Crystal Based Calorimeter R&D

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on behalf of the LHCb SpaCal R&D Group

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Introduction

R&D towards radiation hard and fast 5D electromagnetic sampling calorimeters for future upgrades and projects with the specific use case of the LHCb Upgrade II in LS4.

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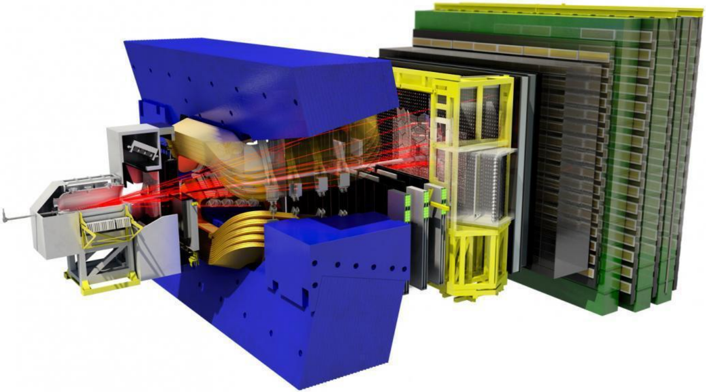
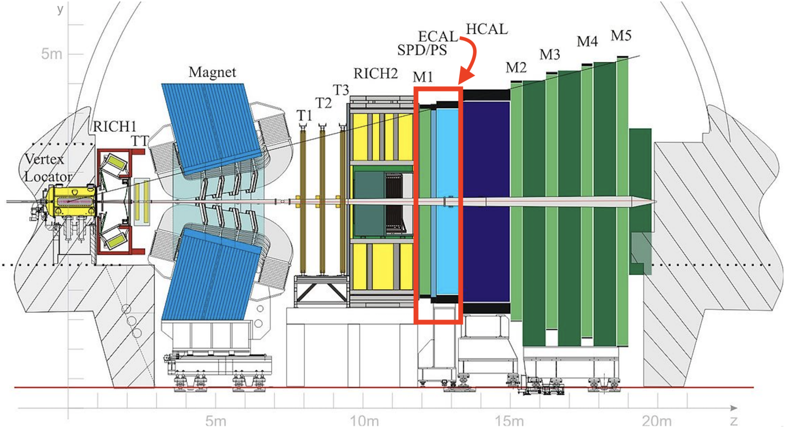


Single-arm forward particle spectrometer at CERN LHC investigating:

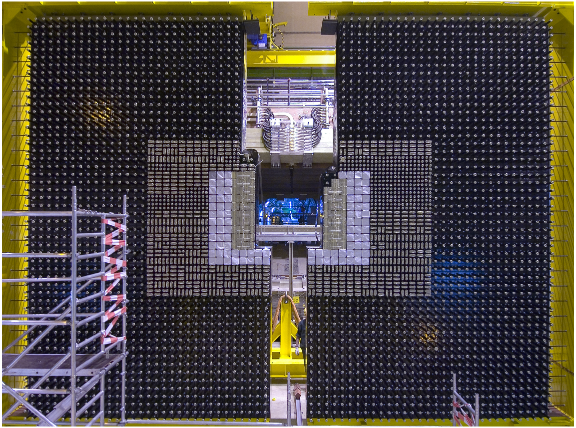
- Parameters of CP symmetry violation.
- Physics of the b-quark and the B-mesons (produced in the forward direction).

