ECAL - Testbeam Results and Simulations

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on behalf of the LHCb SpaCal R&D Group, ITEP and IHEP

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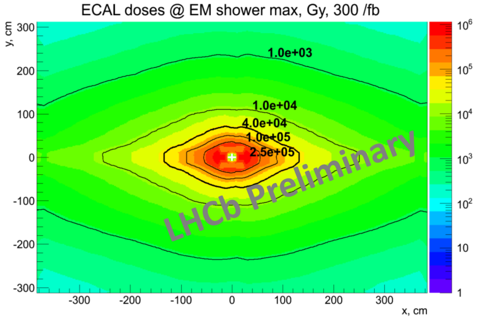
With future LHC upgrades the expected radiation dose will naturally divide ECAL in *at least* 3 different areas.



- Simulations suggest that the centremost will receive a dose up to 1 MGy.
- Necessary a radiation hard and dense material.
  $\rightarrow$ Crystals

  YAG and GAGG are possible candidate materials.

Detector requirements:

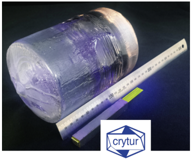
- High radiation hardness
- Small cell size and Moliere radius
- Good energy resolution
- Good time resolution

$\Longrightarrow$ **Crystal Spaghetti Calorimeter**

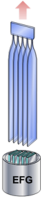
Crystal Fibres

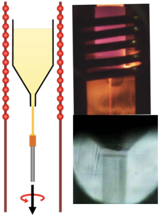
Crystal fibres can be grown employing different techniques.

Czochralski	EFG	μ-PullingDown



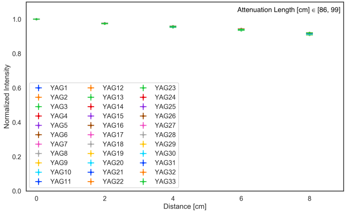
R&D led in the framework of the Intelum Project, ERP grant 644260

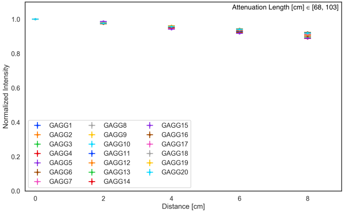




As of today, Czochralski technique already provides YAG and GAGG fibres of the desired quality:

- YAG $1 \times 1 \times 100$ mm^3 (*Crytur*)
- GAGG $1 \times 1 \times 100$ mm^3 (*Fomos*)

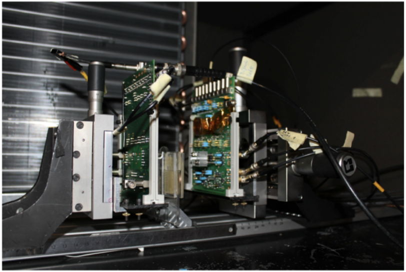




Measuring Equipment

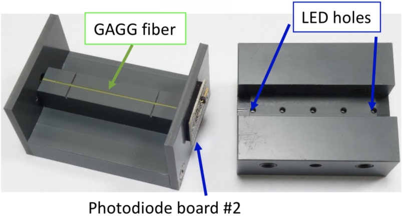
Several benches for in-depth bulk and fibre crystals characterization are already setup and working at CERN.

- Attenuation Length
- Light Yield
- Coincidence Time Resolution
- Decay Time
- Rise Time



CTR Bench developed by Stefan Gundacker.

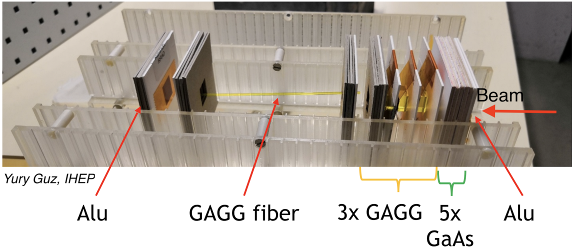
Attenuation length bench for quality control (Yury Guz).



