FCAL: forward detectors

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On behalf of the FCAL collaboration

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FCAL Collaboration

FCAL is a worldwide detector Research & Development collaboration.

~ 70 physicists join their effort to develop the technologies of special calorimeters in the very forward region of future experiments at e^+e^- colliders

FCAL collaborates with the Detector Concepts ILD and SiD of the ILC and works together with CLICdp.

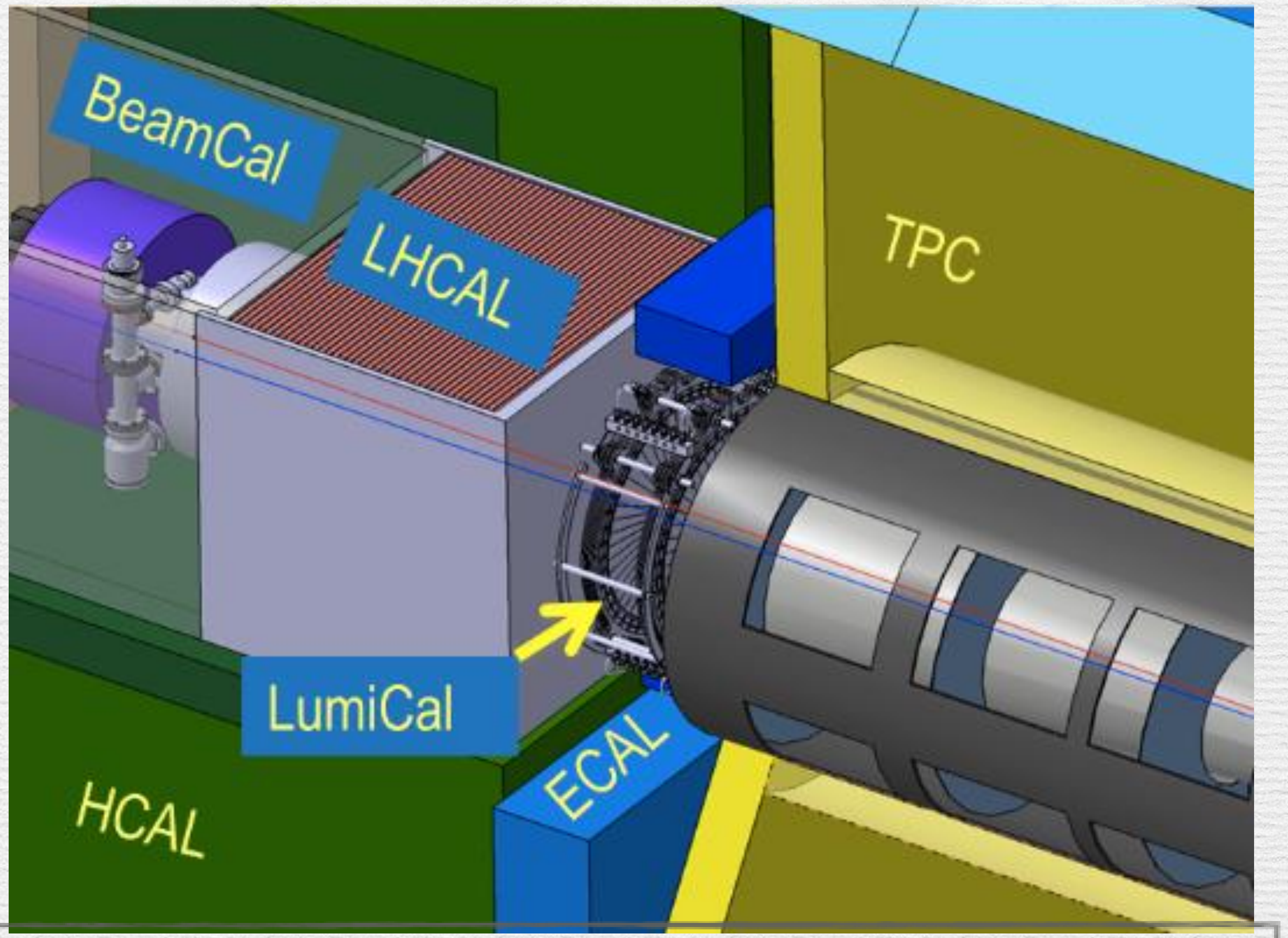
FCAL detectors in LC Experiments

LumiCal

- Precise integrated luminosity measurements;
- Extends a calorimetric coverage to small polar angles. Important for physics analysis.

Design

- electromagnetic sampling calorimeter;
- 30 layers of 3.5 mm thick tungsten plates with 1 mm gap for silicon sensors;
- symmetrically on both sides at ~2.5m from the interaction point for ILD.



BeamCal

- Complete the coverage of e.m. calorimetry down to very small angles to reject SM backgrounds w/ far-forward activity;
- Bunch-by-bunch luminosity measurements;
- Beam diagnostics and tuning;
- similar construction, with tungsten absorber but radiation hard sensors (GaAs, CVD diamond)

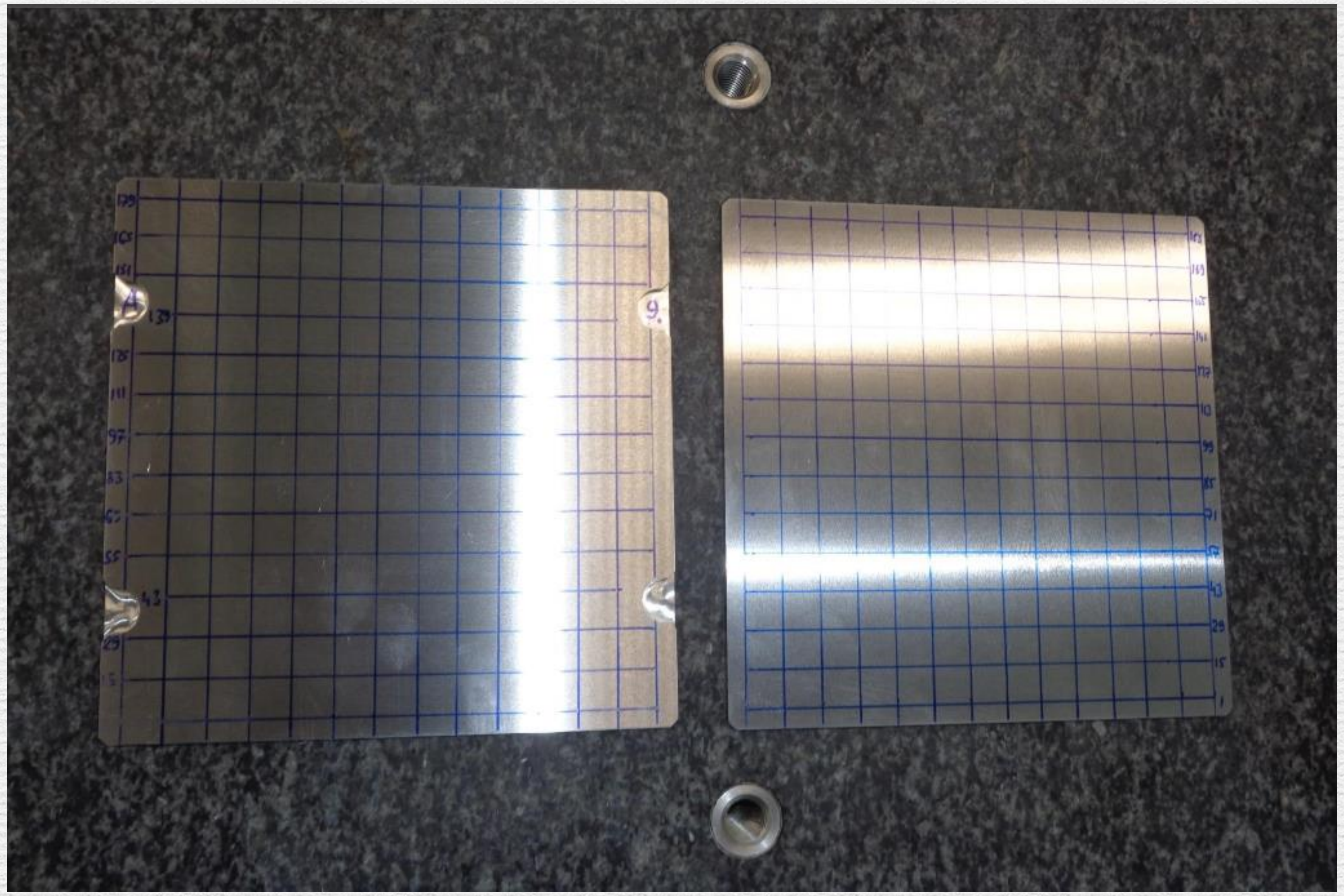
LHCal

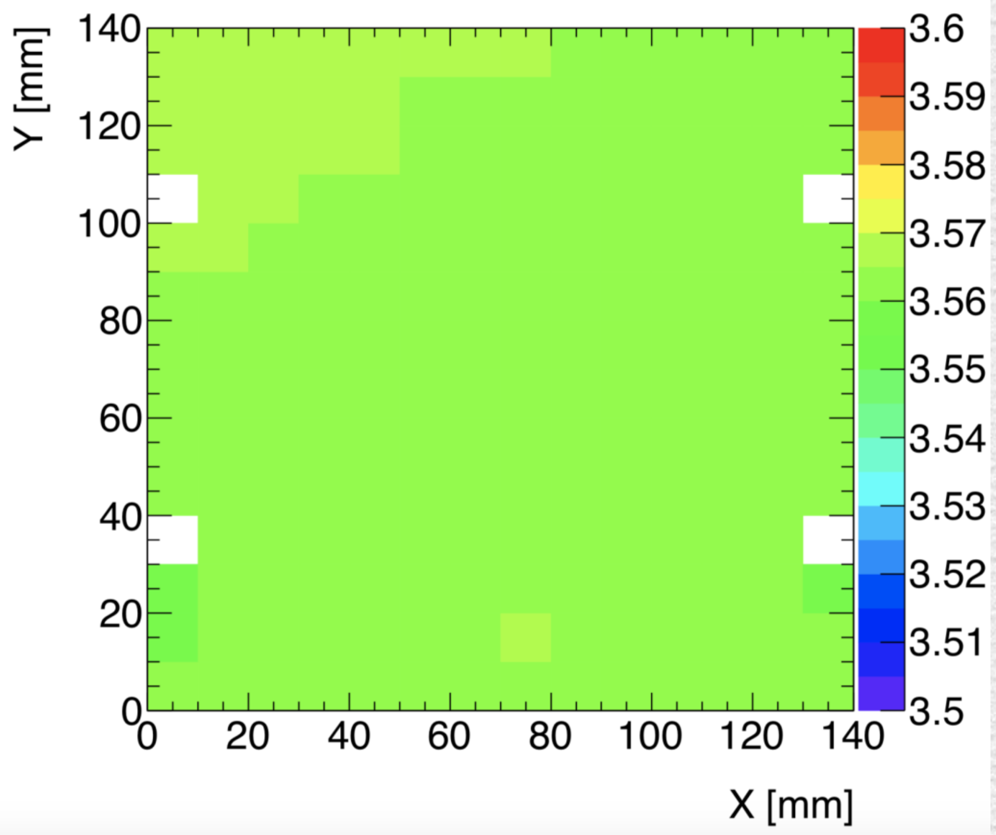
- extends the coverage of HCAL;
- Sampling calorimeter (silicon)
- 29 layers of 16mm thickness. Absorber : tungsten or iron. Simulation exists

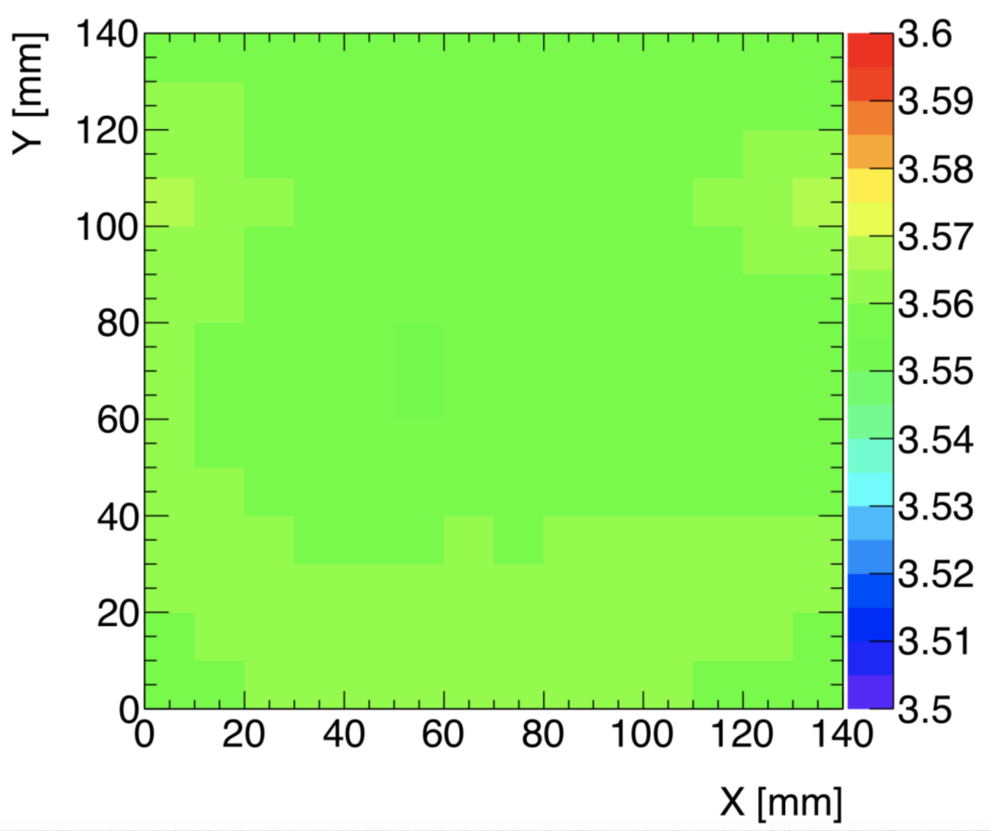
performance tests of prototype detectors in the beam

Tungsten plates

- 10 new tungsten absorber plates
- High requirements to geometrical accuracy (~50 µm for thickness) make it difficult to use pure W.
- the absorber alloy : 93% tungsten, 5% nickel & 2% copper.
- Good flatness ~30 µm observed
- Glued to permaglass frame
- Used in assembled calorimeter in 2019/2022 beam test campaigns