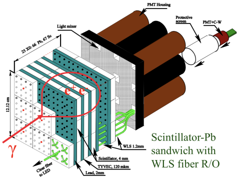
The LHCb Experiment

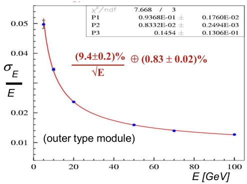


- Design: forward spectrometer with planar detectors
- Size: 21m long, 10m high and 13m wide
- Weight: 5600 tonnes

The LHCb ECal







LHCb Electromagnetic Calorimeter (ECal)

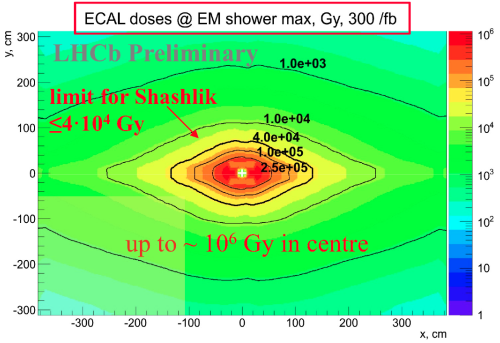
- Dimension: 7.76×6.30 m^2
- Horizontal acceptance: 1.4° - 17°
- Vertical acceptance: 1.4° - 14°

Shashlik ("*skewer*") technology:

- 4 mm thick scintillating plastic tiles.
- 2 mm thick lead tiles.
- WLS fibres running through the tiles.

Motivations

With future LHC upgrade (High-Luminosity LHC), the expected radiation dose will greatly increase depending on the position on the ECal surface.



- Simulations suggest that the centremost area will receive a dose up to 1 MGy.
- No WLS fibres rad hard enough $\Longrightarrow$ Crystals

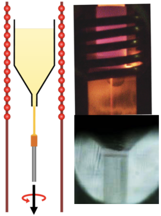
  Scintillating crystal garnets are possible candidate materials.

Detector requirements:

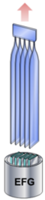
- Radiation hardness: $\simeq 1$ MGy
- Cell size: $\simeq 2 \times 2$ cm^2 $\Longrightarrow$ **Crystal Spaghetti Calorimeter**
- Time resolution: $\simeq 40$ ps
- Energy resolution as it is now.

Crystal Fibres Production

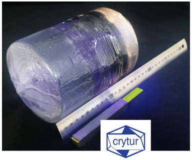
μ-PD Technique

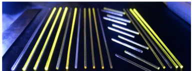


EFG

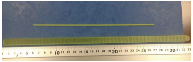


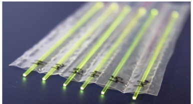
Czochralski
and machining





Several types of Fibers from ILM; Lyon





Square fibers 1x1x10mm³

R&D ongoing to produce them with a high optical quality in a cost-effective and scalable way!

See talk RD18, **E. Auffray**.

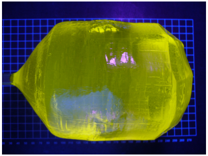
Intelum

Crystal Fibres for SpaCal

Due to the best achievable quality at present, Czochralski-grown fibres were selected for the onset of the SpaCal project.

YAG

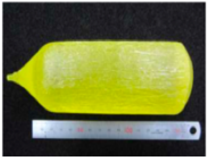
$Y_3Al_5O_{12}$:Ce



(Crytur)

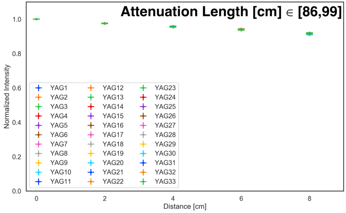
GAGG

$Gd_3Al_2Ga_3O_{12}$:Ce

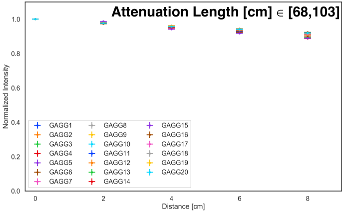


(Fomos)