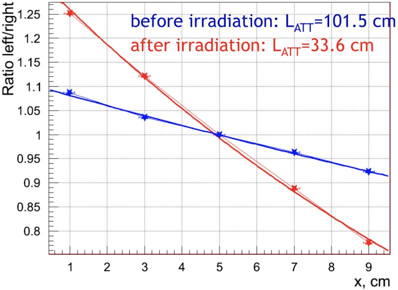
Radiation Hardness

Between September and October 2018, GAGG samples were irradiated with protons.

- Irradiation: $3.5 \cdot 10^{15}$ p/cm^2, 24 GeV (1.03 MGy)
- 3 GAGG cubes 1cm^3
- 1 GAGG fiber, 1x1x100 mm^3
- 2 Aluminium dosimeters, 1 cm^2



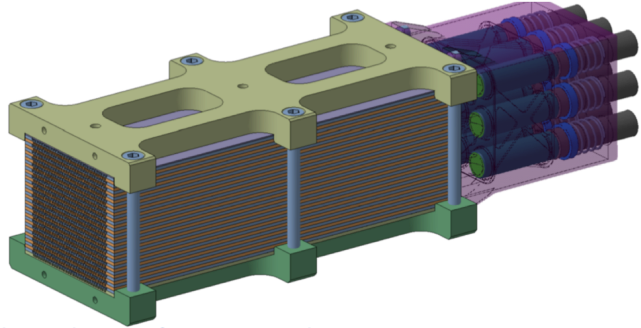
- GAGG Fiber - 1x1x100 mm^3



- Results compatible with previous tests.
- An attenuation length of 33 cm with an X_0 of 8 mm adds 2.5% to the energy resolution constant term.
- Other Cerium-doped Garnets are expected to have similar properties.
- **Crystals are a viable option.**

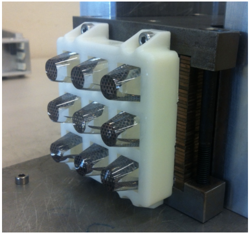
The Absorber

Absorber made of Tungsten/Copper alloy plates.

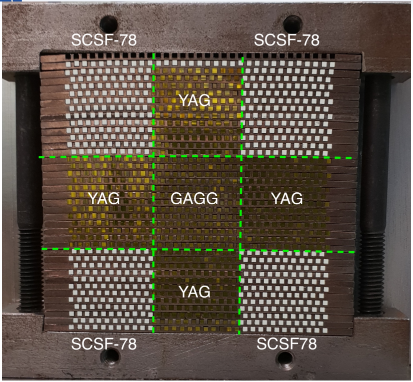


N.Siegrist, H. Gerwig, CERN

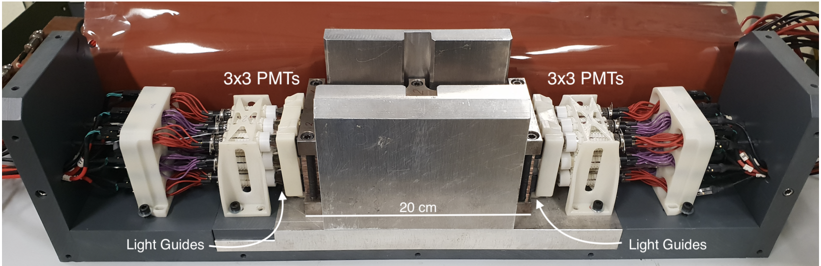
- Density of 14.9 g/cm^3
- $1.5 \times 60 \times 200$ mm^3 plates
- $1 \times 1 \times 200$ mm^3 grooves carved into each plate
- Shifted holes positions in adjacent plates
- 200 mm long to reach 25 X_0
- PMT-Fibers coupling via PMMA light guides $\longrightarrow$



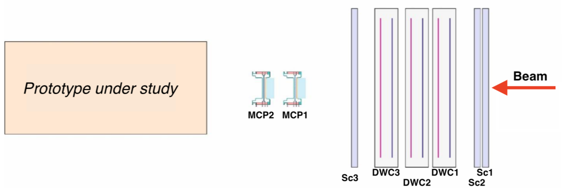
2018 Beamtest SpaCal Prototype



- 549 Plastic fibers → 20 cm long
- 1374 Crystal fibers → 10 cm long
  - 278 GAGG Fibers
  - 1096 YAG Fibers
    Some old samples (poorer quality) were also employed.
  - Thin layer of Aluminium deposited on the fibers' end facing the inside.
    ⟹ Front and back sections are isolated.
- PMMA Light guides
- Front and back readout