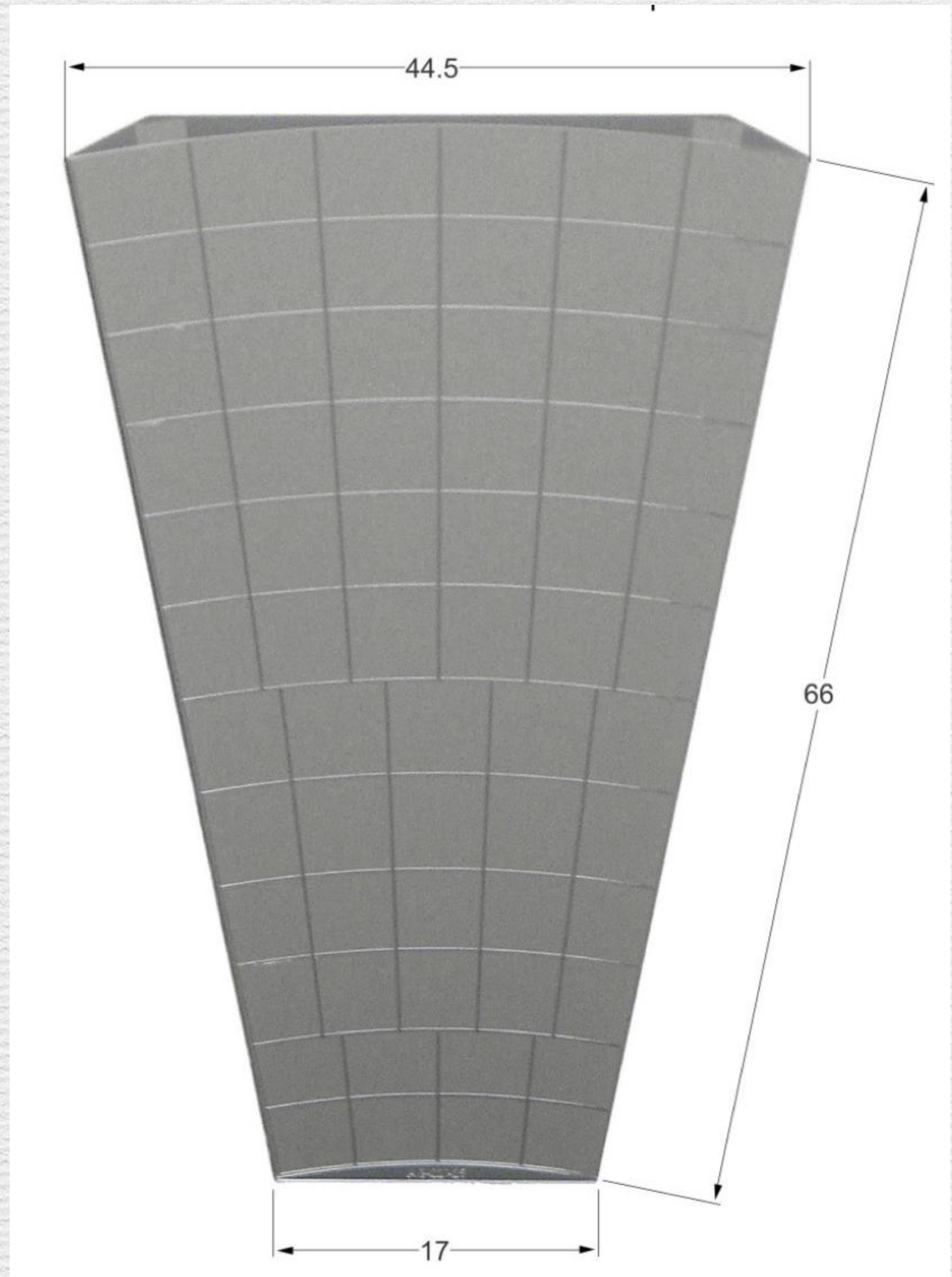
Dimensions 140x140x3.5 mm

Designed in JINR Dubna

Enough plates for $20X_0$

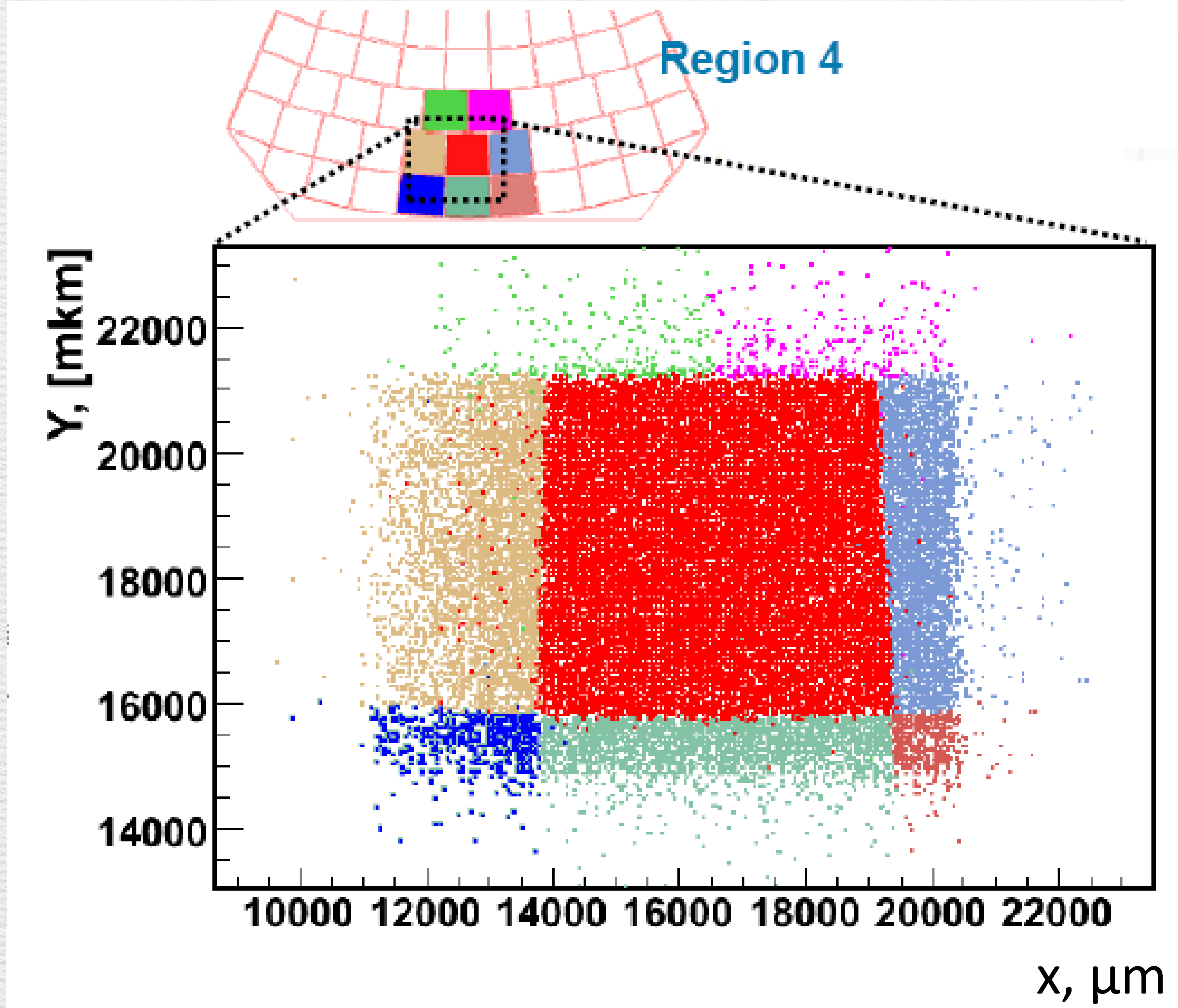
BeamCal

Baseline sensor: GaAs

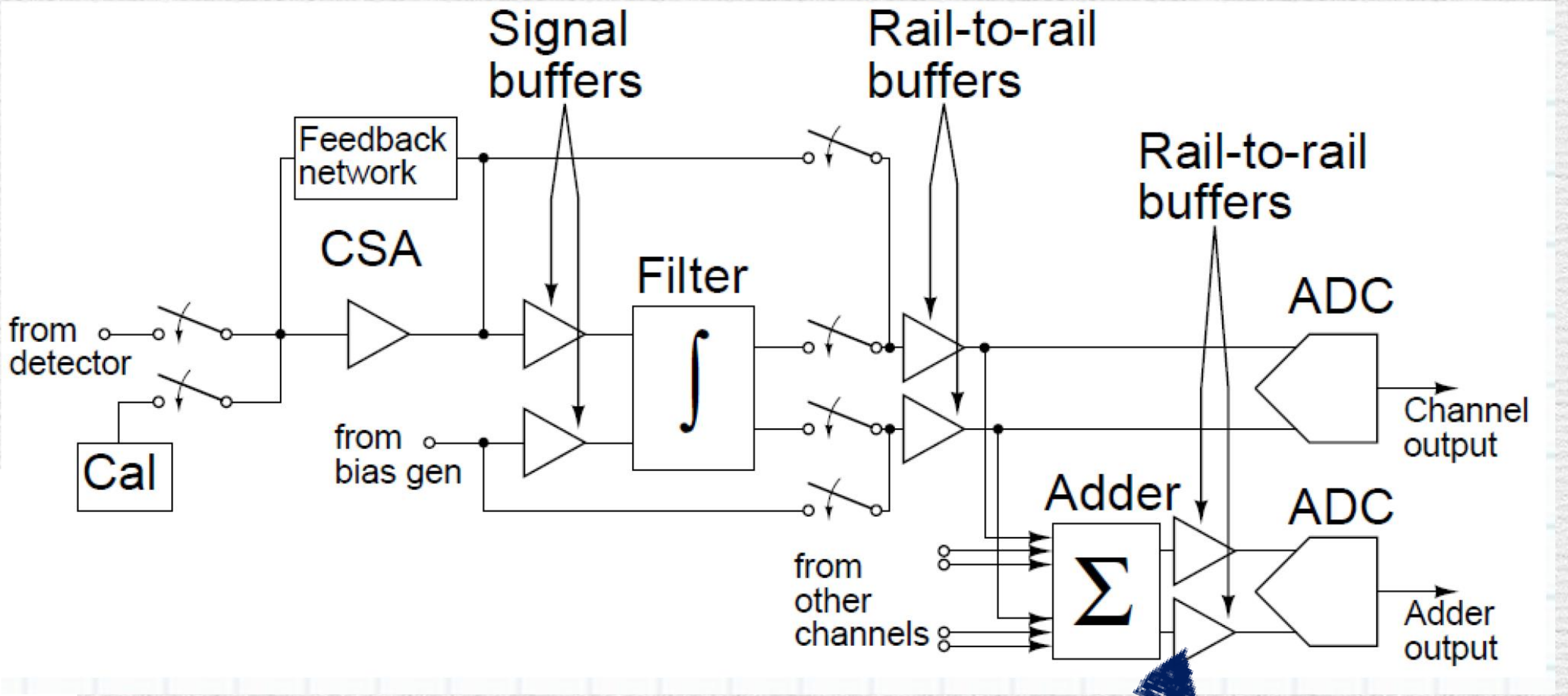


Designed in JINR Dubna

Thickness 500 µm
High resistivity (10^7 Ωm)
S/N for MiPs ≈ 20

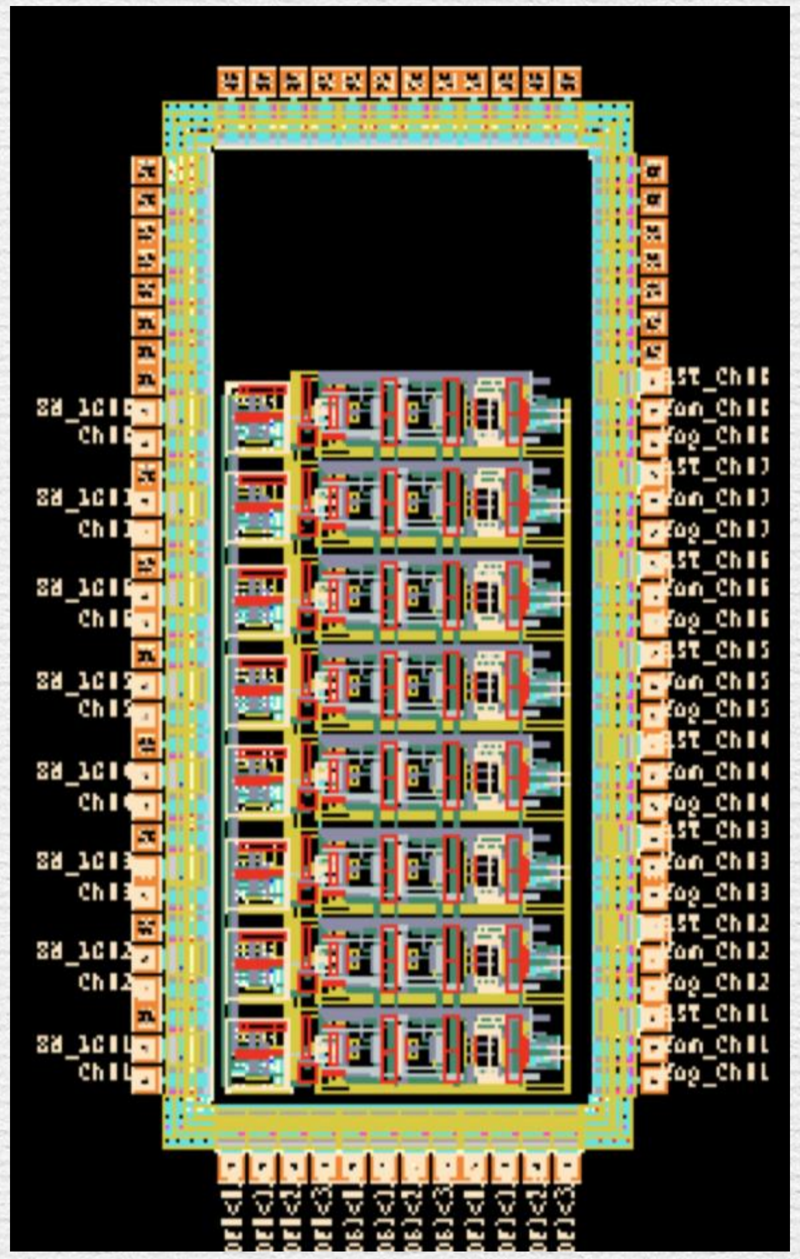


Test-beam fully instrumented detector plane



Dedicated ASIC development with fast OR to be used in the feedback system

BeamCal ASIC v3 Design



Designed at Pontificia Universidad Católica de Chile

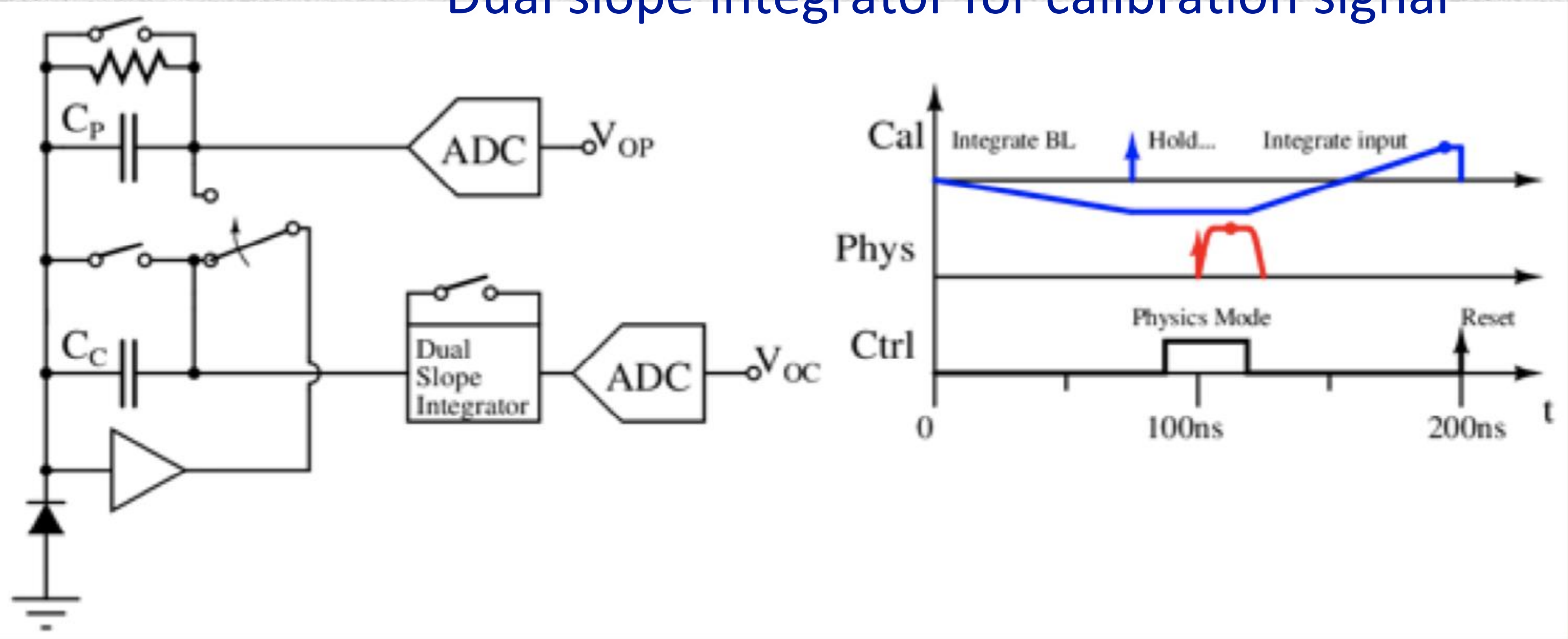
Different sensor materials: GaAs, Si, Diamond, Sapphire;
Different sensor segmentation – input capacitance;
Different MIP response and maximum signal: 0.8 pC – 30 pC.

Specification	Value
Q_{in}	> 2.8 fC
ENC	< 1000 - 1500 e^- rms
Number of channels	8
Maximum input rate	1 / 554ns
Baseline restoration	1%

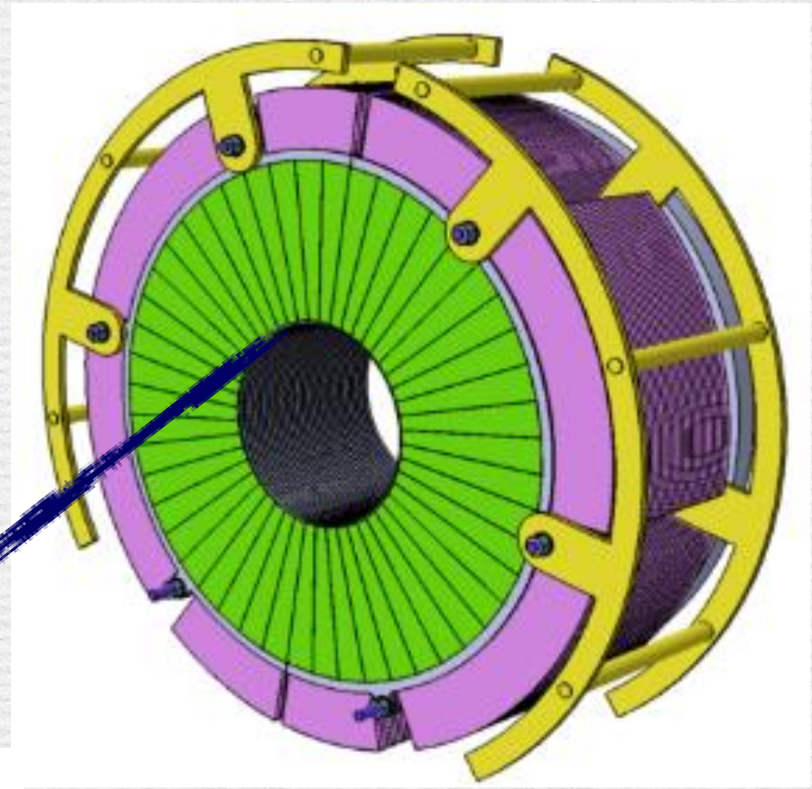
- Firstly, BeamCal is hit by beam halo (muons)
  - – MIP deposition, low noise electronics
  - – Clean environment
  - – Good for calibration
- ~25ns later, BeamCal is hit by collision scattering
  - – Large deposit energy
  - – Physics readout

- Pad Capacitance: ~20pF (New Sapphire Design)
- Programmable time constant
- Active baseline restoration
- Programmable baseline restoration current

Dual slope integrator for calibration signal



LumiCal silicon sensor



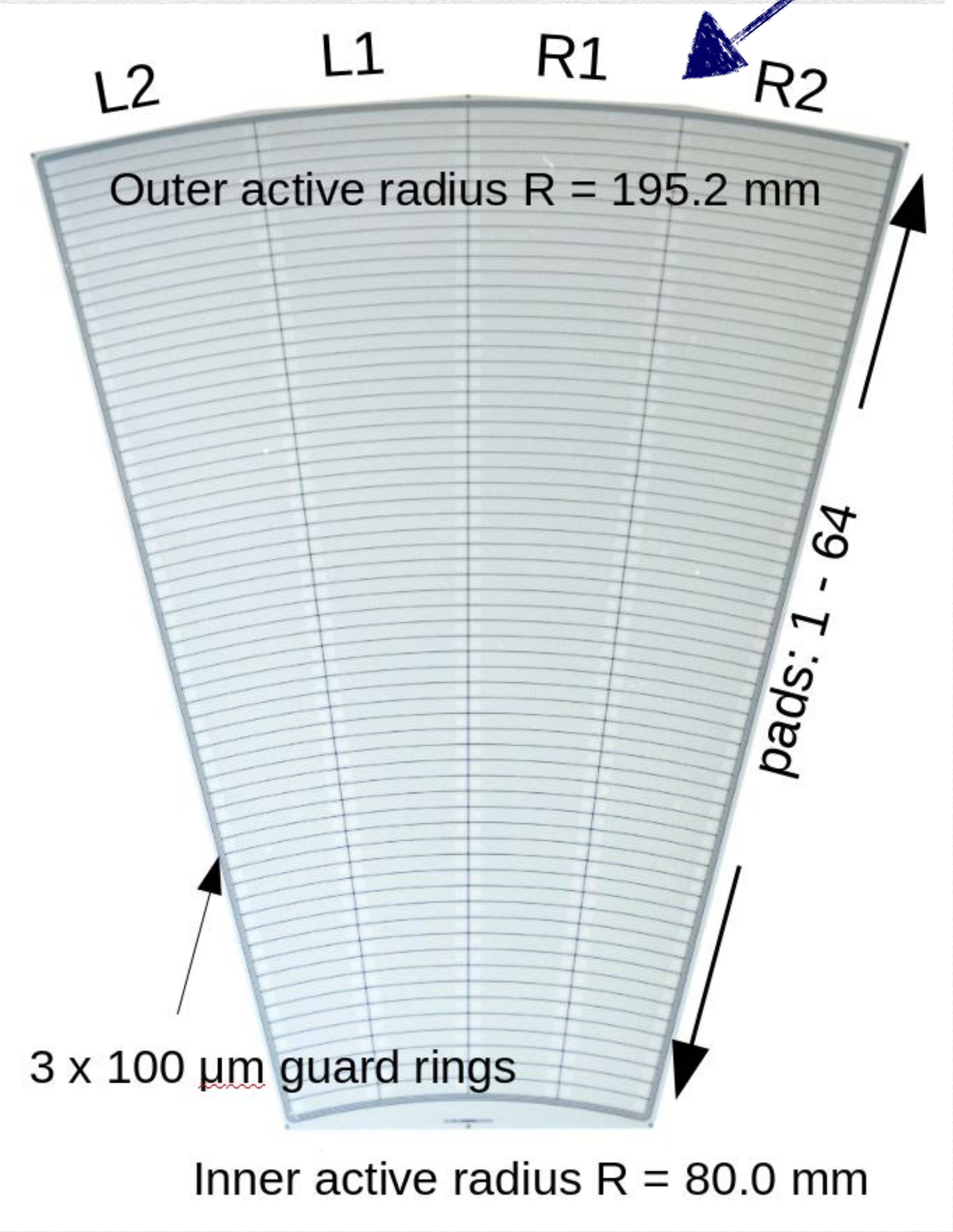
LumiCal is a Si-W electromagnetic sampling calorimeter

- Compact design provides
- small Molière radius;
- bigger fiducial volume;
- better HE particle detection on top of background.

- Challenging requirements on geometrical compactness

Silicon pad sensor prototype is designed for ILD; produced by Hamamatsu

- thickness 320 µm
- DC coupled with readout electronics
- p+ implants in n-type bulk
- 64 radial pads, pitch 1.8 mm
- 4 azimuthal sectors in one tile, each 7.5°
- 12 tiles make full azimuthal coverage



Designed in IFJ PAN Cracow

2014 Test Beam at CERN

- 4 LumiCal detector planes equipped with dedicated electronics (32 channels)
- 4.5 mm between tungsten plates

Procedure was developed for 2014 beam test of LumiCal prototype at CERN (PS, 5 GeV e- beam).
Result is
$R_{\mathcal{M}}$ =24.0 ± 0.6(stat.) ± 1.5(syst.) mm
(Eur. Phys. J. C 78 (2018) 135.)

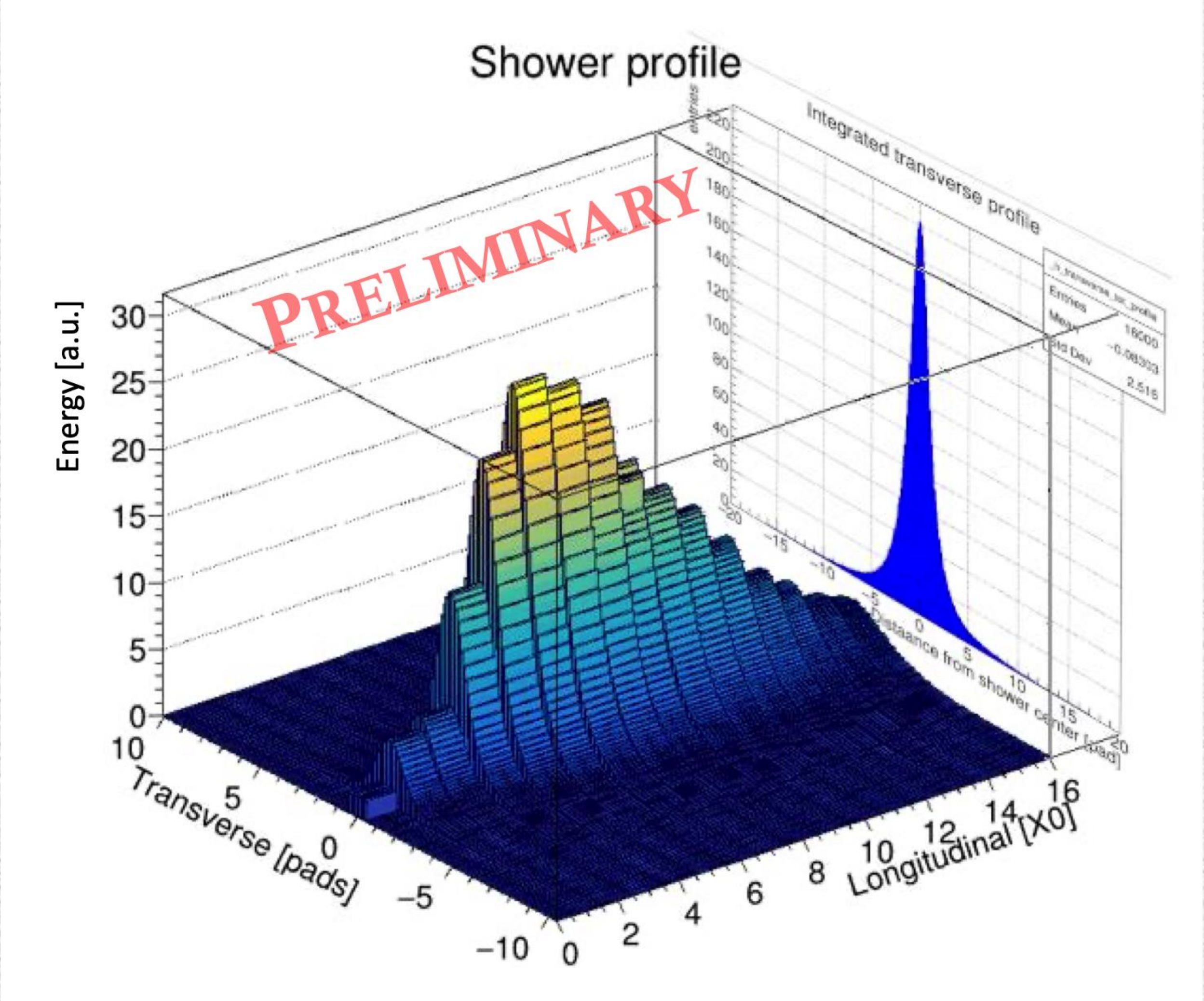
2016 Test Beam at DESY

- 8 LumiCal detector planes equipped with APV (2k channels)
- 1 mm between tungsten plates

The effective Molière radius is
8.1 ± 0.1 (stat) ± 0.3 (syst) mm

2020 Test Beam at DESY

- 15 LumiCal detector planes equipped with APV (2k channels) and FLAME dedicated readout
- 1 mm between tungsten plates