- YAG $1 \times 1 \times 100$ mm^3

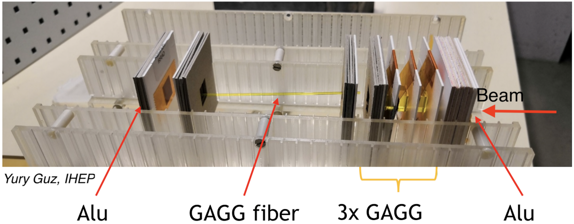


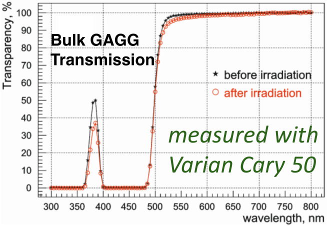
- GAGG $1 \times 1 \times 100$ mm^3

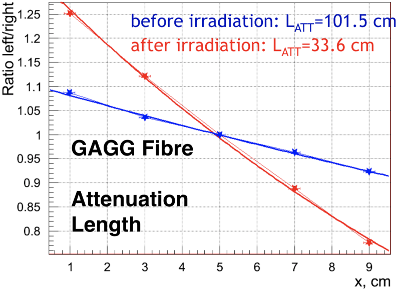


Radiation Hardness

GAGG samples were irradiated with a proton flux of $3.5 \cdot 10^{15}$ p/cm^2, 24 GeV (1.03 MGy) at CERN PS.



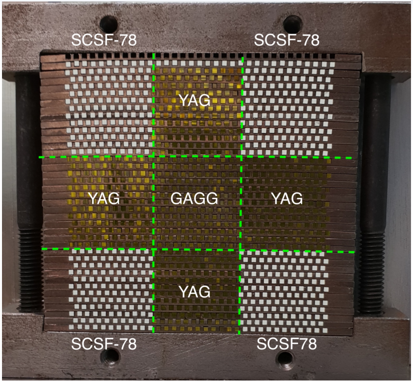




$\Longrightarrow$

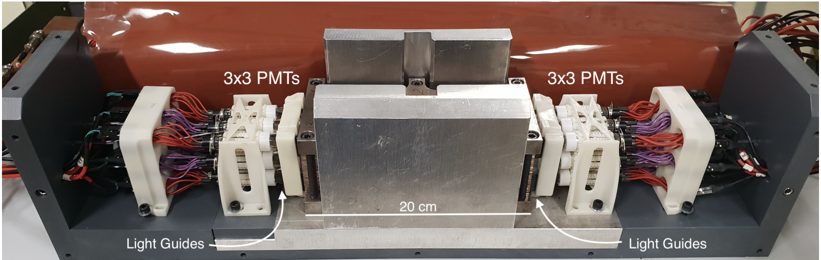
If radiation length $X_0 = 8$ mm, this introduces a constant term 2.5% in the energy resolution for electrons!

The First Prototype

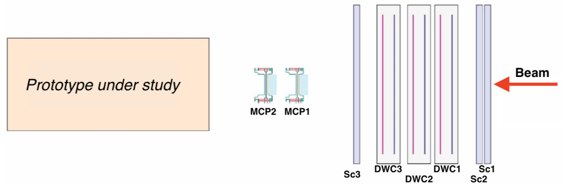


First absorber: old prototype lent by CMS.
Goal: validation of MC simulations.

- Absorber of W/Cu (75/25) alloy.
- Density: 14.9 g/cm^3
- Plates dimension: $1.5\times60\times200$ mm^3
- Cell size: $20\times20\times100$ mm^3
- 549 Plastic fibres $\rightarrow$ 200 mm long
- 1374 Crystal fibres $\rightarrow$ 100 mm long
  - 278 GAGG fibres
  - 1096 YAG fibres
  - Front and back sections are isolated by a thin layer of reflective material.



2018 Beam Test - The Setup

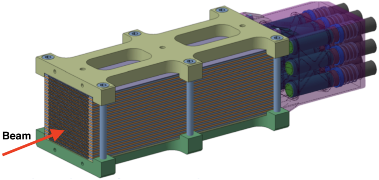


CERN SPS:

- Muons - 180 GeV
- Electrons - 20 GeV

Setup:

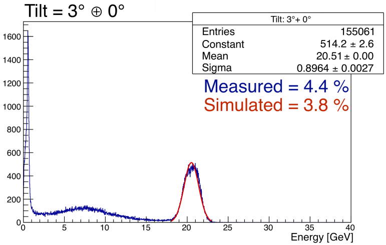
- 3 DWCs for beam tracking.
- 3 Scintillating counters as triggers.
- 2 Cerenkov counters for timing.

