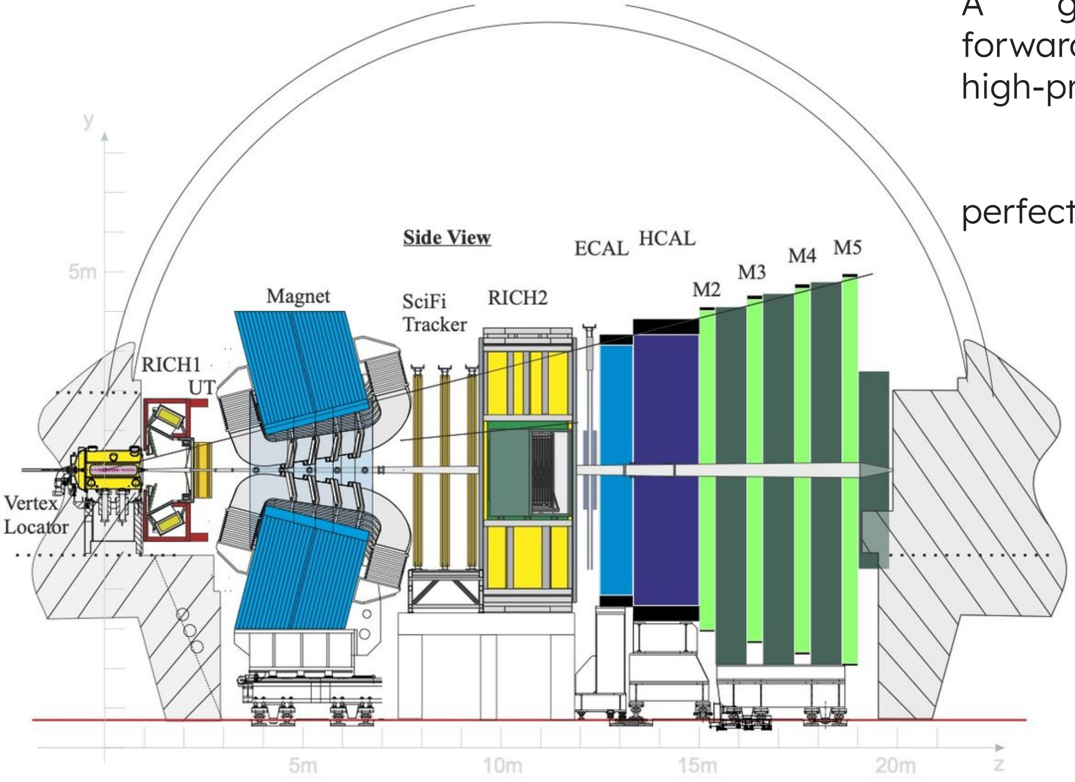
Scintillating sampling ECAL technology for the LHCb PicoCal

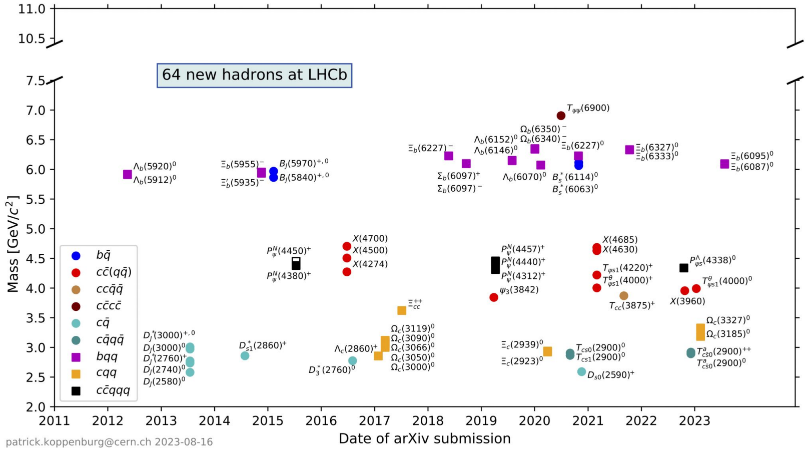
S. Kholodenko (INFN Pisa)
on behalf of the LHCb ECAL Upgrade II R&D group

LHCb experiment

A general purpose spectrometer in the forward direction. (2<η<5), optimized for high-precision heavy-flavor physics.

perfectly suited to to discover new quark bound states.



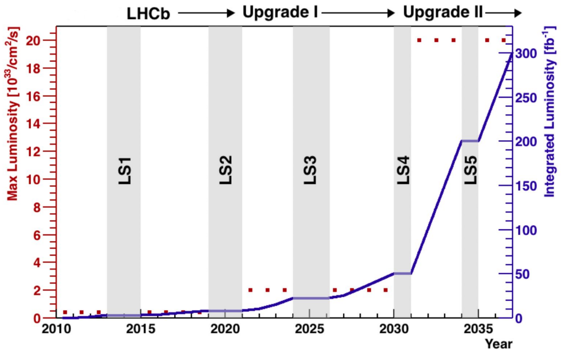


LHCb Detector performance: arXiv:1412.6352;

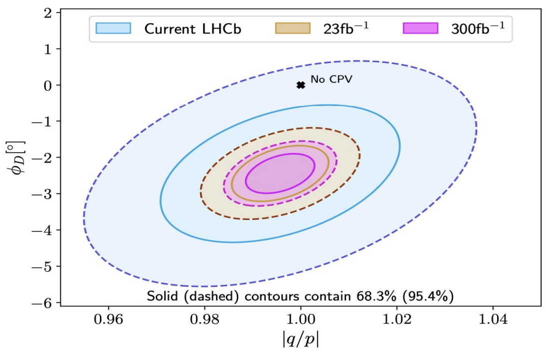
LHCb Upgrade 2 motivation

- A wide range of $\boldsymbol{b \to s\, l^+ l^-}$ and $\boldsymbol{b \to d\, l^+ l^-}$ transitions (many not accessible in the current configuration);
- Measurements of the CP-violating phases γ and ϕ_s with a precision of 0.4° and 3 mrad, respectively;
- Precise Measurement of $R \equiv B(B^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$;
- LFU (lepton flavour universality tests), exploiting the full range of b-hadrons;
- CP-violation studies in charm with 10^{-5} precision.

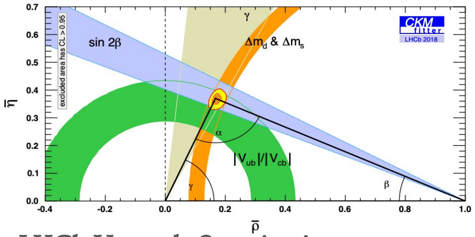
For more details please refer to the Andreas's talk



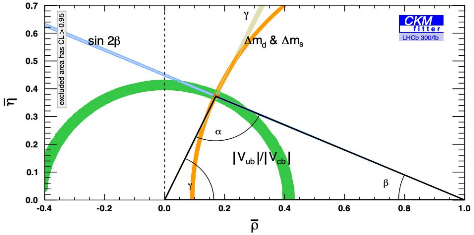
CP violation in charm mixing, |q/p| and ϕ_D.



Current limits



LHCb Upgrade 2 projection

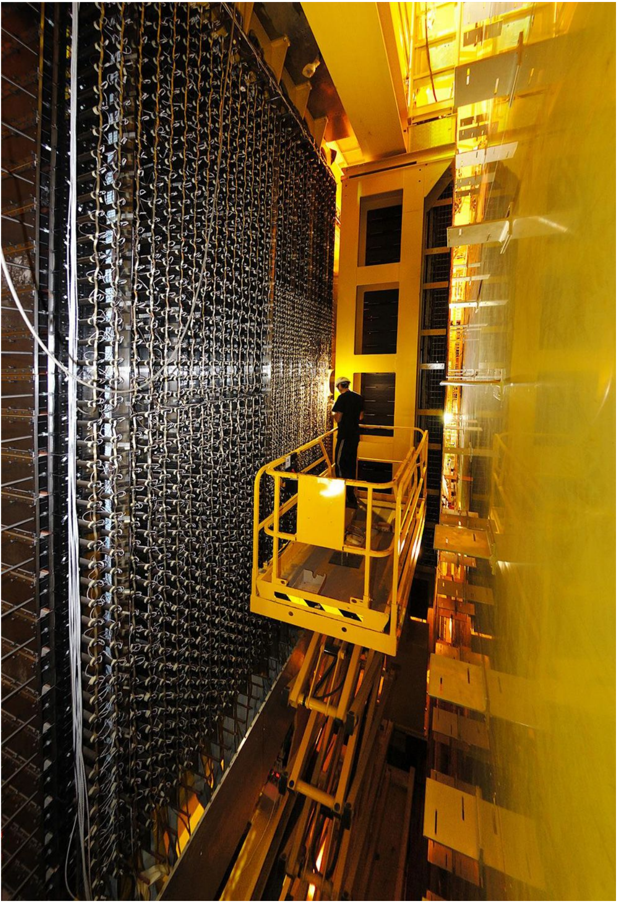


Physics case for an LHCb Upgrade II, https://cds.cern.ch/record/2636441

Framework TDR for the LHCb Upgrade II. https://cds.cern.ch/record/2776420

LHCb Particle Identification Enhancement TDR https://cds.cern.ch/record/2866493

Current ECAL



Shashlik technology:
- 4 mm scintillator tiles,
- 2 mm thick lead plates.

Modules:
- XY dimensions: 121.2 x 121.2 mm^2,
- 66 layers of Pb + 67 scintillator tiles.
- ∅1.2 mm Y11 (250) WLS-fibres.

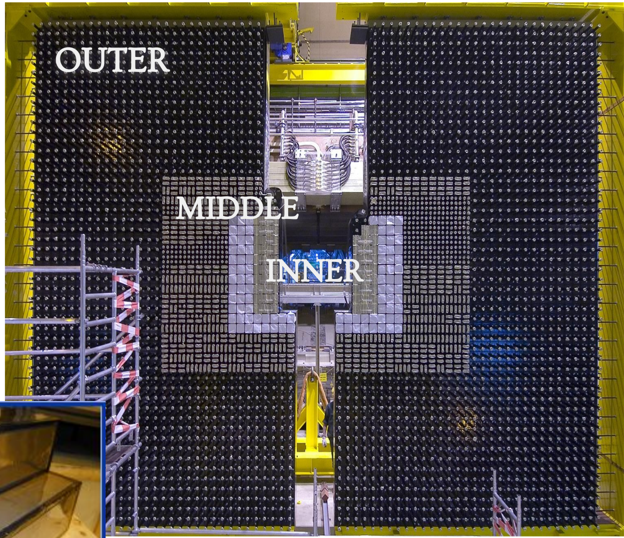
Three zones in granularity
- Inner (9 cells/module),
- Middle (4) and Outer (1)

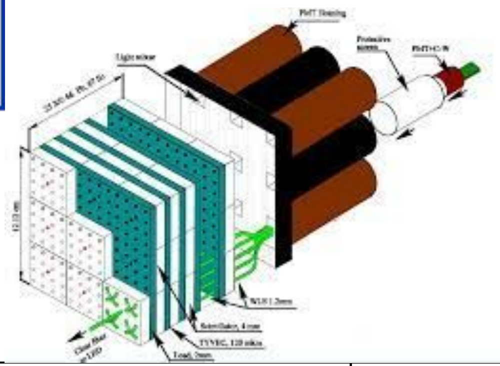
Total:
- 3312 modules,
- 6016 cells, 7.7 x 6.3 m2.