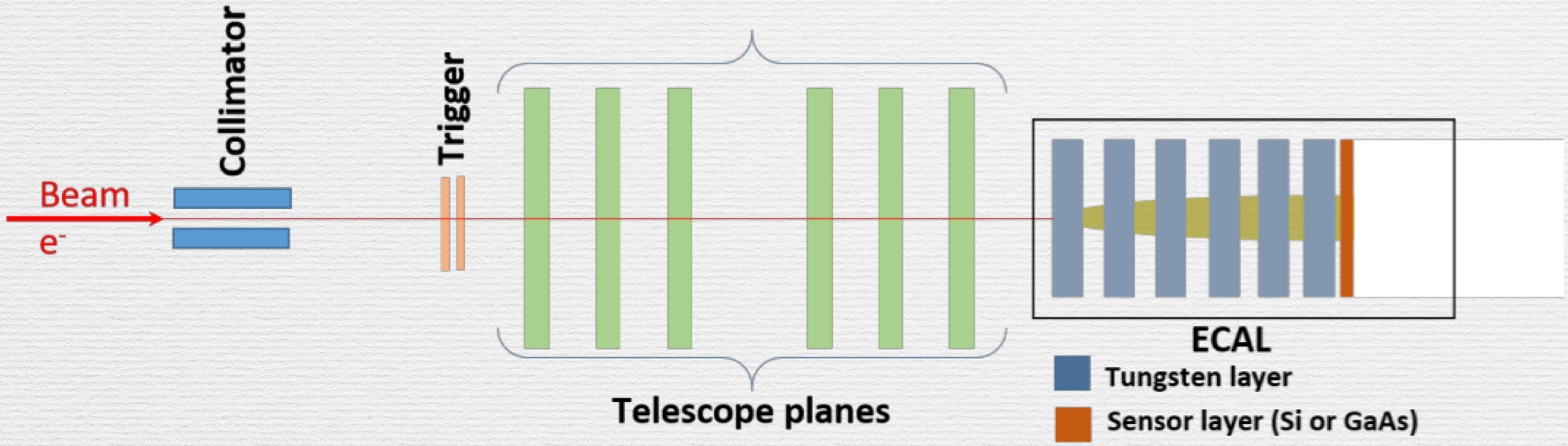


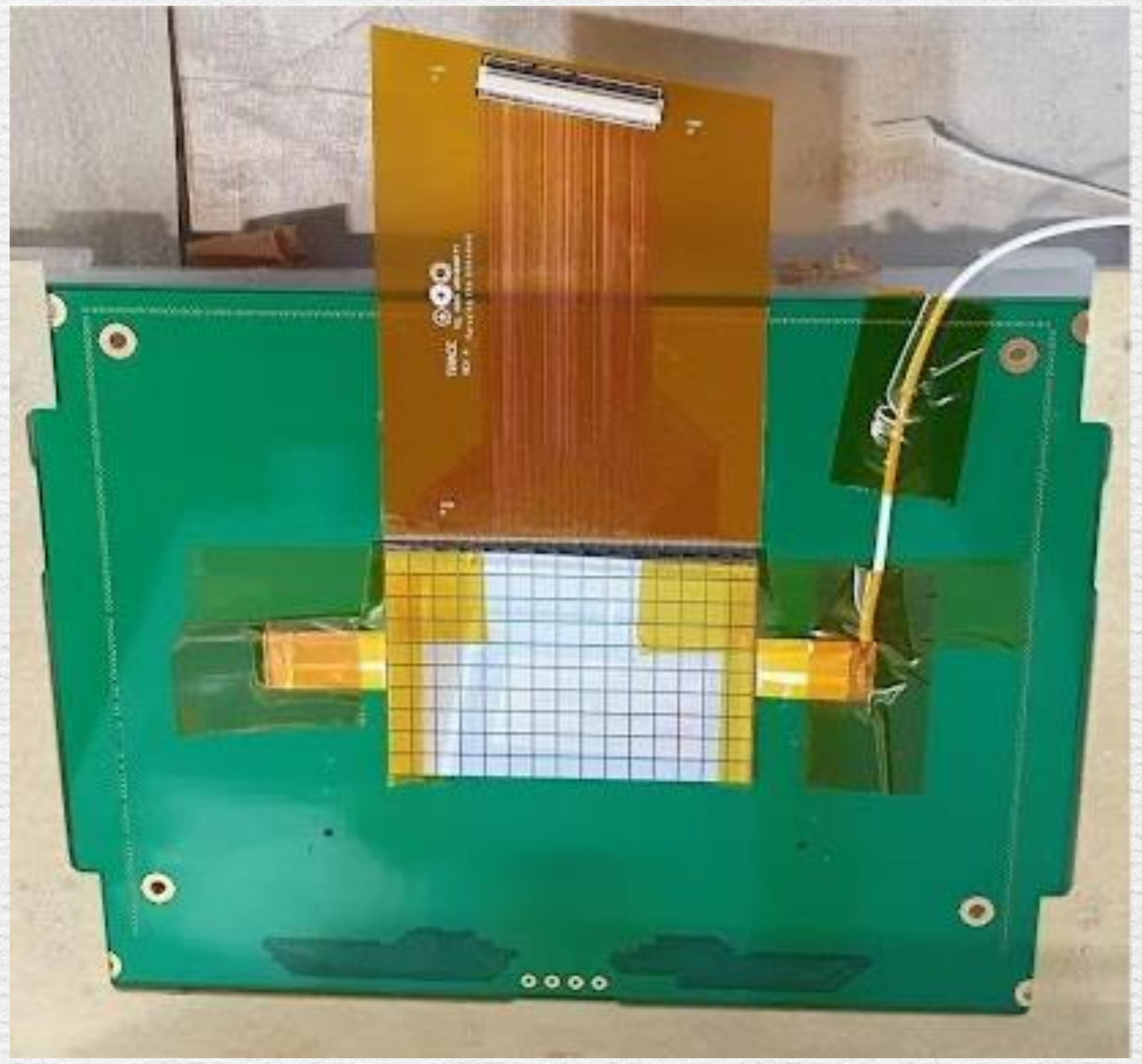
2022 : from forward region to LUXE

- LUXE experiment :e-gamma interaction and creation of e+e-
- Part of FCAL decided to build the electromagnetic calorimeter based (for the e+) based on its knowledge :
  - Thin silicon sensors
  - Dedicated FCAL ASIC

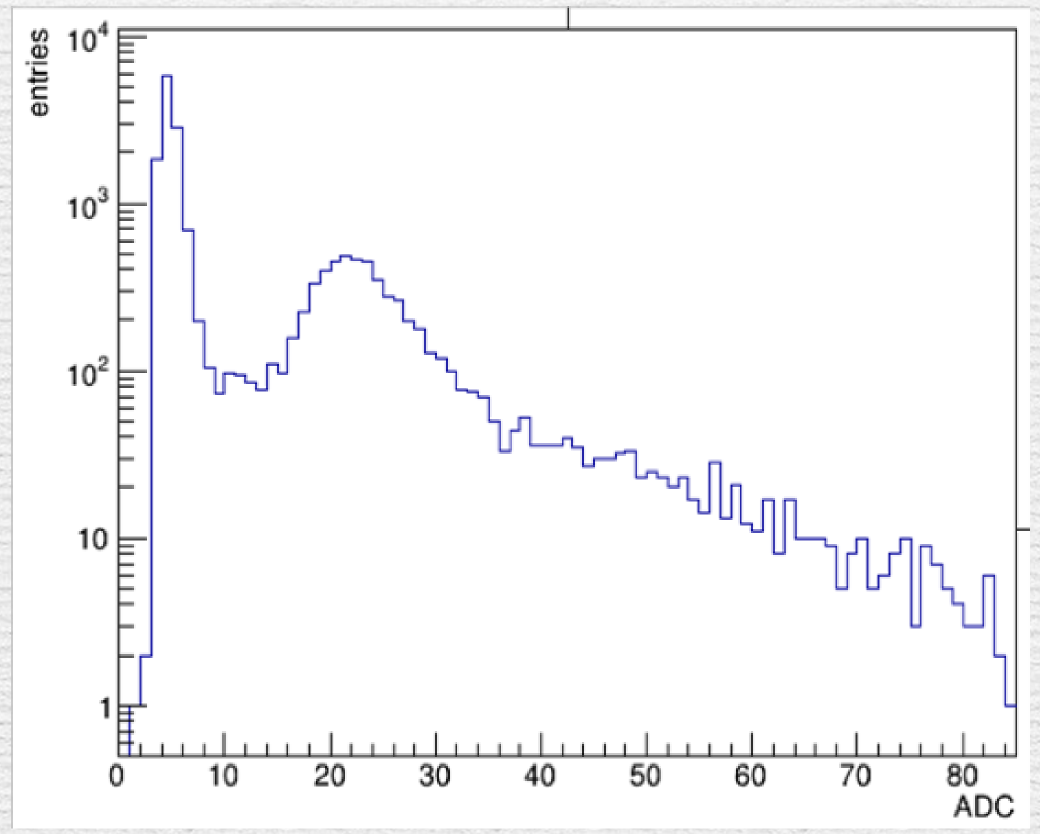
very challenging to move from test beam to real experiment…

Beam test sept 2022 at DESY

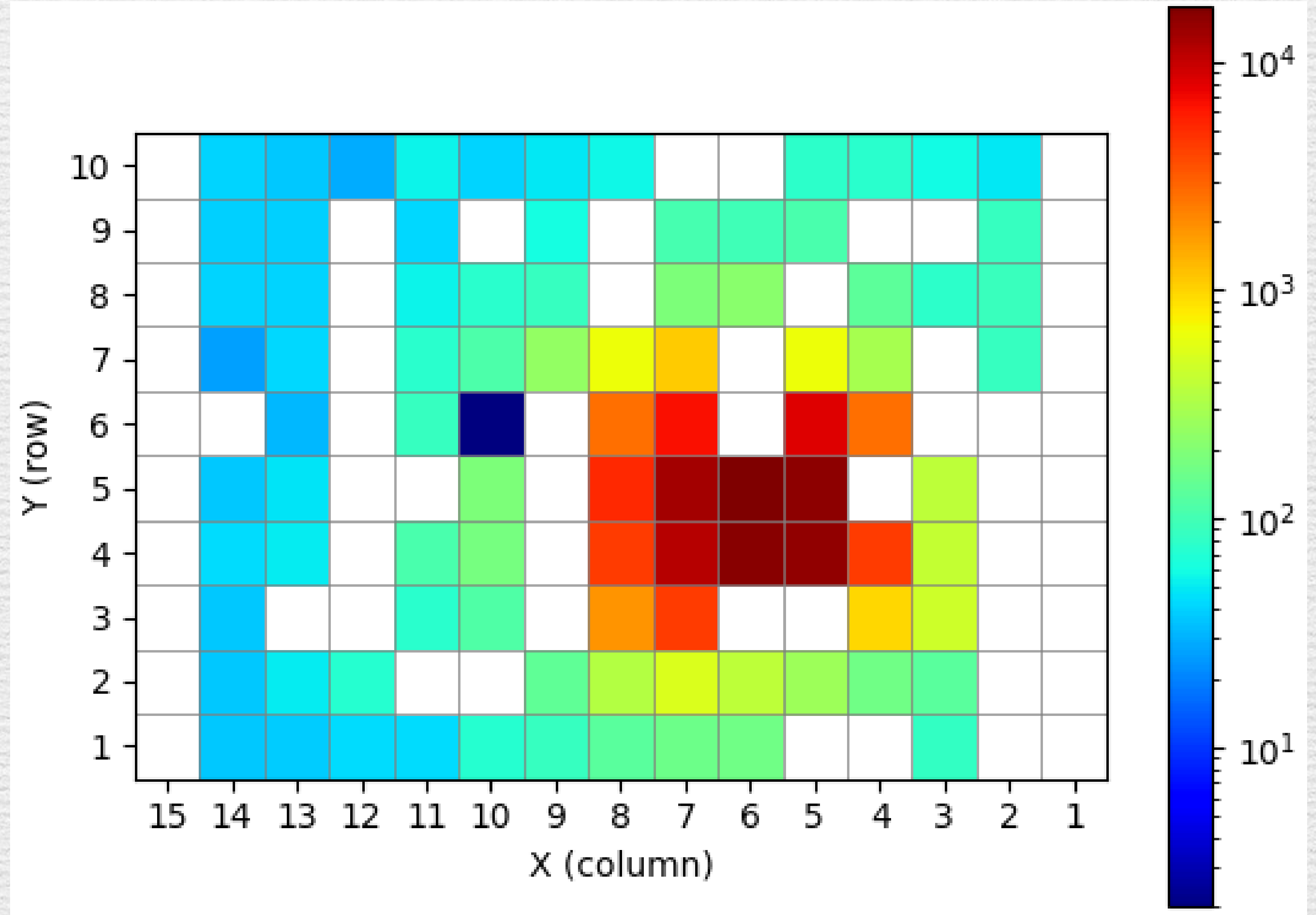




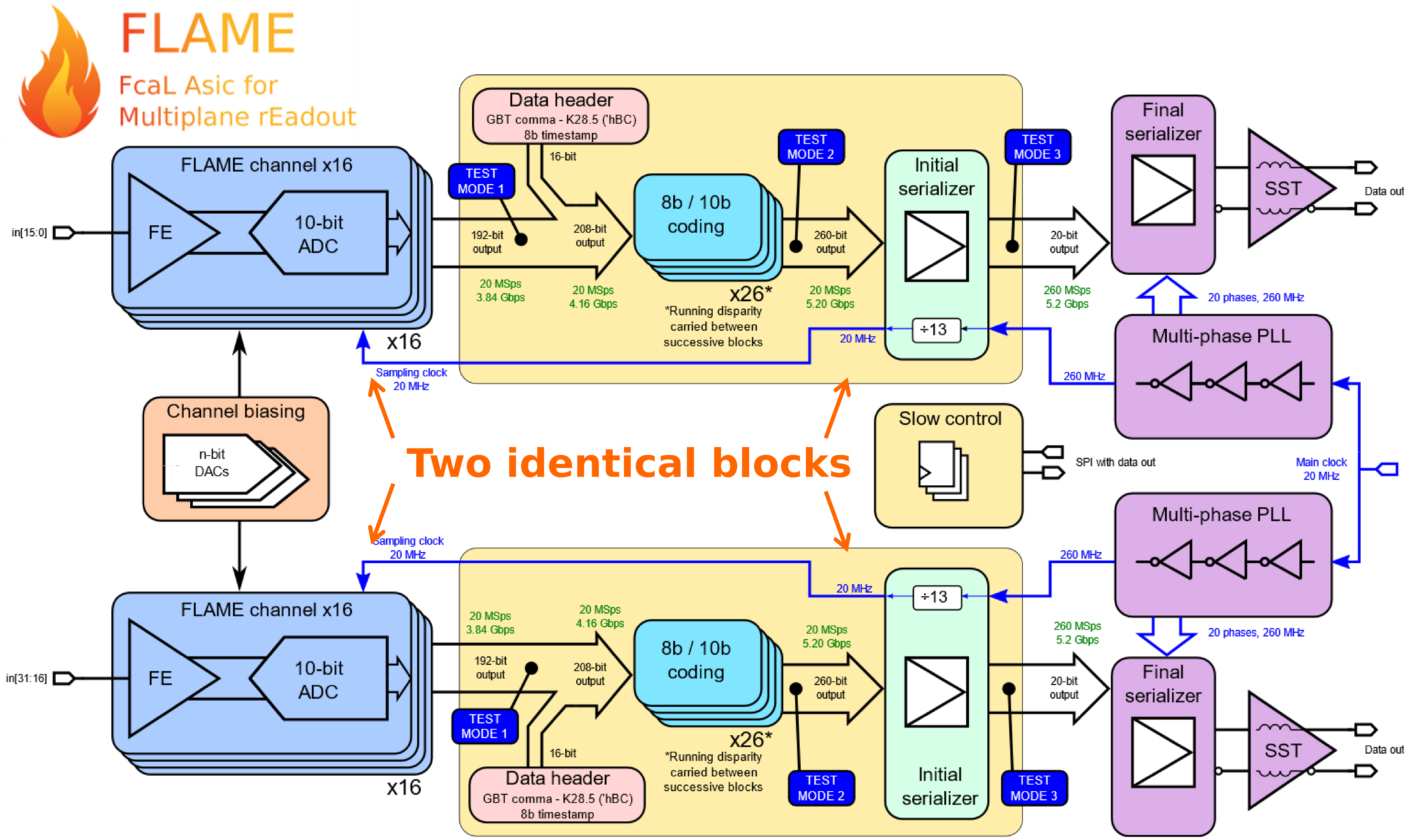
- FLAME will be used in LUXE experiment : similar to FCAL setup except the geometry of silicon detectors and tungsten planes

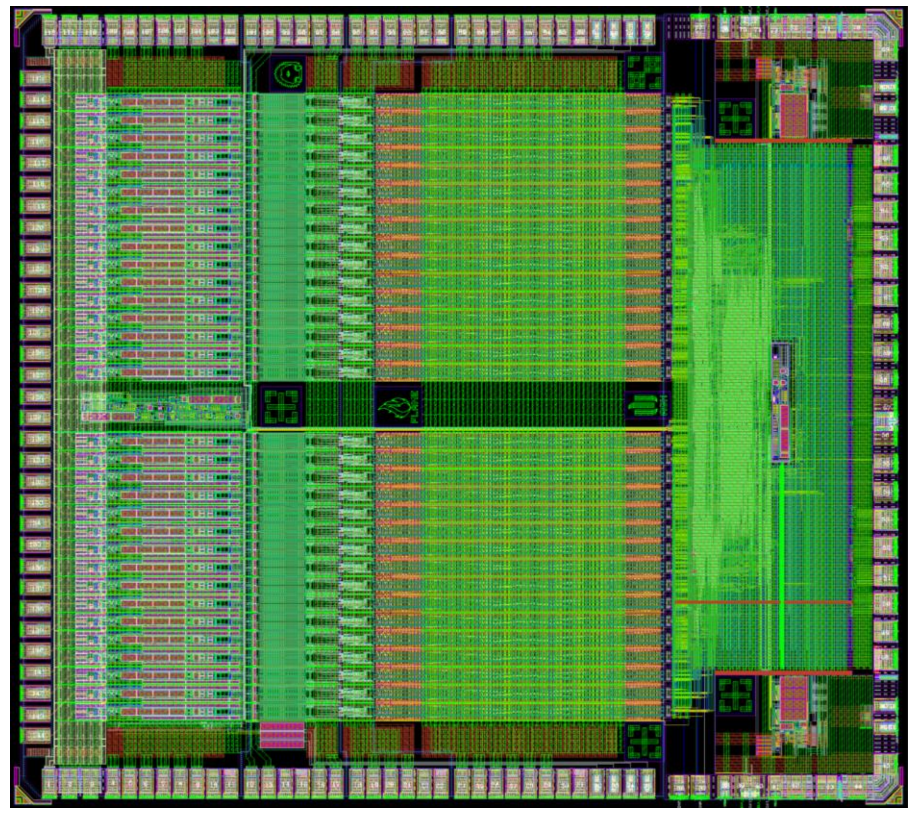


MIP signal



FLAME: 32-channel ASIC in CMOS 130 nm, with FE+ADC in each channel, followed by high speed data serializers and transmission (2 x 5.2Gb/s).





FLAME-based readout was used in FCAL and LUXE testbeams in 2021 and 2022. First data results already presented, detailed analyses in progress...

Ongoing analyses and readout R&D

- A lot of data was collected with FLAME ASIC plus with FPGA back-end. Detailed analyses is ongoing to quantify the performance of deconvolution procedure in amplitude and time measurements.
- **FLAXE** - a modified FLAME version for LUXE ECAL experiment was designed and will be submitted soon

–digital serialization and data transmission circuitry is significantly simplified since very low trigger rate and output data rate is needed in LUXE.