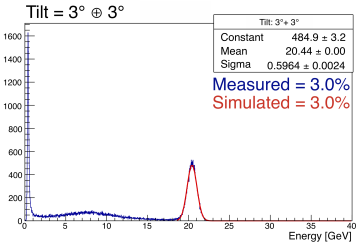


Tilt Angle ($\pm 0.5^\circ$):

- 3° - horizontal plane (azimuthal angle)
- $3^\circ \oplus 3^\circ$ - horizontal and vertical plane (azimuthal $\oplus$ polar angle)
- 90° - horizontal plane (perpendicular to the beam) - Muons only
- 0° - horizontal plane (parallel to the beam) - Muons and electrons timing

Energy Resolution at 20 GeV:
To avoid border effects and leakages, only the events hitting in a 10×10 mm^2 square in the center of the prototype were selected.



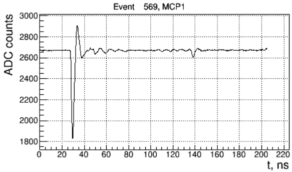


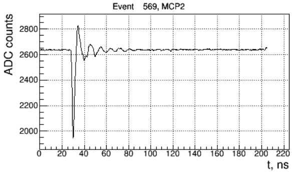
Photoelectrons Yield:
Each PMT is struck by a pulsed LED light.

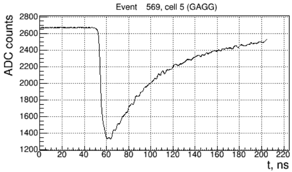
- GAGG / YAG ratio compatible with the one measured in lab.
- Simple but non optimised light guides. Raytracing simulations show a loss of a factor ~ 4

Material	Photoelectrons/MeV	$\pm$
GAGG	9.71	0.22
YAG	6.76	0.16
Plastics	1.15	0.14

2018 Beam Test - Electrons - Timing







The current readout configuration is not optimal for time resolution:

- Light yield hampered by the light guides.
- Readout from the side of the beam entrance worsens timings.

However some measurements were performed on the GAGG front cell (20 GeV electrons):

- Offline CFD technique employed.
- PMT Hamamatsu R12421.
- Corrected for the reference photodetector (MCPs) resolution ($\sigma = 21.8$ ps).

PMT Bias [V]	Time Resolution [ps]
630	85
730	78

2018 Beam Test - Summary

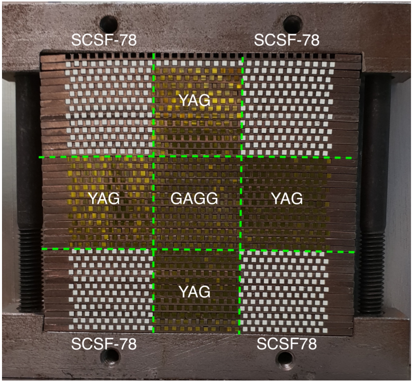
Promising results were obtained in this beam test, encouraging to continue the project.

- Radiation hardness ✓
- High granularity ✓
  Limited by the cell size: 20×20 mm^2.
- Energy resolution (20 GeV electrons):

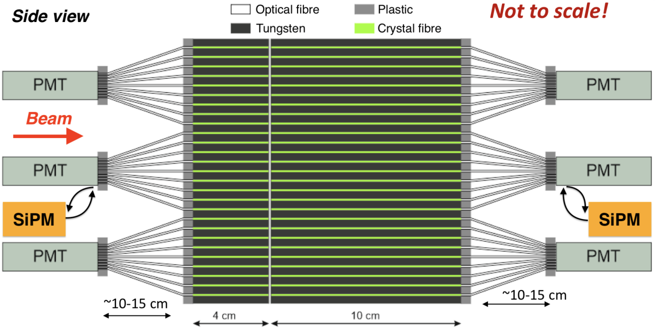
Prototype Tilt	Resolution $\frac{\sigma}{\langle E\rangle}$ [%]
$3^\circ \oplus 0^\circ$	4.4
$3^\circ \oplus 3^\circ$	3.0