Readout PMT R7899-20;
HV: individual Cockcroft-Walton circuit

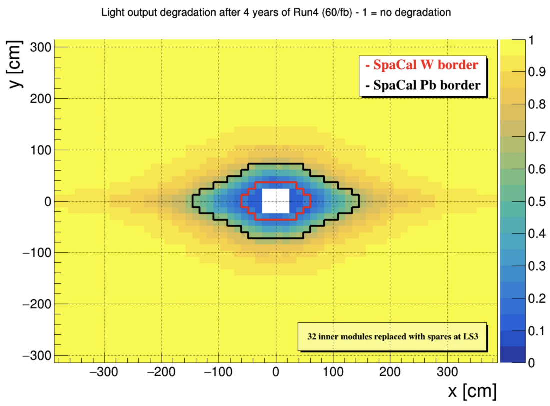
Light yield: ~ 3000 ph.e. / GeV

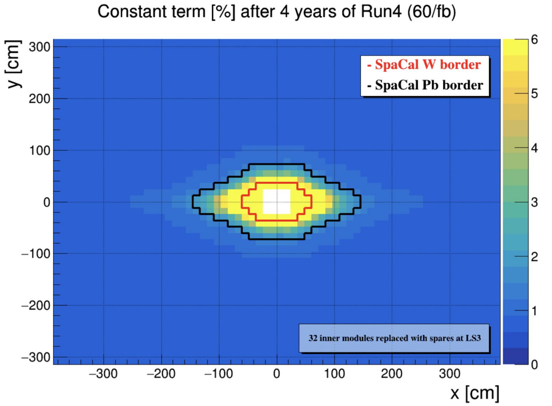
Energy resolution: $\frac{\sigma_E}{E} = \frac{(8.2 \div 9.4)\%}{\sqrt{E}} \oplus 0.9\%$





ECAL performance extrapolated to the end of Run 4





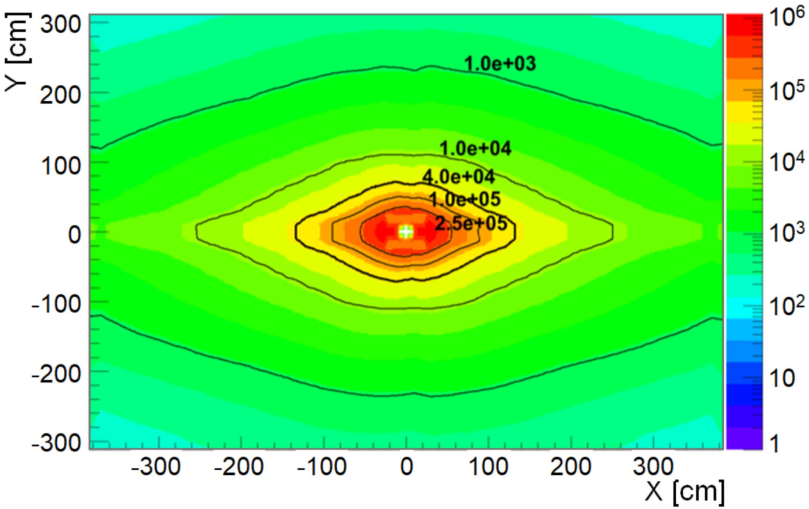
Degradation of the calorimeter performance due to radiation damage in particular in the innermost section of the ECAL.

The degradation of light output at the end of Run 4 for the current ECAL configuration
(assuming 32 innermost modules would be replaced by spares during LS3).

The reduced light output would lead to a significant degradation in the ECAL energy resolution.

ECAL Upgrade 2 requirements

Accumulated radiation dose [Gy] after 300 fb−1



Requirements for the Upgrade II (operation at up to 1.5 x 10^{34} $cm^{-2}s^{-1}$):

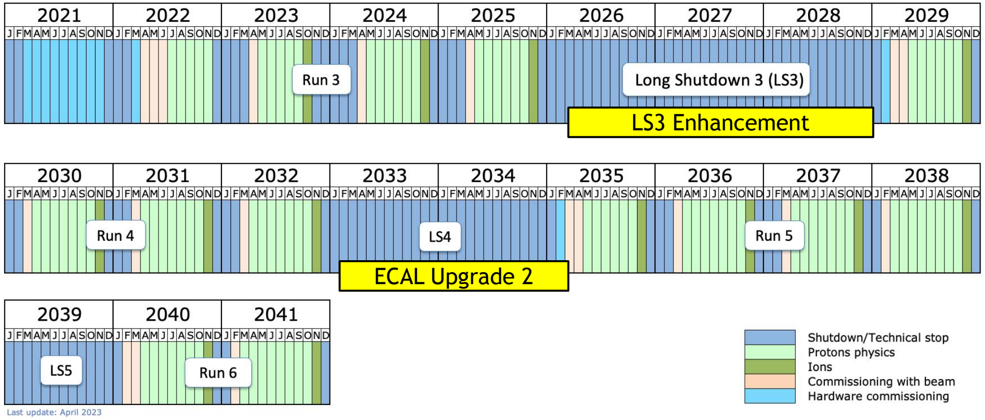
- Sustain radiation doses up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq / cm^2 in the centre
- Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E}\ 1\%$
- Pile-up mitigation crucial
  - → Timing capabilities with O(10) ps precision
  - → Increased granularity in the central region (denser material)
- Better time resolution, less impact of radiation damage, more information for event reconstruction and PID from longitudinal segmentation

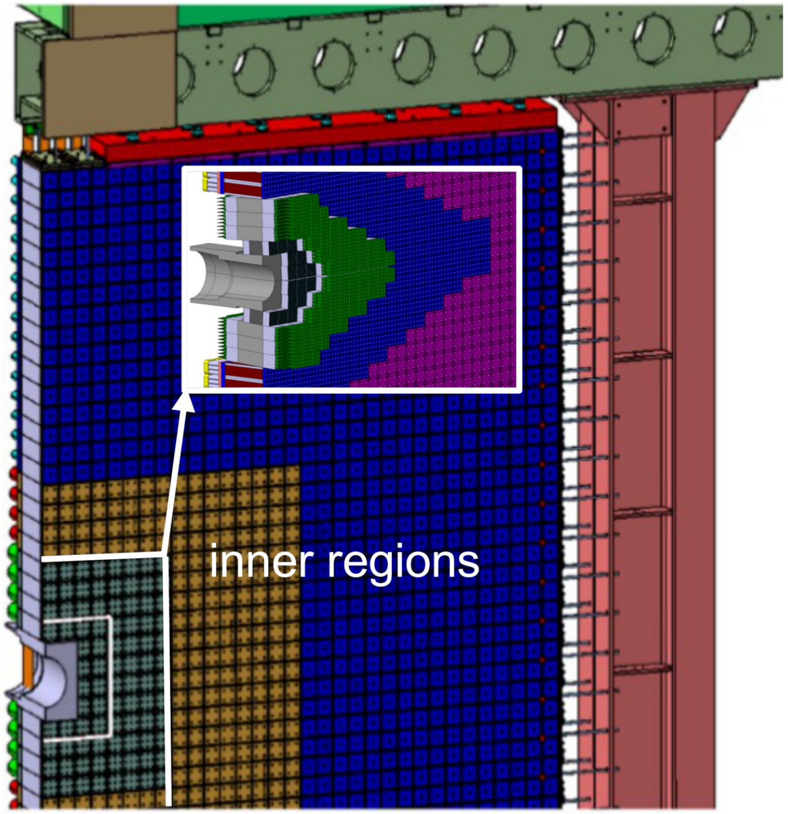
LHCb ECAL upgrade strategy

Run 3 in 2022-2025:
Run with unmodified ECAL Shashlik modules at L = 2 x 10^{33} $cm^{-2}s^{-1}$
(new 40 MHz readout)

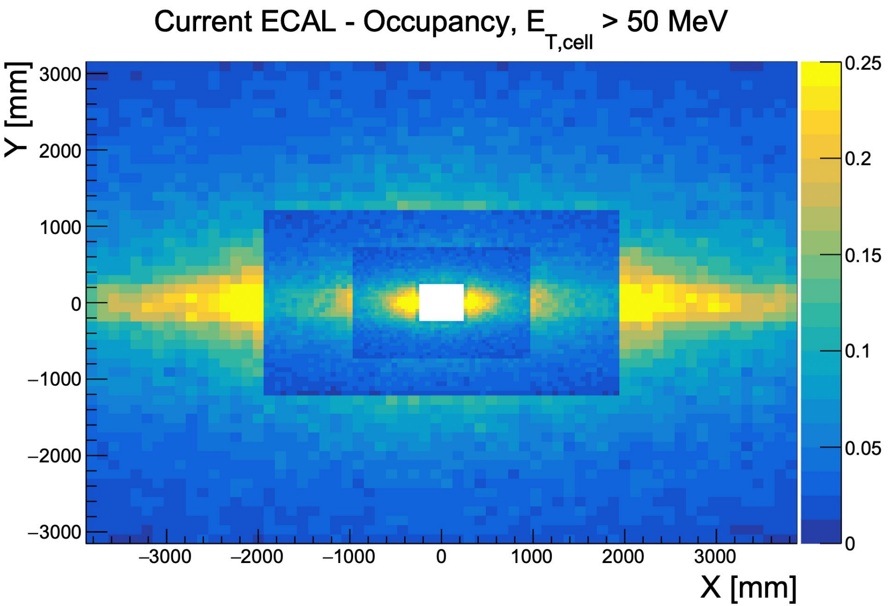
LS3 enhancement in 2026-2028 (TDR approved):
Replacing inner region with Spaghetti type modules (SpaCal) (2x2 and 3x3 cm^2 cells)
+ rebuilt ECAL regions to rhombic shape to improve performance at L = 2(4) x 10^{33} $cm^{-2}s^{-1}$
→ 32 SpaCal-W & 144 SpaCal-Pb modules with plastic fibres compliant with Upgrade II conditions

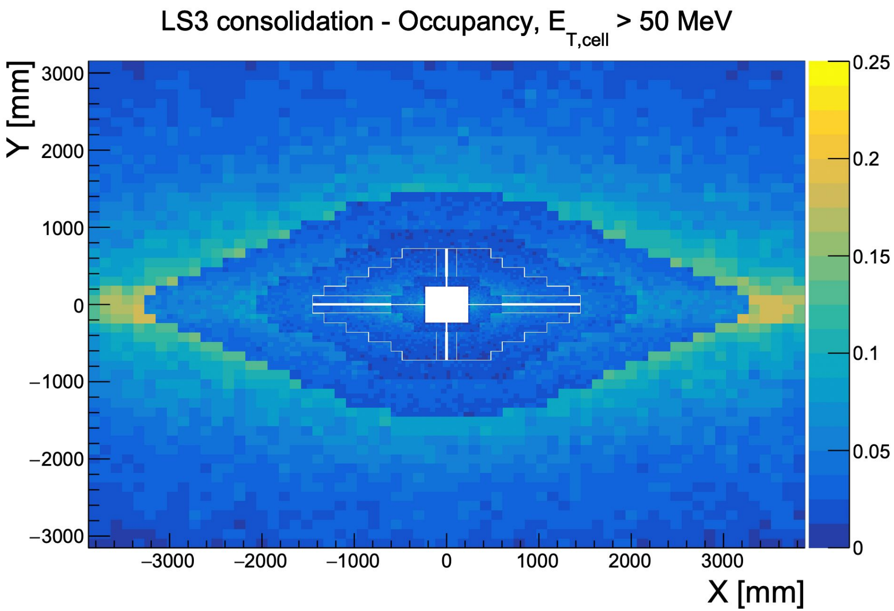
LS4 Upgrade II in 2033/2034:
Introduce double-section radiation hard SpaCal (1.5x1.5 & 3x3 cm2 cells) and improve timing of Shashlik modules for a luminosity of up to L = 1.5 x 10^{34} $cm^{-2}s^{-1}$
→ Innermost SpaCal-W modules equipped with crystal fibres
→ Include timing information and double-sided readout to full ECAL for pile-up mitigation