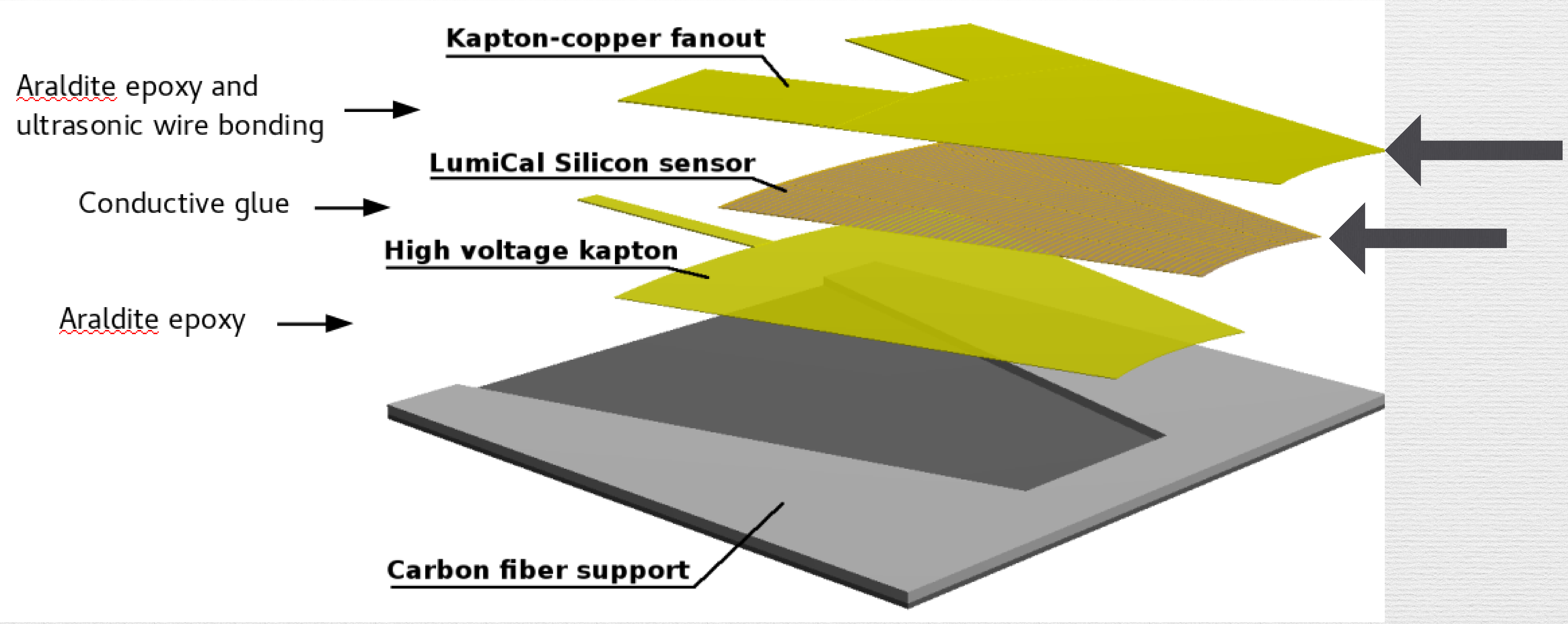
- R&D on readout blocks in CMOS 65nm

–prototype ultra-low power 80 MS/s 10-bit ADC designed&tested

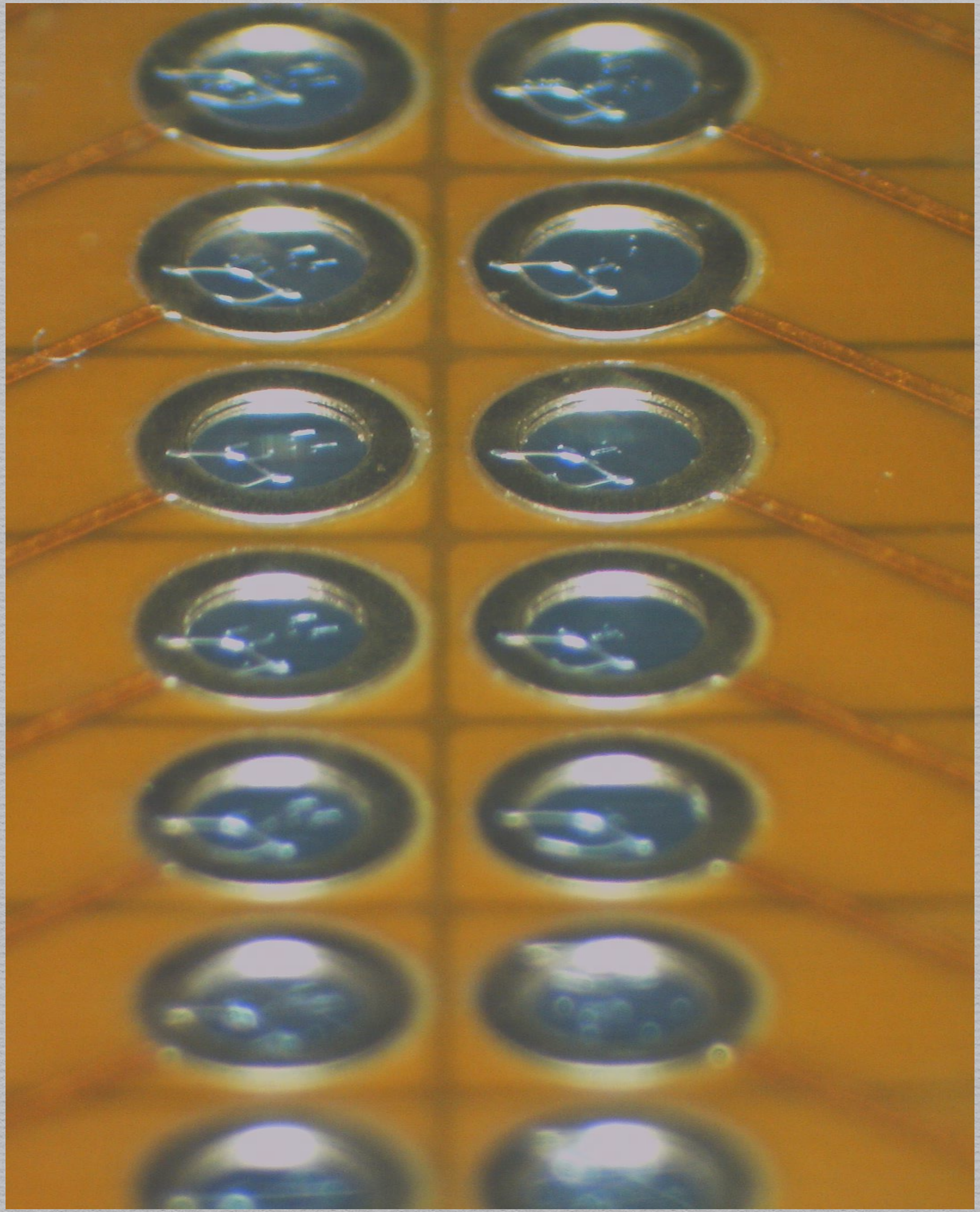
–prototype high speed ~10Gb/s data serializer&transmitter designed and under tests...

- R&D in CMOS 28nm has just started with design of ultra-low power ~200 MS/s 10-bit ADC.

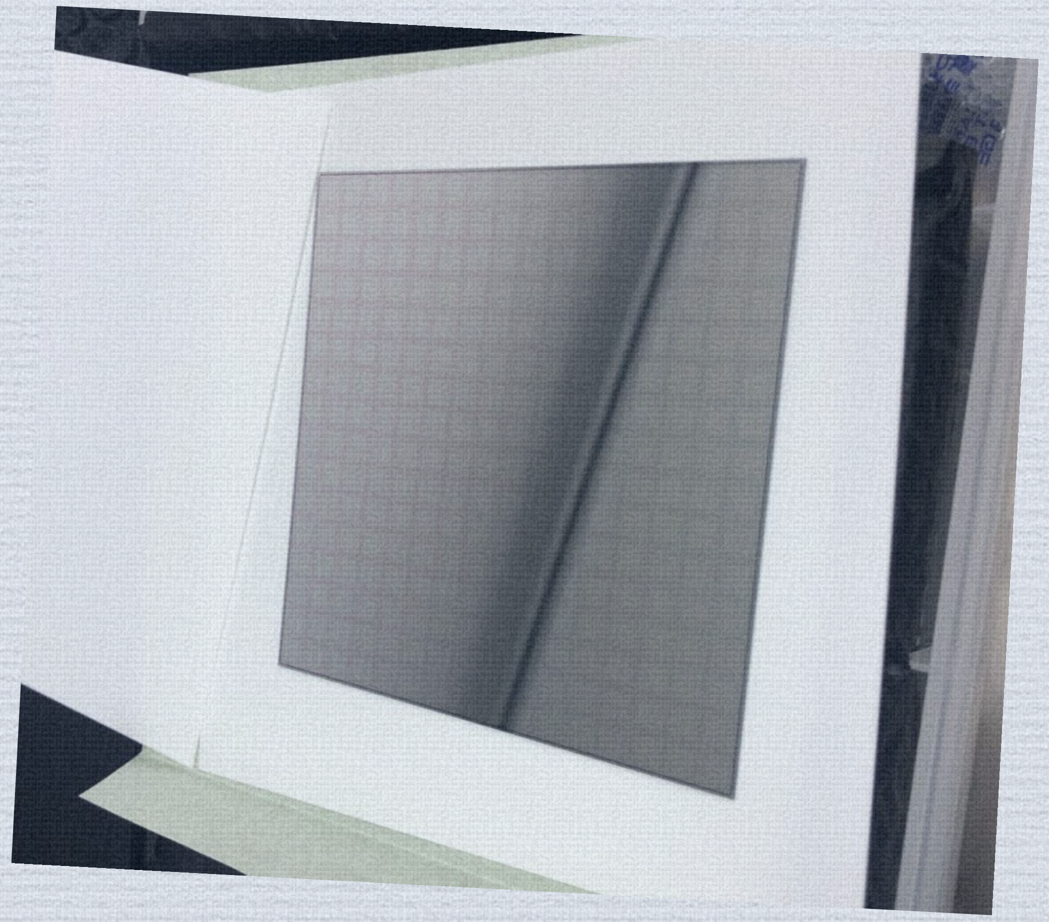
1.Bonding vs gluing



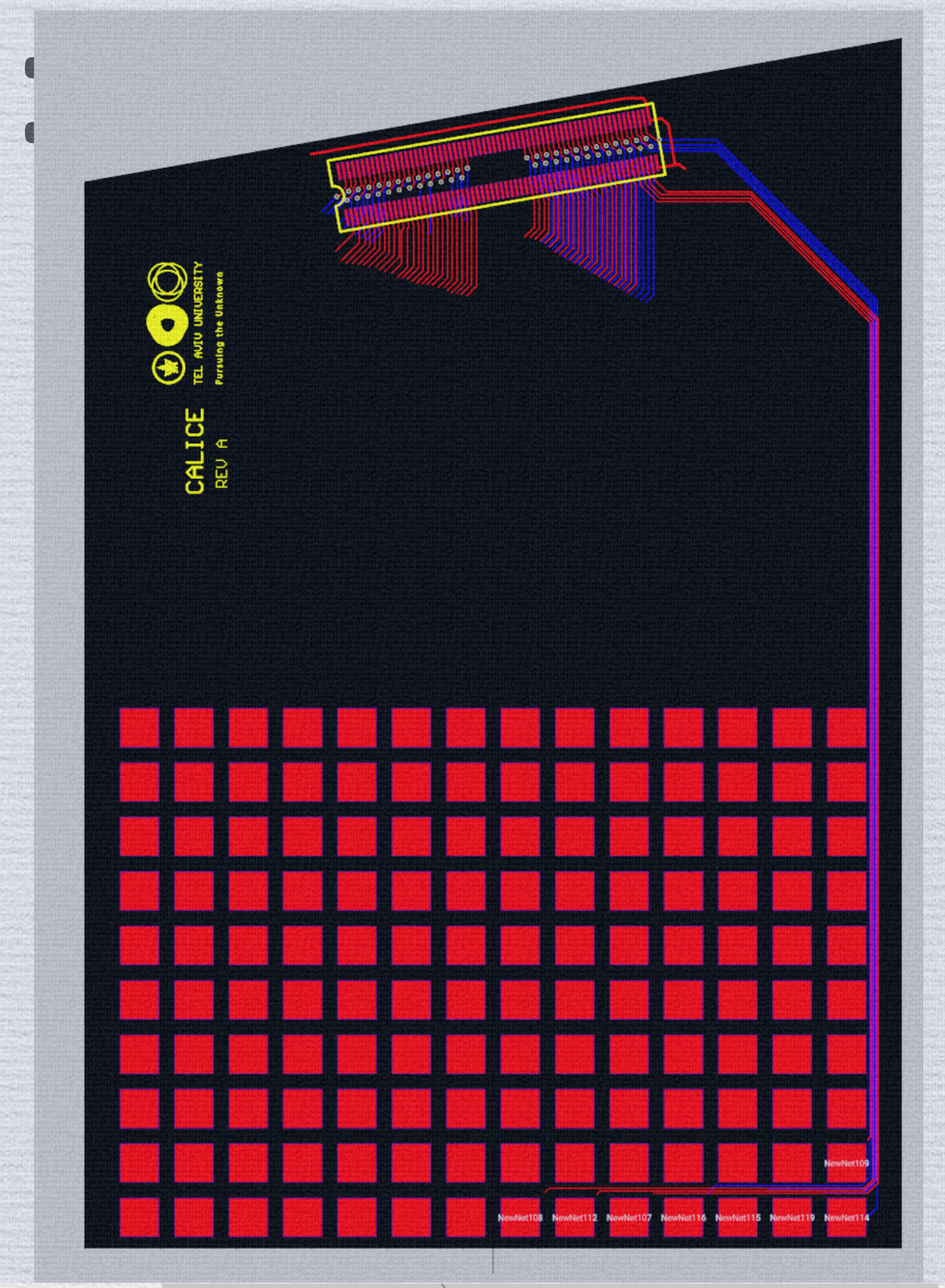
Wire bonding : loop size and fragility



Conductive glue : CALICE

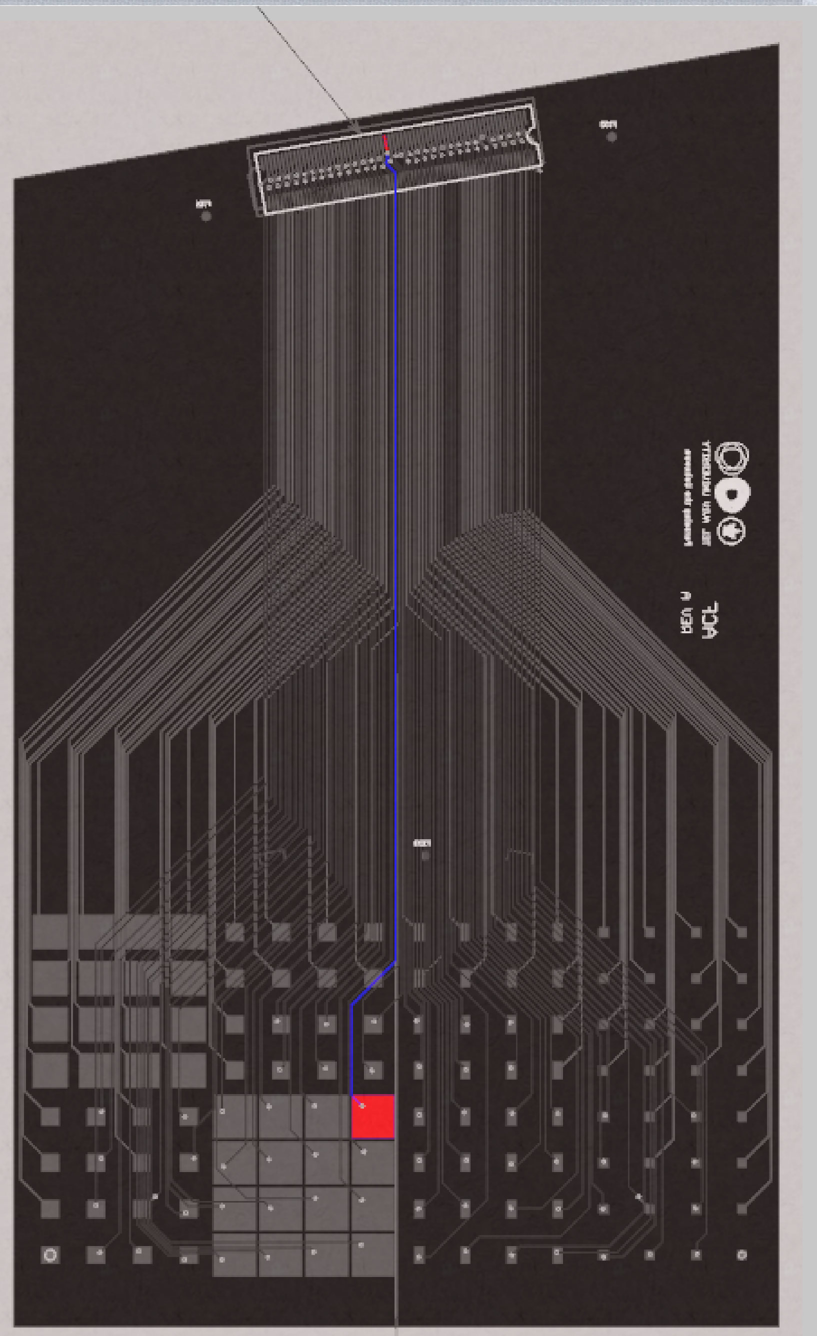


Glue: EJ2189
(silver based)
CALICE standard



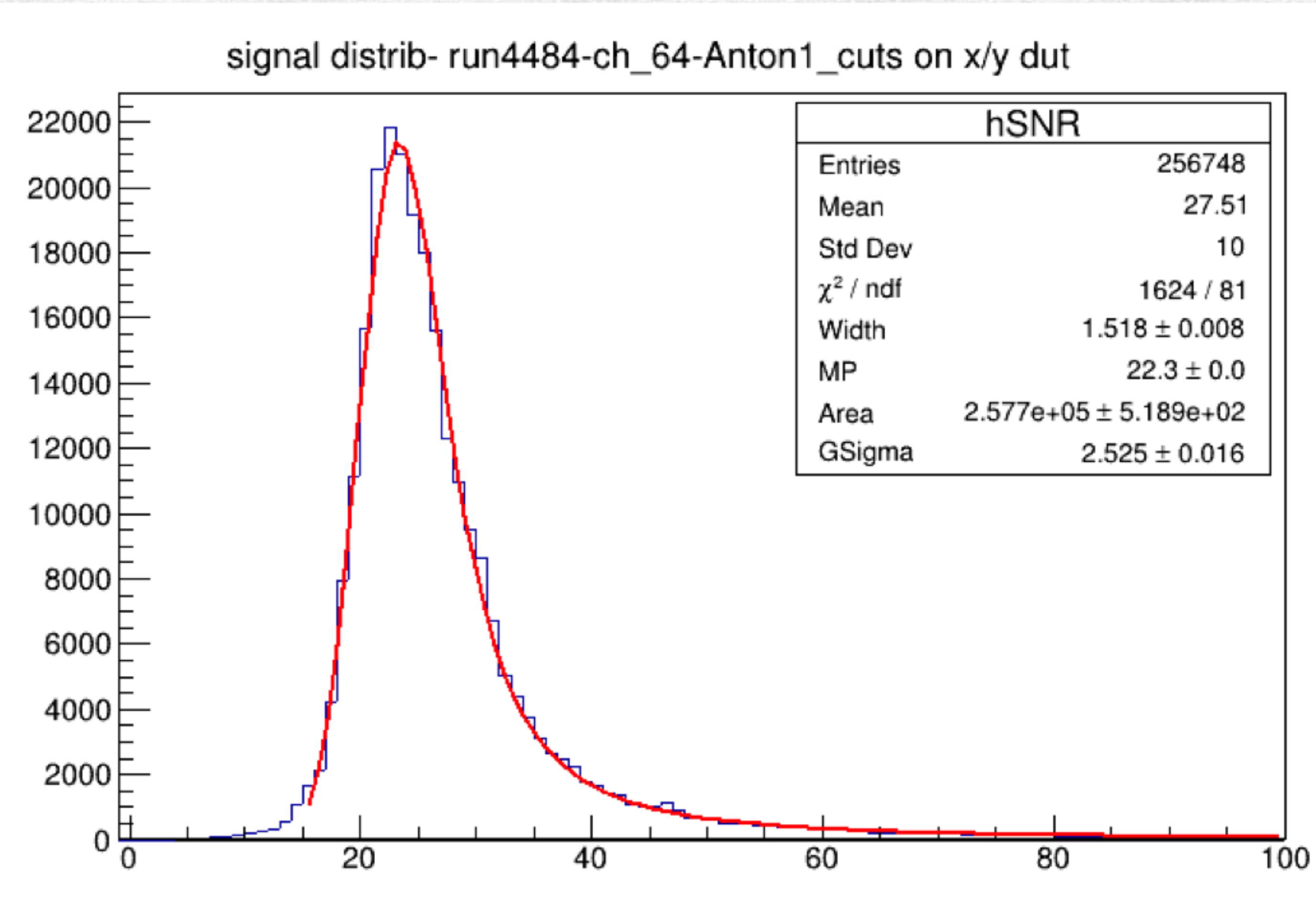
glue our sensor to the flex using Anisotrope Conductive Film

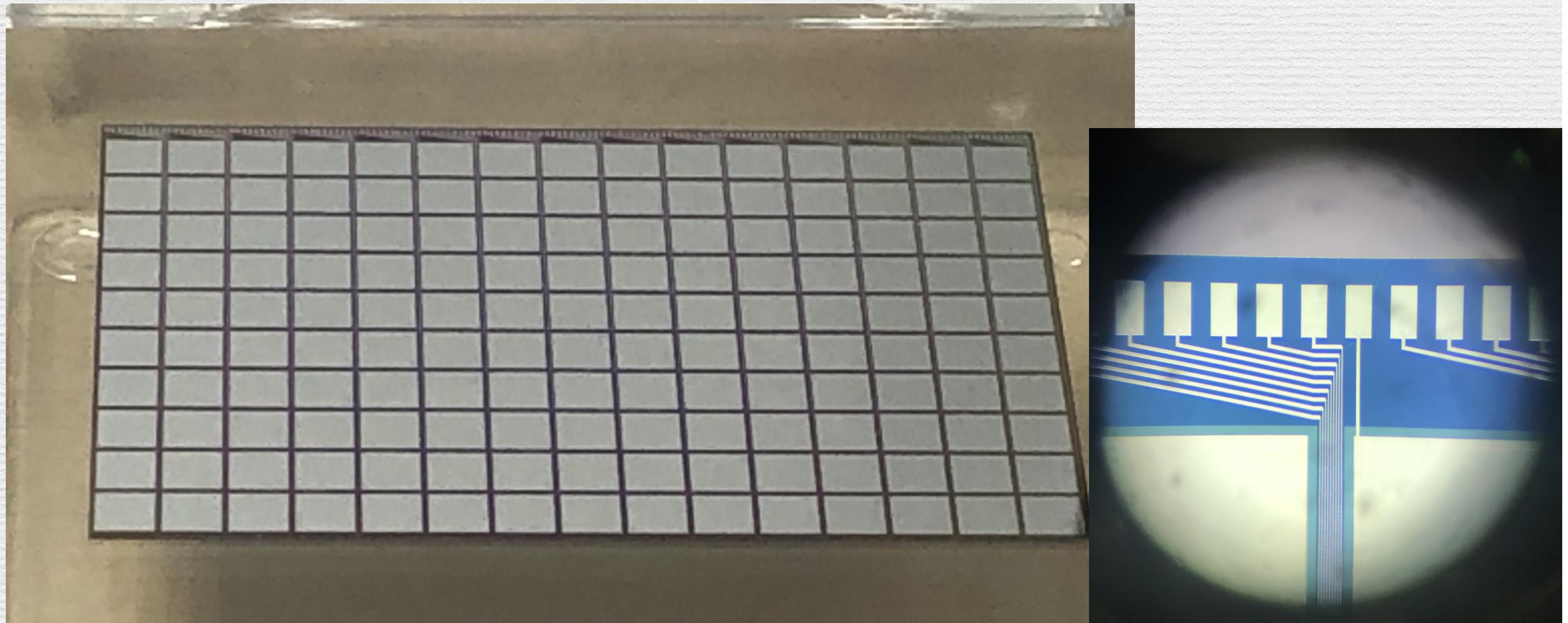
2 types of ACF : 3M (50 um) and Dexerials (3 um after curing)

