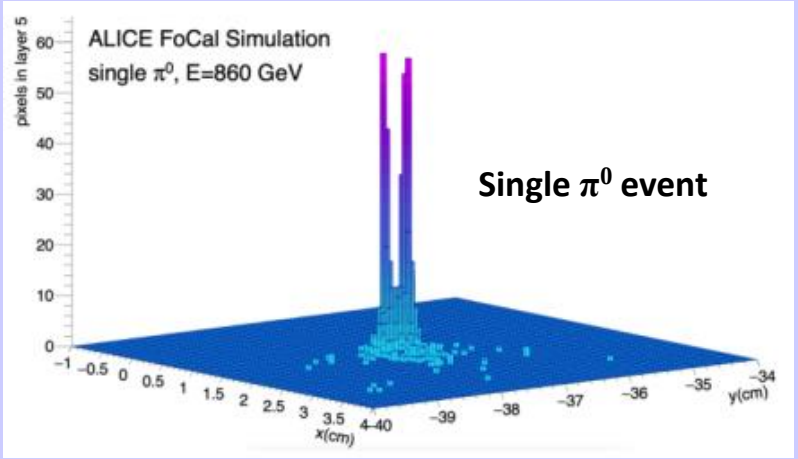
→ Incisive probes of the small-x structure of matter.
→ A key role in the search for evidence of non-linear QCD evolution at small x.

Neutral and vector mesons measurements.

→ Reconstruction of neutral mesons (π_0, $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$).
→ Reconstruction of vector mesons (ϕ, J/ψ, ψ(2S) and Υ) via di-electrons and $W^{\pm}$ and Z^0 weak bosons.

Measurements of azimuthal π^0–π^0 correlations and isolated γ–π^0 correlations at forward rapidity.

→ x and Q^2 dependence of QCD evolution in multiple complementary ways.



Event display for a resolved single π^0 event. (The number of fired pixels in layer 5 as a function of the transverse coordinates).

Figure taken from [3].

Vector meson photoproduction in ultra-peripheral collisions.

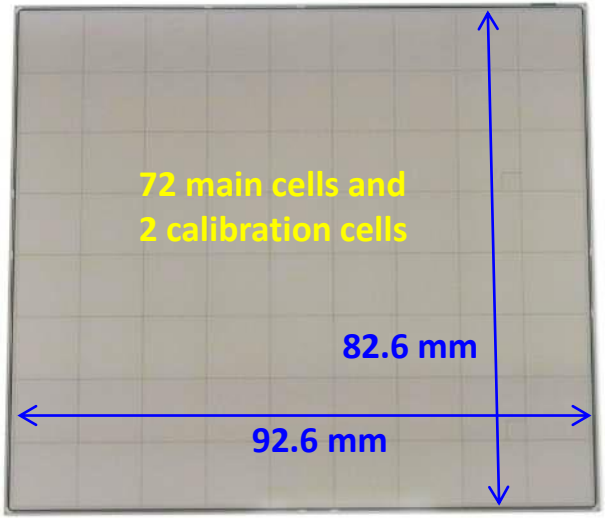
→ Significantly extend the kinematic reach of the current ALICE measurements.

Detector R&D

FoCal-E pads

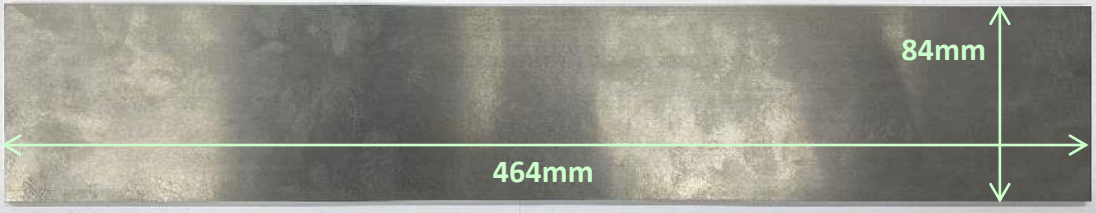
1980 sensors

- **Silicon pad sensors** (Hamamatsu)
  - I-V characteristics,
  - C-V characteristics,
  - Temperature dependence,
  - S/N,
  - Development of a probe station.
- **Wide tungsten alloy plates**
- **HGCROC2 packaging and testing**
  → **HGCROC3-series ASIC** [7]
- **PCB design and trial production**
- **Beam tests**
  - CERN PS and SPS complexes,
  - Tohoku Univ. ELPH.
- **Irradiation tests**



The main sensor from a 6-inch wafer.

A probe station for Q. C.



A tungsten alloy plate (W94%, Ni4%, Cu2%) .

Figures taken from [6].

[7] HGCROC3: the front-end readout ASIC for the CMS High Granularity Calorimeter

HGCROC2 ASIC was originally developed by the OMEGA group for the CMS High Granularity Calorimeter (HGCal).

Detector R&D

FoCal-E pixel

- **Silicon pixel sensors**
  ALPIDE MAPS (developed for the ITS upgrade)
- **Single- and multi-layered flexible micro-cables and boards**

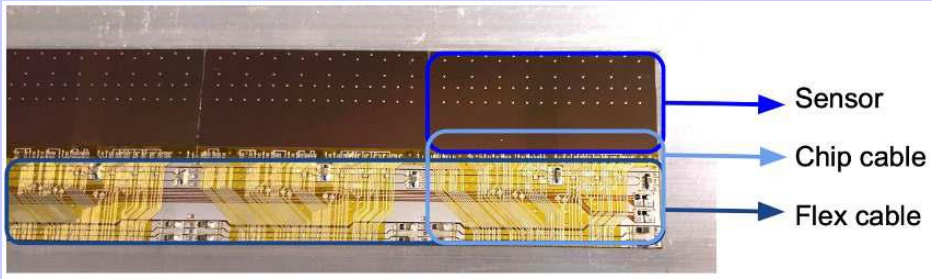


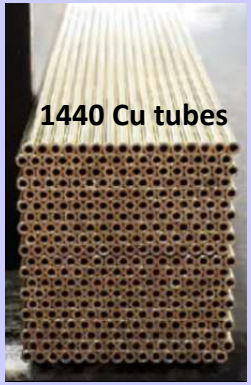
Figure taken from [6].

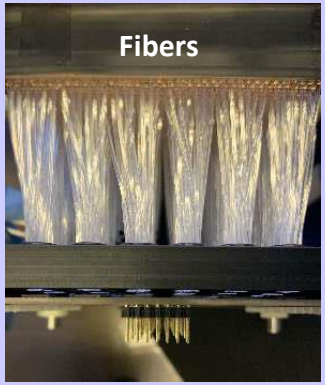
- **Beam tests**
  - CERN PS / SPS complexes.