Run 4 occupancy

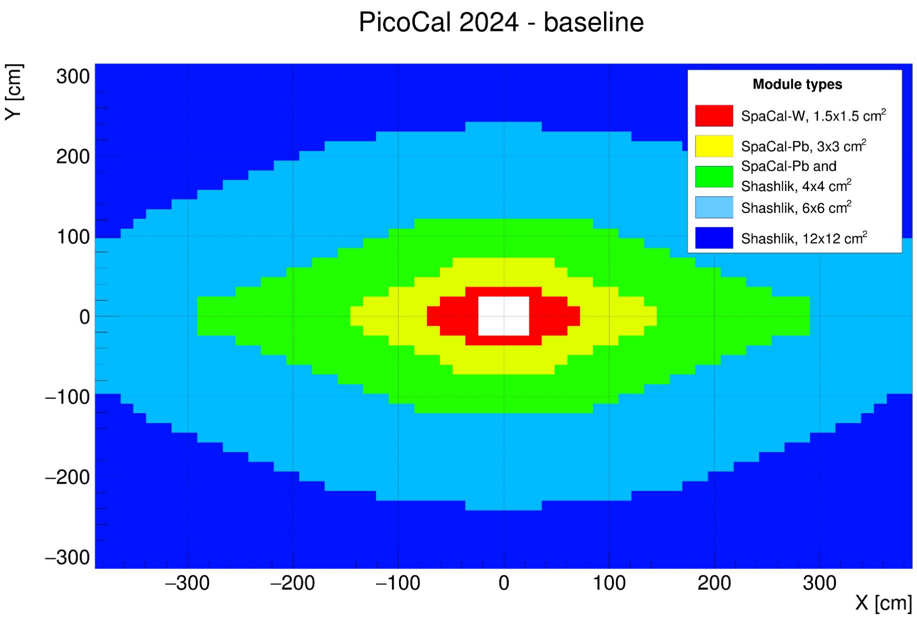




Simulated occupancy per cell assuming a luminosity of 2×10^{33} cm^{-2} s^{-1} in the current ECAL (left), and in the proposed configuration to be installed during the LS3 (right).

Note: SpaCal modules are inclined by 3+3 degree

Run5/6 baseline configuration



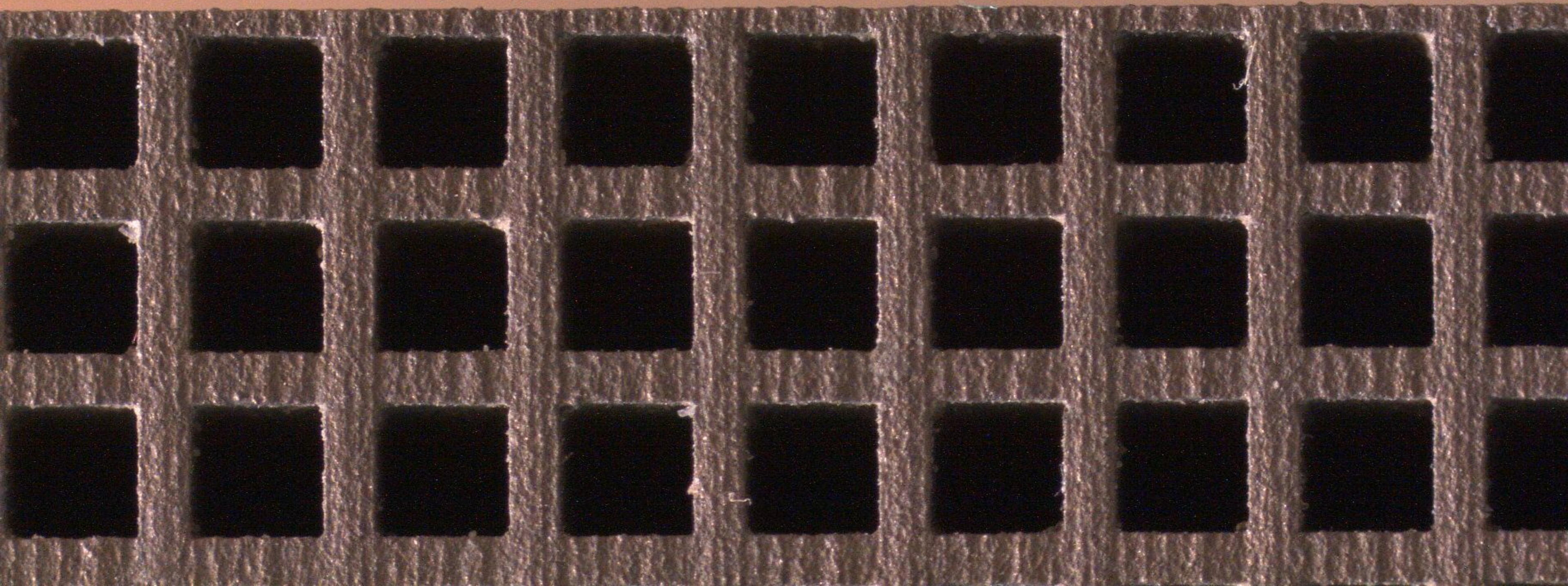
Cell size:	Modules:
1.5 x 1.5 cm2	40 SpaCal-W modules
3 x 3 cm2	136 SpaCal-Pb modules
4 x 4 cm2	272 SpaCal-Pb modules + 176 refurbished Shashlik modules
6 x 6 cm2	448 refurbished Shashlik modules + 896 rebuilt Shashlik modules
12 x 12 cm2	1344 refurbished Shashlik modules

Double-sided readout: 30’976 electronics channels

Refurbished Shashlik modules:
 new fast WLS fibres for better timing

Rebuilt Shashlik modules:
 new scintillator tiles for smaller cell size
 new fast WLS fibres for better timing

Module description



SpaCal modules

Installation	LS3	LS4	LS3/LS4
Aborber	3d-printed W		Lead (Pb)
Fibre type	Polystyrene	GAGG	Polystyrene
Cell size [mm^2]	20 x 20	15 x 15	30 x 30
Molière radius [mm]	18	14.6	~30
Radiation length [mm]	7.2	6.2	~10
Segmentation [mm]	190	45 + 105	290 / 80+210

Three module types:
Polystyrene fibres replaced by GAGG in W absorber during LS4
Long.segmentation during LS4
Absorbers produced for LS3 fully reusable during LS4

SpaCal-W + crystal fibres

SpaCal prototype module with W absorber and garnet crystal fibres:

- Pure tungsten absorber
- 9 cells of 1.5x1.5 cm2 (RM ≈ 1.45 cm)
- 7+18 X0 long segm.
- Reflective mirror between sections

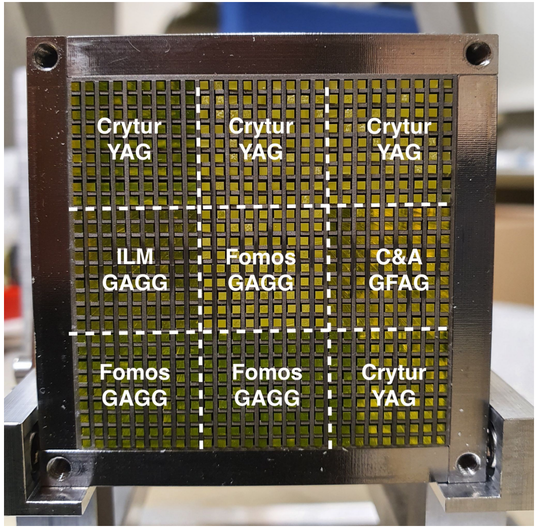
Crystal garnets from several producers:

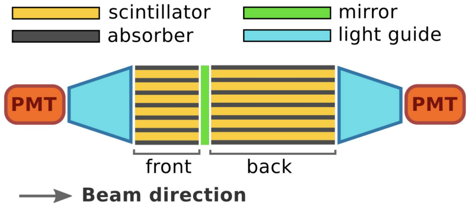
- Crytur - YAG
- Fomos - GAGG
- ILM - GAGG
- C&A - GFAG

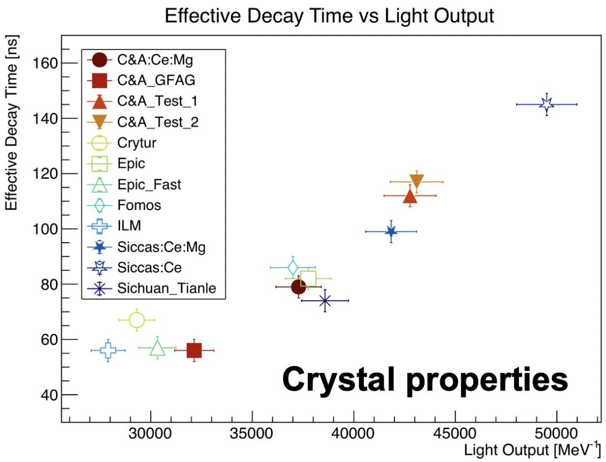
→ Characterised with laboratory measurements

Photon detectors used:

- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 for time resolution

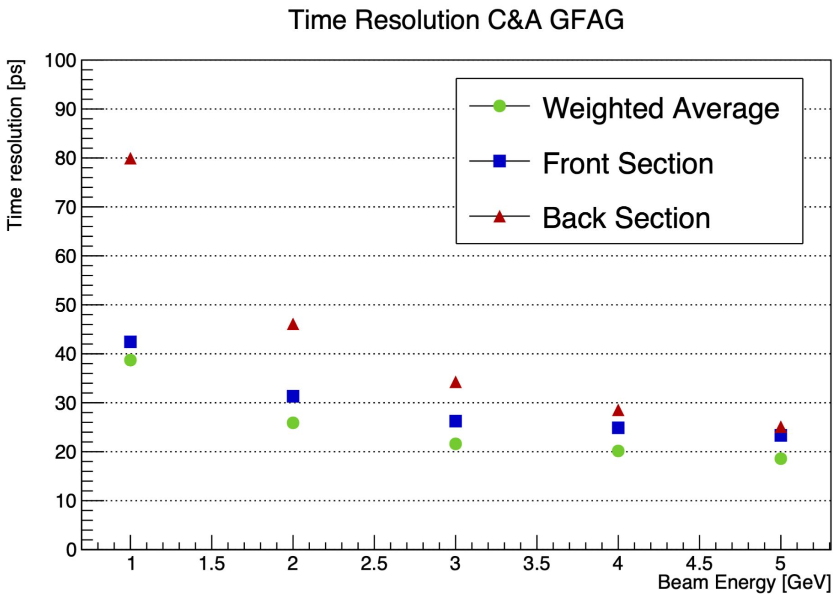


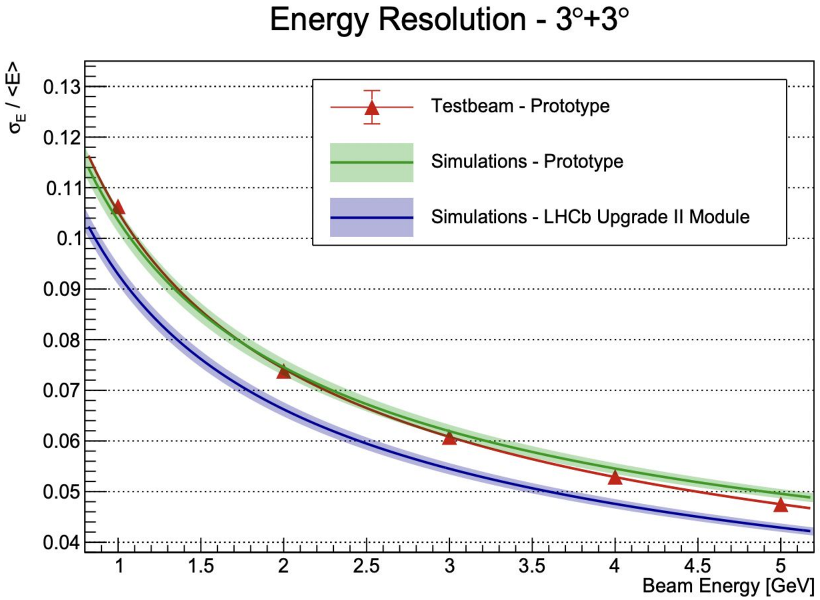




NIM A 1000, 165231 (2021)

