ECAL Technologies

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on behalf of the SPACAL R&D group
(LHCb and Crystal Clear Collaboration)
Outline

➔ Motivation
➔ Investigation on garnet-based crystal fibers
➔ Spacal 2018 & 2019 prototypes: beamtest results
➔ Shashlik beamtest results
➔ Photodetectors and readout electronics
➔ Timing plane
➔ Conclusions and perspectives
Motivation for ECAL upgrade

- Sustain expected **radiation dose**, up to 1MGy and $\leq 6 \times 10^{15}$ cm$^{-2}$ for 1MeV neq/cm$^2$ at 300 fb$^{-1}$
- Introduce **fast timing** resolution (few tens of ps) for pile up mitigation, and better energy reco.
- Increase **granularity** to reduce occupancy
- Keep energy resolution in the order of $\sigma(E)/E \sim 10\%/\sqrt{E} \pm 1\%$

**General upgrade of ECAL**

- Central part (max 32 modules) needs to be replaced already during LS3
- Major upgrade foreseen for LS4 for the rest of the calorimeter, with less demanding radiation requirements

**ECAL doses @ EM shower max, Gy, 300 /fb**

**Limit for Shashlik**
- $\leq 4 \cdot 10^4$ Gy
- Up to $\sim 10^6$ Gy in centre
ECAL upgrade: possible options

<table>
<thead>
<tr>
<th>Homogeneous Crystal</th>
<th>Shashlik Module</th>
<th>Spaghetti Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can require long crystals (order 40 cm) to contain 25 $X_0$</td>
<td>Can be made very compact (~ 15-20 cm)</td>
<td>Can be made very compact (~ 15-20 cm)</td>
</tr>
<tr>
<td>Fixed Moliere Radius</td>
<td>Tunable Moliere Radius</td>
<td>Tunable Moliere Radius</td>
</tr>
<tr>
<td>Good energy resolution, few %/$\sqrt{E}$ (but material budget in front of ECAL should be kept at minimum)</td>
<td>Good energy resolution</td>
<td>Challenging optimization to reach good energy resolution</td>
</tr>
<tr>
<td>Very good homogeneity</td>
<td>No radiation-hard WLS fibers (yet) to transport light</td>
<td>Fibers scintillate AND transport light!</td>
</tr>
<tr>
<td>Large volume of crystal $\Rightarrow$ high cost</td>
<td>Some cost optimization possible</td>
<td>Some cost optimization possible</td>
</tr>
</tbody>
</table>

Started R&D on Spaghetti type module (SPACAL)
Crystal fibers production methods

**μ-PullingDown**

**Edge-defined film-fed growth (EFG)**

**Czochralski**

Feasibility study carried out in the frame of the **Intelum project** (EU Rise grant 644260)
Crystal fibers for SPACAL

Czochralski-technique selected for SPACAL R&D activity, since currently it provides the best quality.

YAG (Crytur) 1 x 1 x 100 mm³

GAGG (FOMOS) 1 x 1 x 100 mm³
Radiation Hardness - GAGG

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

➔ Contribution of 2% to constant term of energy (if radiation length $X_0 = 0.8$ cm)

➔ Performance of GAGG acceptable after ~1 MGy (100 Mrad) irradiation
GAGG samples from several producers characterized in terms of:
- Coincidence timing resolution (CTR) @ 511 KeV
- Light output
- Scintillation kinematics

- Aimed at producing faster crystals speeding up scintillation process
- Influence of co-doping on timing performance (especially on rise-time)

S. Gundacker et al, NIMA A 891 (2018) 42–52
First SPACAL prototype - 2018

Performed at CERN SPS H8: **180 GeV muons and 20 GeV electrons**

- W/Cu alloy absorber (75/25), 14.9 g/cm$^3$
- Module length 20 cm ($25 X_0$)
- Longitudinal segmentation: 10 cm + 10 cm
- 9 cells of 2 x 2 cm$^2$ with Moliere Radius ~1.5 cm
- 1 cell of GAGG and 4 cells of YAG
- 4 cells of SCSF-78 (KURARAY)

**Prototype under study**

Cerenkov counters

Beam tracking

Scintillator counters

**READOUT**

- CAEN TDC V1290N - DWCs readout
- LeCroy ADC 1182 - Amplitude measurement
- CAEN DT5742 digitizer - Waveform recording
Energy resolution with 20 GeV $e^-$

With different tilt angles, selecting events hitting a 10 x 10 mm$^2$ square in the center of prototype.