FoCal-H

- **Si PMs**
- **Scintillating fibers**
- **Detector prototype**

- **Beam tests**
  - CERN PS / SPS complexes





The collector plate
(48 bundles x
30 scintillating fibers)

Figures taken from [6].

All over

- **DAQ system**
- **Mechanical design**
- **Cooling**
- **Installation planning**

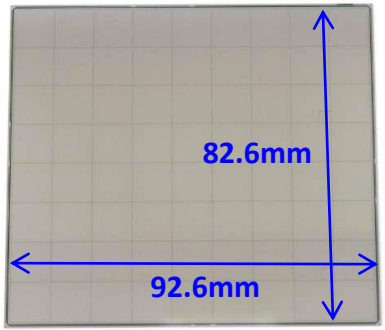
Detector design: FoCal-E assembling

W-plate
(3.5 mm in thickness)

+

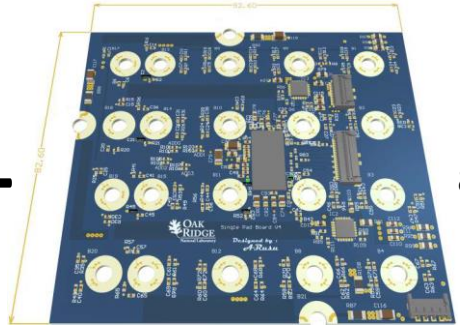
1	2	3	4	5

5 silicon pad sensors
(93 × 83 mm² each)
with PCBs



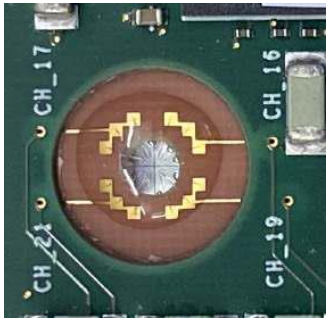
The silicon pad sensor

+



The front-end PCB

and



Wire bonding.

Figure taken from [6].

Detector design: FoCal-E assembling

W-plate
(3.5 mm in thickness)

+

1 2 3 4 5

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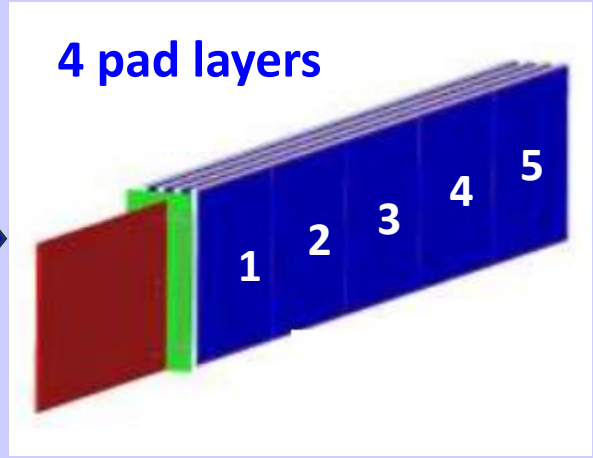
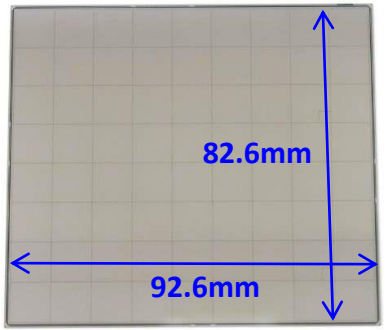
(93 × 83 mm² each)
with PCBs

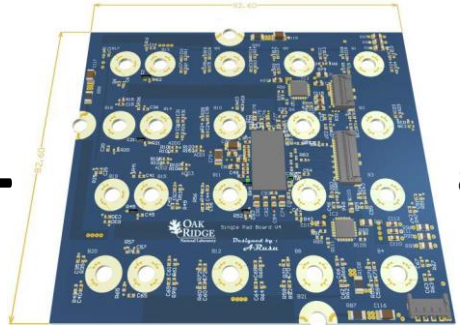
x4





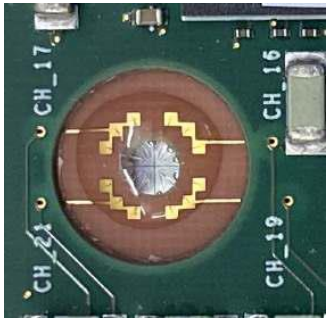
The silicon pad sensor

+



The front-end PCB

and



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Detector design: FoCal-E assembling

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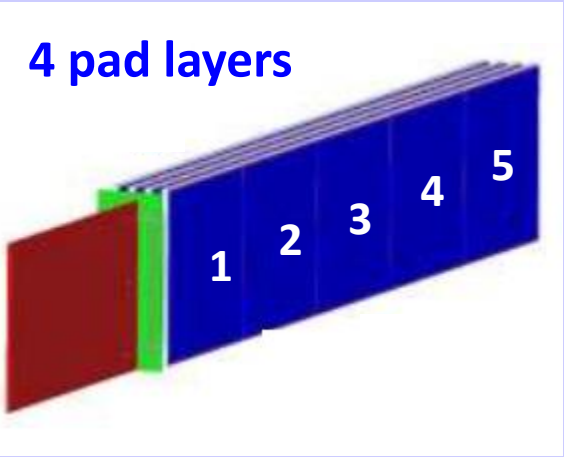
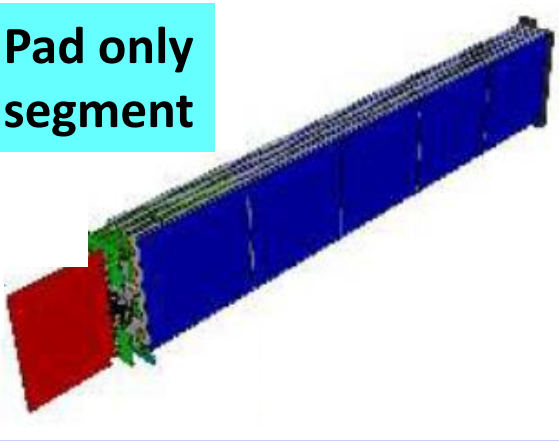
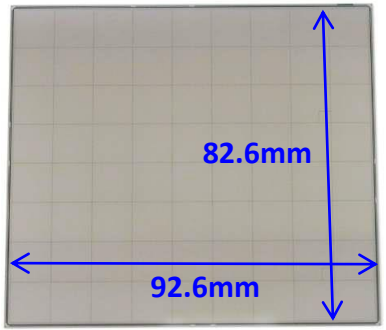