SpaCal-W + crystal fibres (2)



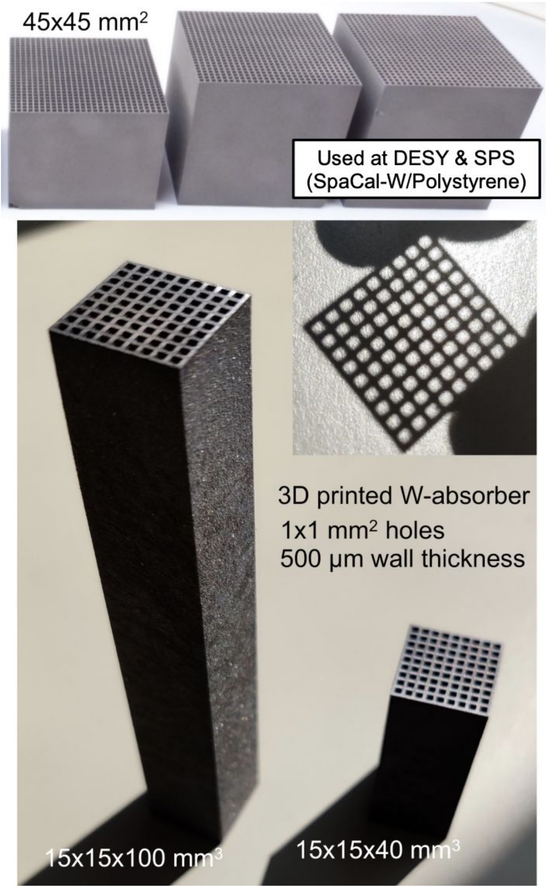


- Incidence angles: $\theta_X = \theta_Y = 3^\circ$, double-sided readout
- ~20 ps time resolution at 5 GeV for GFAG

- Better energy resolution with larger incidence angles
- Data up to 5 GeV give (10.2 ± 0.1)% sampling term and 1-2% constant term for $\theta X = \theta Y = 3^\circ$

NIM A 1045, 167629 (2022)

3d printed W

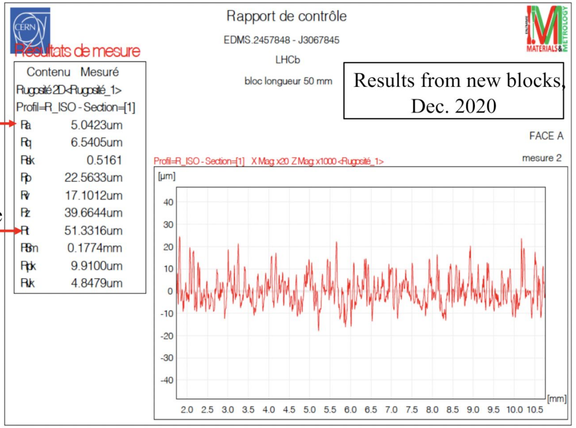


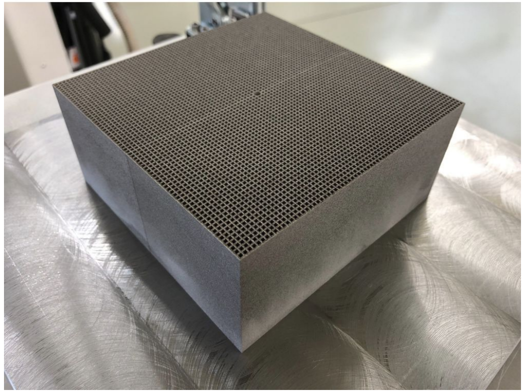
- 3D printing using pure tungsten powder found to be a scalable technology for absorber production
- Smooth surface mandatory to avoid damaging the fibres during module assembly
  → average roughness Ra = 5 µm achieved
- R&D campaign with EOS (Germany):
  → First 15x15 mm^2 cells with up to 10 cm length
  → 45x45 mm^2 pieces
  → Recently 121x121 mm^2 pieces produced
- Module-size pieces recently produced by LaserAdd (China):
  → Two 121x121 mm^2 pieces in 2023
  → Absorber pieces for module-size prototype with crystal fibres expected very soon

Mean roughness

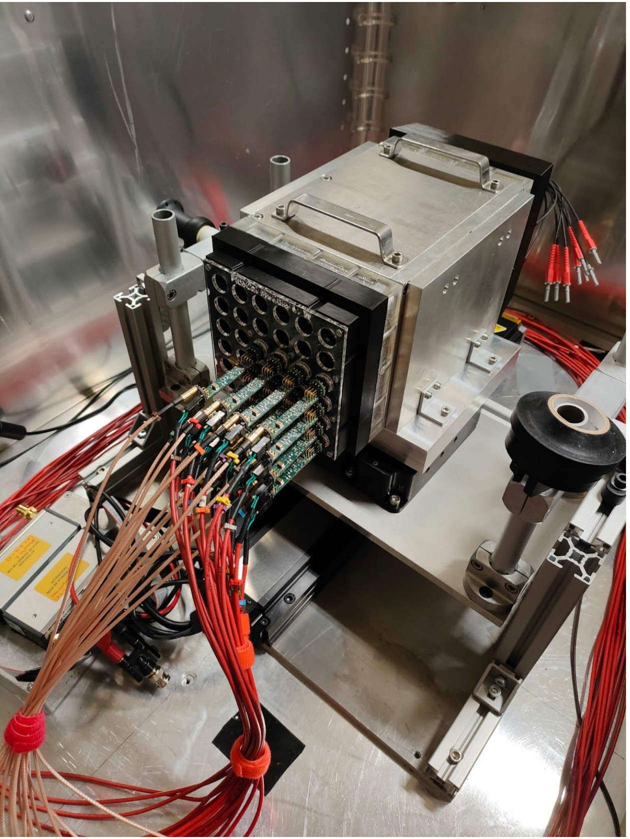
Total height of profile

= distance (max-min)



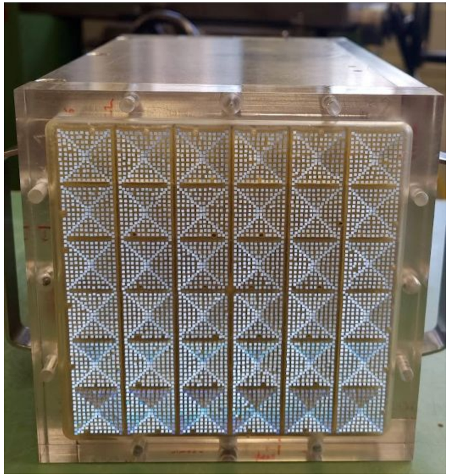


SpaCal-W + Polystyrene fibres (LS3 Enhancement)

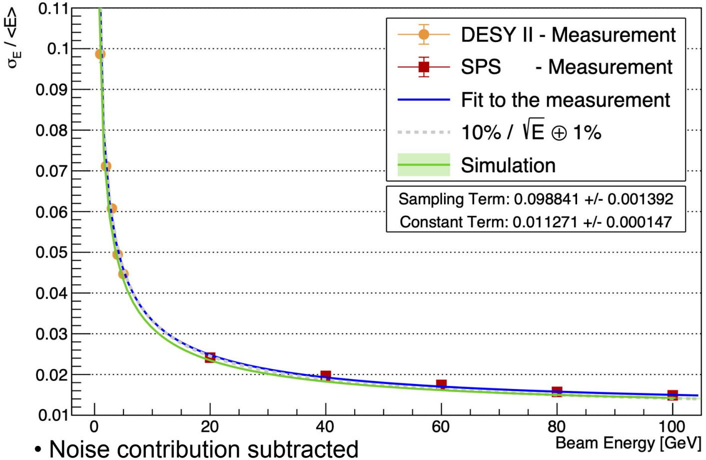


SpaCal with polystyrene fibres and lead absorber:

- 120x120x190 mm^3 3D-printed tungsten absorber from EOS (Germany) filled with single-cladded organic scintillating fibres (1x1 mm^2, Kuraray SCSF-78)
- Single-sided readout on the back side
- Test beams at DESY and CERN SPS in 2023



Energy resolution (DESY & SPS, R14755U-100)

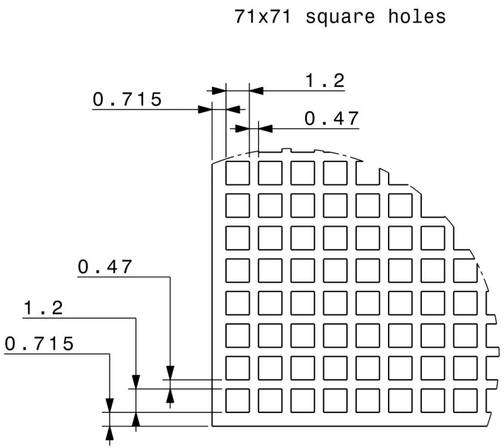


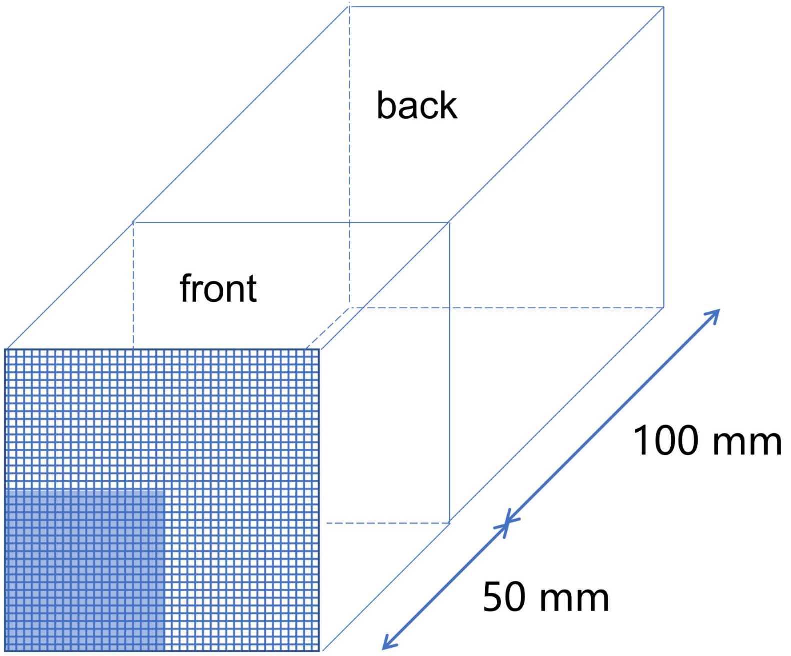
- Noise contribution subtracted
- Sampling term: 9.9%, constant term: 1.1%