- Time Resolution

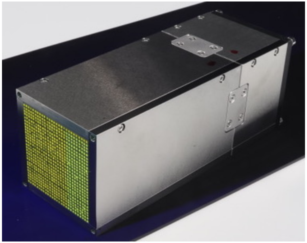
PMTs Bias [V]	Resolution σ [ps]
630	85
730	78



2019 SpaCal Prototype



- Absorber of pure Tungsten 14 cm long.
  Density: 19 g/cm^3.
  2 sections: 4 + 10 cm.
- Cell size: 1.5 $\times$ 1.5 cm^2.
  - 6 YAG cells.
  - 3 GAGG cells.
- Fibre size: 1 $\times$ 1 $\times$ 40/100 mm^3.
- Each scintillating fibre coupled to an optical fibre.
- Test with both PMTs and SiPMs.



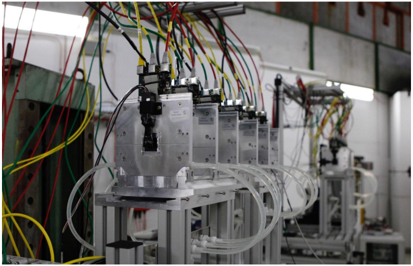
The prototype

2019 Beam Test

Next beam test at DESY, November 2019 and May 2020.

Beam constraints:

- Electrons e^{-}
- Energy $\leqslant$ 6 GeV



Investigate:

- Energy resolution at different angles
- Time resolution
- GAGG and YAG comparison
- Test of PMTs and SiPMs

Goal:

Validation of the Monte Carlo simulation code!

What's Next

First simulation and prototype studies are encouraging and have shown that the Crystal Garnet Spaghetti Calorimeter could evolve towards a viable option for the inner most area of the LHCb Electromagnetic Calorimeter. However, a multitude of studies are still ahead of us:

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  - Enhance garnets timing properties.
  - Verify the radiation hardness of different growth techniques.
  - Test other crystals.

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  - Qualification of a suitable radiation hard photodetector.

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- Fast and radiation hard photodetectors and readout electronics:
  - Design of fast readout electronics.
  - Qualification of a suitable radiation hard photodetector.
- Cost effective technologies for the outer ECAL regions:
  - Search for sufficiently radiation hard WLS fibres.
  - Try the double-side readout shashlik.
  - Experiment with different designs.
  - Inspect other scintillators.

BACKUP

Energy Calibration

In order to find the calibration factors C_i to convert from ADC Channels to Energy, the following procedure was performed:

1. First a set of crude calibration factors μ_i was found making use of the muons as in:

$$\mu_i = \frac{k}{\langle A_i^\mu \rangle} \tag{1}$$

   $\langle A_i^\mu \rangle$ is the mean signal in ADC channels generated by the passage of a muon in the channel i, and k is a fitting constant.

2. Secondly, a new set C_i was found minimizing the deviations from the known mean energy E_0 (20 GeV) value:

$$\begin{cases} \nabla_c \sum_{ev} \left[E^{ev} - E_0\right]^2 = 0 \\ E^{ev} = \sum_i C_i A_i^{ev} \end{cases} \tag{2}$$