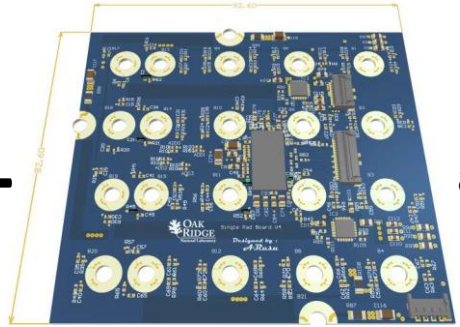


x 2
(2 x 22 = 44 segments)



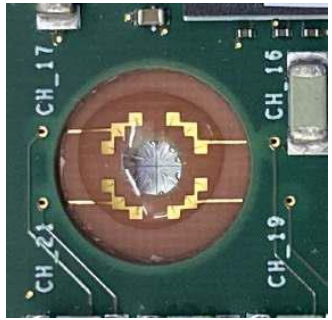
The silicon pad sensor

+



The front-end PCB

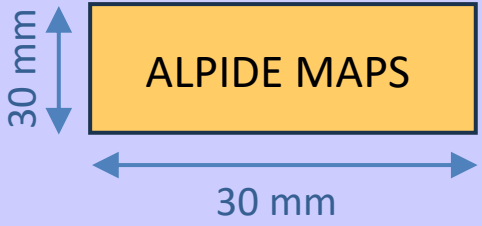
and



Wire bonding.

Figure taken from [6].

Detector design: FoCal-E assembling



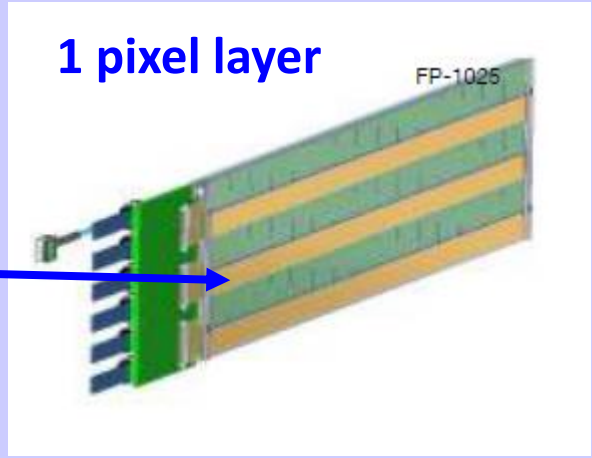


Figure taken from [6].

Detector design: FoCal-E assembling

W-plate
(3.5 mm in thickness)

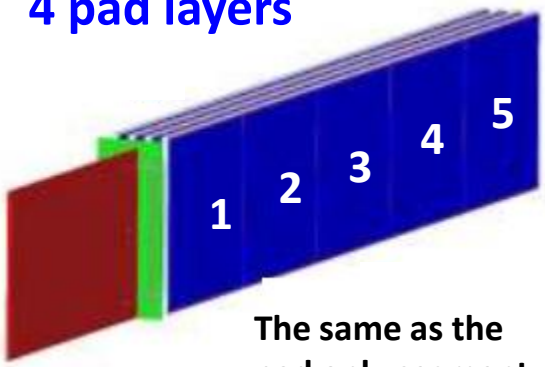
+

1 2 3 4 5

5 silicon pad sensors
(93 × 83 mm² each)
with PCBs

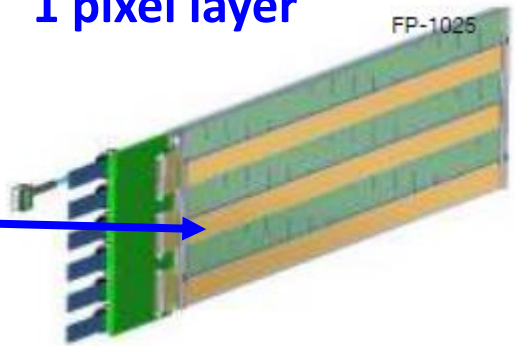
x4

4 pad layers



The same as the pad only segment

1 pixel layer



ALPIDE MAPS

30 mm

30 mm

Figure taken from [6].

Detector design: FoCal-E assembling

W-plate
(3.5 mm in thickness)

+

1 | 2 | 3 | 4 | 5

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x4

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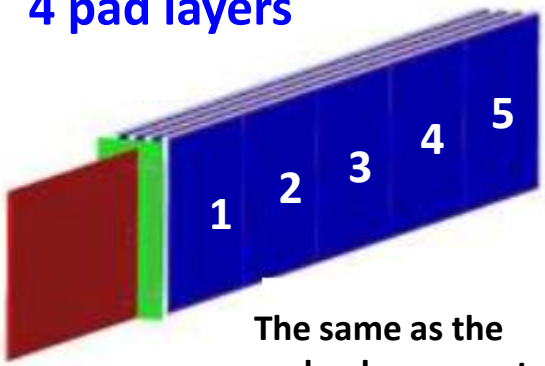
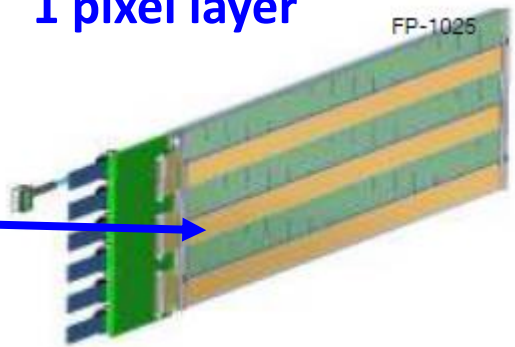


The same as the pad only segment

1 pixel layer

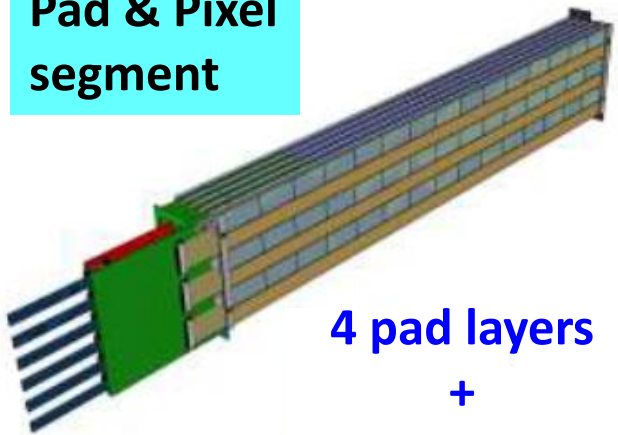


30 mm

ALPIDE MAPS

30 mm

Pad & Pixel segment



4 pad layers
+
1 pixel layer

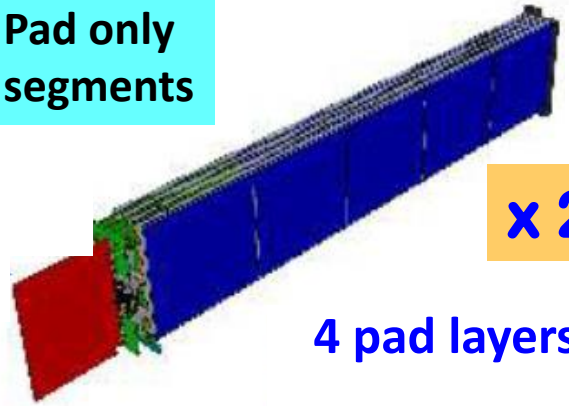
x 3

(3 x 22 = 66 segments)

Figure taken from [6].

