PicoCal Technologies

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on behalf of the LHCb PicoCal Group

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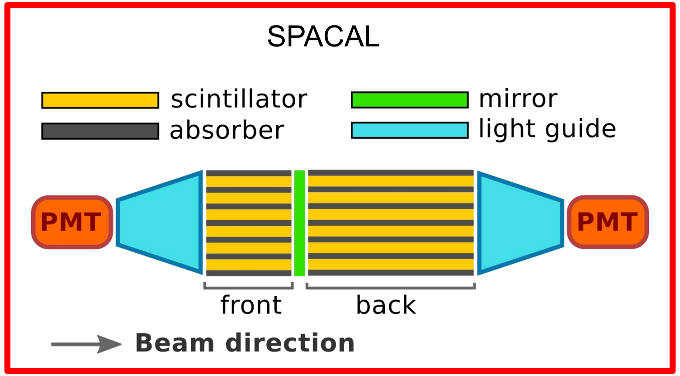
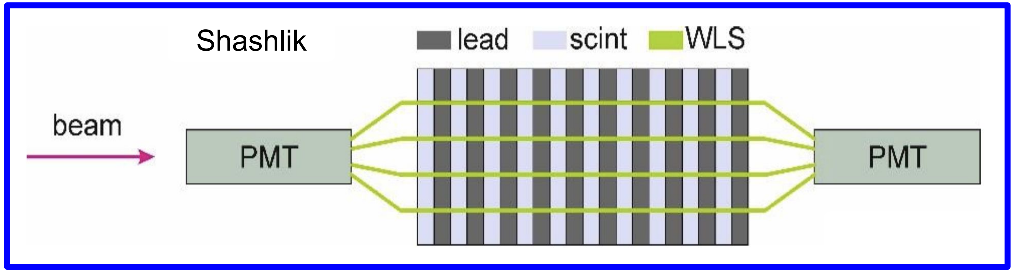
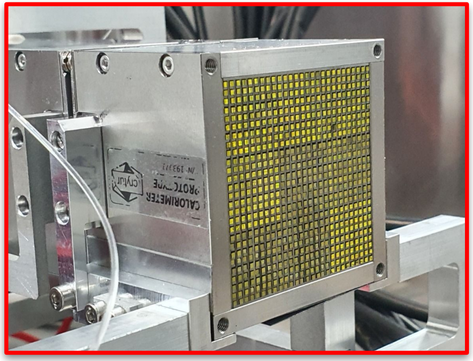
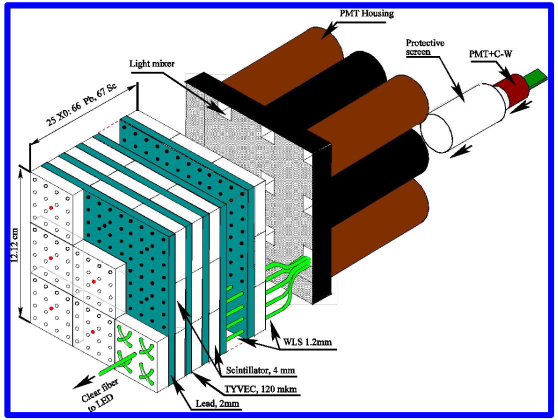
Baseline Technologies









Shashlik (current ECAL):

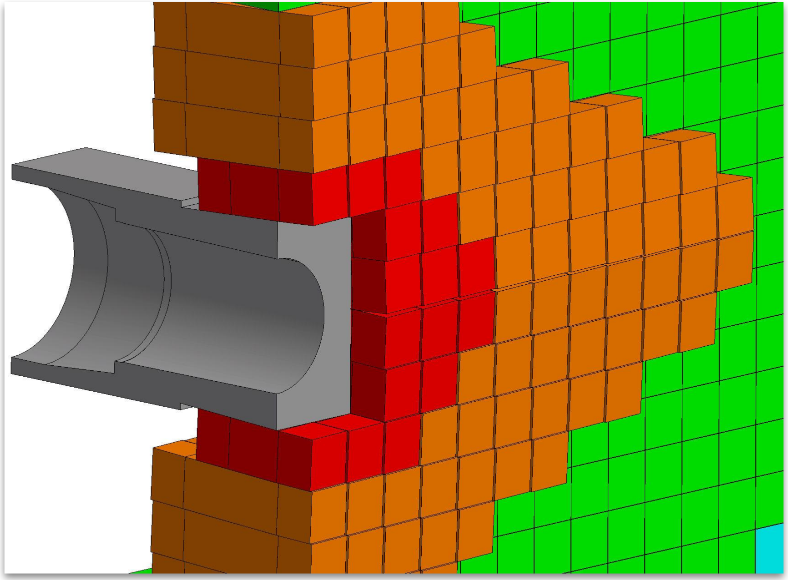
- **Scintillator-Lead sandwich** with WLS fibers
- WLS fibers bundled and coupled to PMT
- Single or double side readout possible
- Radiation tolerant: **40-50 kGy**

SPACAL

- Scintillating **fibres** in dense **absorber**
- Light guides coupling fibers to PMTs
- Single or double side readout possible
- Radiation hard: **up to 1 MGy**

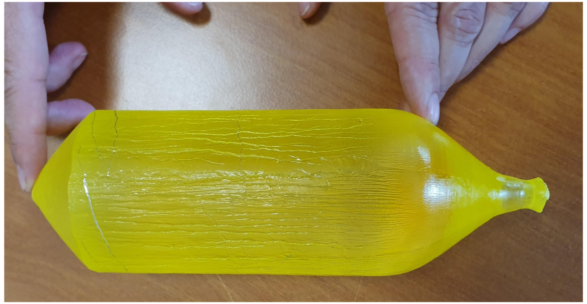
Materials:

- Absorber: Tungsten / Lead
- Fibres: inorganic / organic



I. **SPACAL - W**
   A. W-GAGG
   B. W-Polystyrene
II. SPACAL - Pb
III. Shashlik

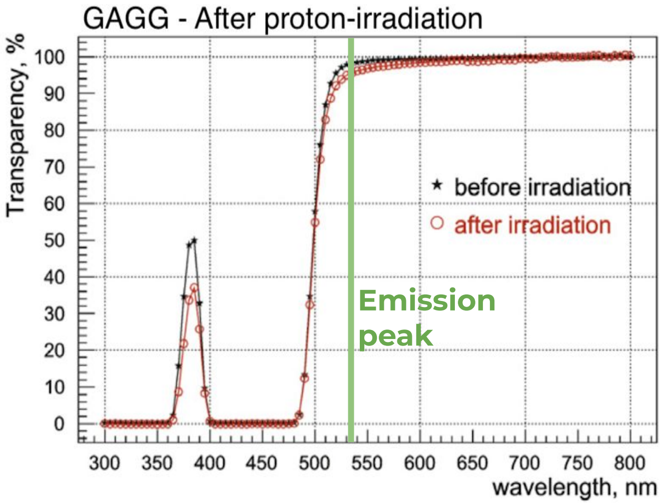
Inorganic Crystals: Garnets



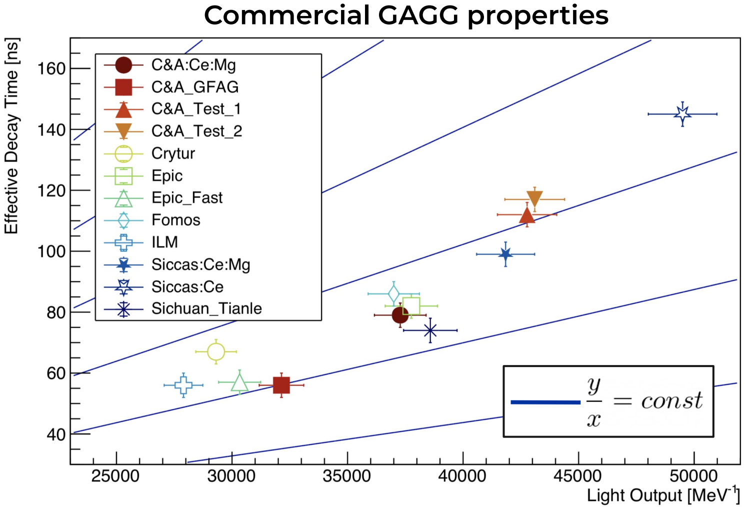
Courtesy of K. Lebbou, ILM

Gadolinium Gallium Aluminium Garnet $Gd_3Al_2Ga_3O_{12}$ (GAGG):

- **High light output** and relatively **fast decay time (~50 ns)**
- **Tunable scintillation properties**:
  - Properties modified by changing **components** and **doping**
- **Radiation hardness** tested up to 1 MGy
  - Induced absorption < 4 m^{-1} @ emission peak