- Leakages must be avoided $\Longrightarrow$ 40×40 mm^2 and 18-22 GeV selection window
- Due to impure beam the procedure is iterate until convergence is reached.
- To help convergence the ratio between front and back calibration factors should be fixed to the muons' ones (*see NIMA 485 (2002) 385*):

$$c_i = \frac{\mu_i}{\mu_{i-9}} c_{i-9} \qquad\qquad i = 10, ..., 18$$

2018 Beam Test - Readout Side

Beam →

Standard

Beam ←

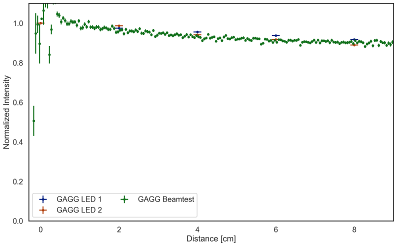
Rotated 180°

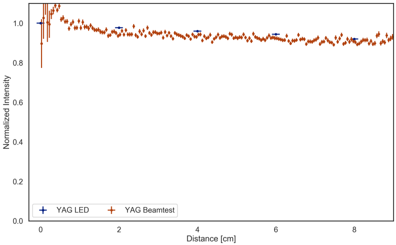
Configuration	PMT Bias [V]	Time Resolution [ps]
Standard	1000	66
Rotated	1000	177

- A shower longitudinal shift Δz produces a time shift $\Delta t = \frac{\Delta z}{c}(n-1)$ in the standard configuration, whereas produces a fluctuation $\Delta t = \frac{\Delta z}{c}(n+1)$ if the particle is entering from the PMT side $\Longrightarrow$ Worse timing.
- The same argument applies also for the SpaCal prototype!

2018 Beam Test - Muons - Attenuation

- Placing the prototype orthogonally to the beam, the light attenuation can be checked.



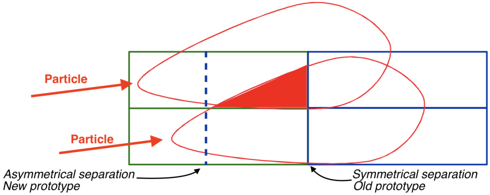


- Attenuation lengths λ compatible with those measured in laboratory.

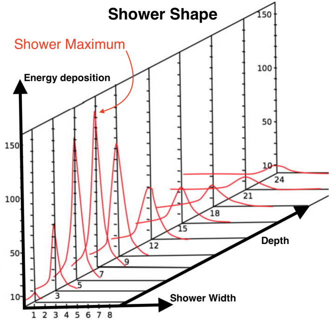
$$\lambda \in [89, 99] \text{ cm}$$

2019 SpaCal Prototype

A new prototype has been designed and built in collaboration with the LHCb reconstruction group.



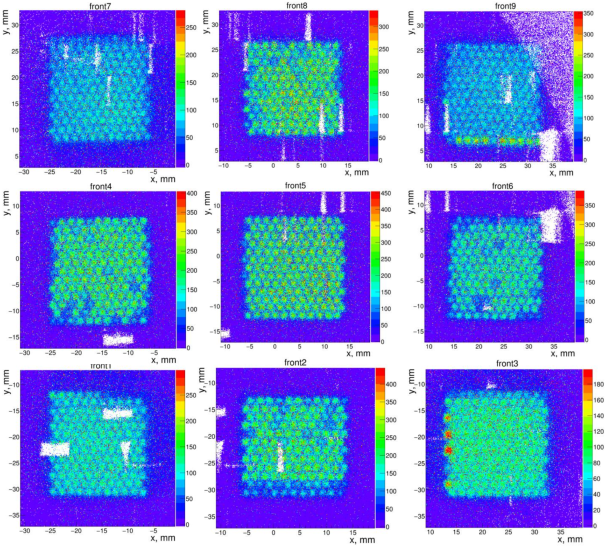
- Shorter front section to enhance shower separation...



- ... but long enough to contain the shower maximum.

2018 Beam Test - Muons - Fibres Granularity

Combining the space information given by the wire chambers and the energy deposition in the prototype it is possible to reconstruct the granularity intrinsically provided by the fibers.



Clearly visible:

- Difference in light yield
- Light guides misplacements
- DWCs inefficient areas
- **Individual fibres resolved.**