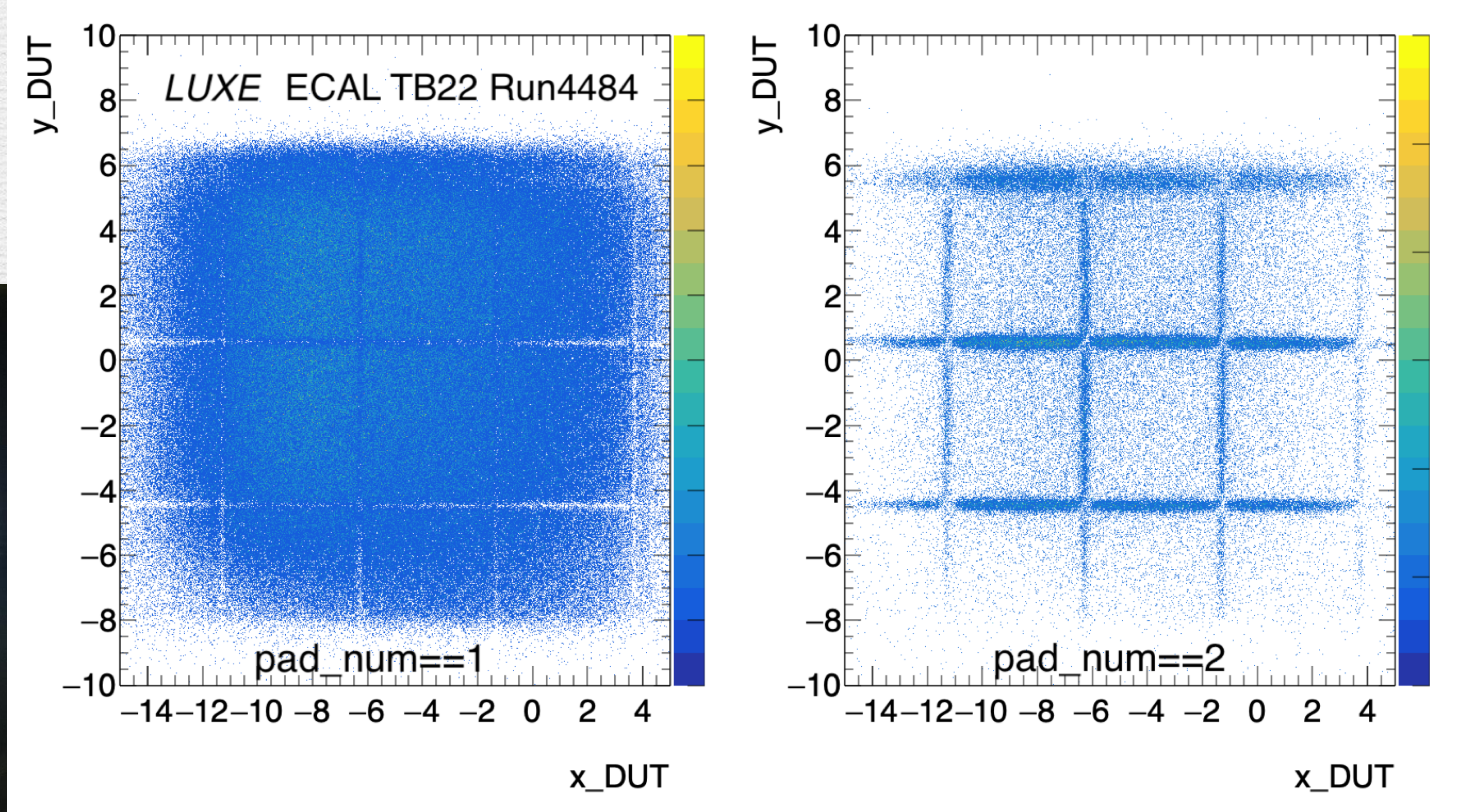


Fanout integrated in the sensor

- Sensors are 500 um GaAs
- Bonding connection to a flex connected to the FEB
- Produce in 2021 and tested in the lab
- Tested in 2022 at DESY : signal, cross talk, noise,…



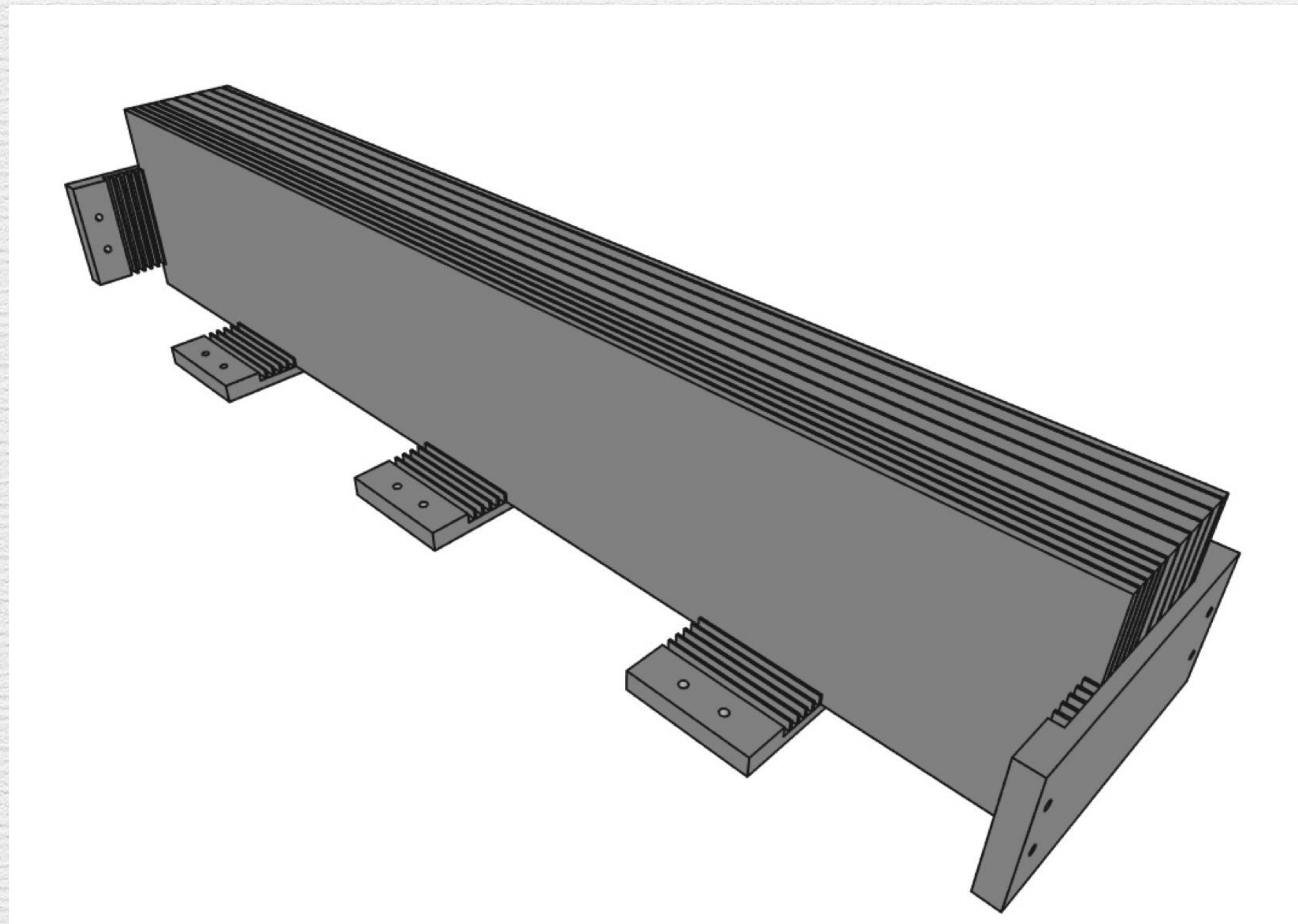




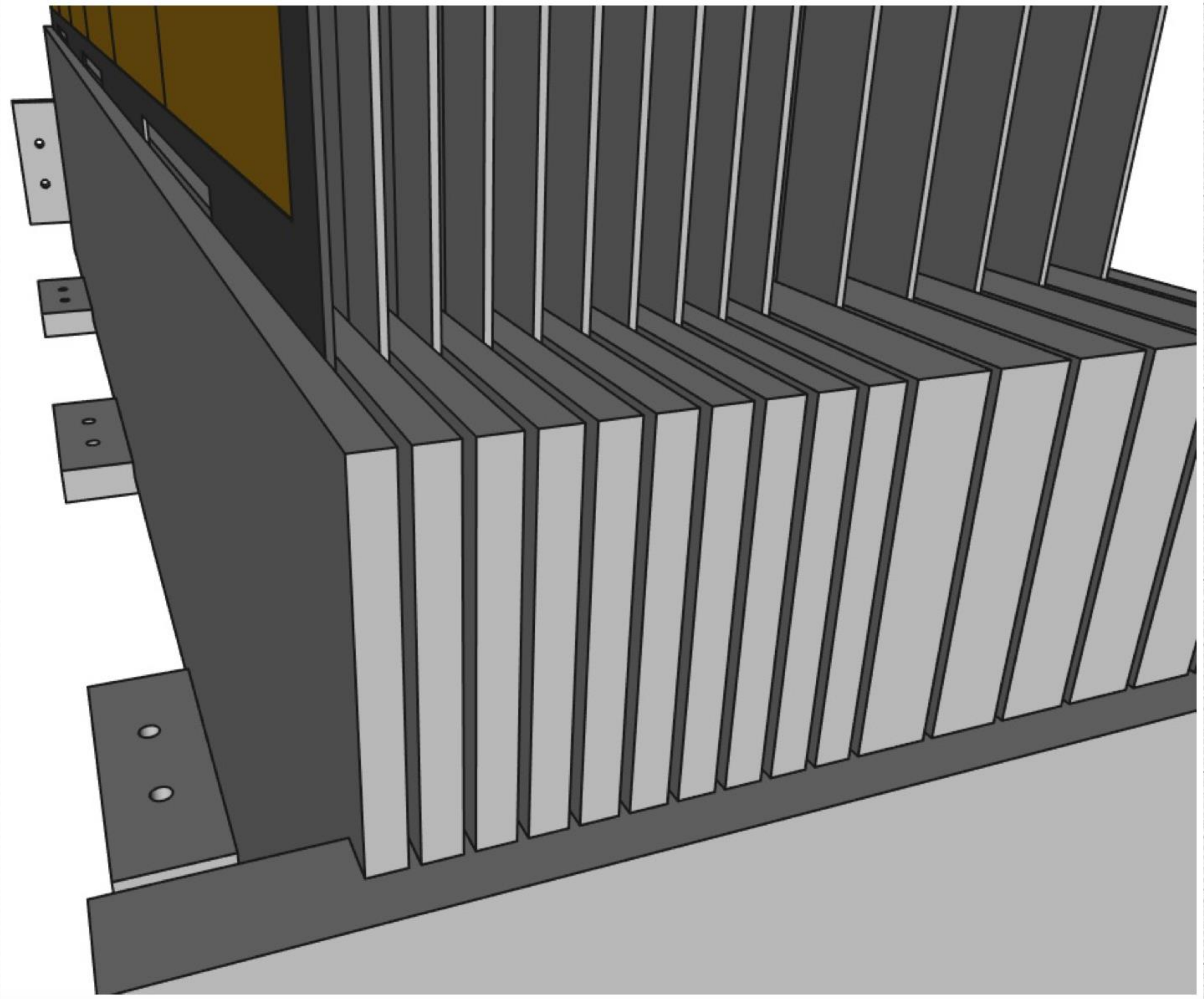
Mechanics

The geometry of LUXE is different from the FCAL, nevertheless, we are facing common problems :

- How to build the detector, layer after layer ?
- How to maintain the sensor on the tungsten planes ?
- Same mechanical frame for sensors and FEB ?
- How to drive the different cables ?



No cooling problems with LUXE



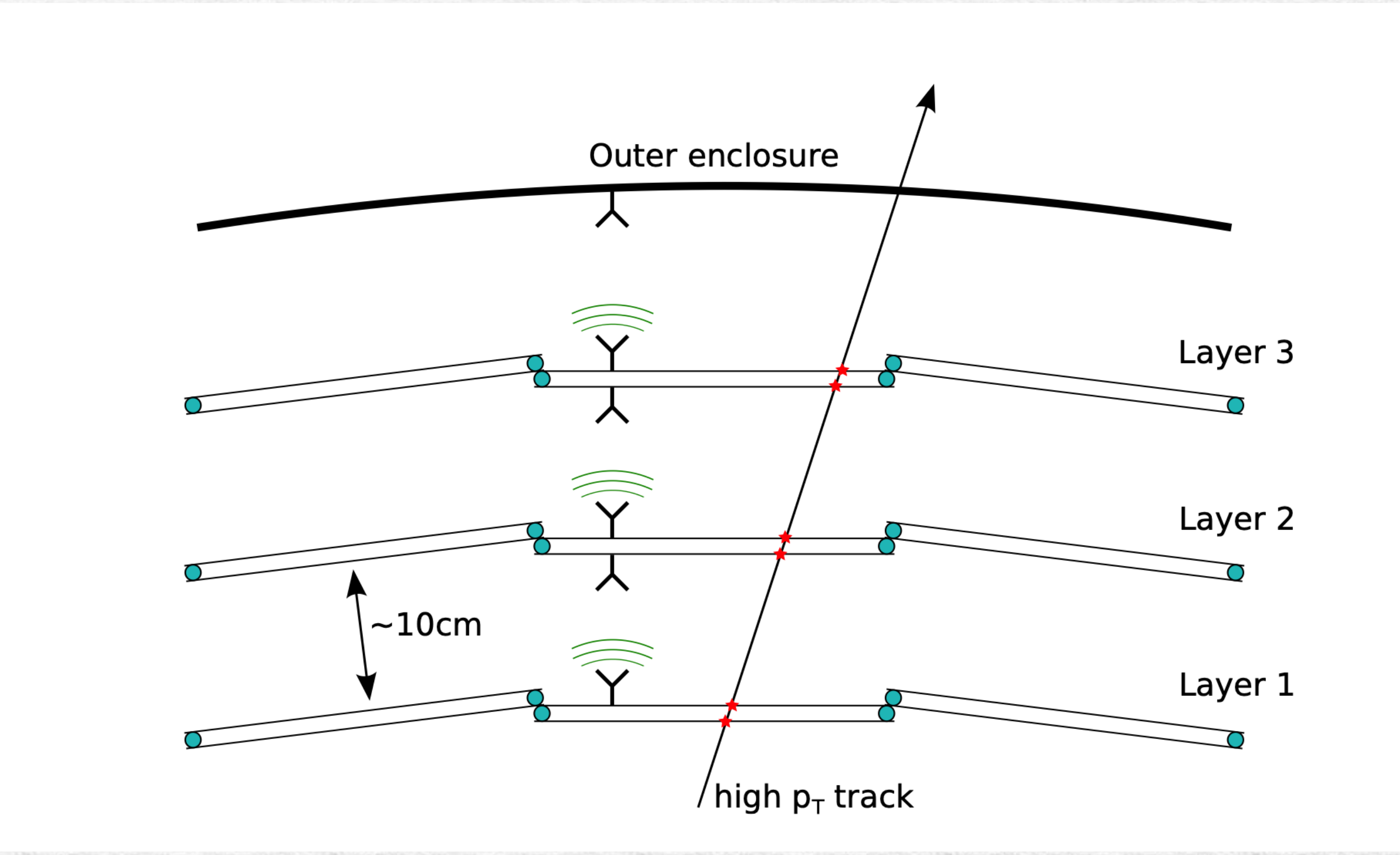
Data transmission

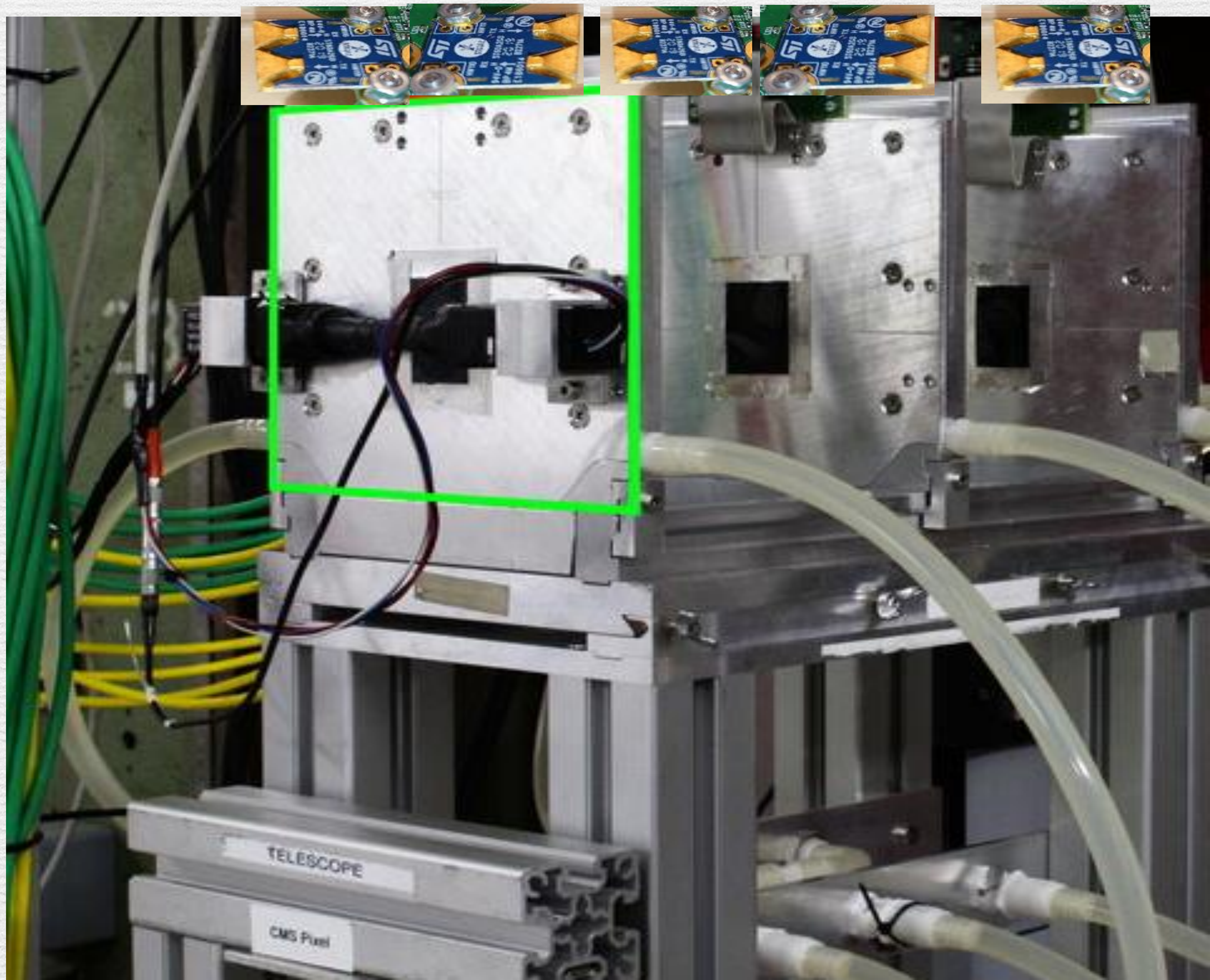
- In 2022, we (WADAPT collaboration) has been granted by AIDAinnova to continue the R&D on wireless data transmission

- Create a mockup with detectors and transmission chip to enable transmission in between layers

- Work on the antennas

- Collaborate to update existing chip





Summary and …

FCAL has developed a design for the very forward region of a detector at an e+e- collider

Three compact calorimeters are foreseen:

- BeamCal for bunch-by-bunch luminosity measurement and electron tagging
- LumiCal for precise measurement of the integrated luminosity.
- LHCal to extend the coverage of HCAL

Sensors for prototypes of BeamCal and LumiCal are designed and fabricated

Dedicated FE ASICs are designed and fabricated

…outlook

LumiCal

- Investigate the gluing of the sensors to the readout/HV planes, but also sensors to tungsten planes.
- Development of miniaturized FLAME front end boards
- Look carefully at the connections FEB - detector readout

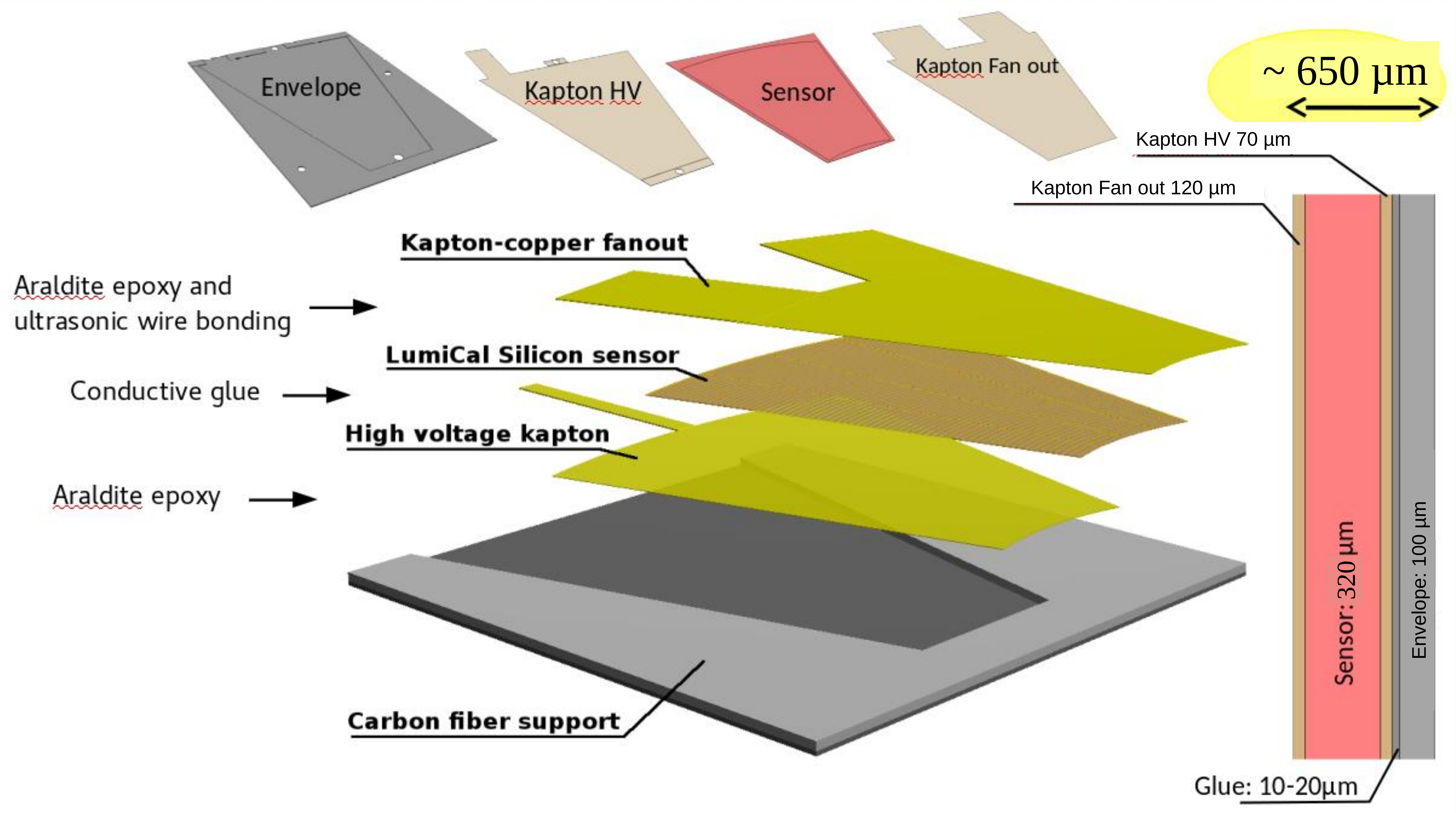
Driven by LUXE

BeamCal

- Develop sapphire sensors and test it
- Finish the development of the dedicated ASIC and test with sensors
- Develop a system to align and monitor the position at the μm level