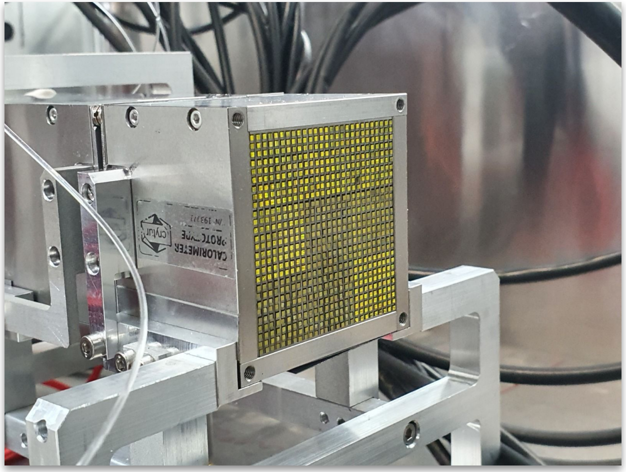


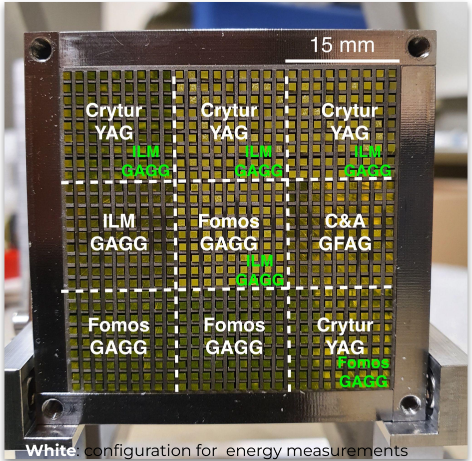
V. Alenkov et al., NIM A 816 (2016) 176



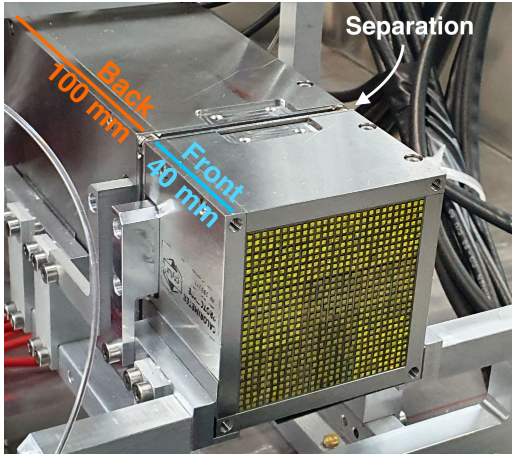
L. Martinazzoli et al., NIM A, 2021, 165231

SPACAL W-GAGG





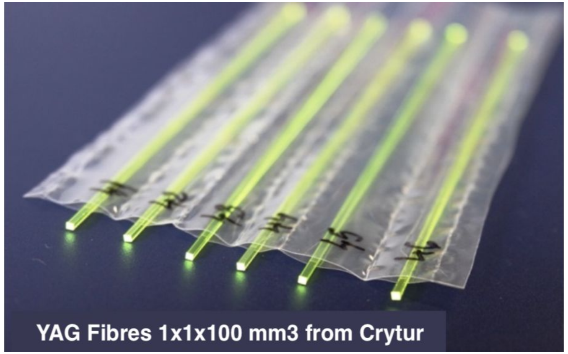
White: configuration for energy measurements
Green: configuration for timing measurements



SPACAL prototype with **W absorber** and **garnet crystals**.

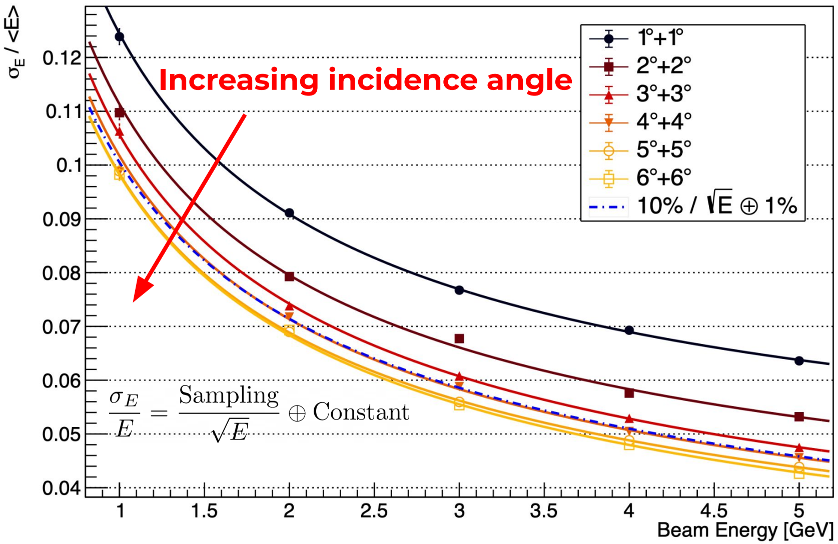
- Absorber in pure tungsten 19 g/cm^3
- 9 cells of 1.5x1.5 cm^2 (Molière radius: ~ 1.5 cm)
- 4+10 cm long (~ 7+18 X_0)
- ESR mirror between sections
- 1x1 mm^2 garnet crystal fibres

Tested at DESY with 1-5 GeV e^-


YAG Fibres 1x1x100 mm3 from Crytur

SPACAL W-GAGG

Energy resolution



- Resolution improves increasing the incidence angle

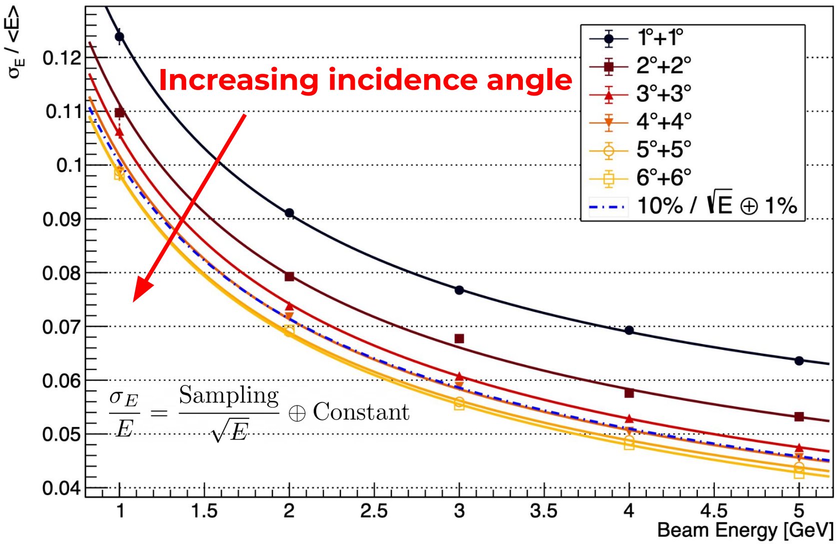
- **Energy resolution at 3°+3°:**
  Sampling term: 10.2%
  Constant term: 1-2%*

*Higher-energy data needed to measure the constant term

NIM A 1045, 167629 (2022)

SPACAL W-GAGG

Energy resolution



- Resolution improves increasing the incidence angle

- **Energy resolution at 3°+3°:**
  Sampling term: 10.2%
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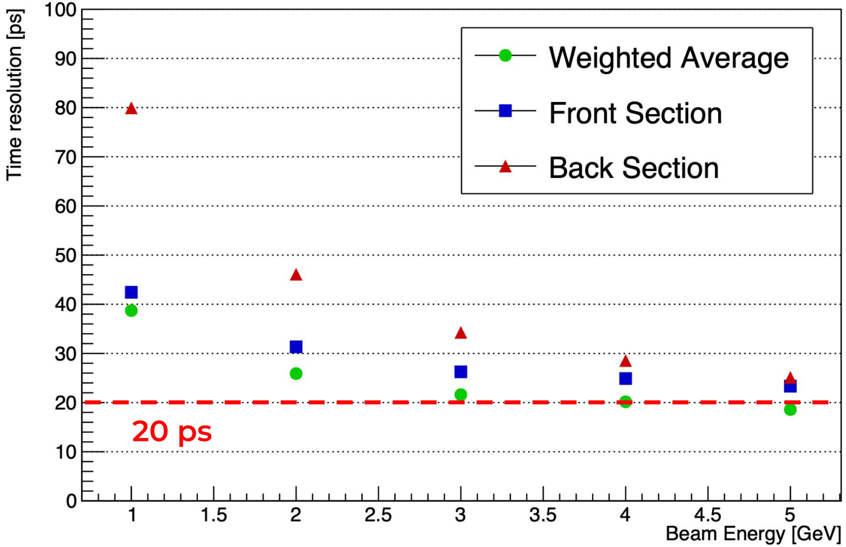
*Higher-energy data needed to measure the constant term

Time resolution



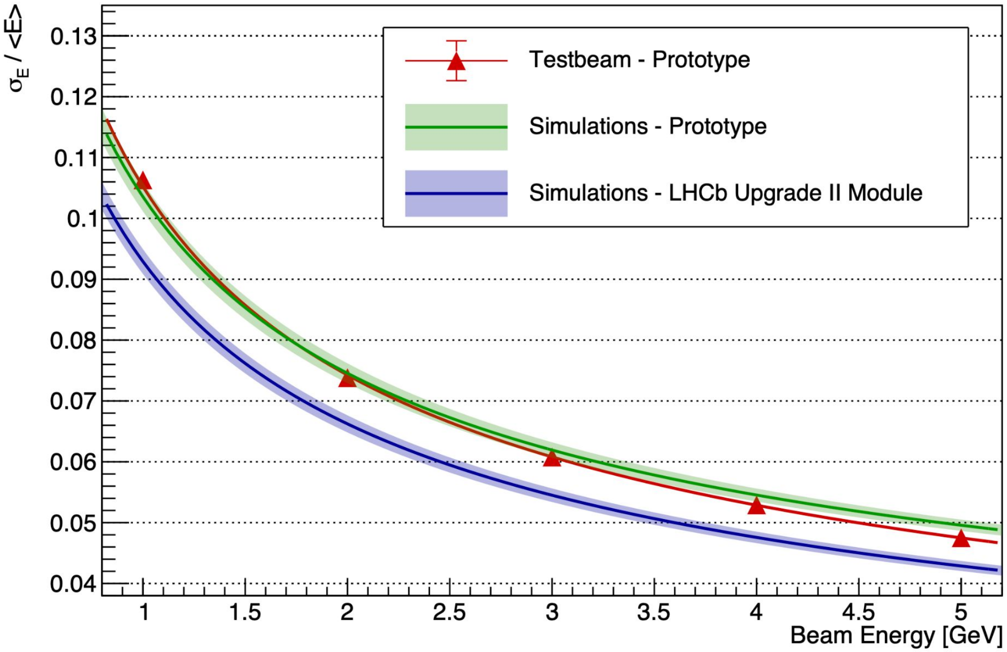
- Time resolution measured at incidence of **3°+3°**
- Measurement in direct contact with fast MCD PMTs for ultimate performance