Detector design: FoCal-E assembling

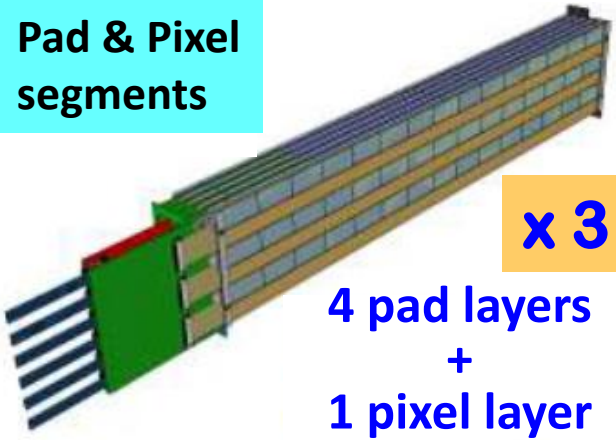
Pad only segments



x 2

4 pad layers

Pad & Pixel segments



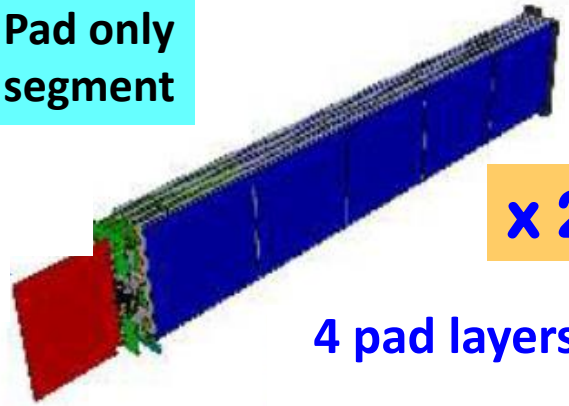
x 3

4 pad layers
+
1 pixel layer

Figure taken from [6].

Detector design: FoCal-E assembling

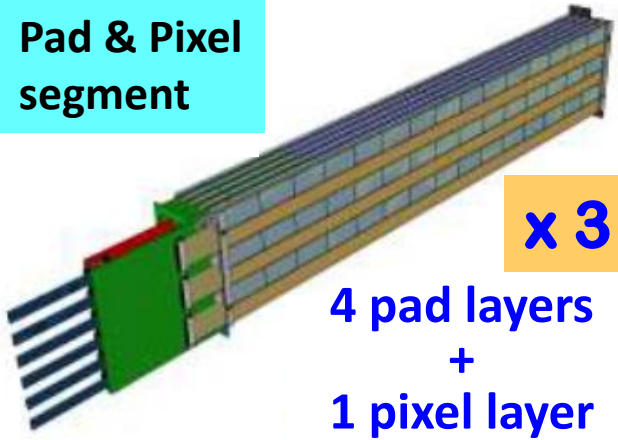
Pad only segment



x 2

4 pad layers

Pad & Pixel segment



x 3

4 pad layers
+
1 pixel layer

FoCal-E module

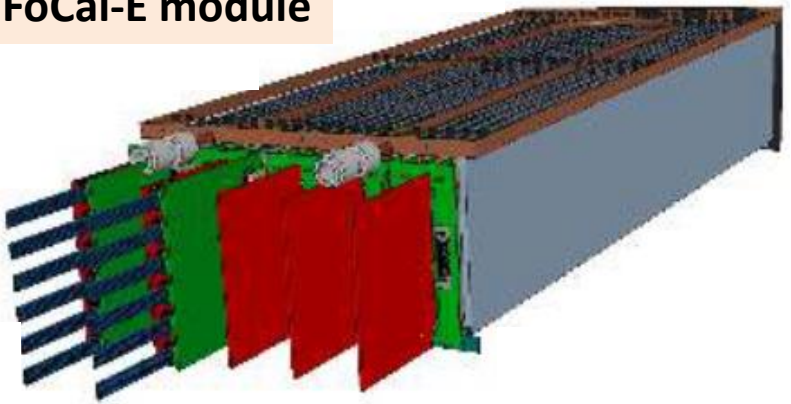
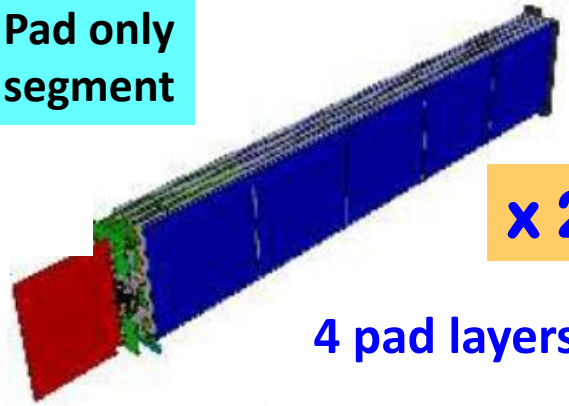


Figure taken from [6].