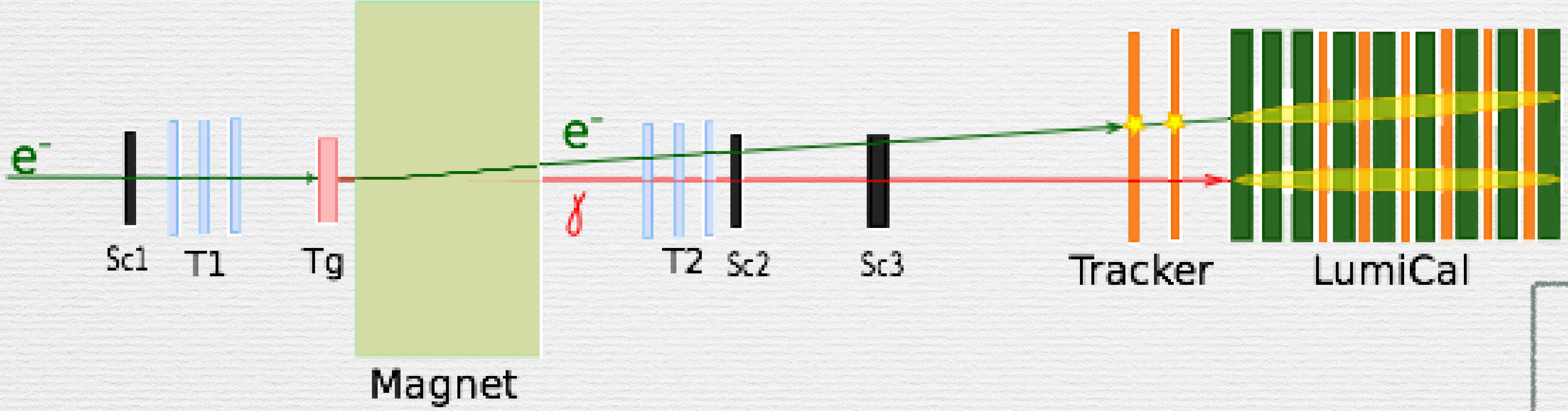
Thank you for attention!

LumiCal thin module prototype assembly



- Compactness is an essential requirement to provide small Molière radius/accurate shower position reconstruction.
- In current LumiCal conceptual design the space between absorbers is 1 mm!
- Carbon fiber support facilitate handling and mounting on tungsten planes

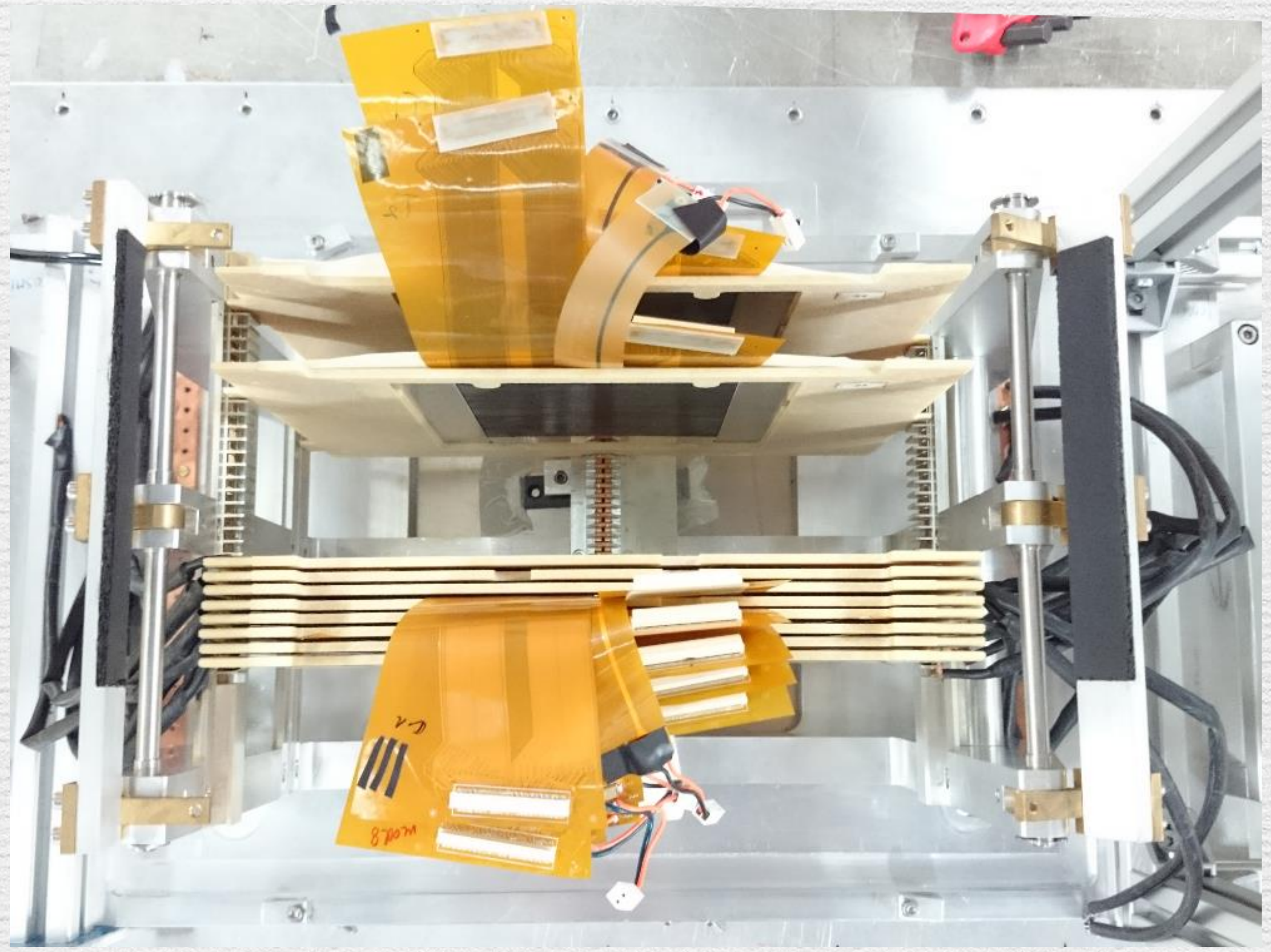
2016 Test Beam at DESY



Sc1, Sc2 and Sc3 are scintillator counters; T1, T2 – three pixel detector planes; Tg – the copper target for bremsstrahlung photon production.

DESY test beam facilities:
- Electron beam 1 – 5 GeV;
- Dipole magnet 1 – 13 kGs;

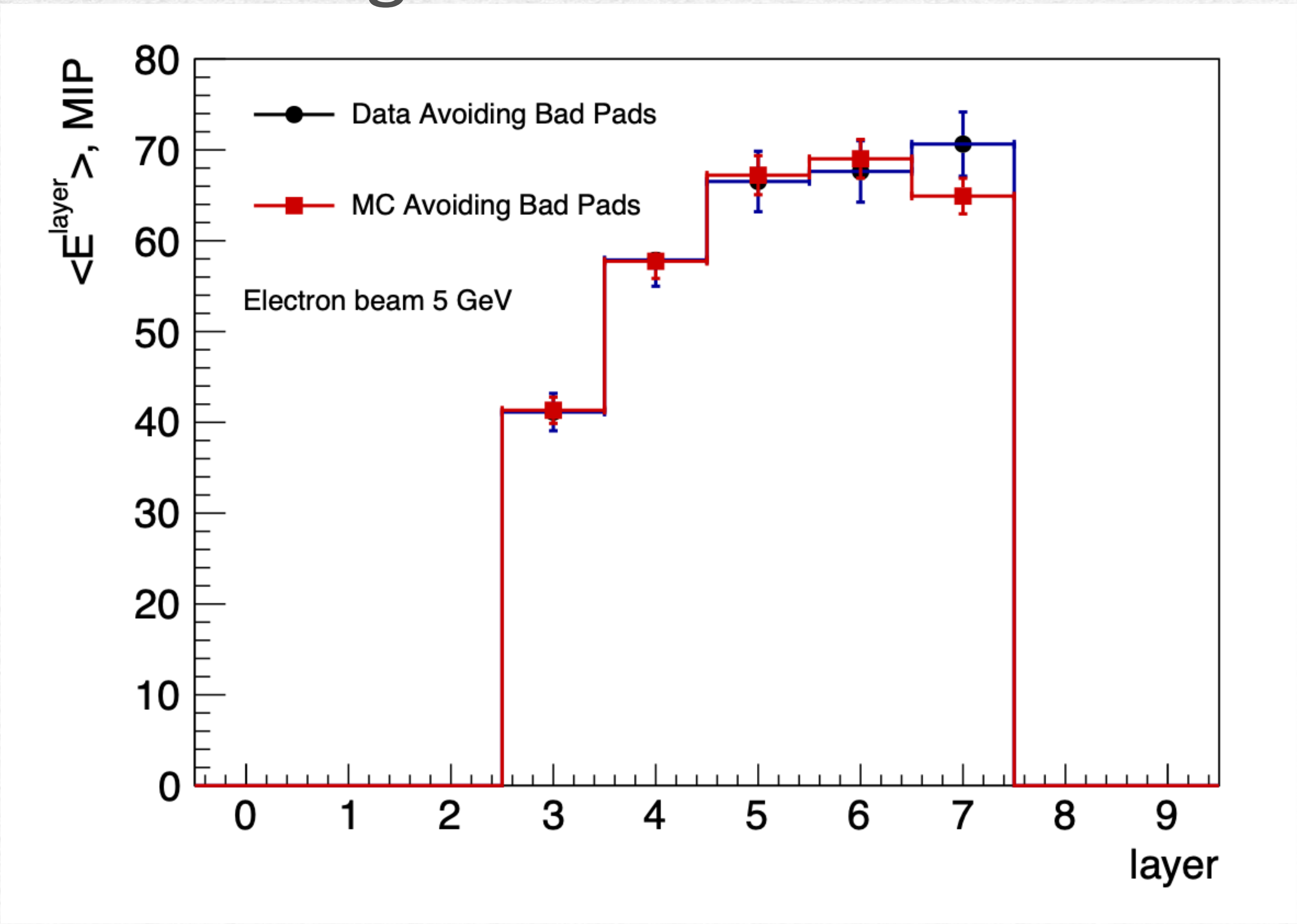
- 8 (256 channels) thin LumiCal modules (> 2k channels);
- 2 - used as a tracker / tagger for e/γ separation;
- 6 - in calorimeter (3 - 8 X0) installed in 1 mm gaps between absorbers;
- DAQ : SRS system, designed by RD51 collaboration;
- EUDET / AIDA beam Telescope : 6 planes with MIMOSA chip;



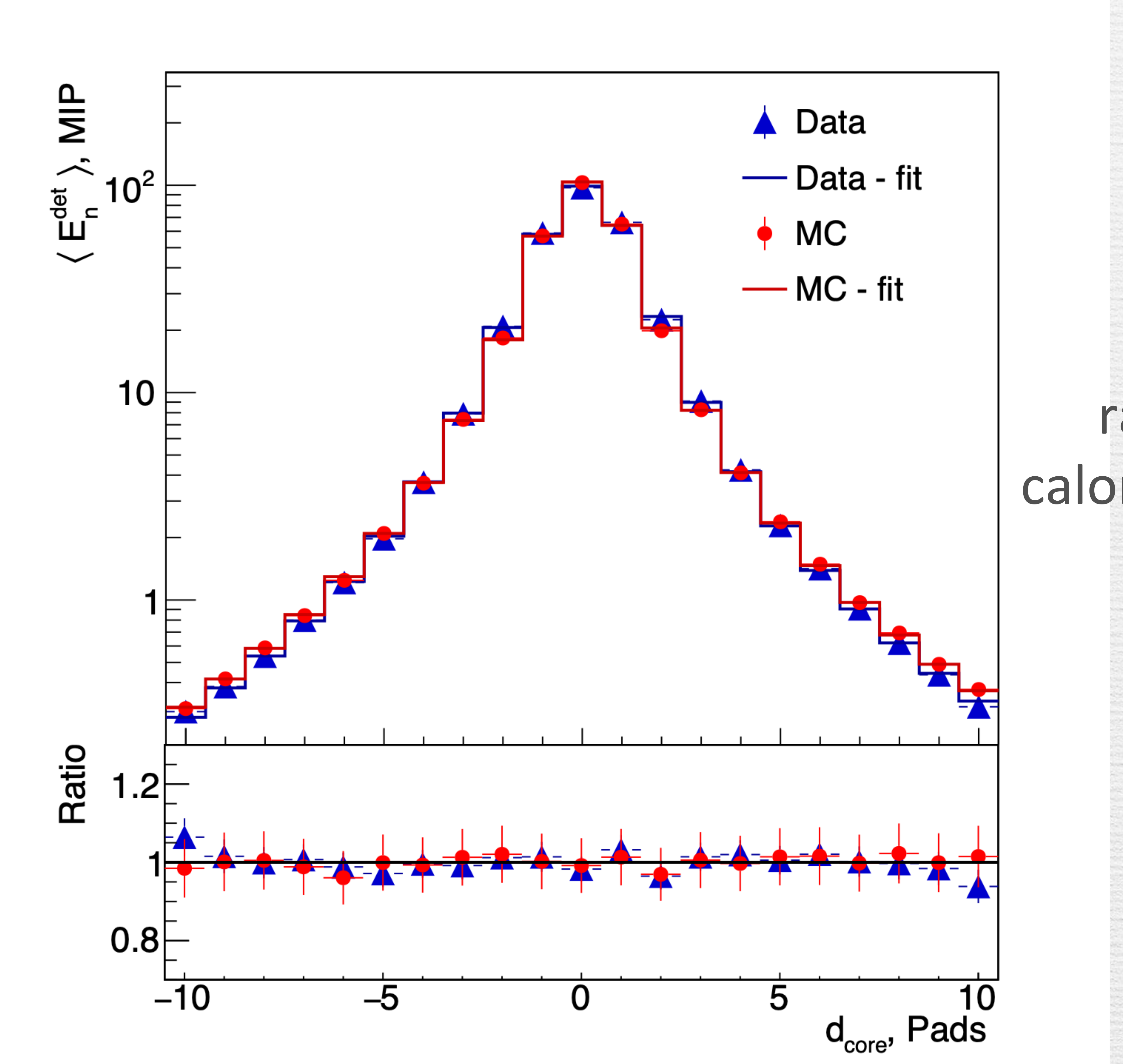
mechanical frame designed at CERN

Shower Study for 5 GeV electrons 2016 test beam

longitudinal shower



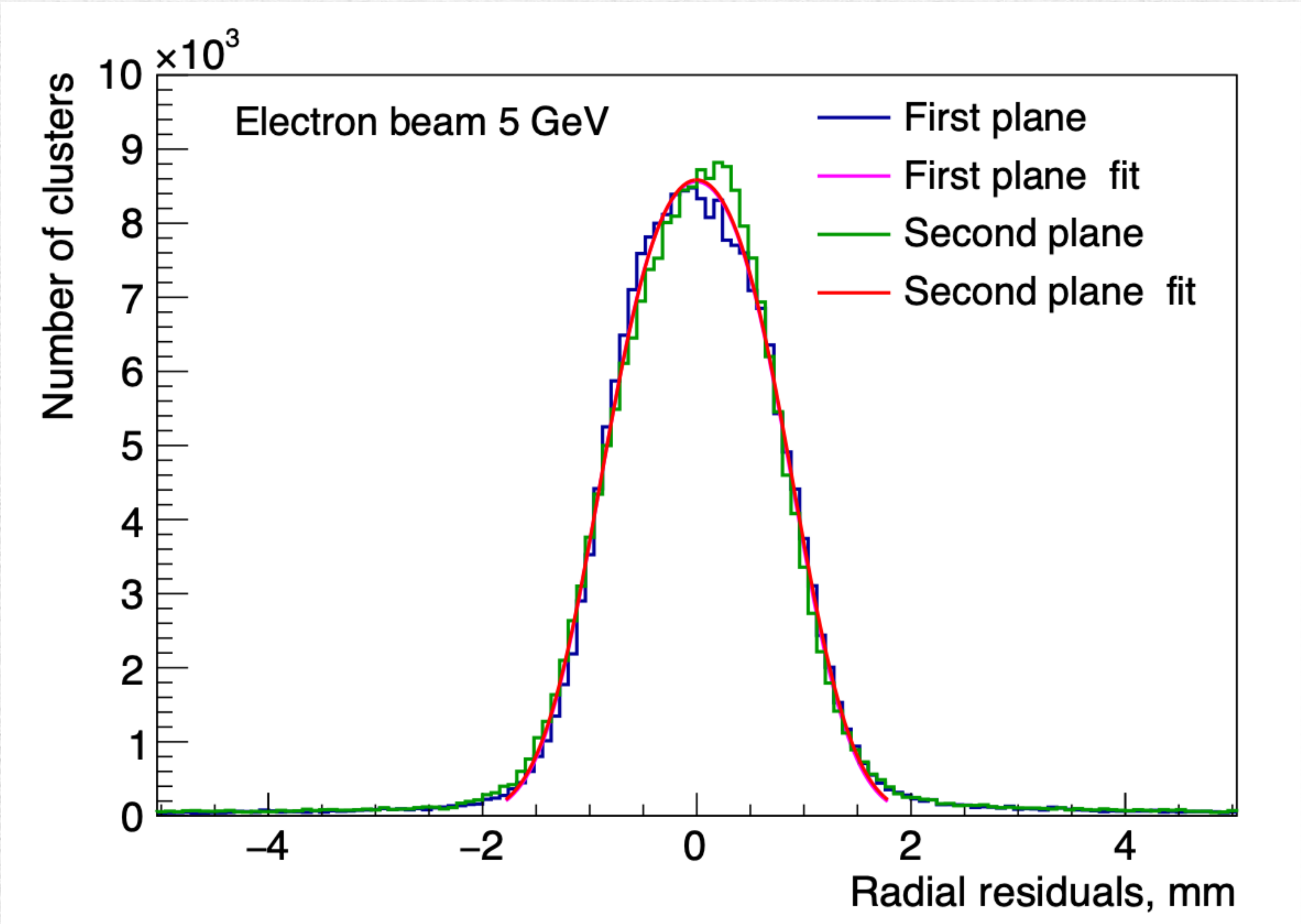
transverse shower



The measurement of the longitudinal and transverse shower size is in good agreement with simulations

The effective Molière radius is
8.1 ± 0.1 (stat) ± 0.3 (syst) mm

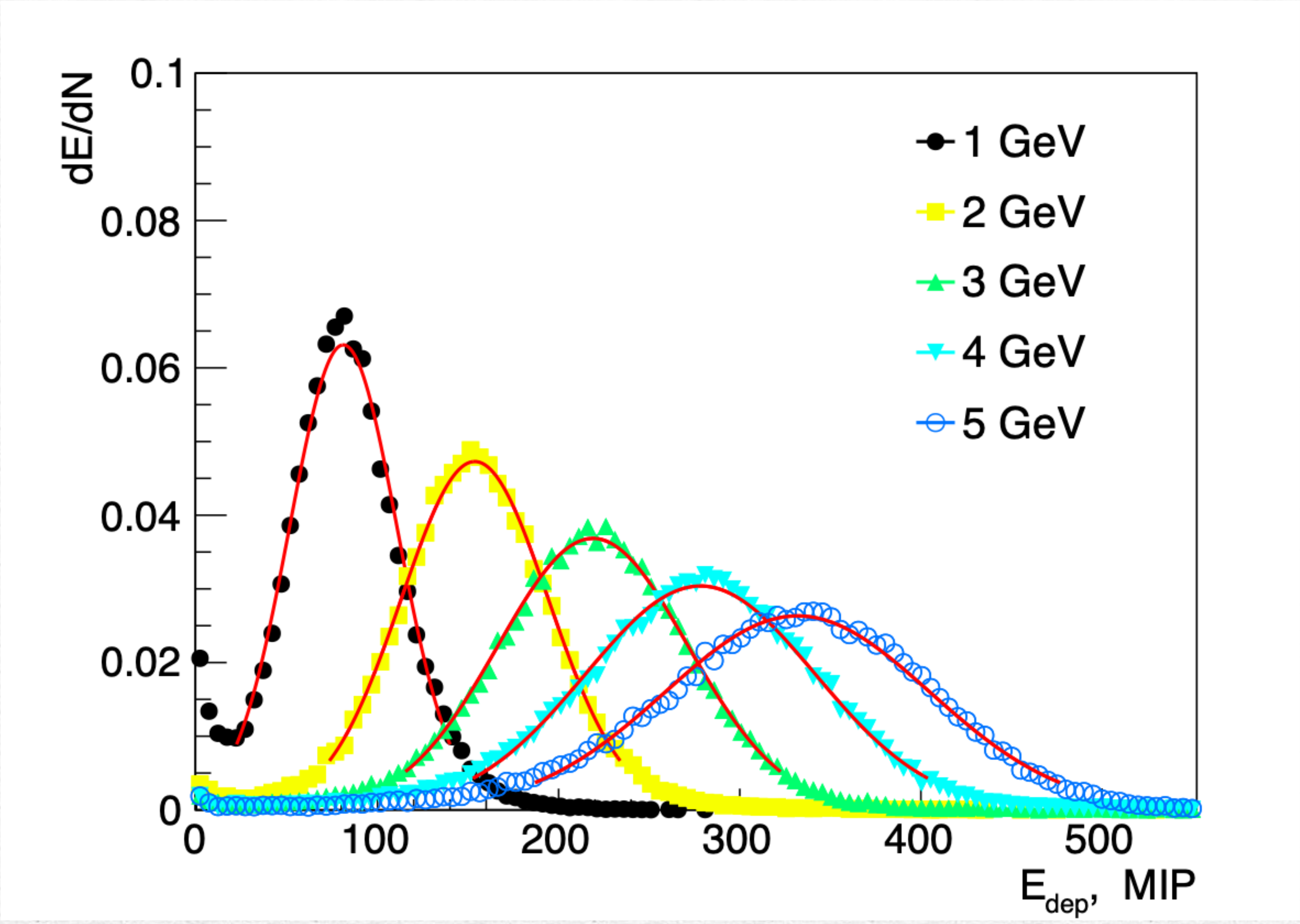
radial position residuals between the calorimeter and tracking planes