- **Time resolution C&A GAGG: 18.5 ± 0.2 ps @ 5 GeV**

NIM A 1045, 167629 (2022)

SPACAL W-GAGG - Monte Carlo

Energy resolution



- Testbeam results to validate Monte Carlo software
  - **Reasonable agreement data-simulations**

- Improvements expected from final design:
  - Less material budget between front and back
  - Shorter pitch between fibres
  - Longer sections

NIM A 1045, 167629 (2022)

Scintillators R&D

Commercial GAGGs have scintillation decay time > 40 ns

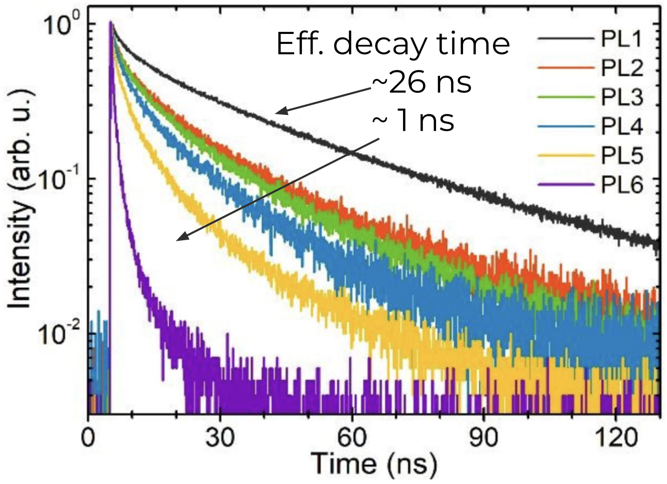
- Time resolution degradation due to spill-over

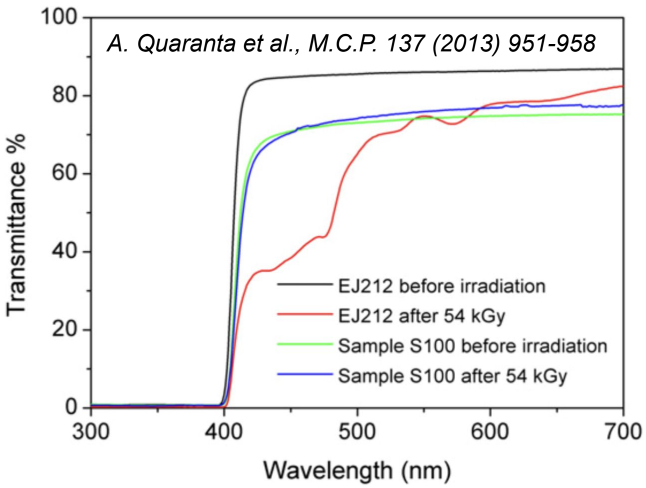
Compositions identified to accelerate scintillation

- Light yield reduced
- Decay time accelerated
- Time resolution kept competitive

R&D focusing on producing **large samples**

Material Advances, 2022, 3, 6842





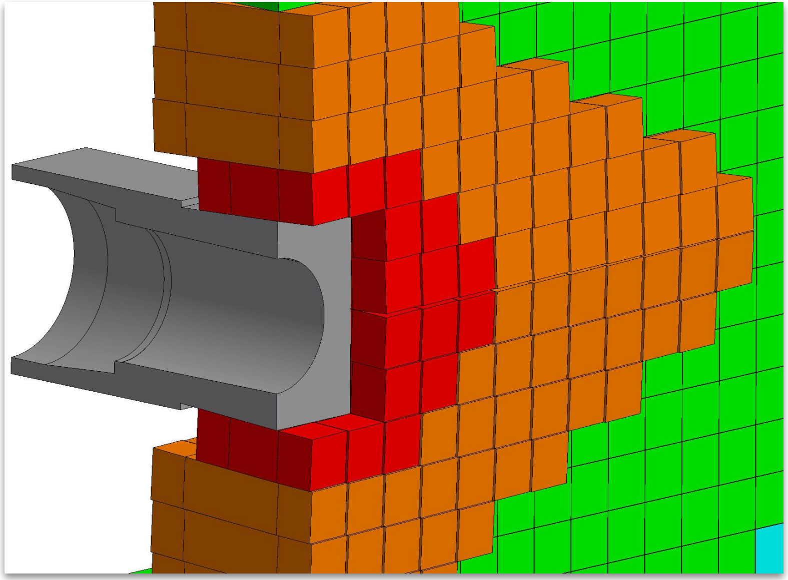
Testing **novel scintillating materials** alternative to plastics:

- Radiation tolerant up to 100-200 kGy
- Timing comparable to commercial plastic
- Cost-effectiveness as polystyrene

Candidates include:

- Polysiloxane hosts
- Organic glasses

R&D ongoing with partners worldwide



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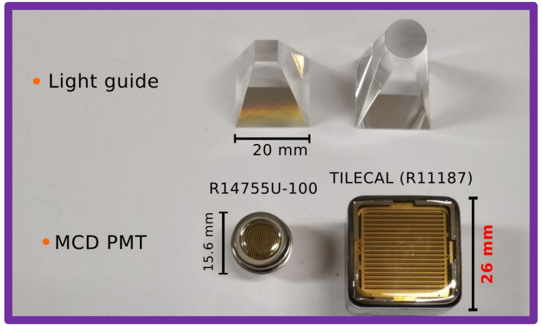
SPACAL W-Polystyrene

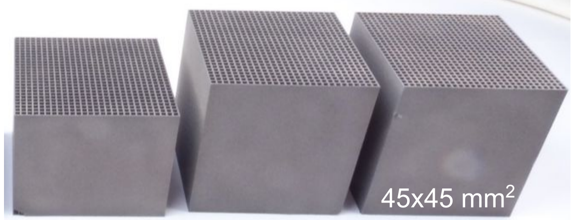
Prototype of SPACAL **W absorber** and **polystyrene fibres**:

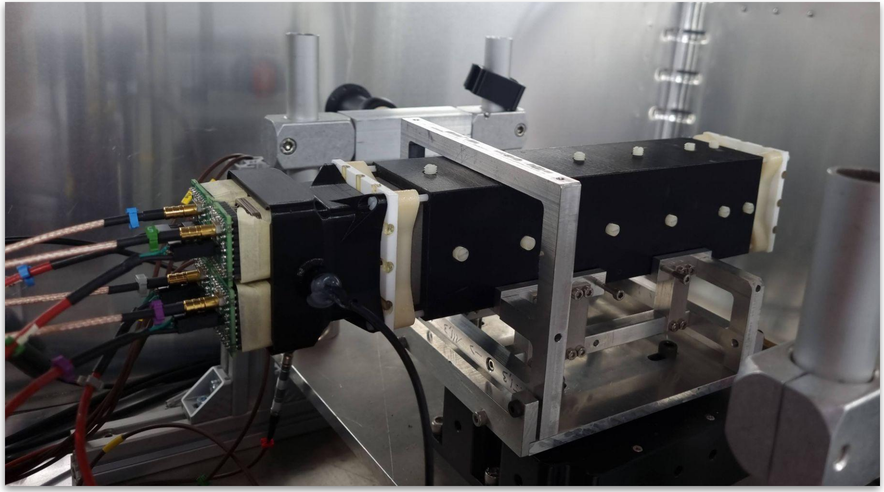
- Pure W absorber **3D-printed**
- 4 cells of 2x2 cm^2 (R_M ~ 1.8 cm) - 19 cm long
- Continuous **Kuraray SCSF-78** square fibres 1x1 mm^2
- Realistic coupling with light guides and candidate PMTs

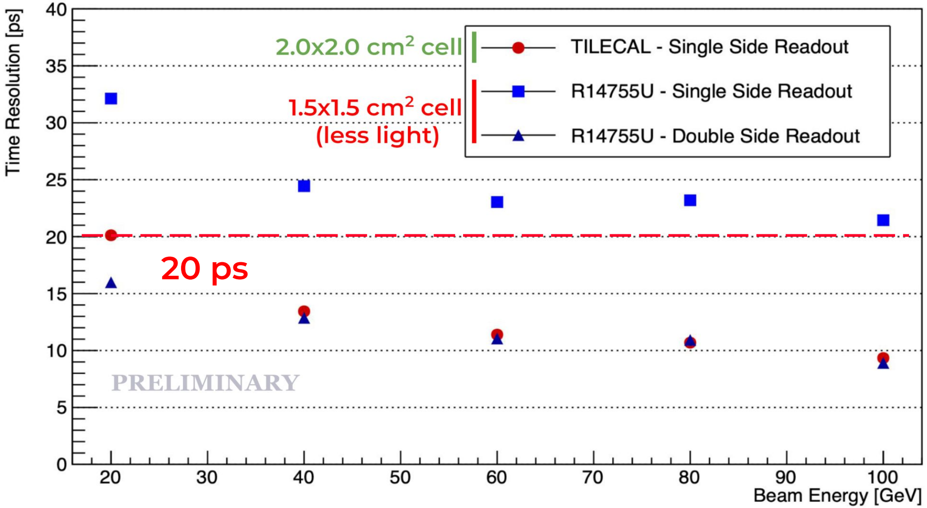
Tested with high-energy e^- at SPS (20-100 GeV)