Detector design: FoCal-E assembling

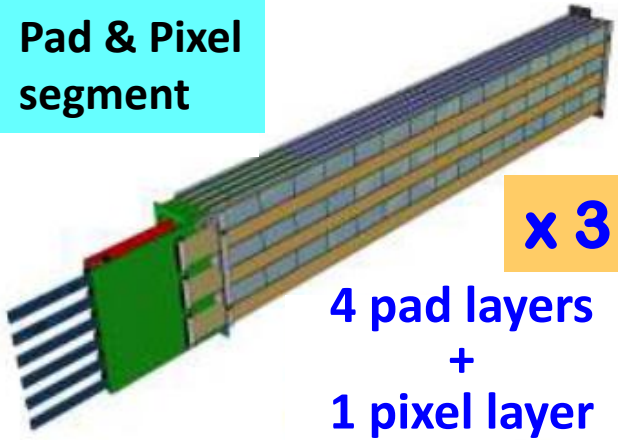
Pad only segment



x 2

4 pad layers

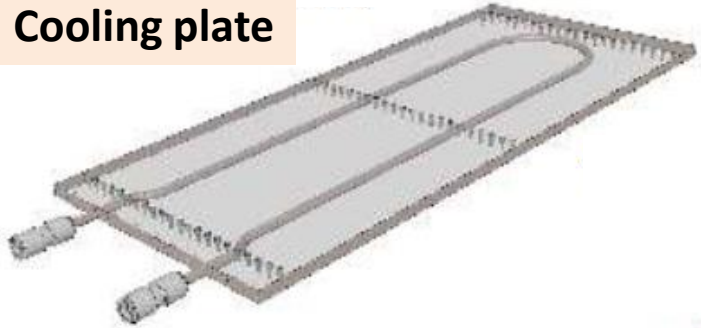
Pad & Pixel segment



x 3

4 pad layers
+
1 pixel layer

Cooling plate



+

FoCal-E module

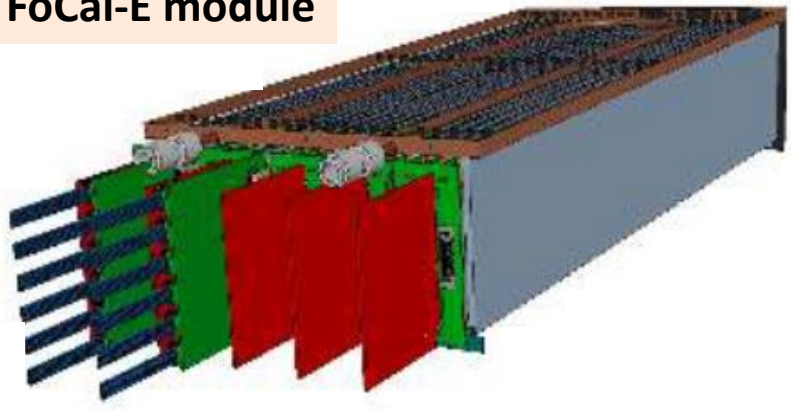
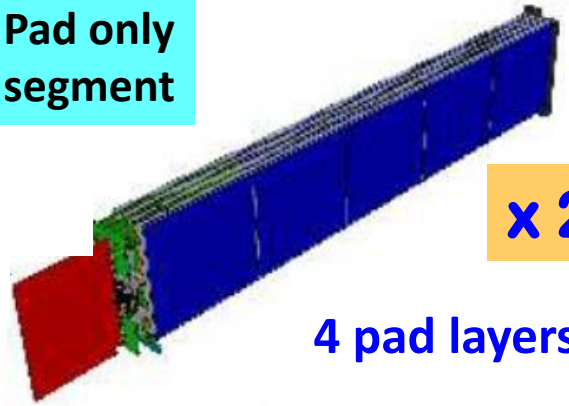


Figure taken from [6].