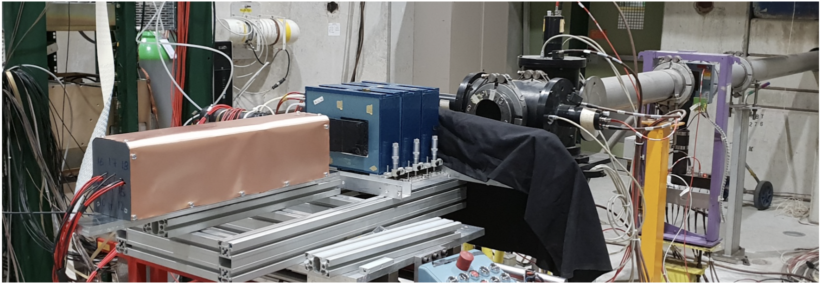


The Setup



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

- **CAEN TDC V1290N** - DWCs readout
- **LeCroy ADC 1182** - Amplitude measurements
- **CAEN DT5742 digitizer** - Waveform recording



Configurations Measured

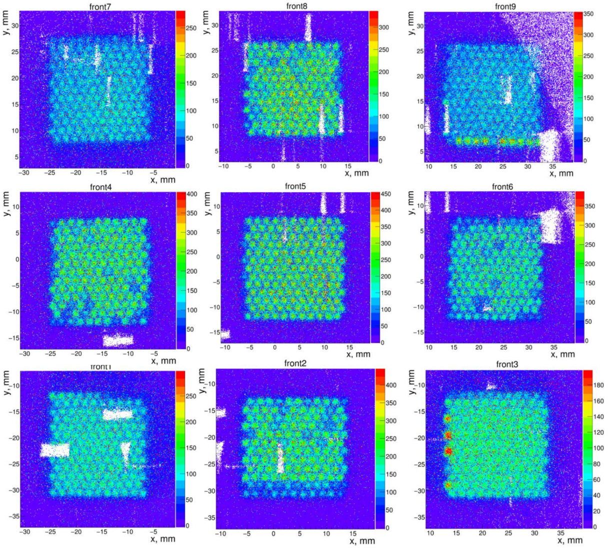
Due to technical difficulties during October at CERS SPS facilities, the highest electron energy available with a sufficient beam purity was 20 GeV.
Some timing measurements were tried also at 30 GeV.

- Beam Particles:
  - Muons - 180 GeV
  - Electrons - 20 GeV

- 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 only

Muons - 0° - Fiber Granularity

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



Clearly visible:

- Poorer quality fibers
- Light guides misplacements
- DWCs inefficient areas

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:

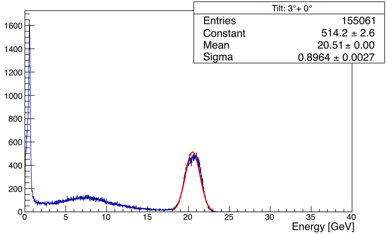
$$c_i = \frac{\mu_i}{\mu_{i-9}} c_{i-9} \qquad\qquad i = 10, ..., 18$$

Electrons - Energy Resolution

To avoid border effects and leakages, only the events in a 10×10 mm^2 square in the center of the prototype were selected.

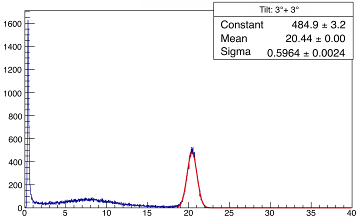
Angle $= 3^\circ \oplus 0^\circ$

- Measured resolution: $\frac{\sigma}{\langle E \rangle} = 4.4$ %
- Simulated: 3.8 %
- *Energy resolution more sensitive to misalignments at low angles.*



Angle $= 3^\circ \oplus 3^\circ$

- Measured resolution: $\frac{\sigma}{\langle E \rangle} = 3.0$ %
- Simulated: 3.1 %



Optical photons not yet implemented in the simulation.