Time resolution:
- **< 20 ps** from 20 GeV
- **~ 10 ps** @ 100 GeV

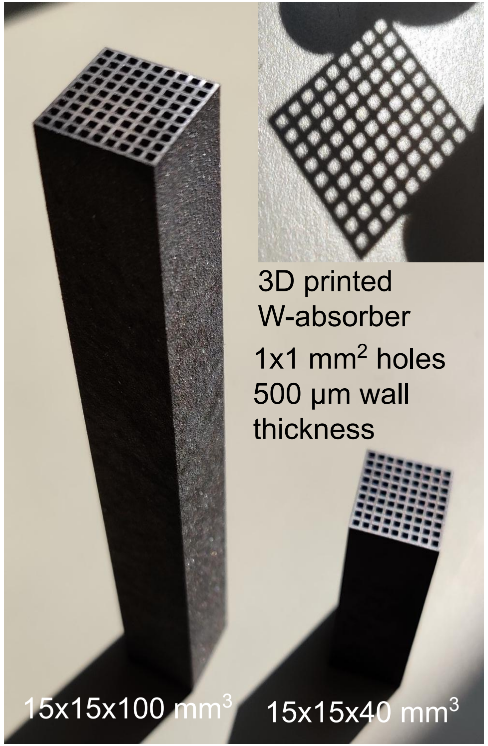


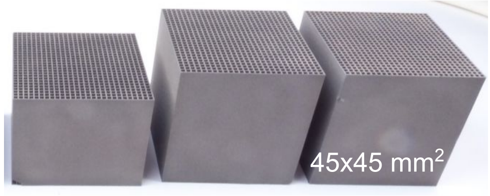






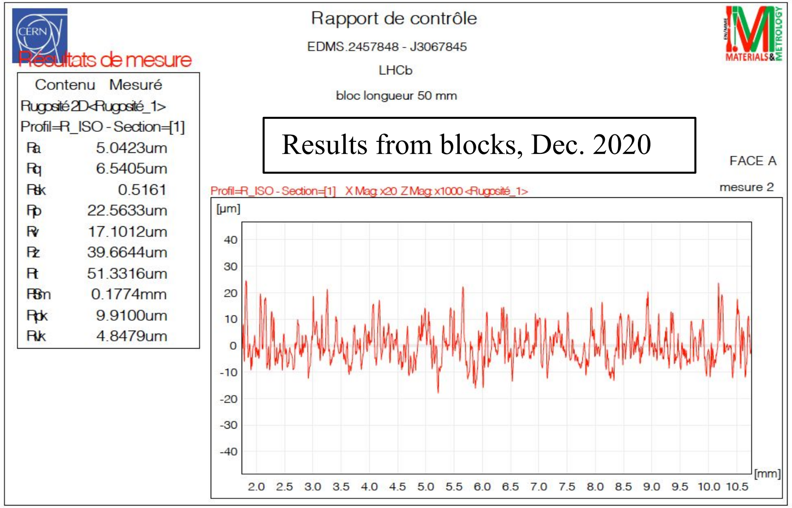
Tungsten 3D-Printing





3D-printing of pure W powder is a **scalable technology** for the absorber production

- **Smooth surface** mandatory not to damage scintillating fibres
  - Excellent roughness R_a = 5 µm achieved
- R&D campaign in collaboration with EOS, Germany
  - 1-cell and 4-cell prototypes produced and tested
  - **Full size 121 x 121 mm² *"Module 0"* delivered at CERN**
- LHCb China carrying on the R&D:
  - First element for full size module at CERN for qualification



Rapport de contrôle

EDMS.2457848 - J3067845

LHCb

bloc longueur 50 mm

Résultats de mesure

Contenu	Mesuré
Rugosité 2D<Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	5.0423um
Rq	6.5405um
Rsk	0.5161
Rp	22.5633um
Rv	17.1012um
Rz	39.6644um
Rt	51.3316um
RSm	0.1774mm
Rpk	9.9100um
Rvk	4.8479um

Results from blocks, Dec. 2020

FACE A

mesure 2

DiMetal-150

DiMetal-100H

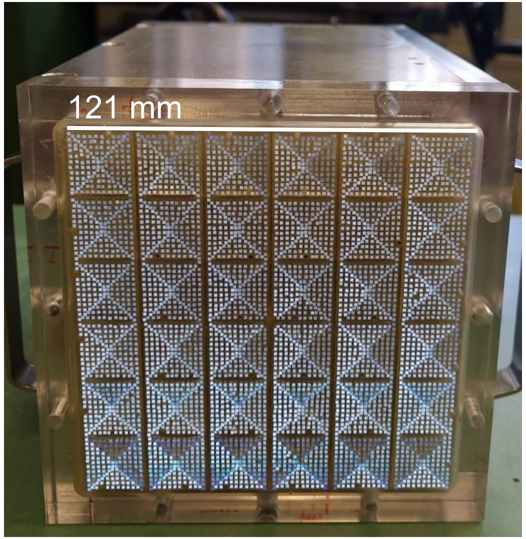
W-Polystyrene *Module 0*

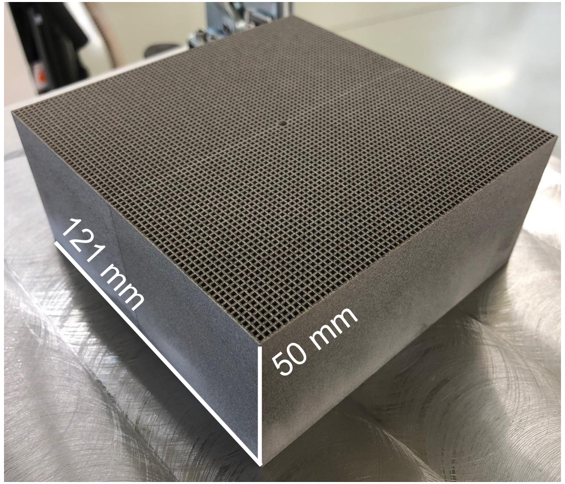
Full size 121x121 mm^2 *Module 0* under construction at CERN:

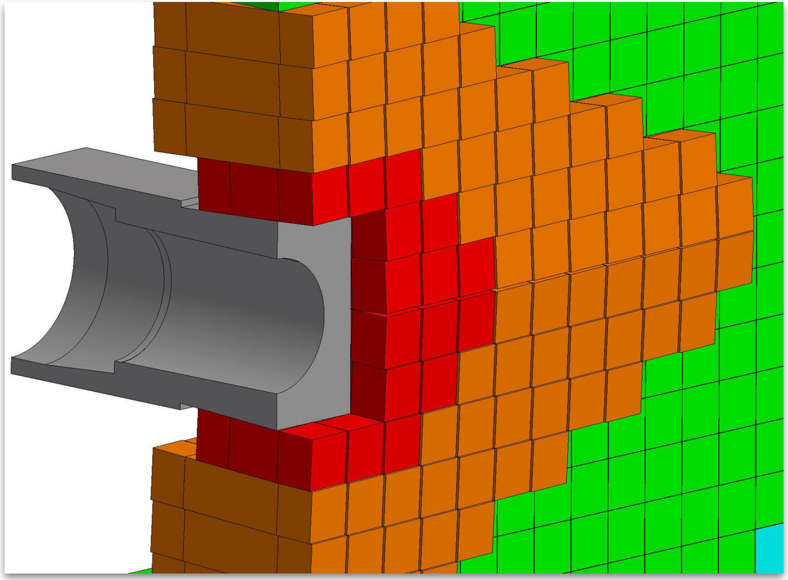
- 3D-printed W absorber
  - **3** x **50** mm + **1** x **40** mm long blocks
- Continuous **Kuraray SCSF-78** square fibres 1x1 mm^2
- **Hollow light guides** made with ESR reflector
- Calibration technique with optical fibres under test

Testbeam in **May (DESY)** and **June (SPS)**

- Everyone very welcome to take part!







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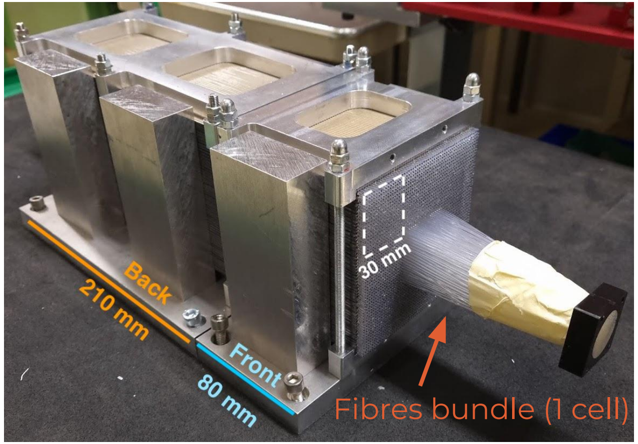
III. Shashlik

SPACAL Pb-Polystyrene

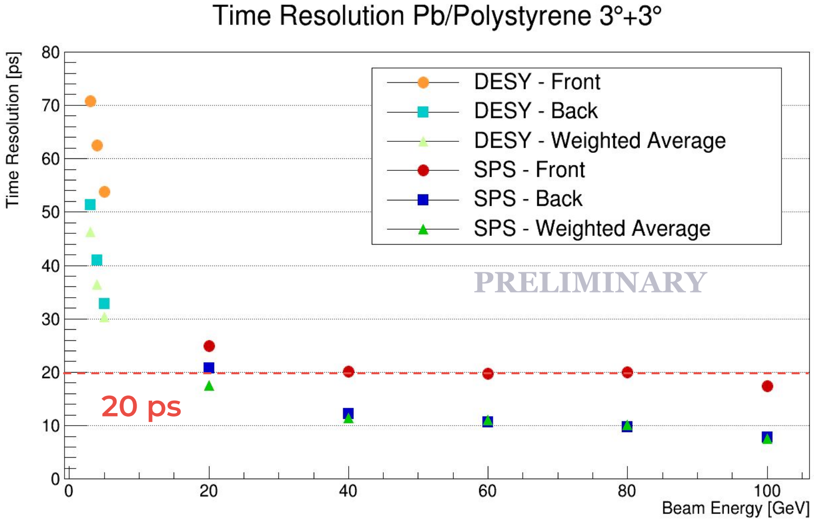
Pb absorber and **polystyrene fibres**:

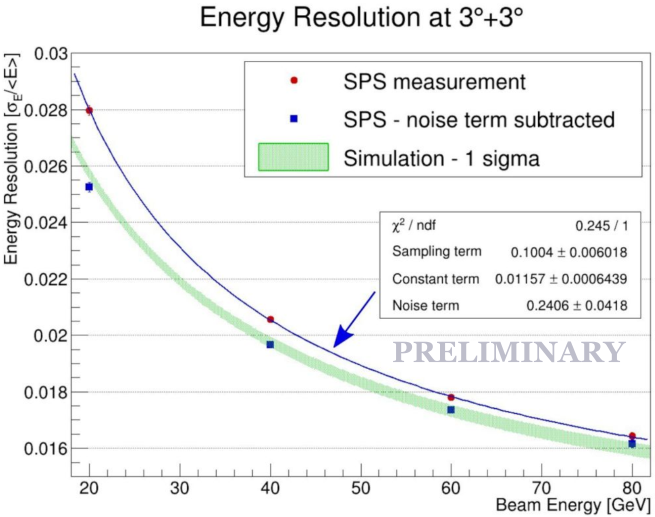
- 9 cells of 3x3 cm^2 (R_M ~ 3 cm)
- 8+21 cm long (7+18 X_0)
- ESR mirror between sections
- **Kuraray SCSF-78** round fibres Ø = 1.0 mm



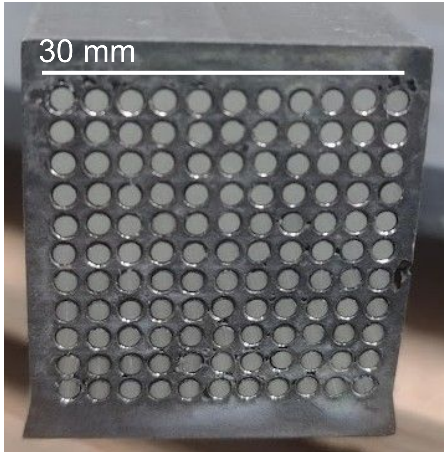
Energy resolution:
Sampling term: **(10.0 +/- 0.6)%**
Constant term: **(1.2 +/- 0.1)%**

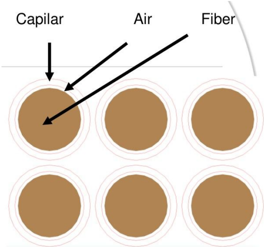
Time resolution: ~ **10 ps** @ 100 GeV

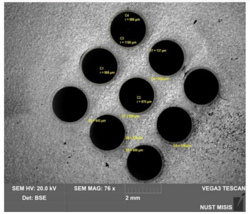




Towards the Pb *Module O*

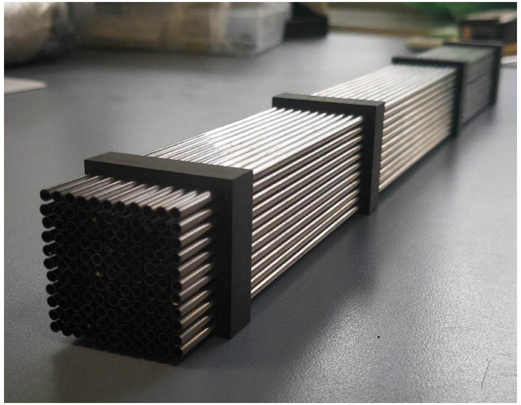


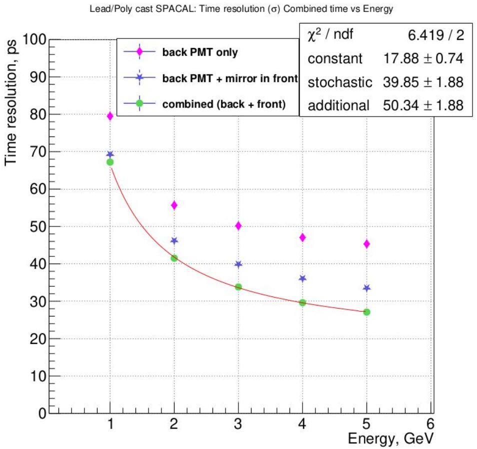




Optimised configuration for mechanical design:
- Round fibres Ø increased 1 mm –> 2 mm
- Use capillary tubes to host fibres

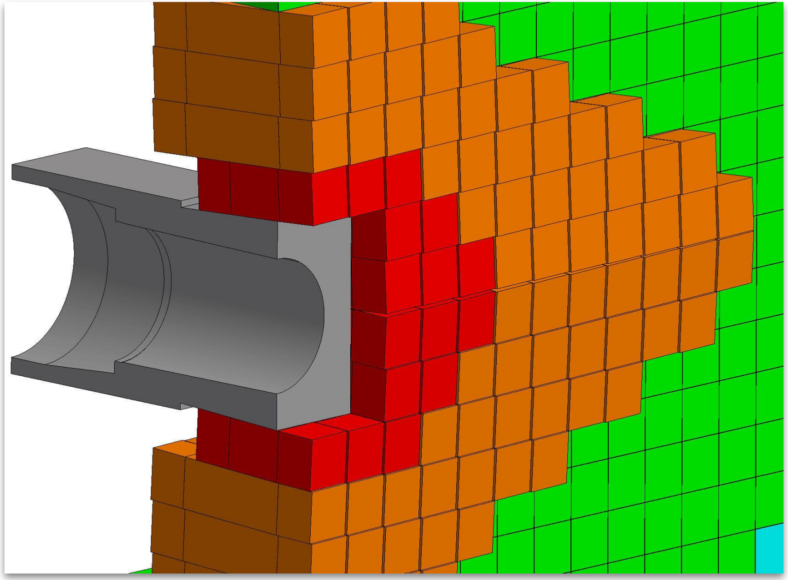
First **1-cell prototype** produced by MISiS, Russia:
- Timing in line with other Pb prototype
- Monte Carlo predicts energy resolution within requirements





New casting procedure under development:

- Aim to produce 9-cell prototype in 2023
- Tooling developed to be re-usable for full size *module 0*



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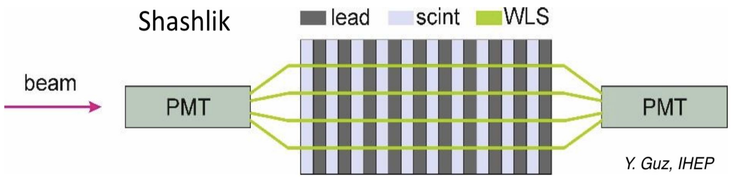
Shashlik

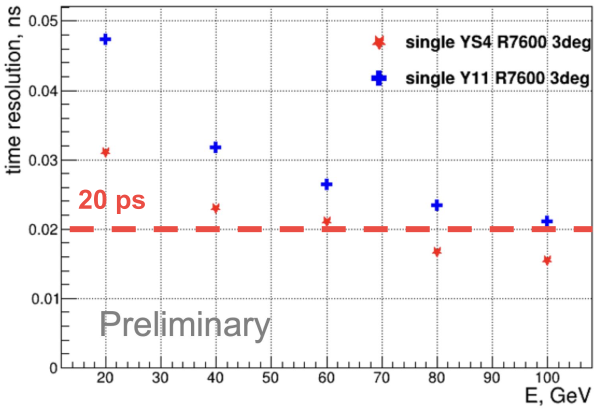
Radiation hardness limit is 40-50 kGy
Already good timing properties to be improved:

- **With faster WLS fibres:**
  - **Kuraray Y11** (7 ns decay time) → Current LHCb
  - **Kuraray YS2** (3 ns decay time)
  - **Kuraray YS4** (1.1 ns decay time)
- With double side readout

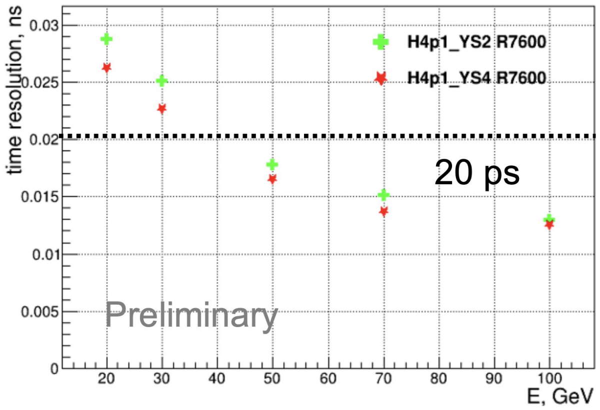


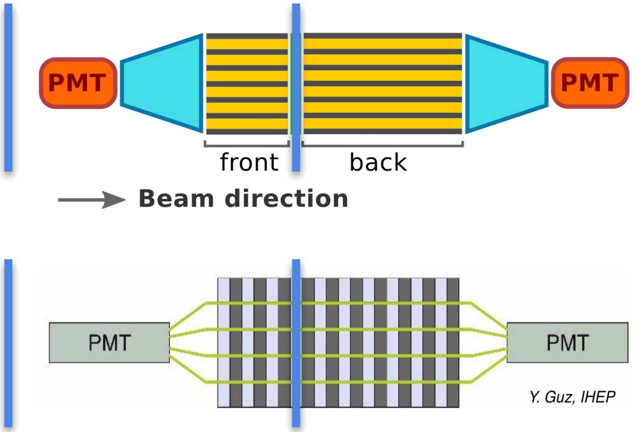
Time resolution at SPS with Hamamatsu R7600U-20 at angle 3°+3°
- **Better than 20 ps above 30 GeV** for double readout

Single-sided readout (CERN SPS 2022)



Double-sided readout (CERN SPS 2021)