Detector design: FoCal-E assembling

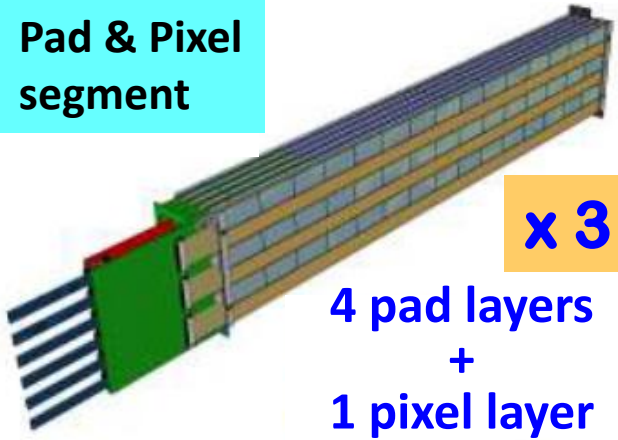
Pad only segment



x 2

4 pad layers

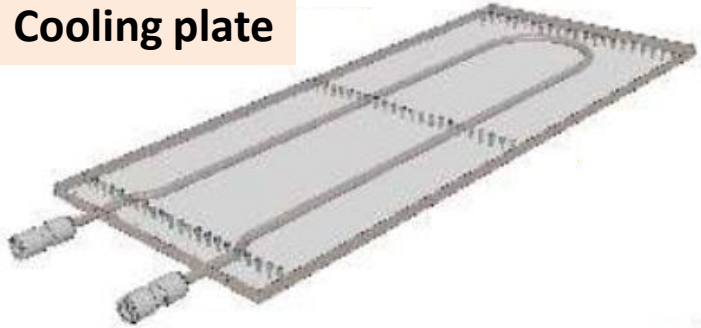
Pad & Pixel segment



x 3

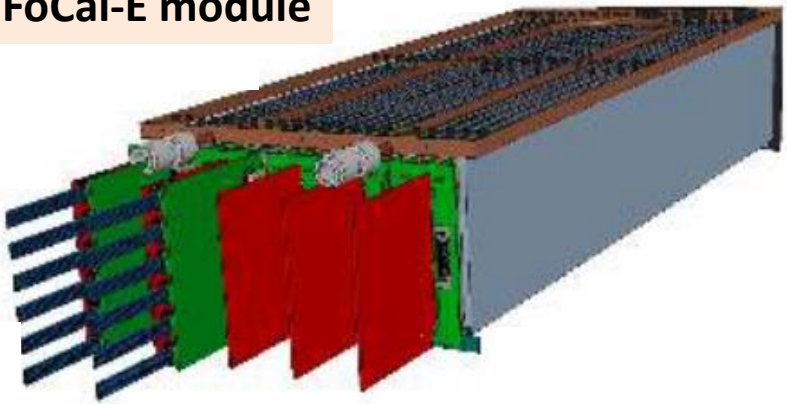
4 pad layers
+
1 pixel layer

Cooling plate

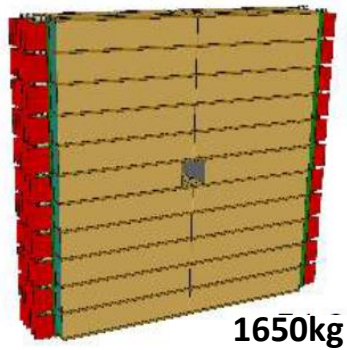


+

FoCal-E module



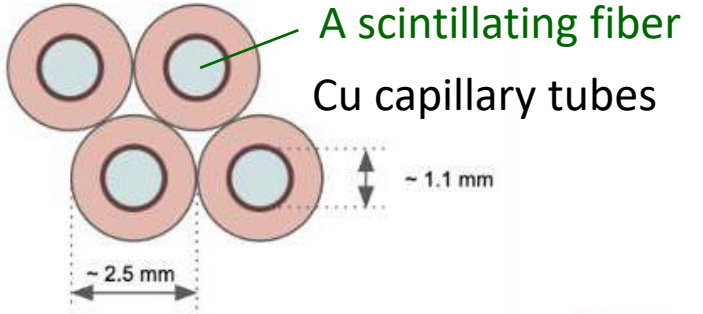
x 24

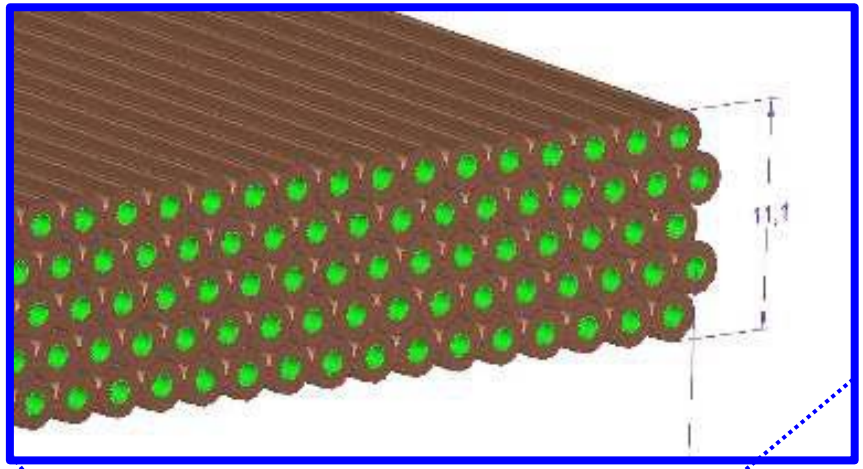


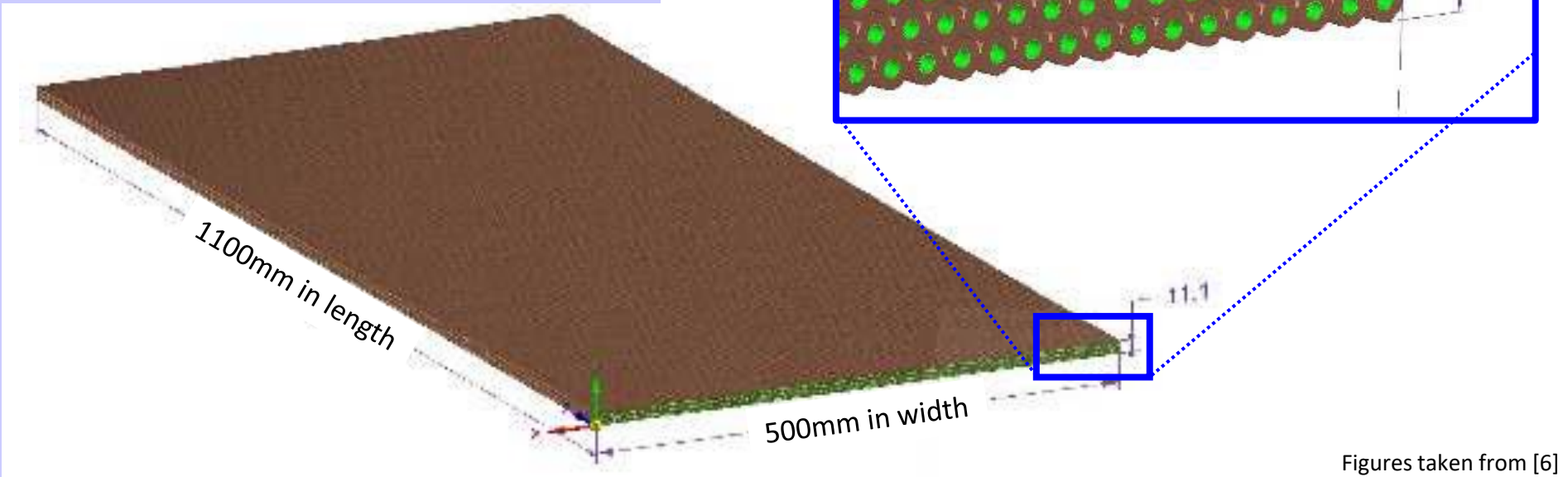
FoCal-E detector

Figure taken from [6].