→ Very good agreement with simulation

SpaCal-W + crystal fibres: prototype 2024

- 3 pieces of 3D-printed tungsten absorber of 121x121x50 mm^3 produced by LaserAdd in China
- Double-sided readout in view of Upgrade II
- 4x4 cells: 1296 GAGG crystal fibres from SIPAT
- Further cells will be equipped with fibres from other producers later
- Assembly at CERN expected in summer 2024

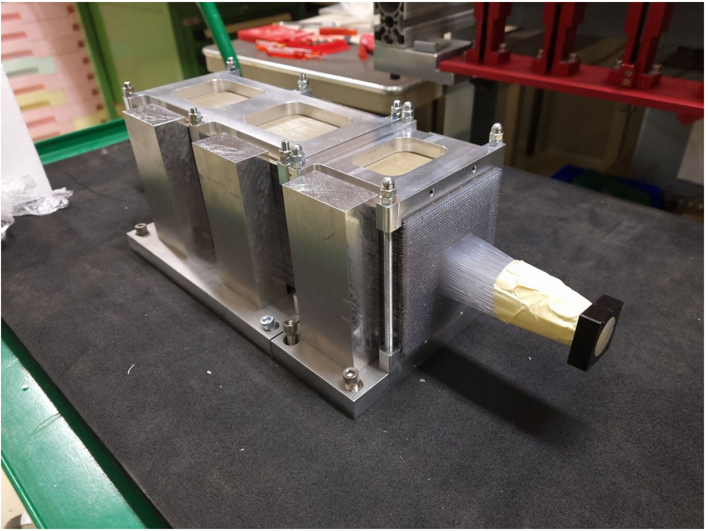


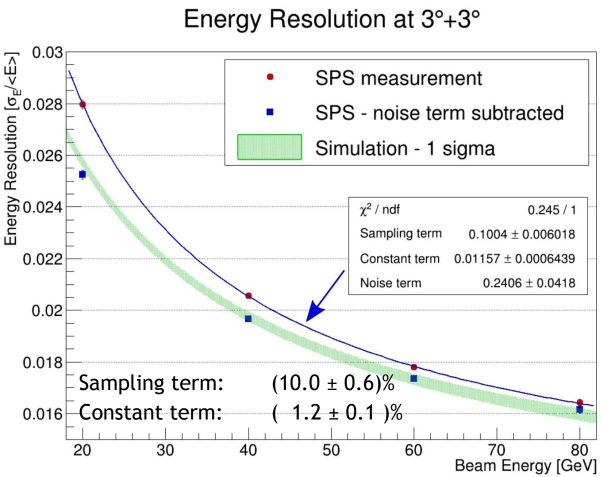


SpaCal-Pb + Polystyrene. First prototype

Module details:

9 cells of 30x30 mm2 (RM ~ 3 cm)
80+210 mm long (7+18 X0)
Reflective mirror between sections
Kuraray SCSF-78 round fibres Ø = 1.0 mm
Light guides 100 mm long
Grooved lead sheets

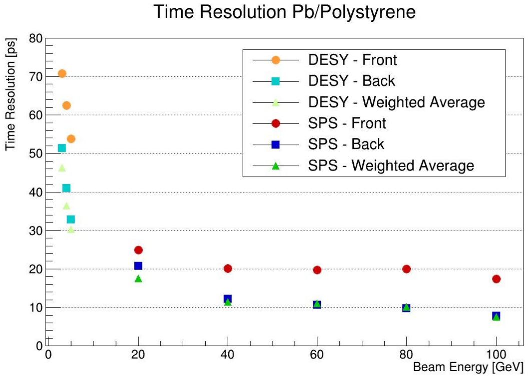




Incidence angles: $\theta_X = \theta_Y = 3^\circ$
double-sided readout
PMT in direct contact

__Energy resolution:__
PMT = R7899-20 (current ECAL)

__Time resolution:__
PMT = R11187



SpaCal-Pb. Single-cell prototypes with casting technique

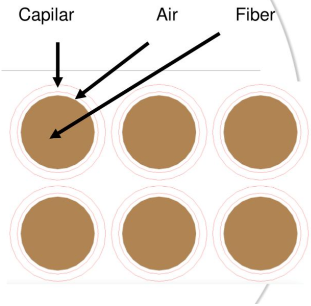
Base material: Babbitt BK2

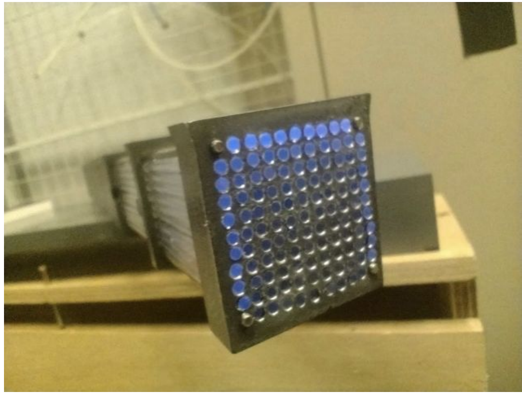
(~97% Pb + 1.5% Sn, 0.3%Ca, 0.2%Na, …)

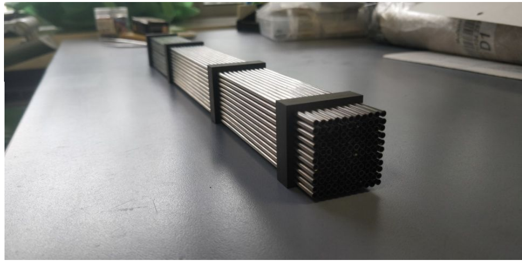
∅ 2.1 mm capillary tubes: AISI 321 (12X18H10T)

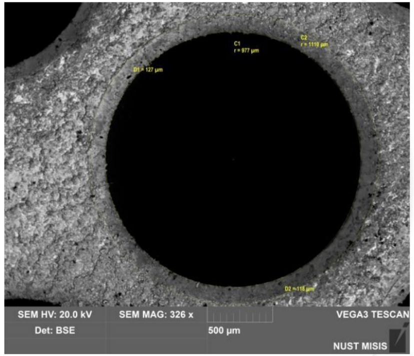
(Cr 17,0%-19,0%, Ni 9,0% ÷ 11,0%, Fe 70%, Mn ≤ 2,0%, Si ≤ 0,8%, …)

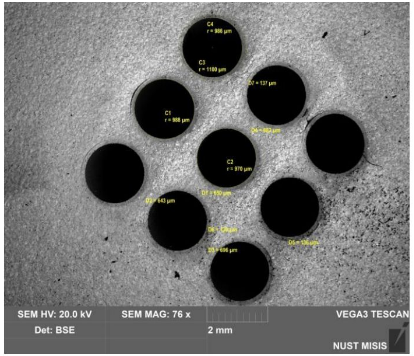
Fibres: ∅ 2 mm Kuraray SCSF-78

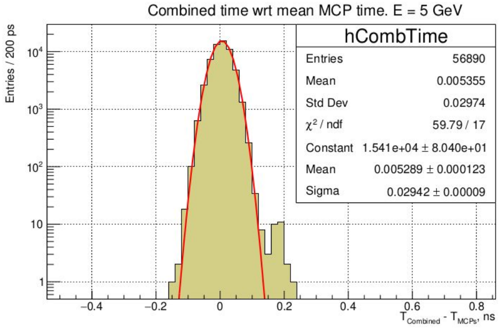






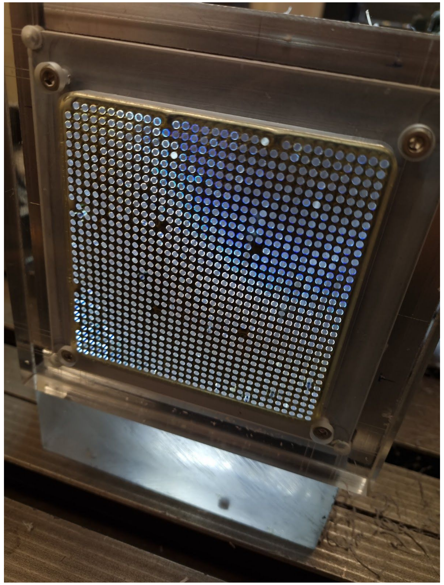


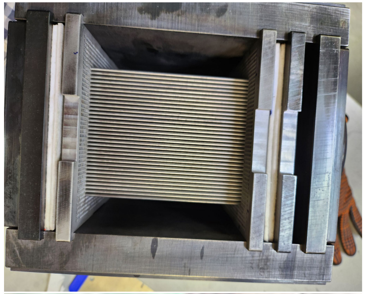


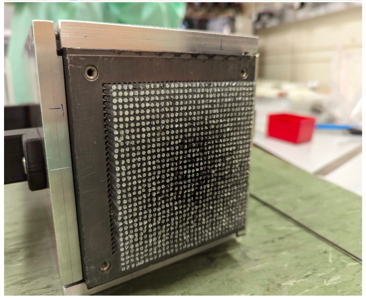


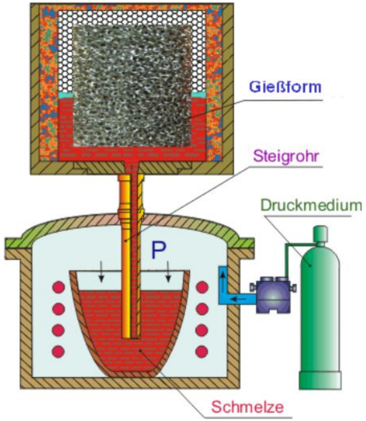
SpaCal-Pb + Polystyrene fibres

- Lead absorber produced using low-pressure casting by MTH & ICM in Germany
- Prototype with 90x90 mm^2 active area equipped with round SCSF-78 scintillating fibres of 2 mm diameter tested at DESY in December 2023
- Next prototype with 121x121 mm^2 active area and using SCSF-3HF scintillating fibres of 1.5 mm diameter in preparation, targeting test beam in June 2024 at CERN