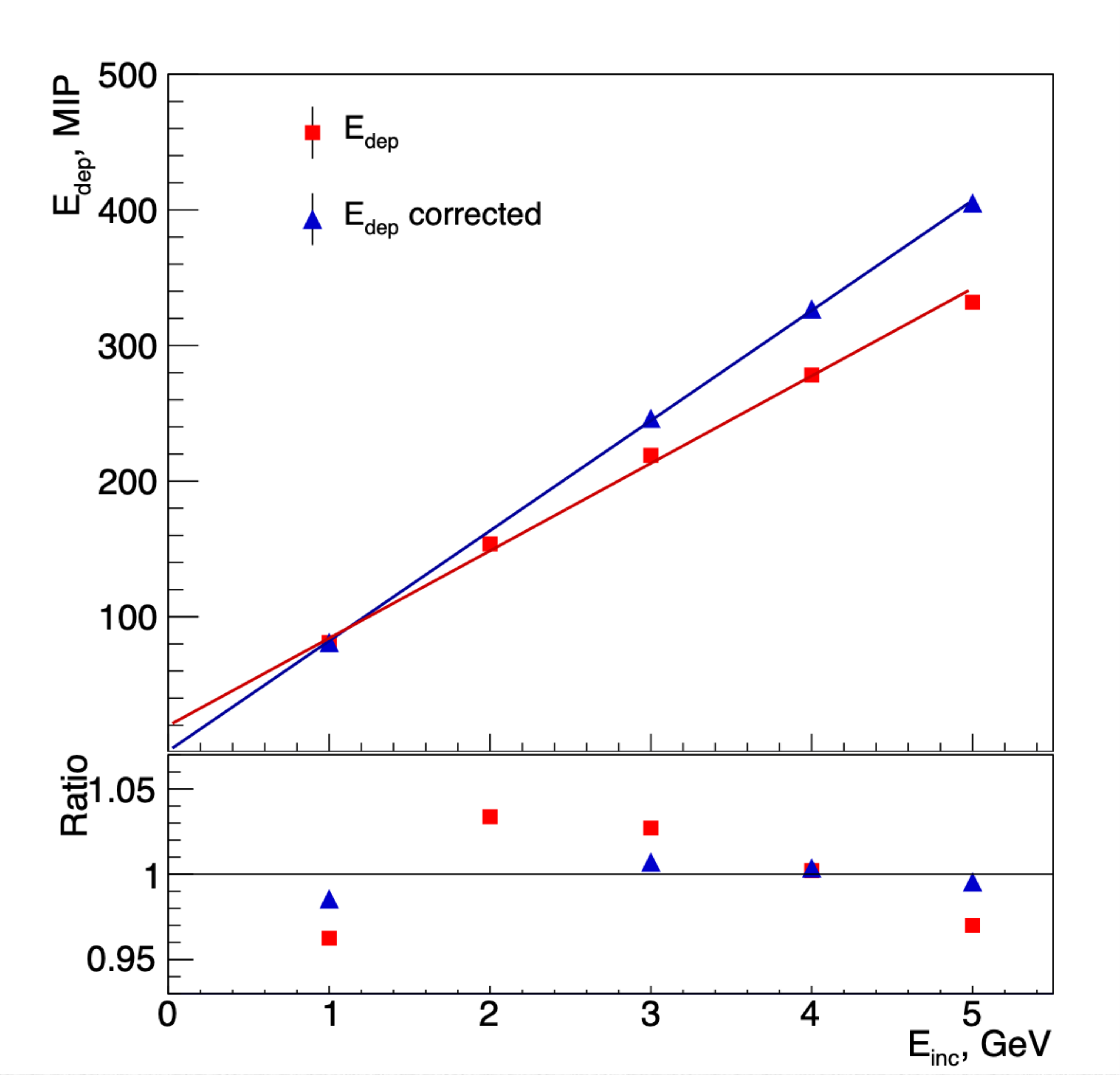
The resolution of the shower position reconstruction (440±20) μm

Eur.Phys.J. C79 (2019) no.7, 579

LumiCal Energy Response



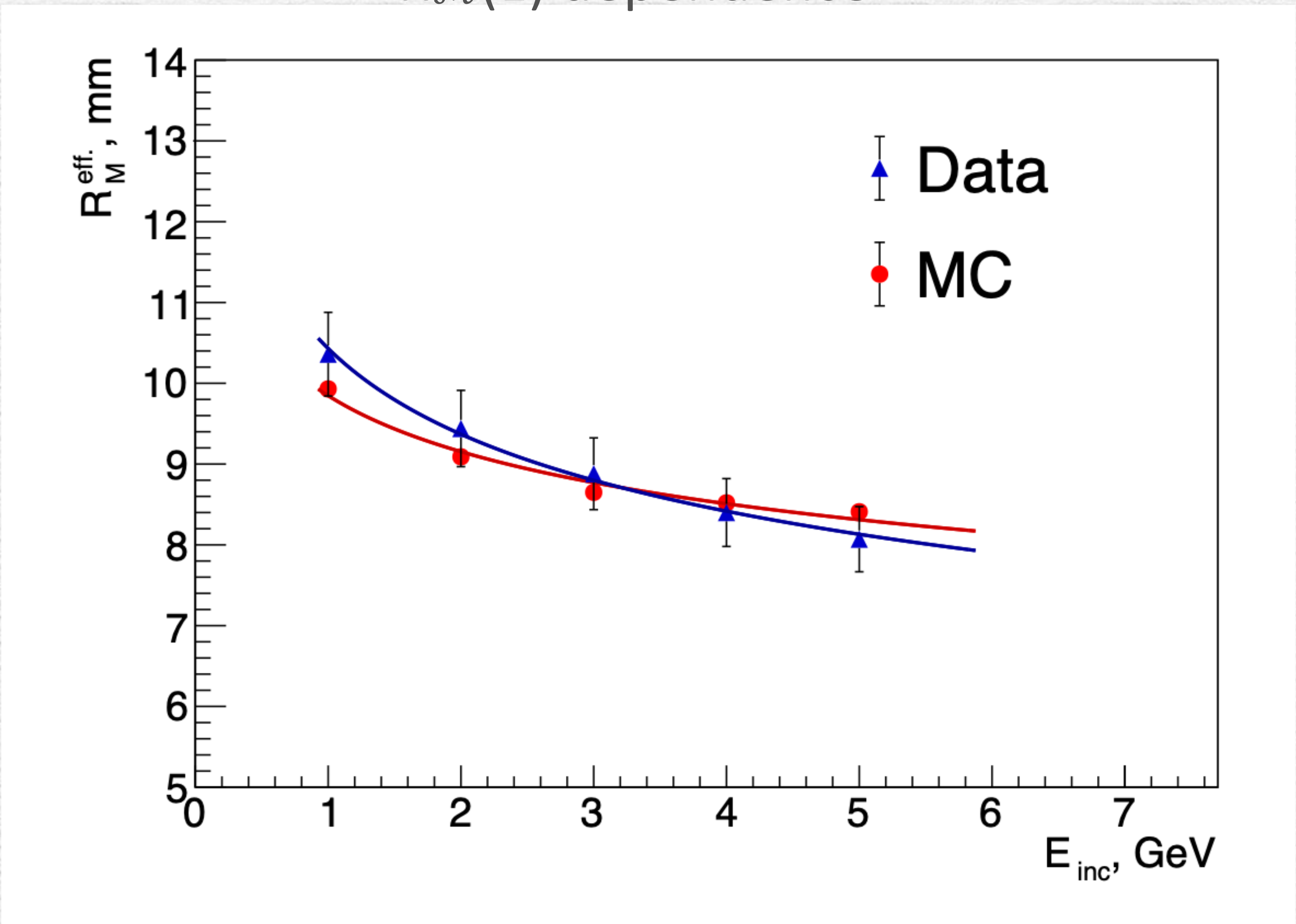
LumiCal prototype demonstrates good linear response to the beam of 1 – 5 GeV.



Small nonlinearity is explained by limited number of sensitive planes.

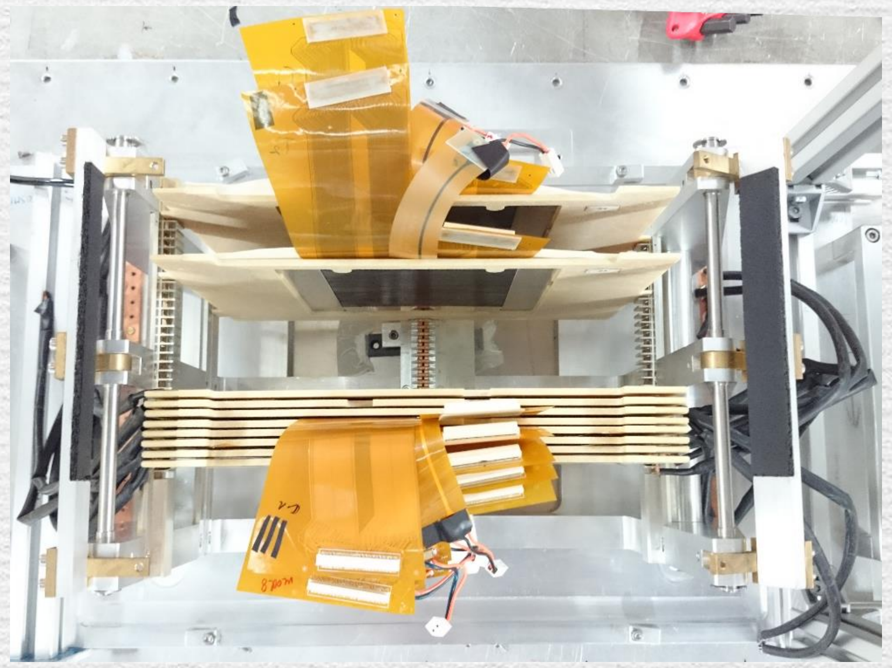
Tested and corrected in MC.

$R_{\mathcal{M}}$(E) dependence

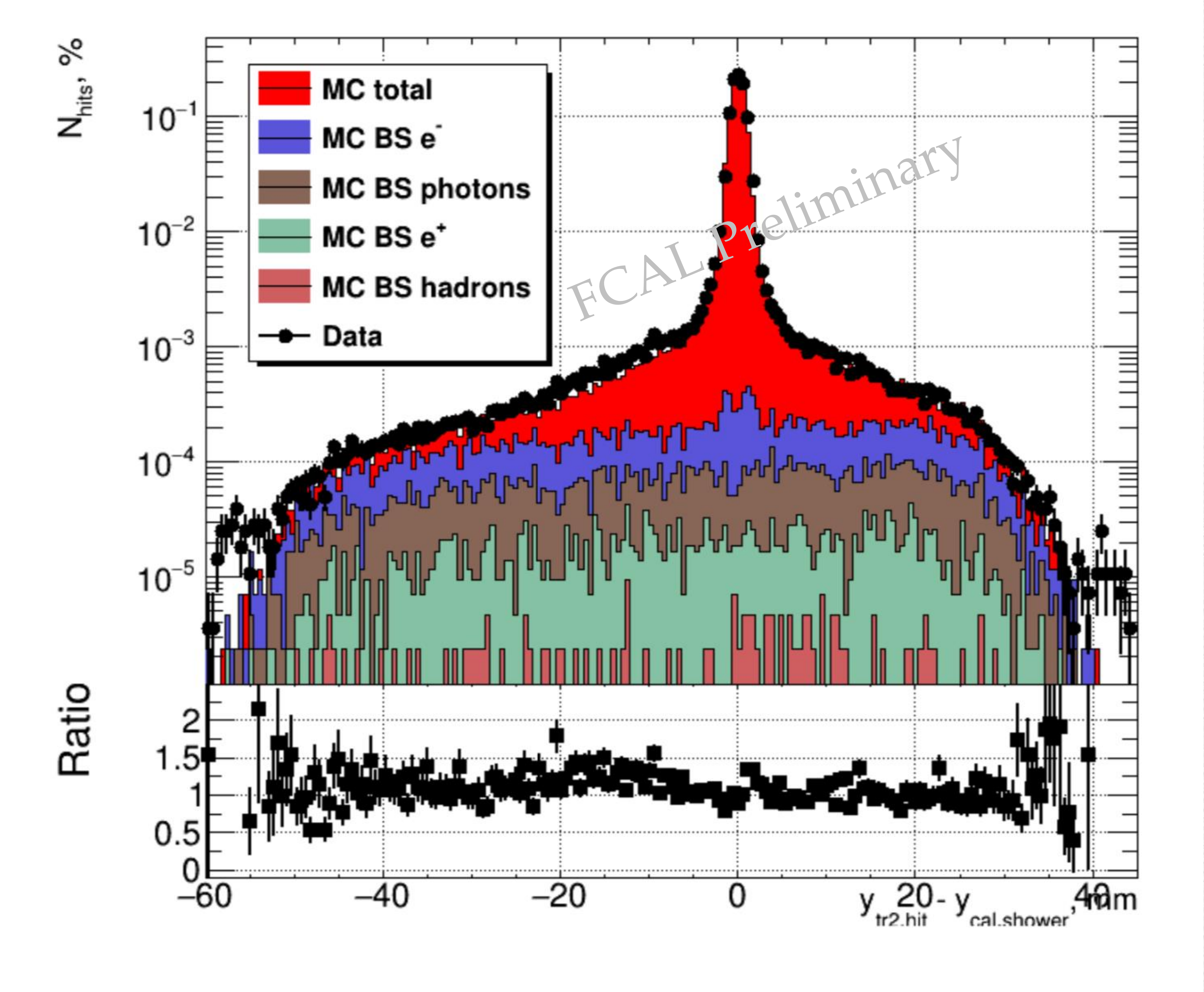


$R_{\mathcal{M}}$ shows slight dependence on E is explained by the fact that for higher energies smaller fraction of the shower is deposited in calorimeter with only 6 working layers

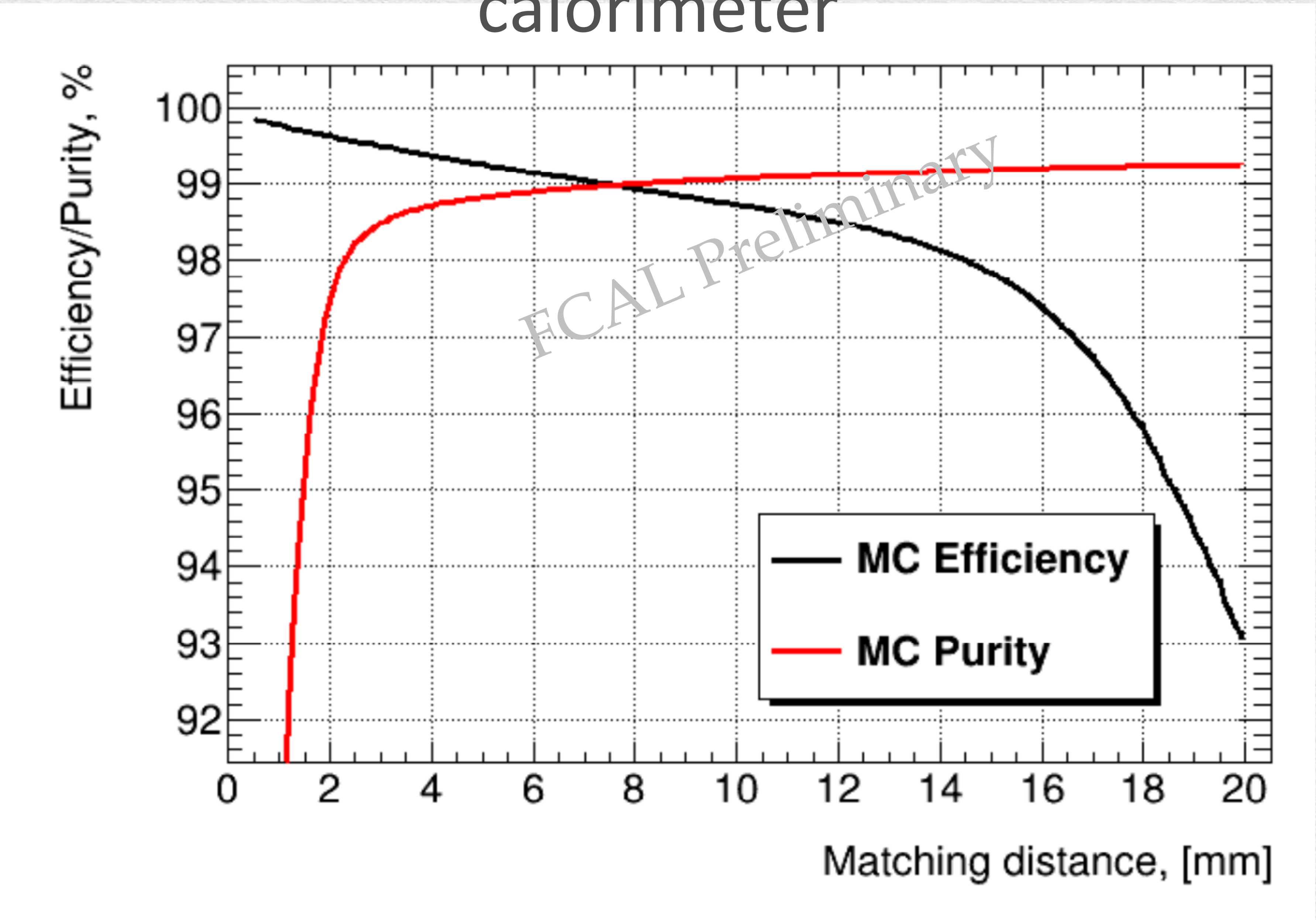
Electron-photon identification in tracking layers in front of LumiCal



The composition of back scatters observed in tracking planes



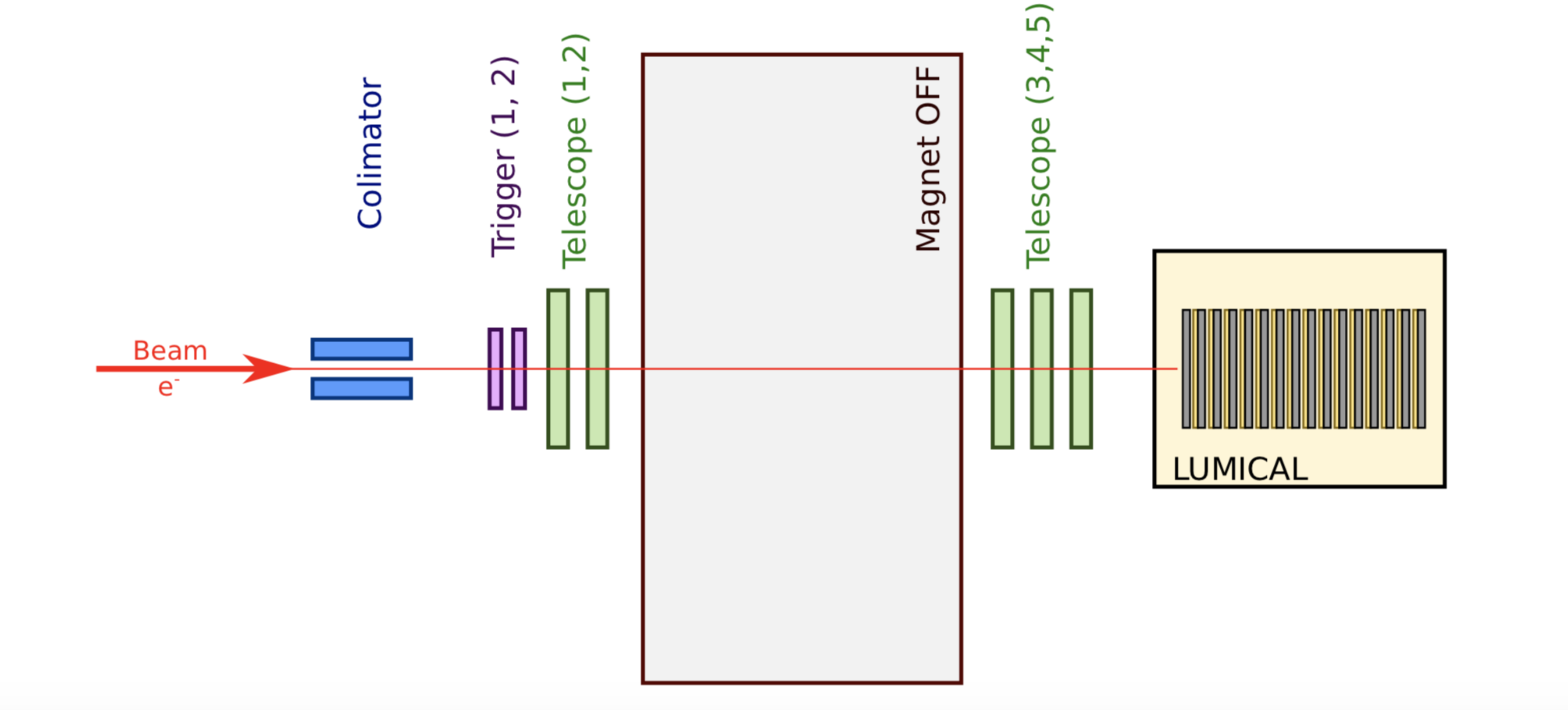
Efficiency and the purity of photon ID as a function of distance between the hits in tracking planes and shower position in calorimeter