Detector design: FoCal-H assembling

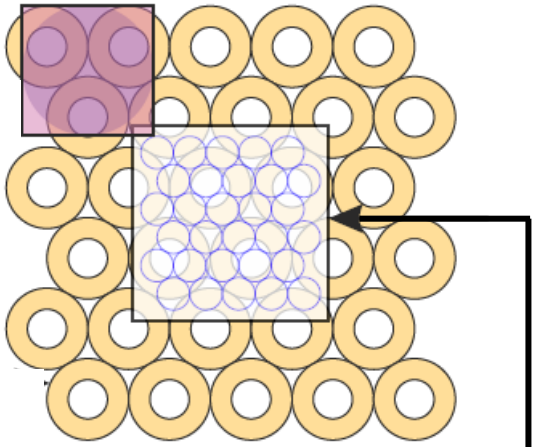




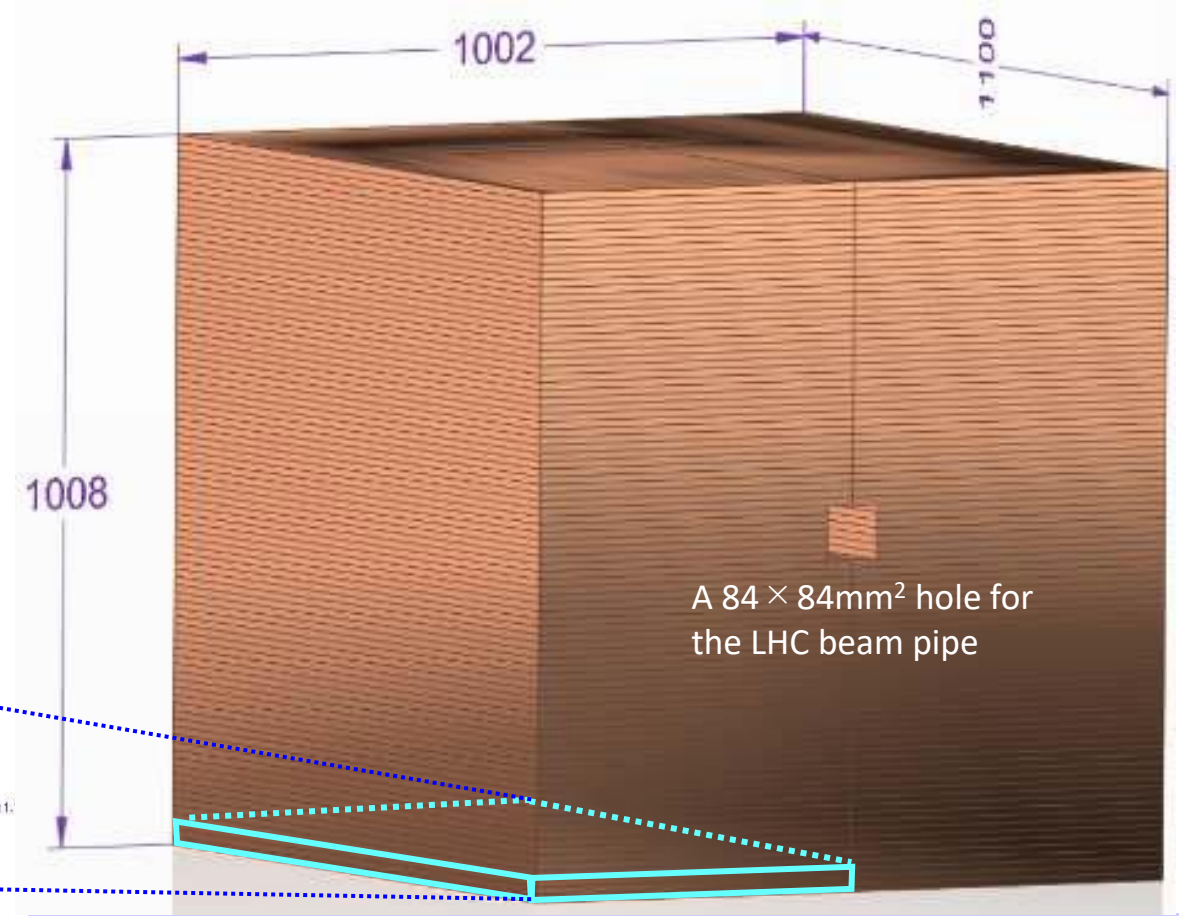


Figures taken from [6]

Detector design: FoCal-H assembling



30 copper tubes
→ A set of corresponding fibers
→ One 6x6 mm² SiPM



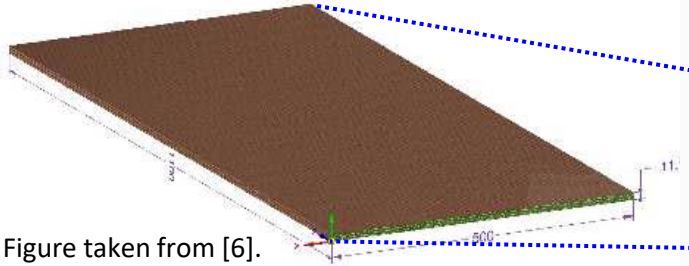
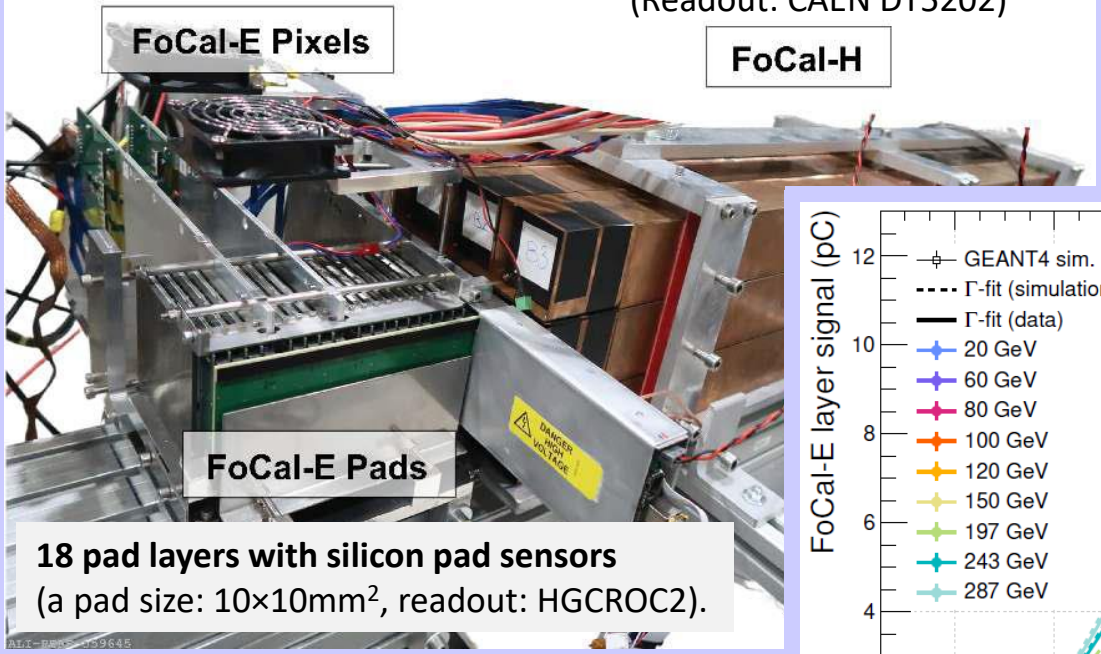


Figure taken from [6].

Beam test results of mini-prototype

2 pixel layers with APLIDE MAPS.

9 Cu + Scintillation-fiber modules
(Readout: CAEN DT5202)



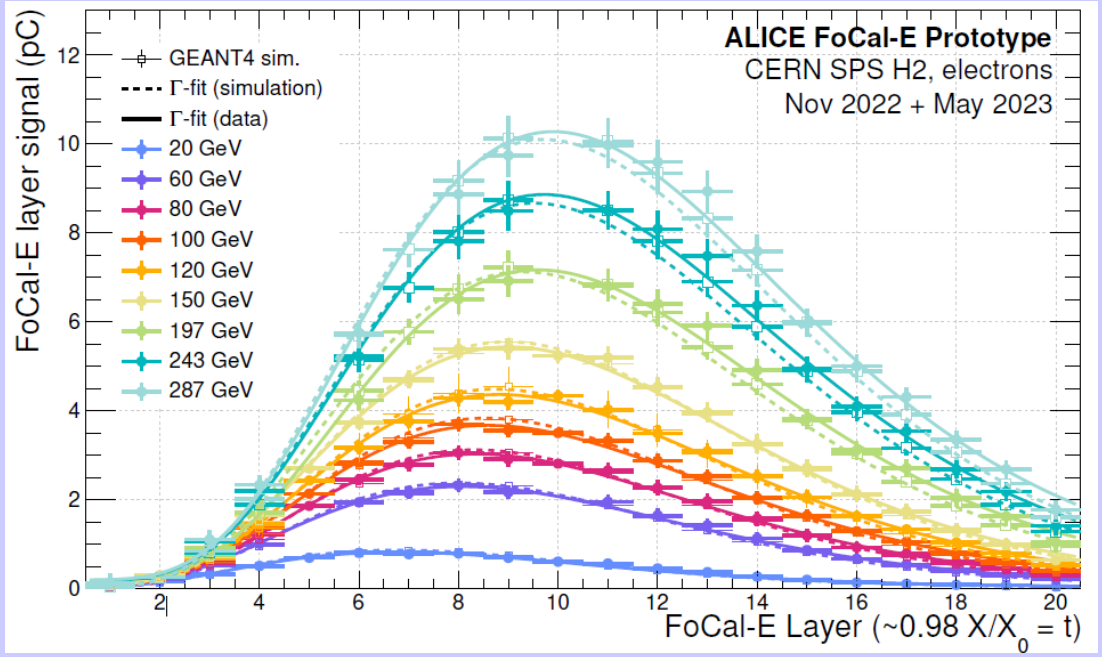
18 pad layers with silicon pad sensors
(a pad size: 10×10mm^2, readout: HGCROC2).