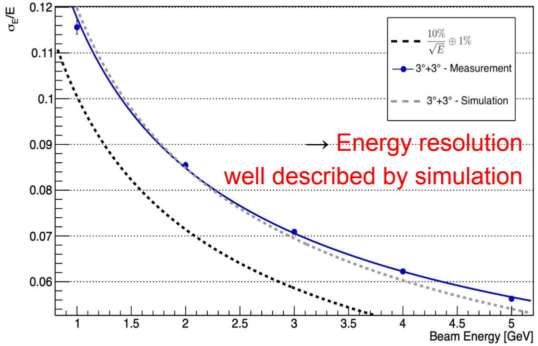




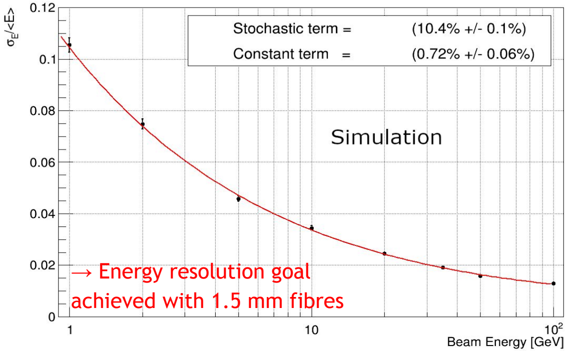




Measurement, DESY, 2 mm fibres



Simulation, 1.5 mm fibres



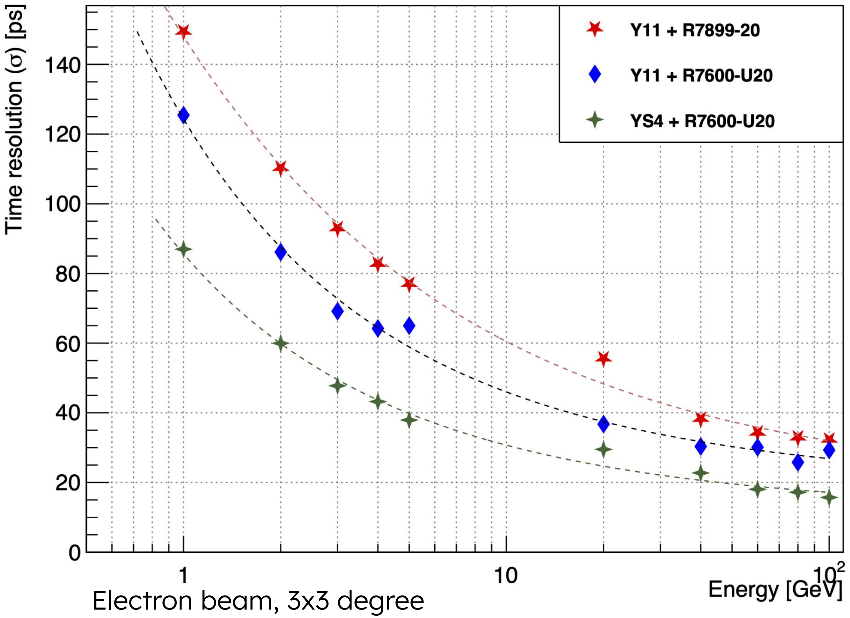
Shashlik: R&D towards Upgrade 2

• Current LHCb Shashlik modules have good time properties, further improvement could be by

- PMTs with smaller transit time spread (e.g. R7600-U20)
- Replacing WLS fibres:
  - **Y11** (7 ns decay time) → currently used in ECAL
  - **YS2** (3 ns decay time)
  - **YS4** (1.1 ns decay time)

• Measurements at DESY and SPS with current (R7899-20) and faster (R7600-20) PMT, single-sided readout, $\theta_X = \theta_Y = 3°$

ECAL outer module (1-cell shashlik, 121x121 mm^2)



Electron beam, 3x3 degree
Incidence angles: $\theta_X = \theta_Y = 3°$

Summary

- The innermost 176 modules of the LHCb ECAL need to be replaced during LS3 due to radiation damage
  - → SpaCal technology with W and Pb absorbers meets all requirements for this region
  - → TDR recently approved!
- The Upgrade II in LS4 introduces picosecond-level timing capabilities and more demanding radiation hardness requirements
  - → Better than 20 ps achieved with Shashlik and SpaCal technology at high energy
  - → Crystal fibres in the central region
- Comprehensive R&D ongoing:
  - → Test beam measurements with prototypes
  - → Detailed Monte Carlo simulations
  - → Study of novel absorber production techniques
  - → Study of suitable PMTs and development of readout electronics
  - → Investigation of new radiation-hard and fast scintillators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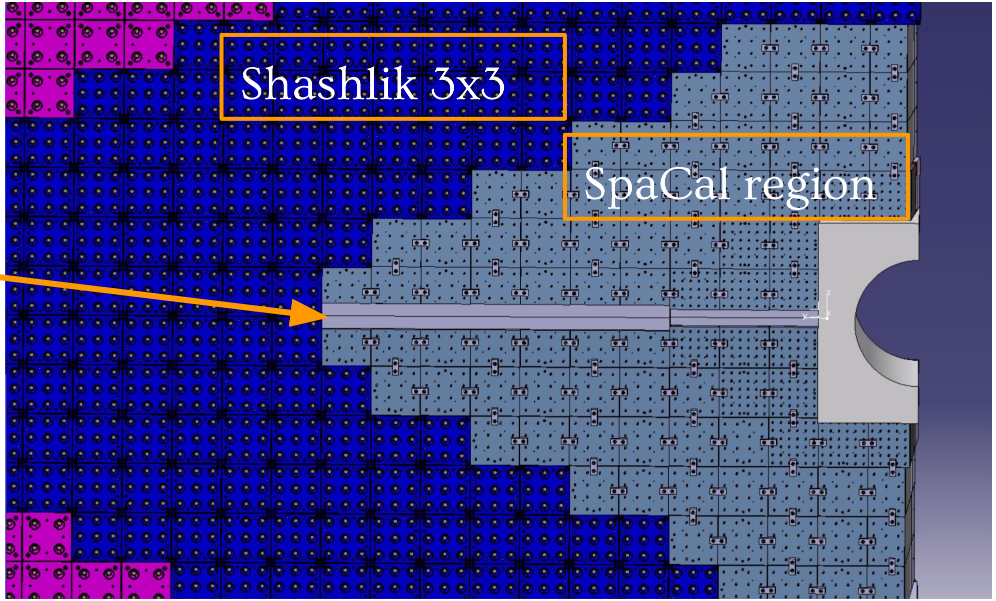
Thank you for your attention!
Many thanks to the organizers for creating such a wonderful conference!

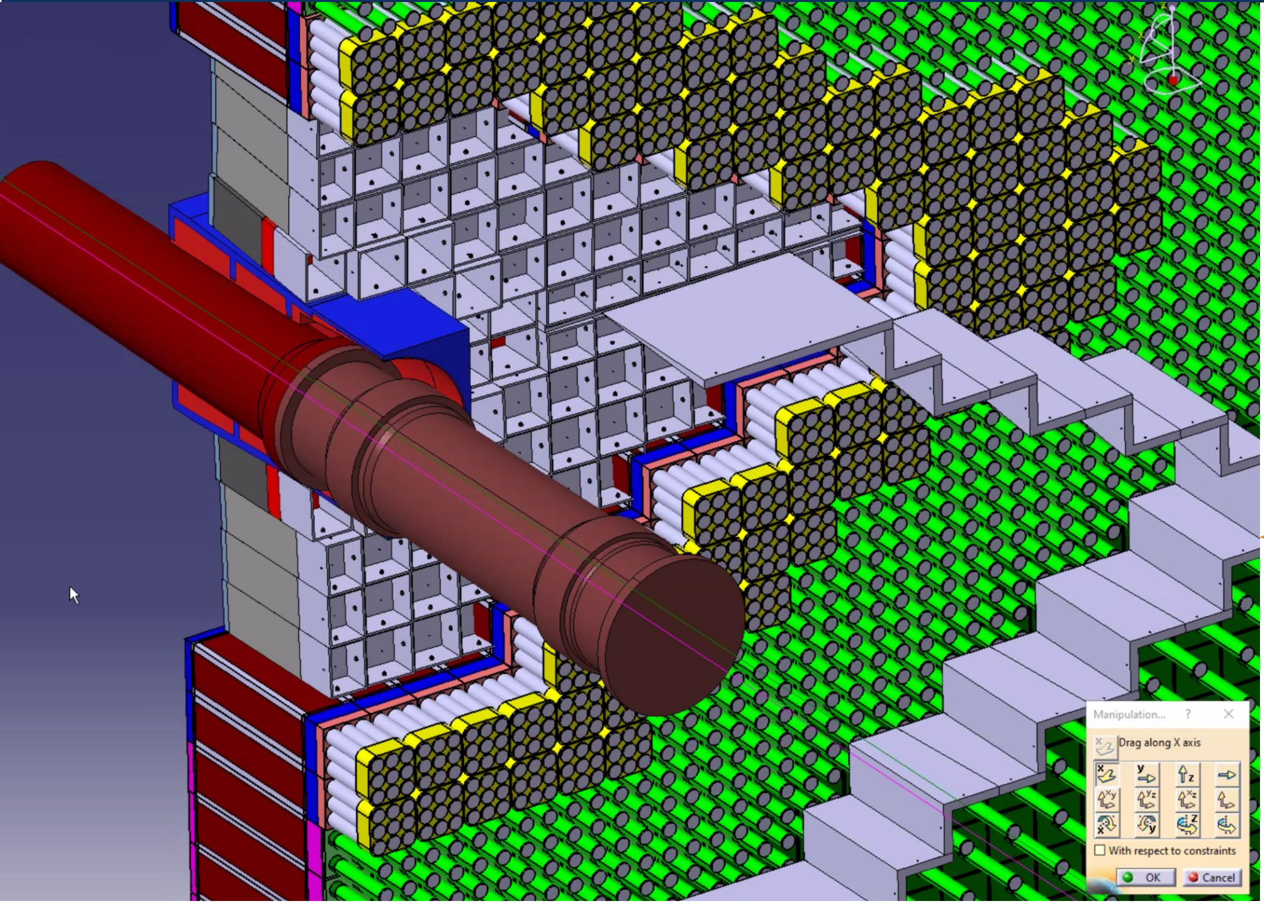
Supplementary slides

Inclination of the SpaCal region

LS3 layout. Front view



Inclination of the SpaCal region (back view)



Inclination system

3D-printed W load test

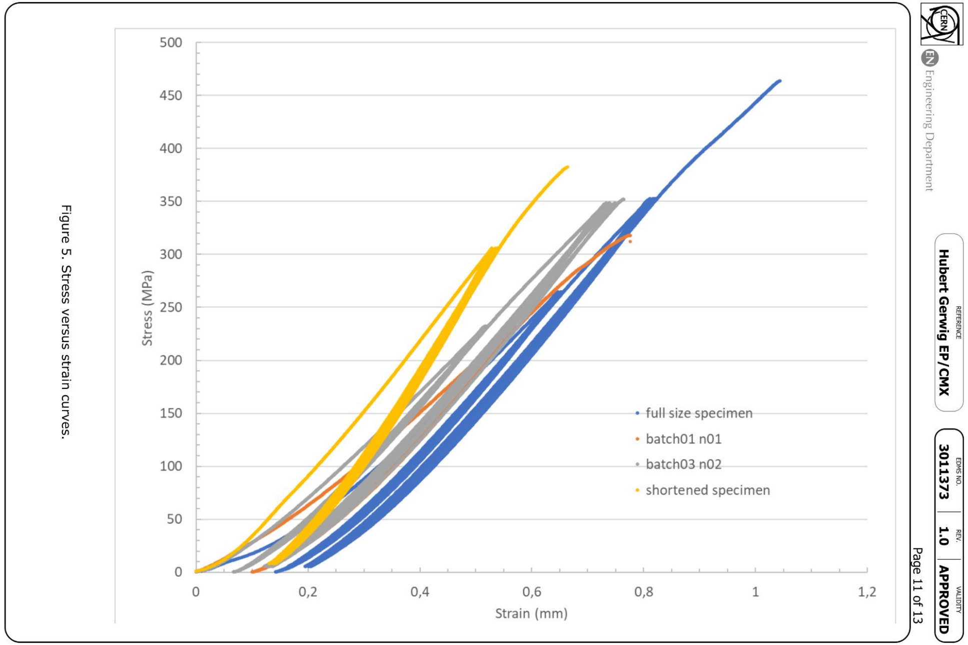
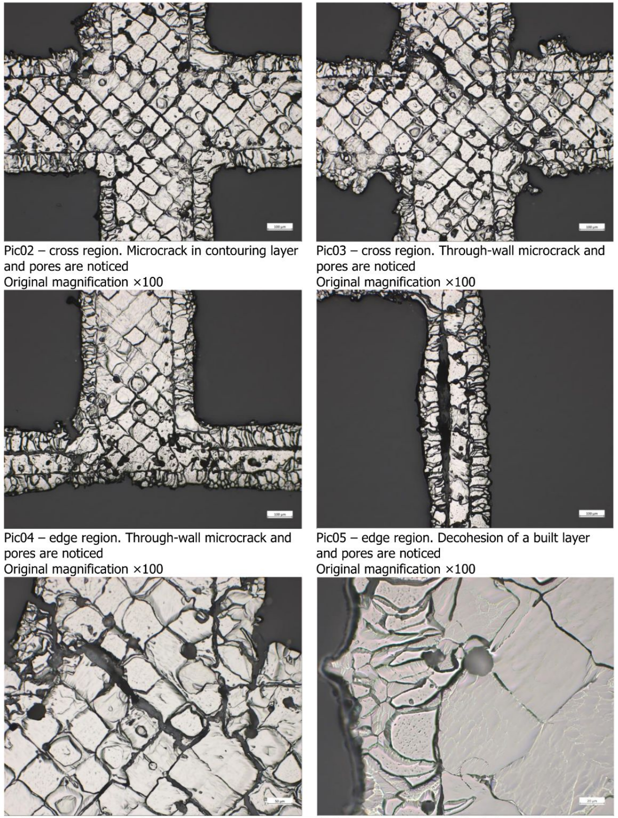


Figure 5. Stress versus strain curves.