Beyond the baseline: **Timing Layer**

Beyond the baseline: Timing Layer

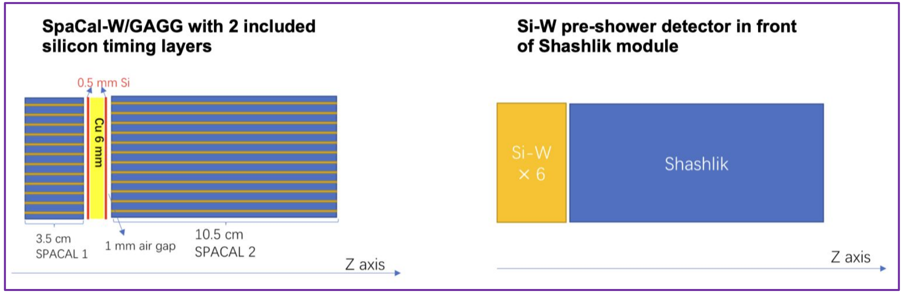
A high-granularity **timing layer** could improve **timing** and **position** to perform shower imaging with **potential reconstruction benefits**

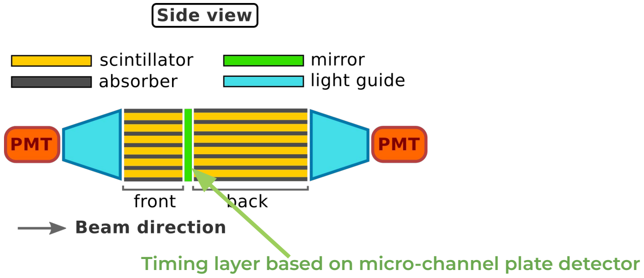
- **Si-W** as pre-shower detector or in shower maximum
- **LAPPD** in shower maximum

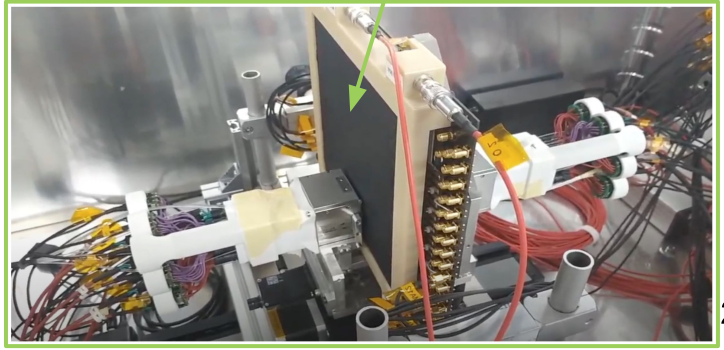
Si-W option investigated in Monte Carlo simulations

LAPPD tested in multiple beamtimes at DESY and SPS:

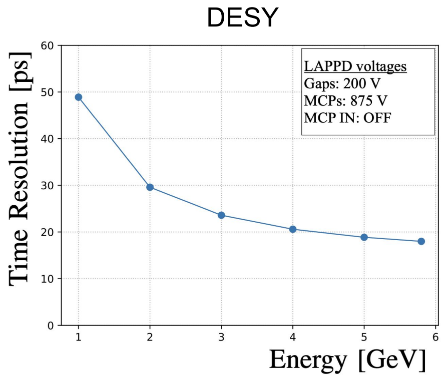
- Used in **i-MCP** configuration —> photocathode off
  - Signal due to secondaries produced in the MCP
  - Better radiation hardness and aging
- R&D ongoing to cope with high-rate environment (e.g. smaller pore size)
- Random forest regressor to combine info from different pixels

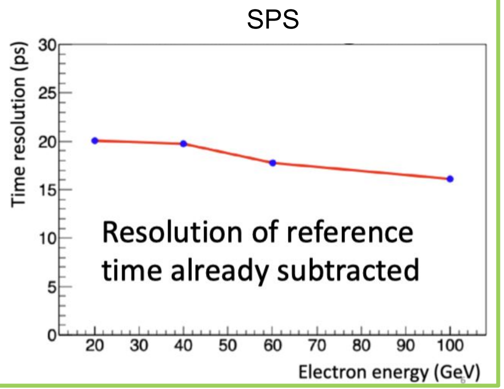






LAPPD Time Resolution





Conclusions

Conclusions

The scintillating sampling technologies tested can meet the requirements for the **ECAL UII PicoCal baseline**

- **Energy resolution** $\sigma(E) / E \approx 10\% / \sqrt{E} + 1\%$ for the optimised configuration
- **Time resolution** **better than 20 ps** for high-energy electron beams
- **Radiation hardness** **up to 1 MGy** for SPACAL with crystal fibres

Now focus on **production of *Module 0*** demonstrators:

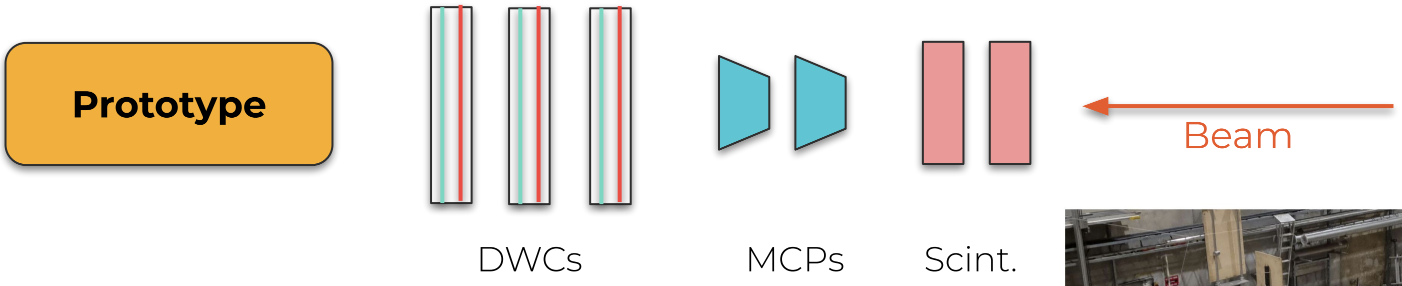
- **SPACAL W-Polystyrene** produced —> **ready** to be tested in May/June
- **SPACAL Pb-Polystyrene** under production —> **expected in 2023**

R&D continuing in all areas:

- Techniques for absorber production:
  - 3D-printing tungsten —> Collaboration with LHCb China
  - Lead casting —> R&D contracts with firm
- Scintillating materials:
  - Accelerating GAGG scintillation to fight spillover
  - Novel cost-effective scintillator **radiation tolerant** to ~100-200 kGy
- Fast PMTs radiation tolerant and with good linearity and light guides

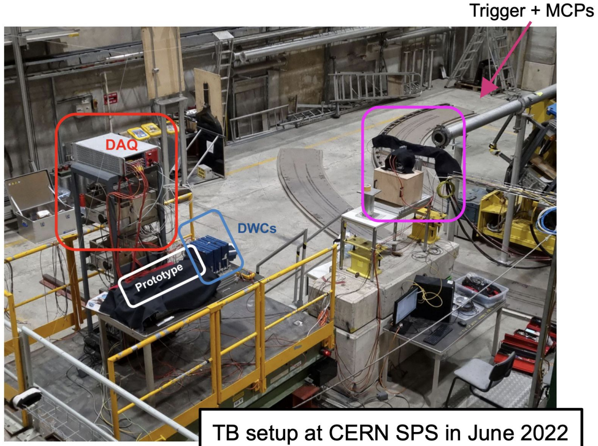
Back-up

Testbeam Set-up



Set-up from the beam:

- **2 scintillating pads** for trigger
- **2 MCP-PMTs** in combination as time reference (T_0)
  - Intrinsic time resolution of **15 ps**
- **3 Delay Wire Chambers** for tracking
- Prototype enclosed in a dark box
  on a stage with 2 rotating axes (azimuth + altitude)



TB setup at CERN SPS in June 2022

Pulses recorded with V1742 CAEN digitizer (DRS4-based), 5 Gs/s, bandwidth 500 MHz

Gadolinium Gallium Aluminium Garnet (GAGG)

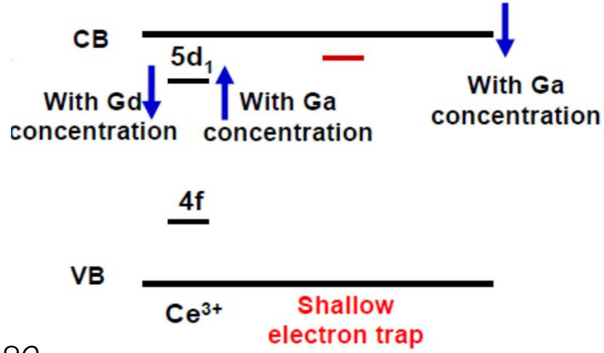
Courtesy of K. Lebbou, ILM

Ce-doped multi-component garnets discovered in 2011.
Amongst them is Gadolinium Gallium Aluminium Garnet $Gd_3Al_2Ga_3O_{12}$:

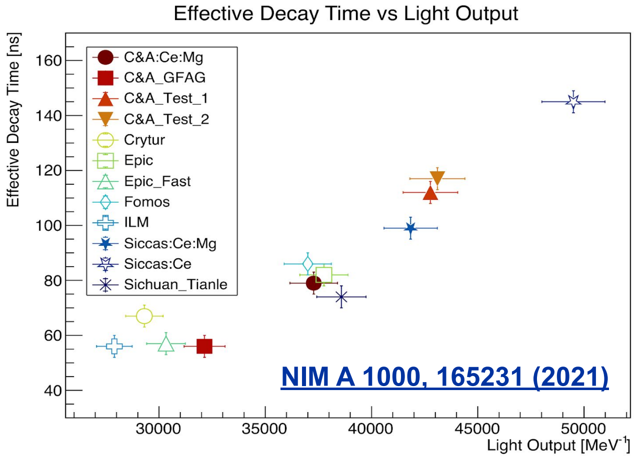
- **High light yield** and **fast scintillation**
  K. Kamada et al., Cryst. Growth Des. 2011, 11, 10, 4484–4490
- **Tunable composition**
  K. Kamada et al., Optical Materials 36 (2014) 1942–1945
- **Acceleration** of scintillation **via divalent ions codoping** (e.g. Magnesium)
  K. Kamada et al., Optical Materials 41 (2015) 63–66

	light yield (photons/MeV)	first decay time (ns)	second decay time (ns)
$Gd_3Al_4Ga_1O_{12}$	15 895	316 (100%)	
$Gd_3Al_3Ga_2O_{12}$	**45 931**	**221 (100%)**	
$Gd_3Al_2Ga_3O_{12}$	**42 217**	**52.8** (73%)	282 (27%)
$Gd_3Al_1Ga_4O_{12}$	17 912	42.2 (34%)	90.5 (66%)
$Gd_3Al_0Ga_5O_{12}$	0	*ND	*ND