Longitudinal shower profiles for 20-300 GeV electrons compared to simulations and fits of Γ-distributions. Figures taken from [3]. →

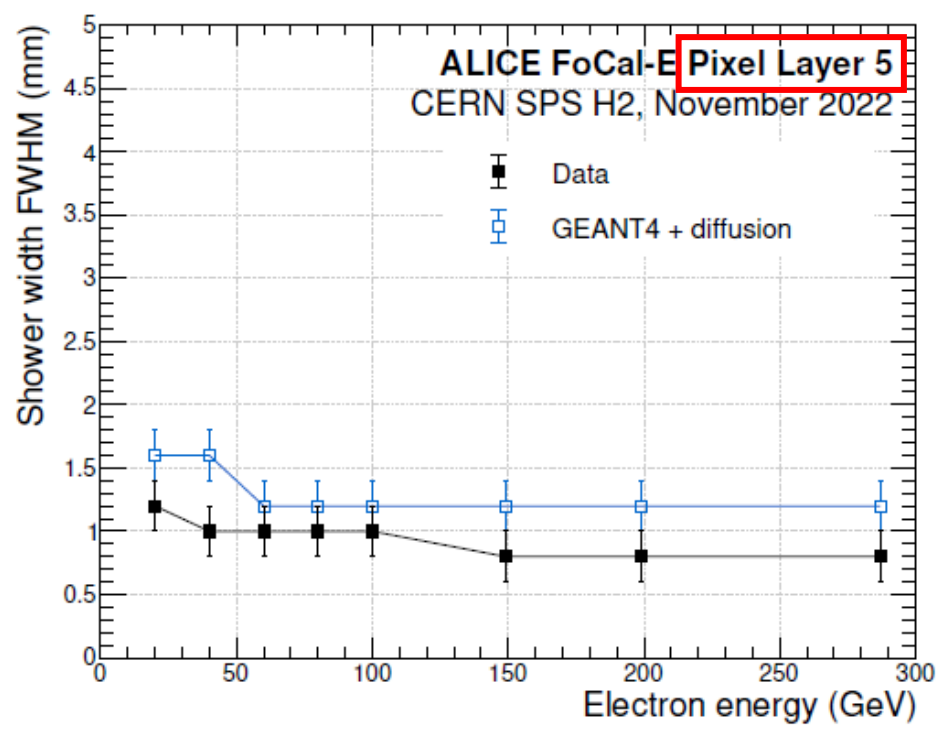
Pad layers fulfill the physics requirements.

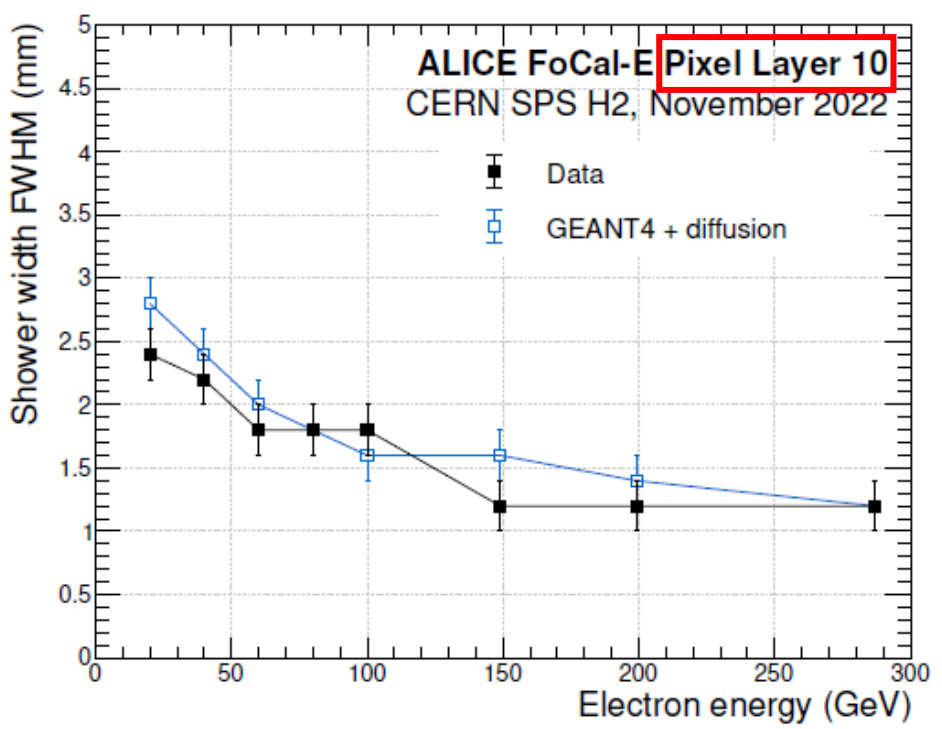
→ **Very clean signals and good stability for the *Minimum Ionizing Particles (MIPs)* measurement.**

→ **Less than 3% of the relative energy resolution at energies larger than 100 GeV.**



Beam tests of mini-prototype (Pixel layers)





Measured and simulated FWHM (Full Width Half Maximum) versus electron energy.
The error bars represent an uncertainty of 0.2mm. Figures taken from [5].

→ **Well described by simulations demonstrating the ability of the calorimeter to resolve two-showers.**

Summary

- FoCal is optimized to measure isolated photons at most forward rapidity for $p_{\mathrm{T}} \gtrsim 4$ GeV/c., unexplored regions of small-x and low Q^2.
- Simulation results show abilities of FoCal for small-x gluon dynamics.
- Beam test results indicate that the FoCal fulfills the physics requirements.
- Technical Design Report was officially approved by LHCC this year.
- Mass production will start soon.
- The data is expected in Run 4 from 2029.

Thank you for your attention !