Pic02 – cross region. Microcrack in contouring layer and pores are noticed
Original magnification ×100

Pic03 – cross region. Through-wall microcrack and pores are noticed
Original magnification ×100

Pic04 – edge region. Through-wall microcrack and pores are noticed
Original magnification ×100

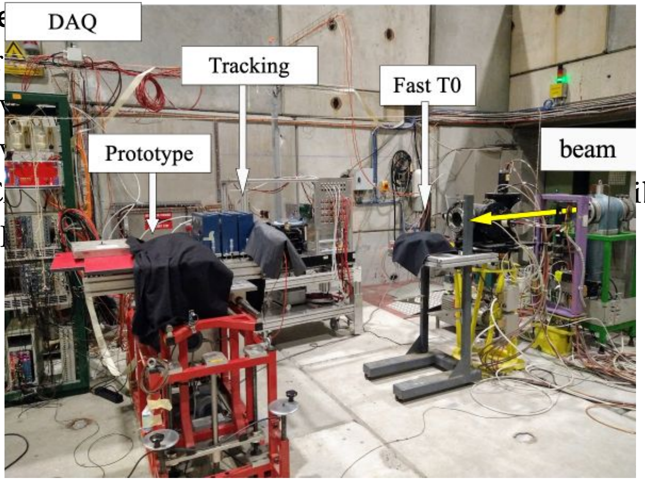
Pic05 – edge region. Decohesion of a built layer and pores are noticed
Original magnification ×100

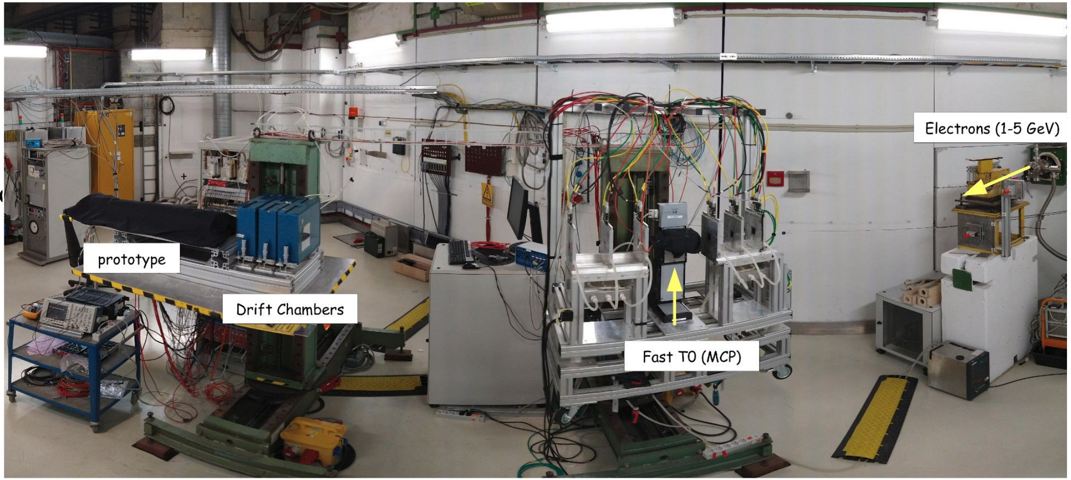
Pic06 – cross region, detailed view of a microcrack. Pores are visible
Original magnification ×200

Pic07 – cross region, detailed view of the built microstructure. Pores are visible
Original magnification ×500

Figure 3. Micrographs.

Beamtests: CERN H4 / H8 and DESY T24





CERN H4: electrons: E = 20 – 300 GeV
DESY T24: electrons with E = 1 – 5.8 GeV
CERN H8: muons and hadrons (p = 150 GeV/c)

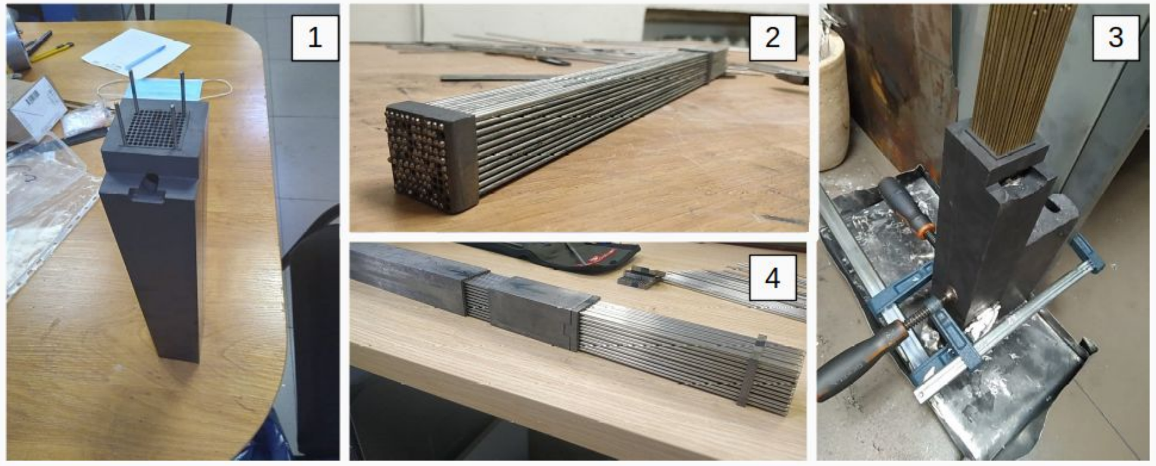
First single-cell prototype

produced in MISIS in 2021

Base material Garth's typographic alloy:
Pb 84% - Sb 12% - 4% Sn

Extractable rods

⇒ holes ⌀2.2 mm to host ⌀2 mm scintillating fibres

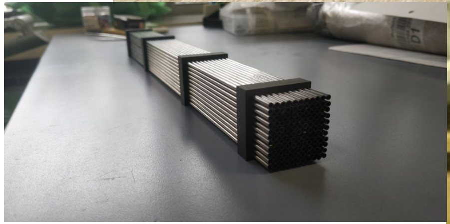


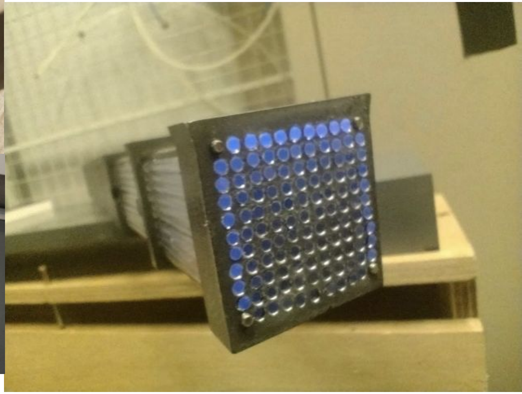
Single-cell object was tested for time resolution. Result was quite optimistic

But there was an issue found with the material
⇒ activation of the antimony makes usage of Garth's typographic alloy impossible

+ Holes after extracting steel rods were way too large (air between absorber and fibers)

Second single-cell prototype





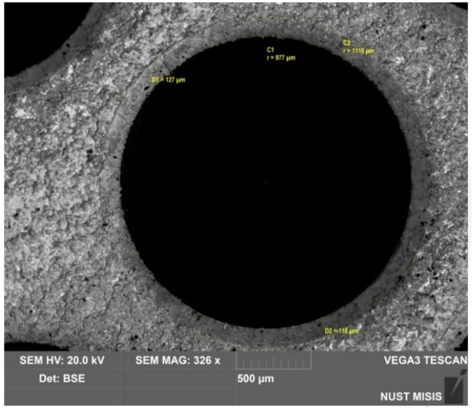
produced in MISIS in 2022

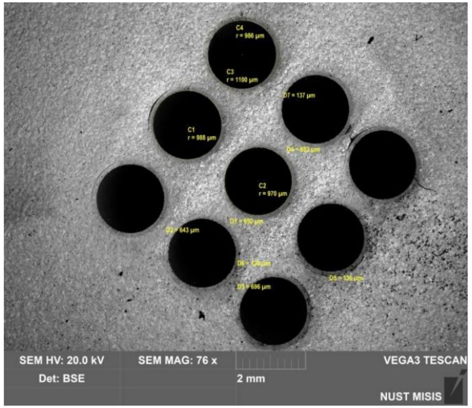
<u>Base material:</u> Babbitt BK2

(~97% Pb + 1.5% Sn, 0.3%Ca, 0.2%Na, ...)

<u>∅ 2mm capillary tubes:</u> AISI 321 (12X18H10T)

(Cr 17,0%-19,0%, Ni 9,0% ÷ 11,0%, Fe 70%, Mn ≤ 2,0%, Si ≤ 0,8%, ...)