Electrons - Photoelectrons Yield

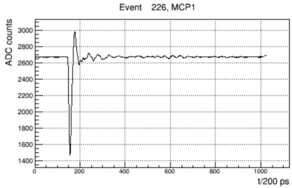
Once the detector has been calibrated in energy, is then possible to retrieve the Photoelectrons Yield.

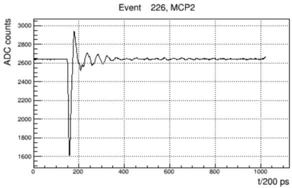
- Each PMT is illuminated by a pulsed LED light.
  Poisson statistics provides the signal amplitude of a single photoelectron.
- Knowing the energy calibration factor, the photoelectrons yield can be retrieved:

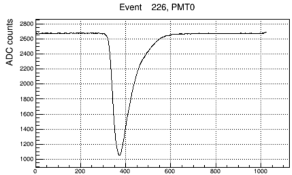
Material	Photoelectrons/MeV	$\pm$
GAGG	9.71	0.22
YAG	6.76	0.16
Plastics	1.15	0.14

- Photoelectron yield hampered non negligibly by the light guides.
  Preliminary raytracing simulations show an improvement of a factor of $\sim$4 with air coupling.

Electrons - Timing







Yury Guz, IHEP

The timing was measured applying a CFD technique offline.

- SpaCal GAGG cell:
  - Readout - PMT Hamamatsu R12421.
  - Corrected for the reference resolution.

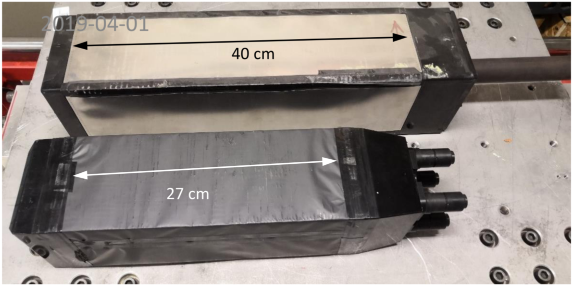
PMT Bias [V]	Time Resolution [ps]
630	85
730	78

- Current readout configuration is supposed to greatly decrease (factor $\sim$ 2-3) the time resolution.

The MPCs reference resolution is 21.8 ps.

Timing - Present ECal Module

In addition to the SpaCal prototype, the timing properties of a current LHCb ECal Shashlik module and of a novel more compact Shashlik module were tested.



- Present ECal Shashlik module:
  - Readout - PMT Hamamatsu R7899-20.
  - Electrons energy: 20 and 30 GeV.

Beam Energy [GeV]	PMT Bias [V]	Time Resolution [ps]
20	800	69
30	800	56
30	750	57
30	700	77

Timing - Compact Shashlik Module

The shorter module was tested in the standard configuration and rotated by 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!
- Later found out that noisy PMTs were used $\Longrightarrow$ Overall time resolution deteriorated.

Conclusions

The Crystal Spaghetti Calorimeter was proven to be a viable option for the inner area of the LHCb Electromagnetic Calorimeter:

- Crystals were shown to satisfy the radiation hardness requirements.
- Granularity provided by the fibers, shower dimensions by the absorber.
  - Pure tungsten absorber - The option is being discussed with MISIS at present.
- A decent energy resolution was found just out of the box.
  - Light raytracing - Currently being implemented in the full simulation code.
  - Different absorber production techniques - Joint effort with MISIS ongoing.
  - In-line absorber grooves geometry - Being simulated now.
  - Non-symmetrical longitudinal segmentation - Being investigated now.
  - Light guides are inefficient and deteriorate the energy resolution - Different solutions to be investigated.
- Time resolution is close to the desired values for both the SpaCal and the Shashlik modules.
  Improvements are expected to come from:
  - Tuning of the crystals properties - Joint effort with Crytur and Fomos ongoing.
  - Different readout schemes - To be investigated.
  - Ad hoc electronics - Research ongoing (*ICCUB, IFIC*)

Future beamtest planned at DESY in November 2019.