K. Kamada et al., Cryst. Growth Des. 2011, 11, 10, 4484–4490



New GAGG Compositions

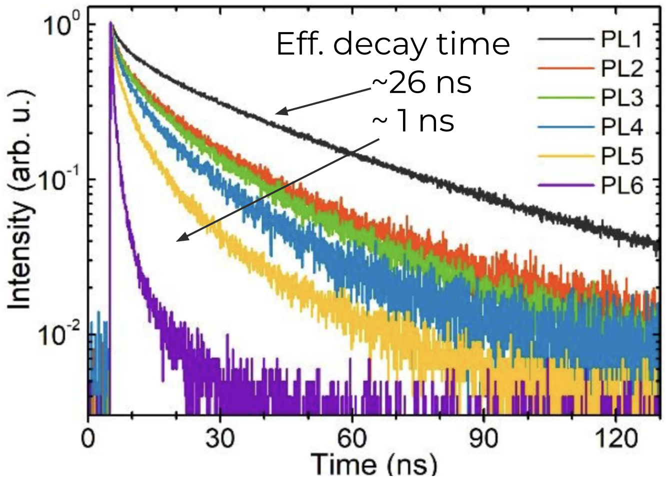


- Current GAGG have scintillation decay time >40 ns
  - Time resolution degradation due to spill-over
  - Pulse shaping techniques (e.g. cable clipping) can recover partially the performance

- Too large light yield can reduce lifetime of the PMTs

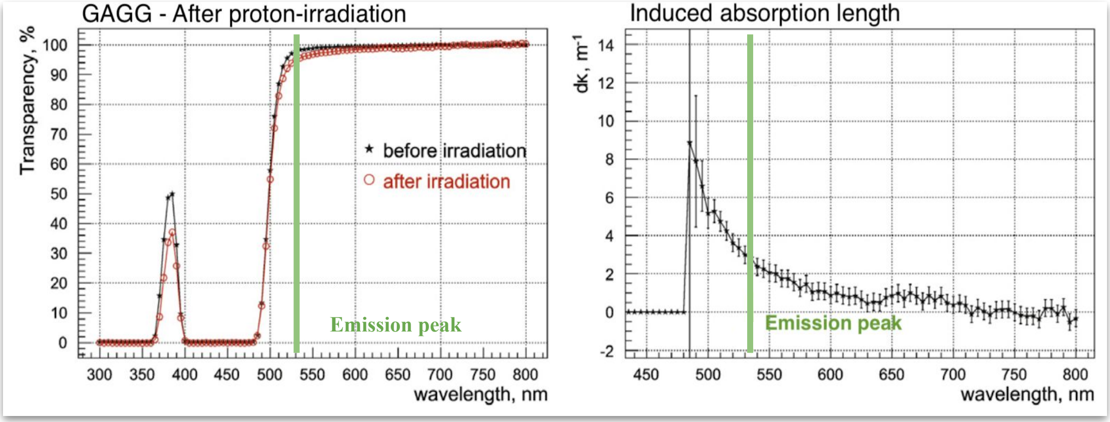
Novel GAGG compositions developed to quench scintillation

- Light yield reduced
- Decay time accelerated
- Time resolution kept competitive



Material Advances, 2022, 3, 6842

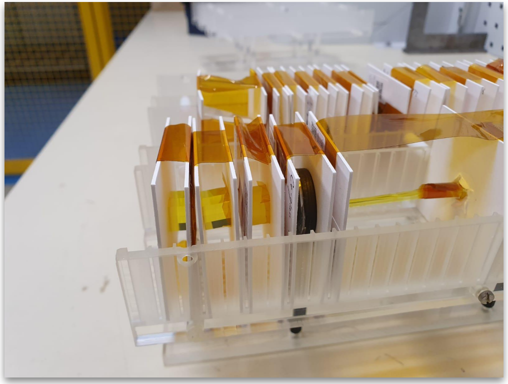
Radiation Hardness



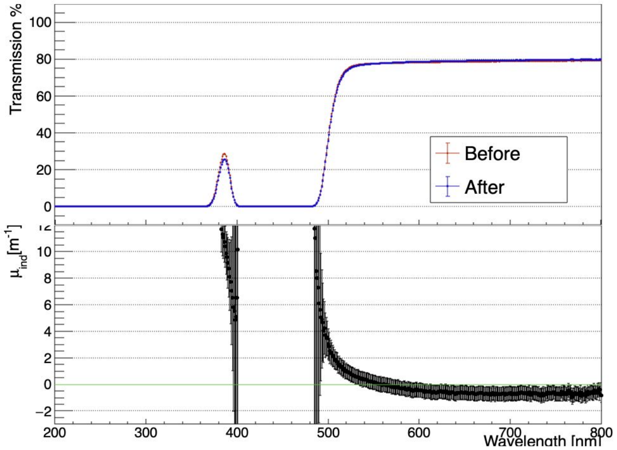
Garnet crystals are **radiation hard**

- Irradiated with protons of 24 GeV/c up to 910 kGy (3.1x10^{15} p/cm^{-2})
  - Induced absorption below 4m^{-1} at the emission peak

V. Alenkov et al., NIM A 816 (2016) 176



C&A GFAG



New samples irradiated to 1x10^{15} p/cm^{-2}

Induced absorption below 2m^{-1} at the emission peak

Radiation Hardness - Fibres

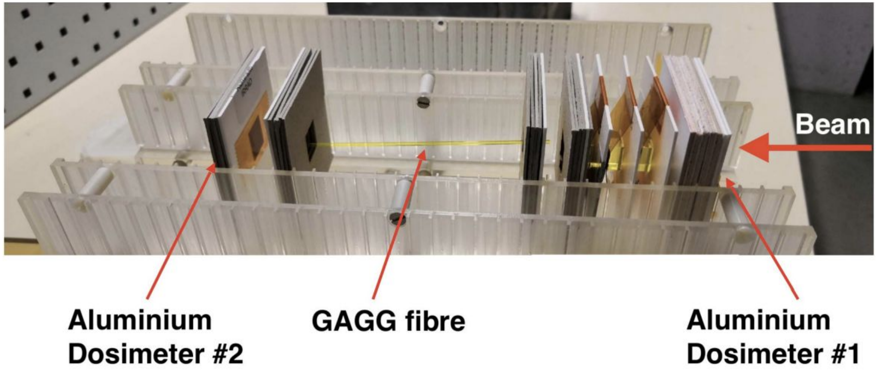


Fig. 2. Setup employed in the irradiation test at CERN PS. One GAGG fiber and three 1-cm^3 GAGG cubes (not discussed here) are placed between two aluminum dosimeters, one upstream, and the other downstream, employed to measure the radiation dose.

[IEEE Trans. on Nuc. Sci., 67, 6, 1003-1008, 2020]

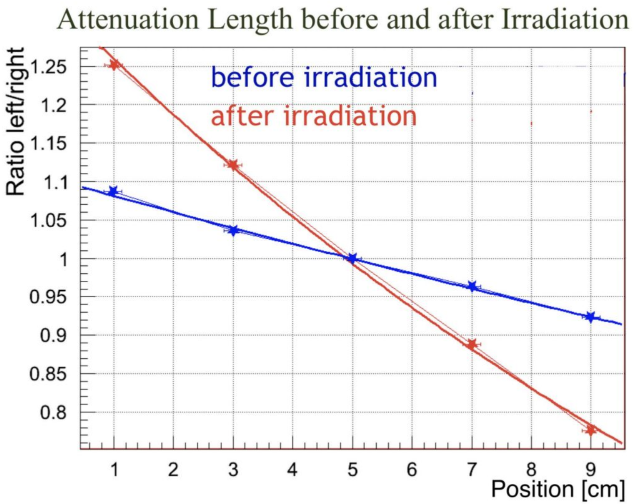


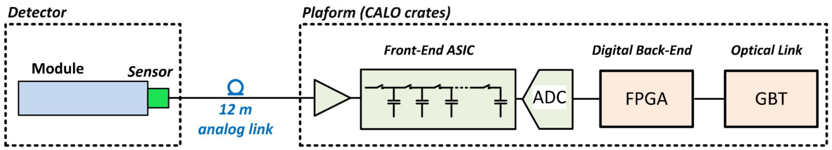
Fig. 8. Ratio between the signals of the two GAGG fiber ends measured before (blue) and after (red) irradiation. The fit functions are as in 1.