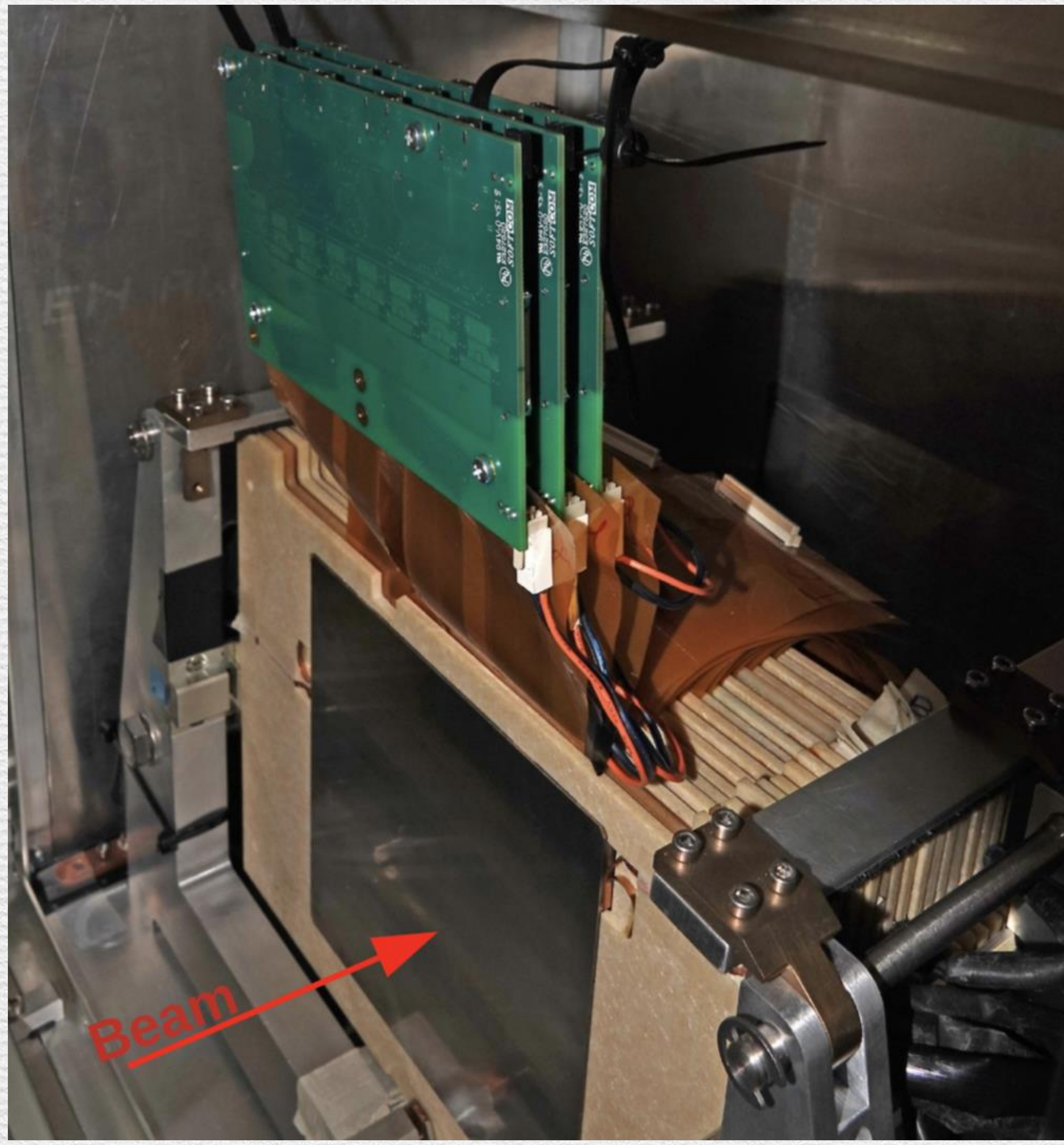
photon / electron identification efficiency more than 90% at 2.5 mm matching distance

This is still under study, adding to the MC the inefficiency of certain pads

2020 Test Beam Campaign at DESY



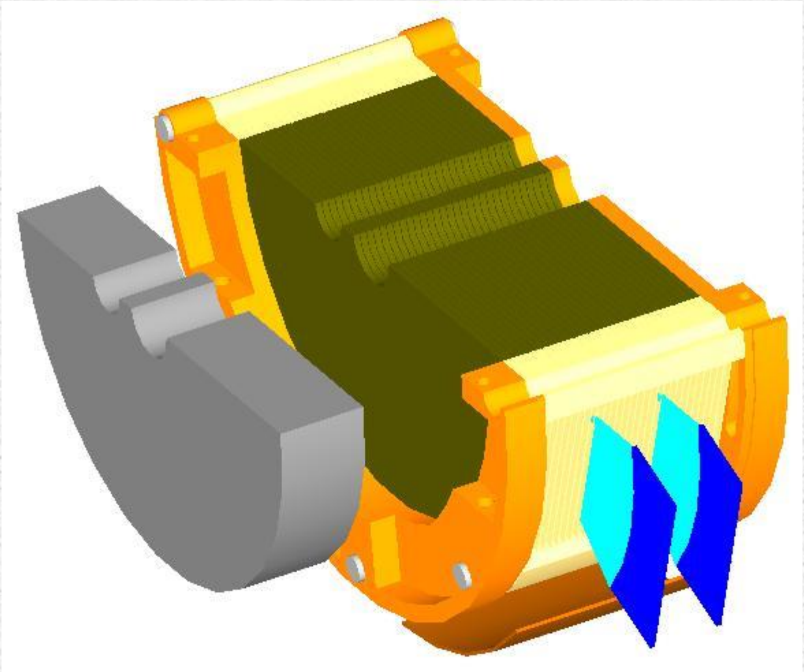
DESY test beam facilities:
- Electron beam 1 – 5 GeV;
- Dipole magnet 1 – 13 kGs;



- LumiCal prototype with 15 sensitive sensor layers
- 3 planes equipped with FLAME dedicated LumiCal Readout (Slides 23-24)
- Others - with double gain readout using APV25
- Edge scan for fiducial volume study
- Data collection with tilted calorimeter to study bias in position reconstruction
- Test electron/gamma response

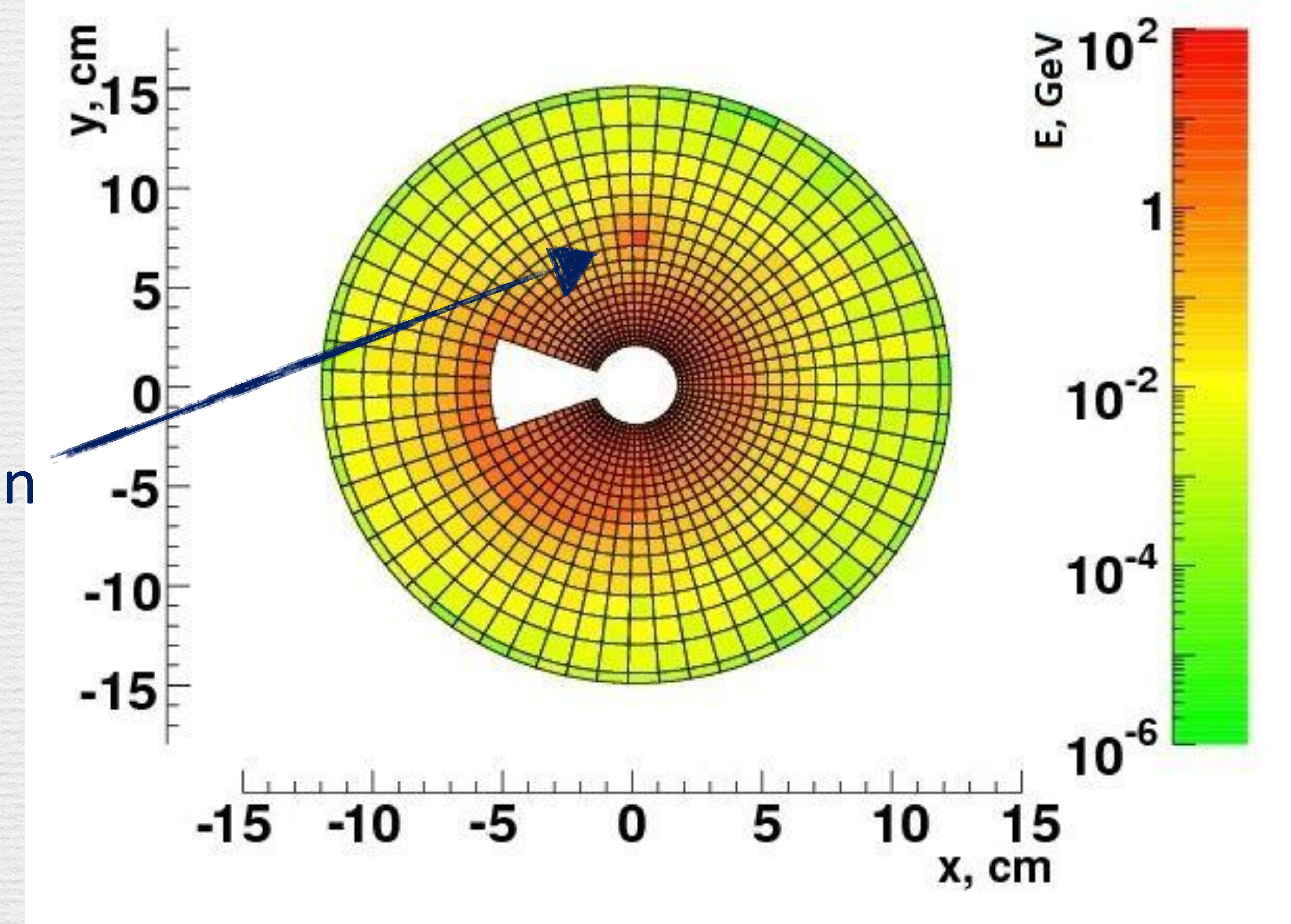
- Data Analysis is in progress….

BeamCal



Beamstrahlung at linear colliders (due to nm bunch sizes)

Low energy electron deposition per BX

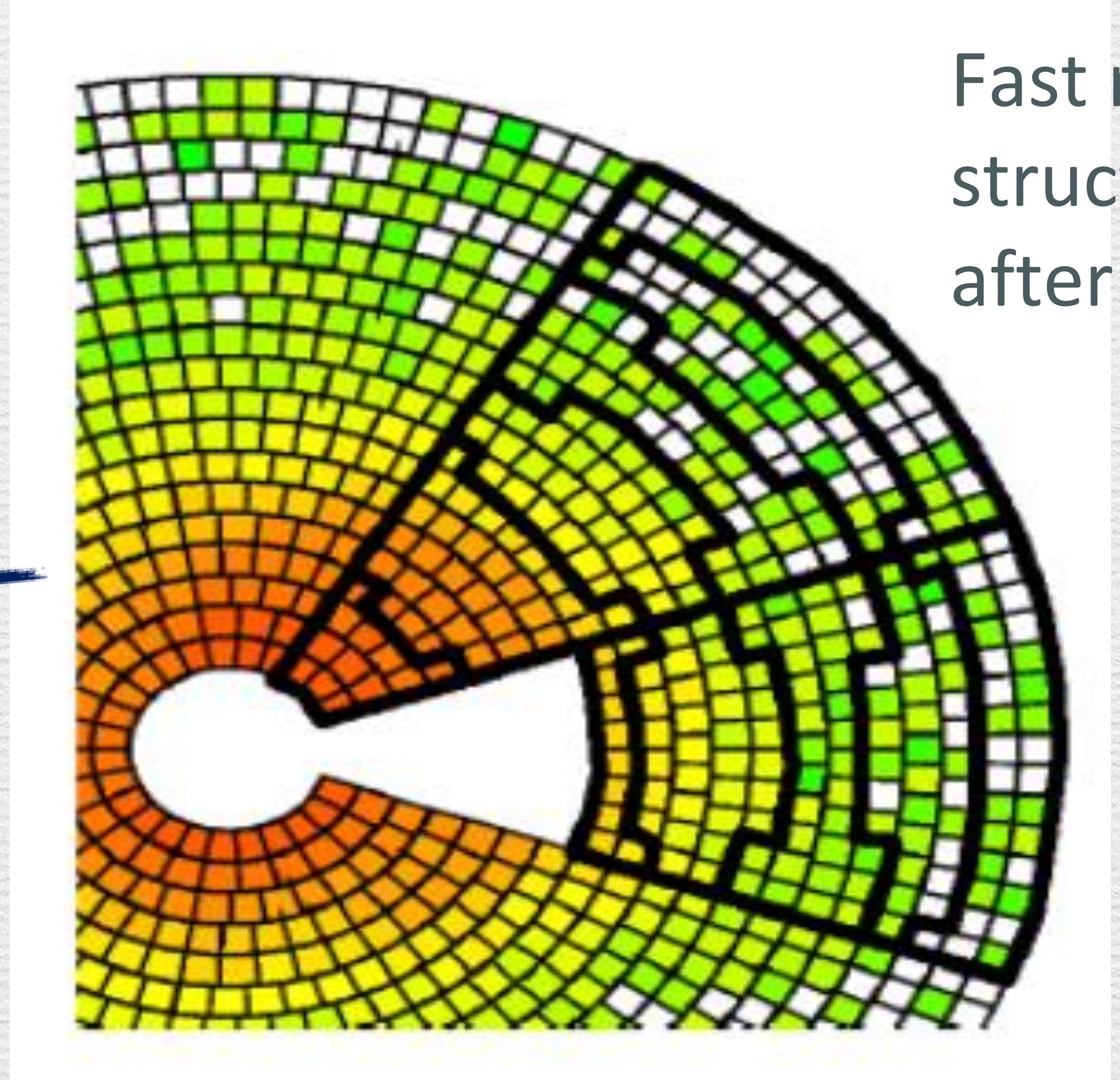


Single high energy electron

- Fast luminosity estimate using beamstrahlung (bunch-by-bunch at ILC)
- Beam parameter estimation
- Fast feedback to the machine
- Low angle electron tagging

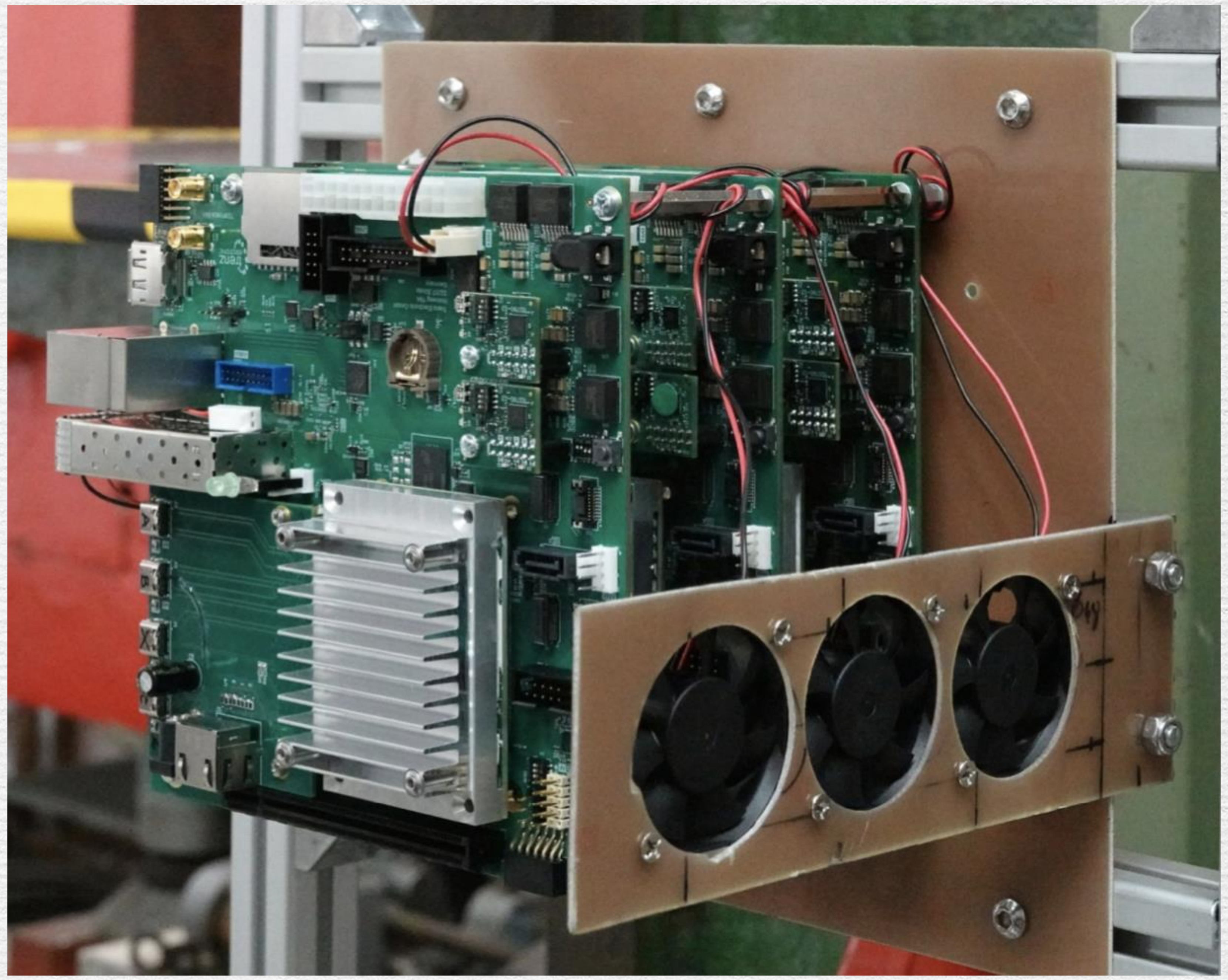
Beam parameters and luminosity measurement

beam parameter	unit	nom.	resolution, 14 mrad: no E_γ	resolution, 14 mrad: with E_γ
σ_x	nm	655.0	700. ± 49.	660. ± 43.
$\Delta\sigma_x$	nm	0.0	7. ± 30.	17. ± 20.
σ_y	nm	5.7	5.8 ± 7.1	5.1 ± 2.7
$\Delta\sigma_y$	nm	0.0	-0.53 ± 0.97	0.26 ± 0.80
σ_z	μm	300	331. ± 67.	295. ± 31.
$\Delta\sigma_z$	μm	0.0	3. ± 56.	4. ± 35.



Fast readout of structured areas after each BX

FLAME – in beam test 2020 at DESY

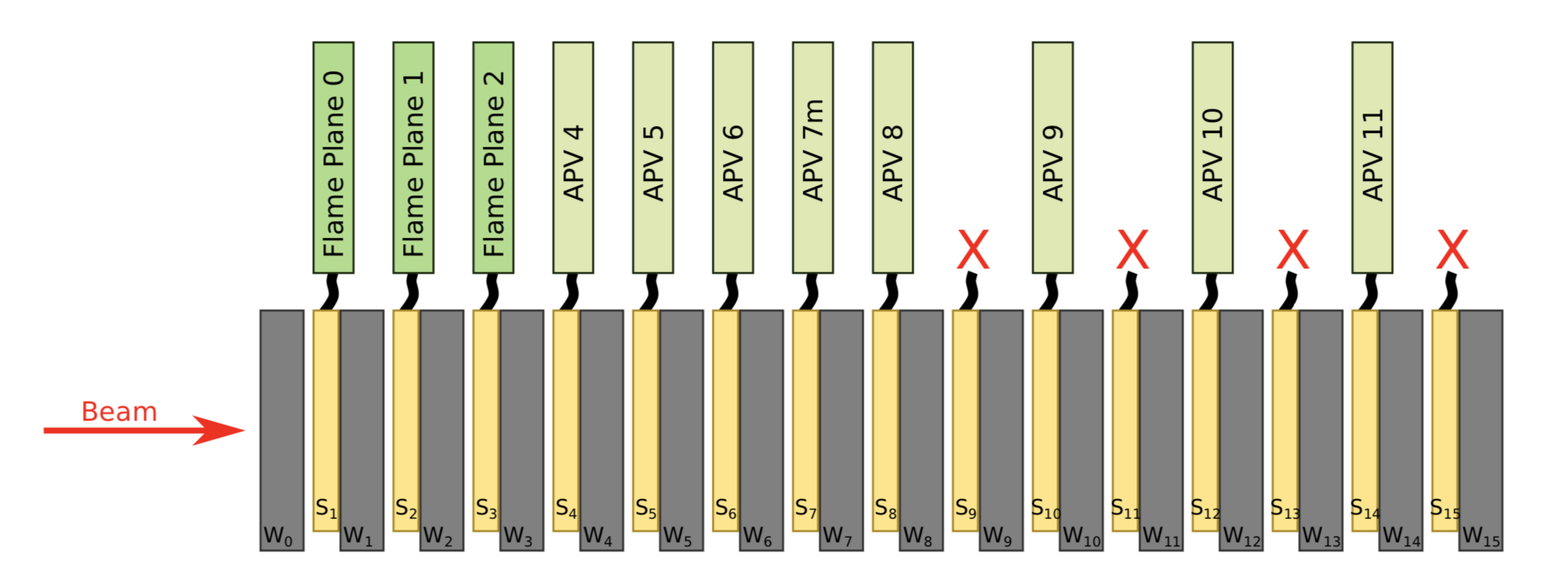


Analogue front-end comprising:

- Charge sensitive preamplifier with variable gain:
- High gain – for test beam - up to 200 fC with MIP sensitivity
- Low gain – for shower development (up to 6 pC)
- Differential CR-RC shaper with 50ns peaking time

10-bit multichannel SAR ADC

- Sampling rate up to 50 MSps
- DNL, INL < 0.5 LSB
- ENOB > 9.5
- Ultra low power consumption (below 1 mW per channel at 40 MSps)



- 3 complete readout cards with 128 channels each
- Stack (15 sensor layers (S1 - S15)) was scanned by connecting consecutively each three sensors

First Test-Drive was successful!