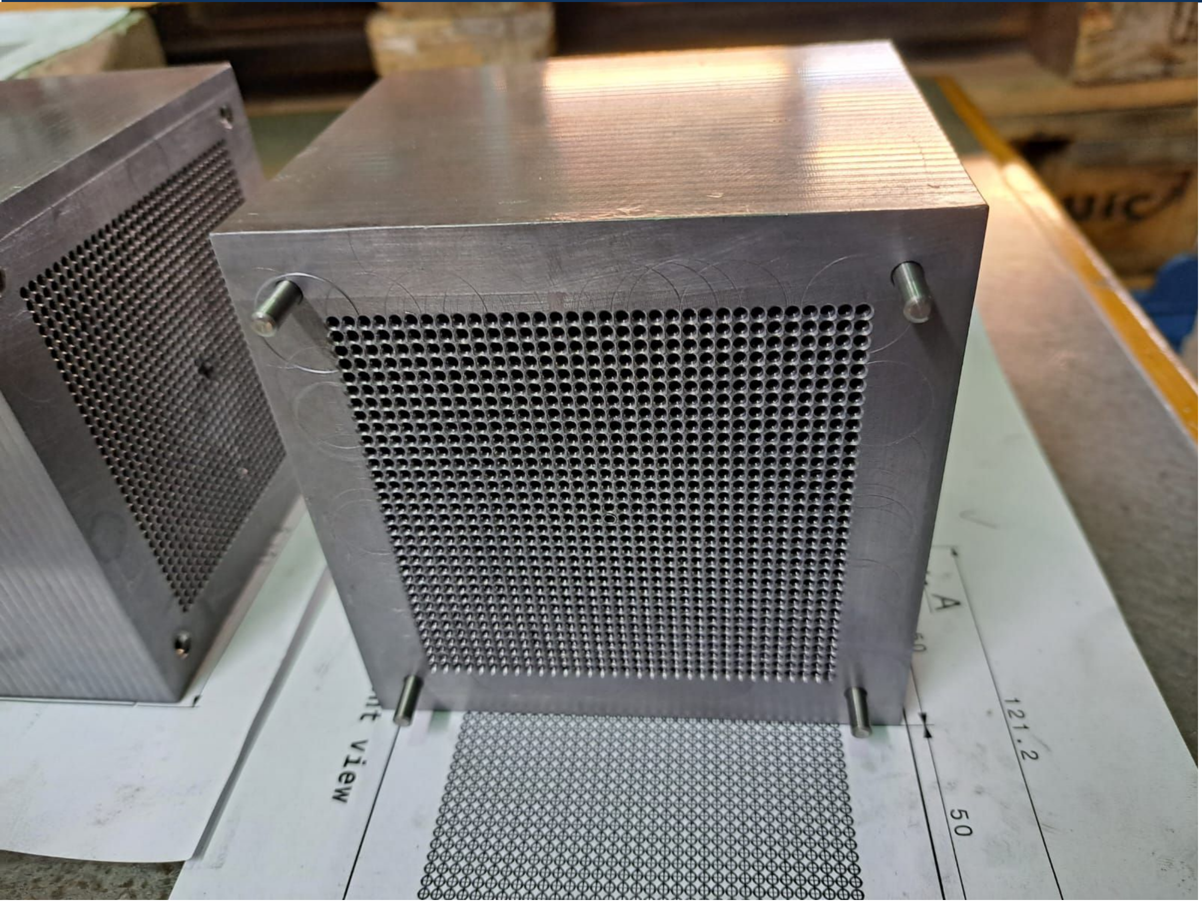


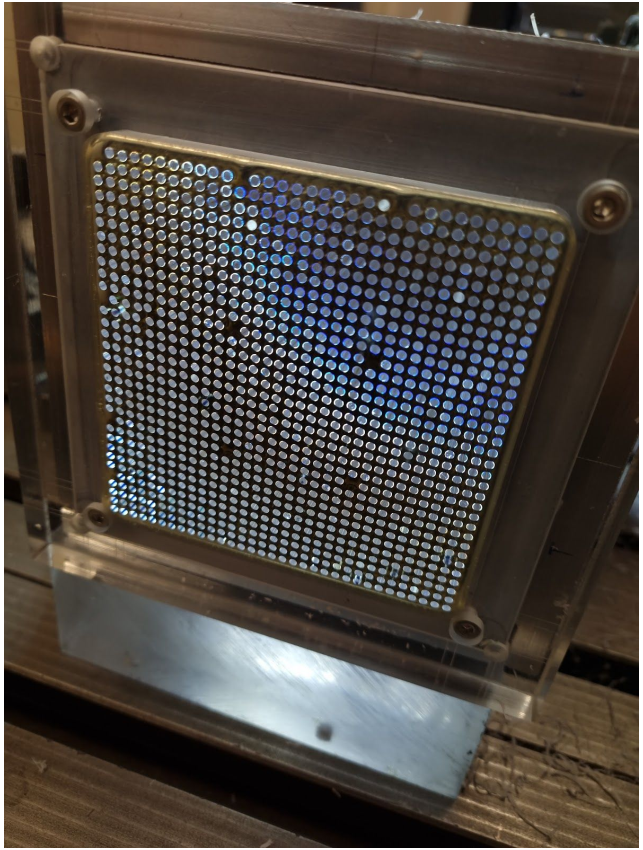


Horizontal mold casting

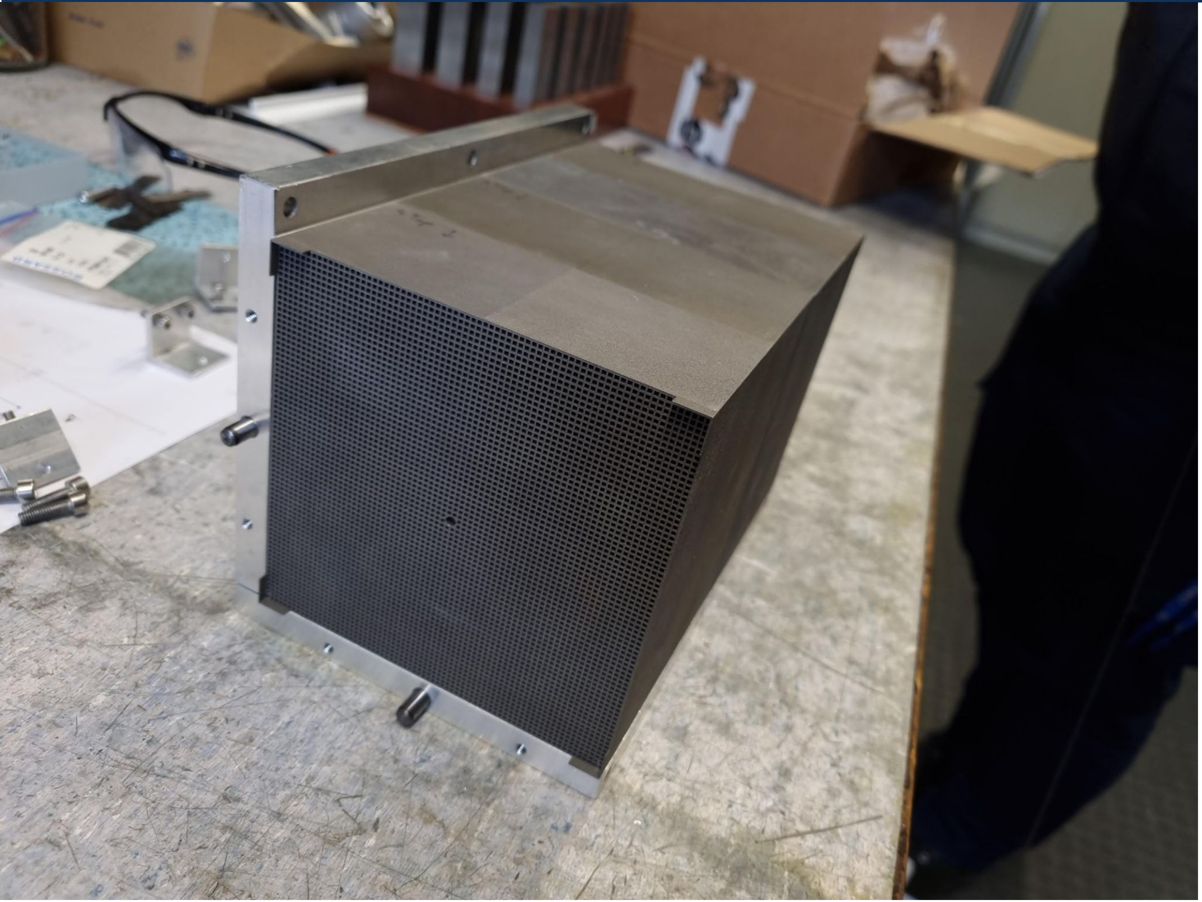
Vertical mold casting

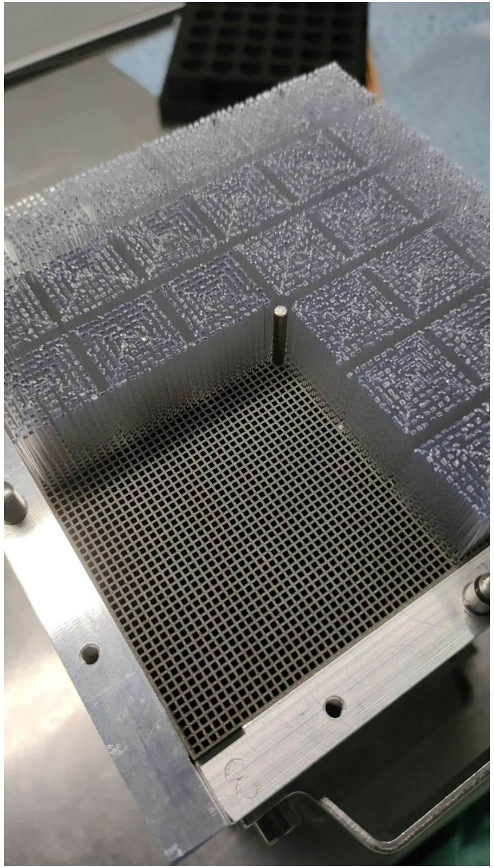
Assembly: SpaCal-Pb + Polystyrene fibres



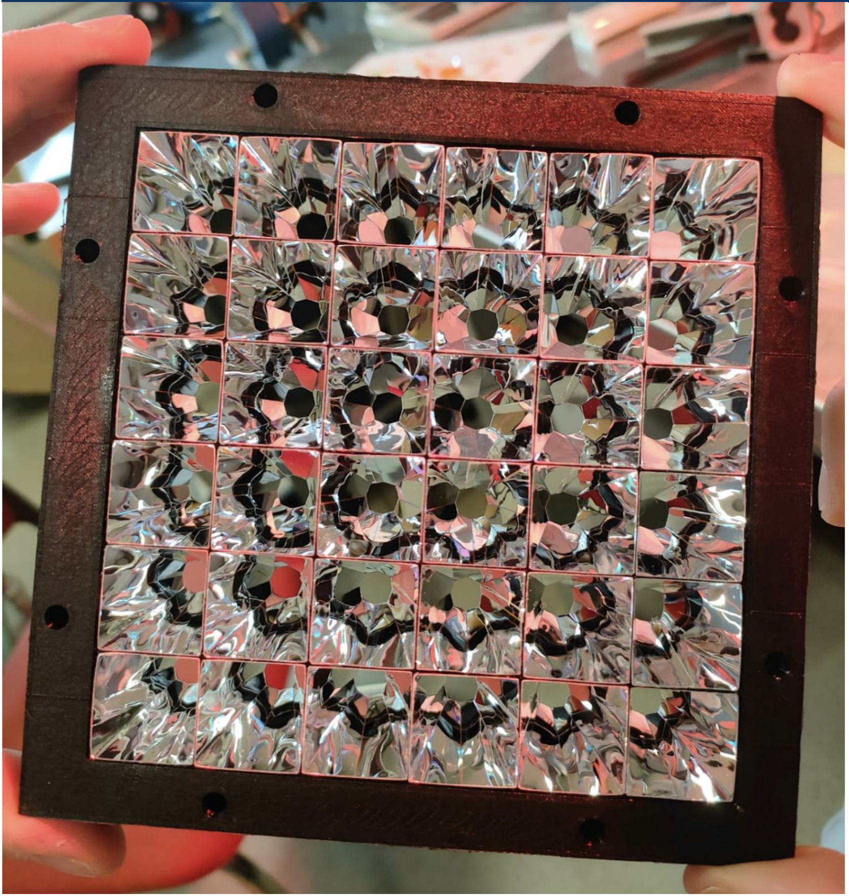


Assembly: SpaCal-W + Polystyrene fibres





Hollow light-guides



Lightguide geometry determined by the PMT + cell size (requirement - uniform response over the surface. Non-uniformities contributes to the constant term of energy resolution)

Different options under study:

- R11176 (single-cell suitable for SpaCal-Pb)
- R7600-M4 (similar dimensions multi-anode pmt, SpaCal-W)
- R9880 (small round PMT)