TABLE I

MEASURED ATTENUATION LENGTH OF THE GAGG FIBER BEFORE AND AFTER IRRADIATION

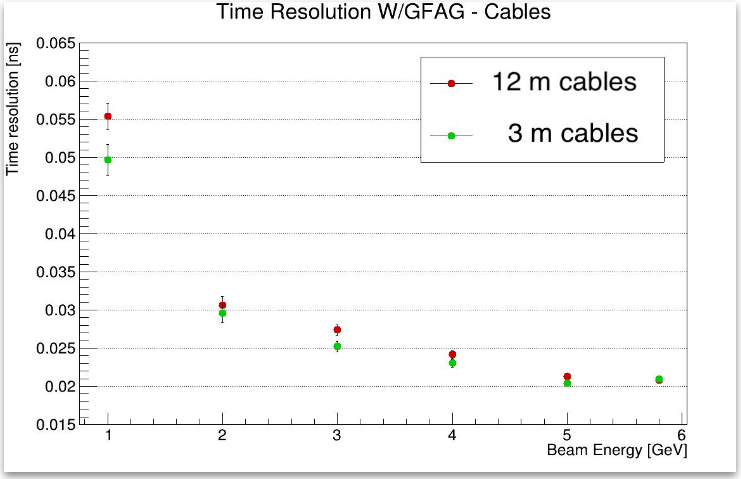
GAGG fibre	λ_{att} [cm]
Before irradiation	101.5
After irradiation	33.6

Time Resolution - Extra

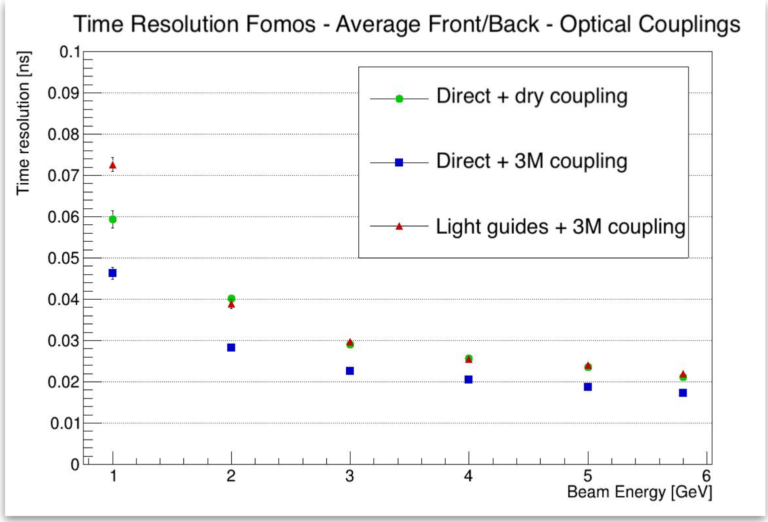


Tested the **current** 12 m long cables at the front and the back instead of 3 m long ones

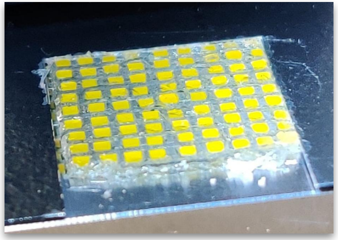
- **No major degradation of time resolution observed**
- Low-attenuation cables to be studied



N.B. plot not comparable to previous slide due to different settings



- Fomos GAGG cells with 3M optical coupling
  - Direct contact + **dry (air)** coupling
  - Direct contact + **optical** coupling
  - **Light guide + optical** coupling on both sides



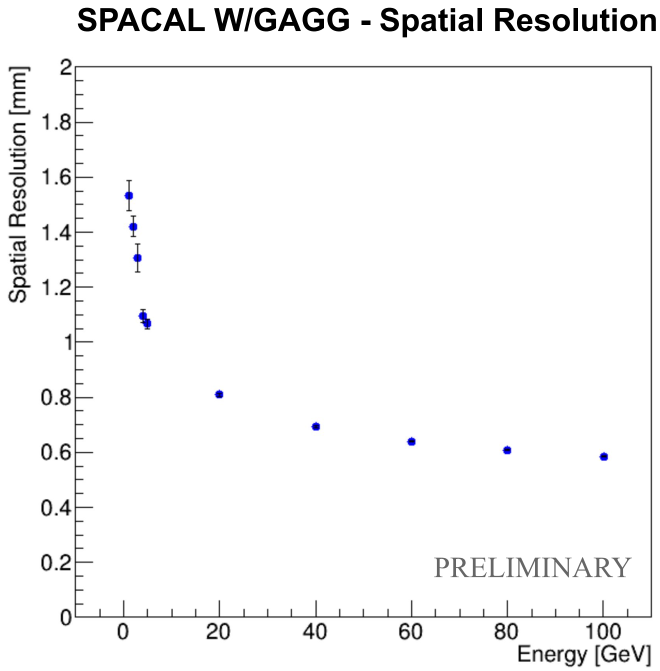
Spatial and Angular Resolution

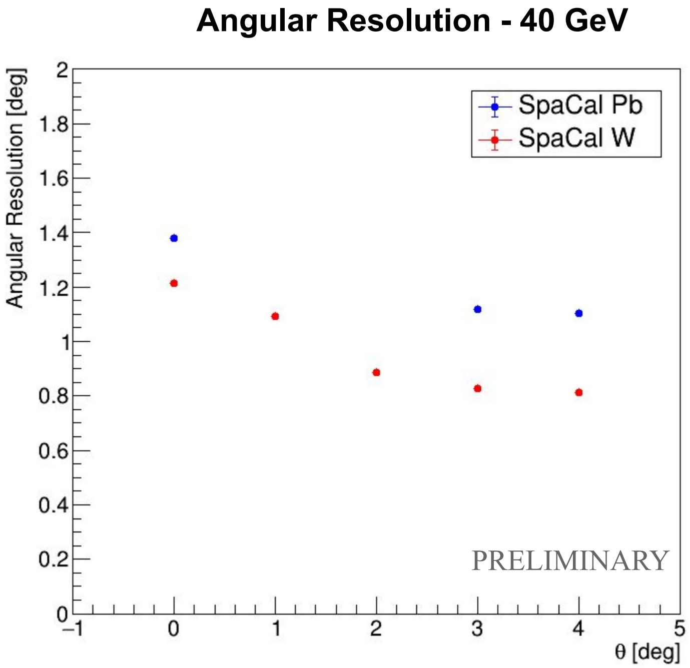
Measured spatial resolution of SPACAL **W-GAGG** with 3x3 cluster @ 3°+3°:

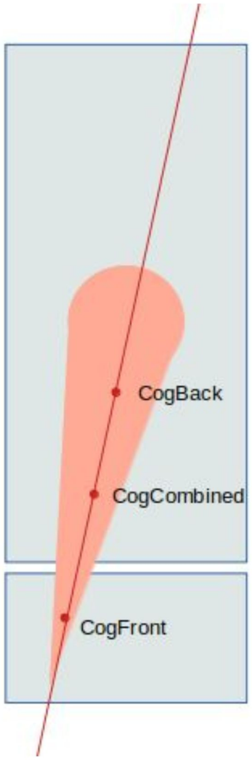
- **<1 mm above 20 GeV** combining the front and back sections

Longitudinal segmentation is a handle **to measure the incidence angle** of the particles:

- Angular **resolution ~1°** at 40 GeV

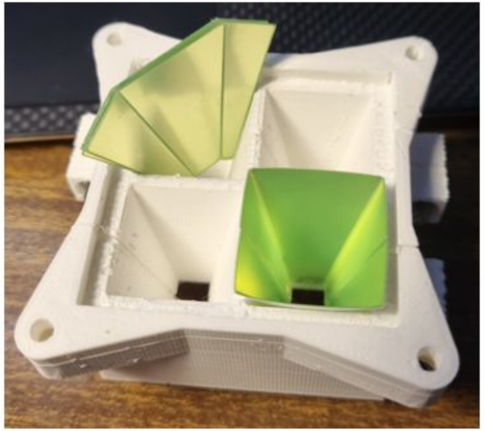


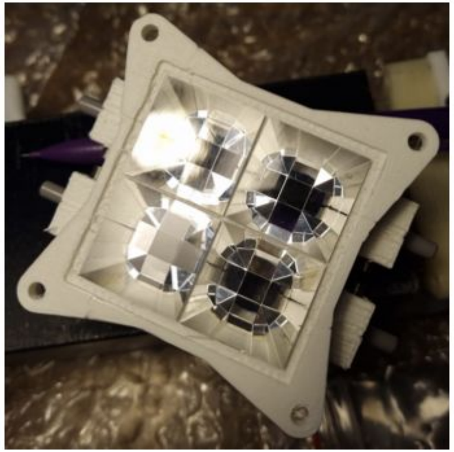




CERN-THESIS-2022-087

Readout





Hollow light guides coated with reflective material
(focus of recent test beams)
→ Intrinsically radiation hard
→ Most cost effective solution

PMT: R7899-20

Used on ECAL/HCAL runs ½

Low timing uniformity over photocathode

10 dynodes

PMT: 7600U-20

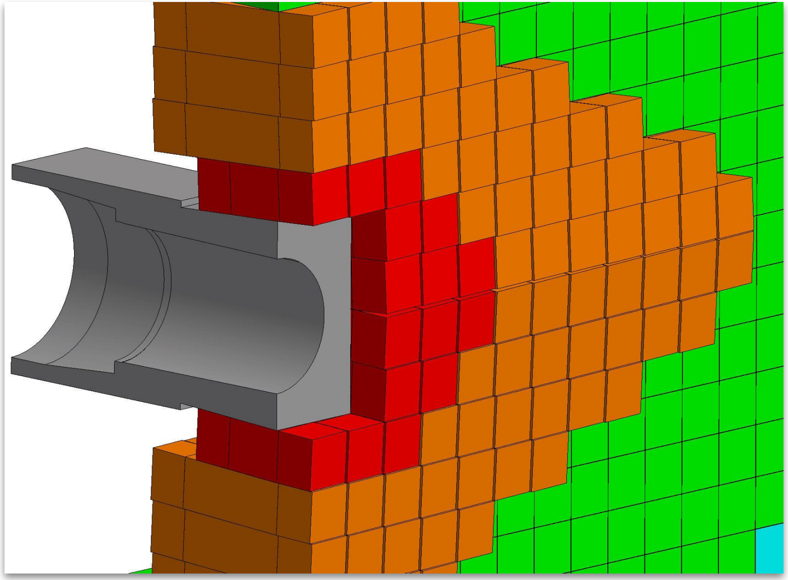
- MCD 2020
- Good timing
- Relatively high gain (10 dynodes)

PMT: R11187

- TILECAL
- Good timing
- Lower gain (8 dynodes)

PMT: R14755U-100

- Lower gain (6 dynodes)
- Good timing
- Smaller but still 1-2 mm large



I. SPACAL - W
   A. W-GAGG
   B. W-Polystyrene
II. SPACAL - Pb
III. Shashlik