<table>
<thead>
<tr>
<th>Material</th>
<th>Photoelectrons/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAGG</td>
<td>9.71 ± 0.22</td>
</tr>
<tr>
<td>YAG</td>
<td>6.76 ± 0.16</td>
</tr>
<tr>
<td>Plastic</td>
<td>1.15 ± 0.14</td>
</tr>
</tbody>
</table>

$\rightarrow$ GAGG/YAG ratio compatible with lab measurements

$\rightarrow$ Efforts to improve light coupling (ray-tracing simulations show factor ~4 light loss)
Timing resolution with 20 GeV $e^-$

Time measurement on GAGG front cell:

- PMT Hamamatsu R12421
- Offline CFD technique
- Corrected for MCPs reference photodetectors resolution ($\sigma = 21.8$ ps)
- Best value $\sigma_t = 73$ ps
2019 SPACAL prototype

➔ Shorter front section to improve time resolution

➔ Shorter front section to enhance shower separation
2019 SPACAL prototype

Beam test at DESY: 1 to 5 GeV electrons

Palaeoabsorber

➔ Pure tungsten absorber
  ➢ 14 cm long
  ➢ Density 19 g/cm³
  ➢ 6 YAG cells
  ➢ 3 GAGG cells

➔ Cell size 1.5 x 1.5 cm²

➔ Each scintillating fiber coupled to optical fiber

➔ Possibility to test with both PMTs and SiPMs
Energy resolution

Measured with electrons, for various beam angles, from 1 to 5 GeV

<table>
<thead>
<tr>
<th>Angle [°]</th>
<th>Sampling term [%]</th>
<th>Constant term [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 + 0</td>
<td>13.3</td>
<td>5.1</td>
</tr>
<tr>
<td>-1.5 + 0</td>
<td>12.2</td>
<td>4.4</td>
</tr>
<tr>
<td>1.5 + 0</td>
<td>13.7</td>
<td>5.7</td>
</tr>
<tr>
<td>-3 + 0</td>
<td>11.1</td>
<td>4.9</td>
</tr>
<tr>
<td>3 + 0</td>
<td>11.6</td>
<td>5.4</td>
</tr>
<tr>
<td>6 + 0</td>
<td>11.0</td>
<td>3.9</td>
</tr>
<tr>
<td>1.5 + 1.5</td>
<td>12.6</td>
<td>3.1</td>
</tr>
<tr>
<td>3 + 3</td>
<td>11.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

➔ Clear dependance on incident angle
➔ Overall higher Ph.e. values wrt TB2018
➔ But poor homogeneity among cells of same scintillator type (problematic coupling via clear fibers)

Material | Front [Ph.e./MeV] | Back [Ph.e./MeV]
--- | --- | ---
GAGG | 19 ± 2 | 11 ± 4
YAG | 14 ± 2 | 10 ± 2
However, plenty of useful information gained in the dataset acquired

Better understanding of main factors affecting timing resolution

- Photo-detector TTS most likely to play dominant role (both absolute value and non-uniformity)
- Impact of light collection/coupling
- Useful information for tuning of MC simulations (see later)

Strategies already in place to improve timing resolution in view of next test beam

- Test faster photo-detectors (PMTs, SiPMs)
- Mitigate impact of TTS non uniformity: light mixers, MA-PMTs, SiPMs

Keep in mind that energy range is quite far from region of interest (> 10 Gev)

Performance with PMTs worse than expected

Tests with SiPMs show better results (up to 113 ps for GAGG @ 5GeV) suggesting we are not extracting full potential

Resolution affected by non-uniformity of Transit Time Spread (TTS) over PMT photocathode

Use of clear fibers prevents light mixing, as opposed to TB2018 configuration

GAGG @ 5 GeV (R7899-20 PMTs)

<table>
<thead>
<tr>
<th>Angle [°]</th>
<th>Front σₜ [ps]</th>
<th>Back σₜ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3+3</td>
<td>188</td>
<td>155</td>
</tr>
</tbody>
</table>
Timing resolution - shashlik modules

Shashlik technology can be used in Upgrade II in outer part of ECAL and provide timing information

![Beam Test 2018](image1.png)

<table>
<thead>
<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td>20</td>
<td>800</td>
<td>69</td>
</tr>
<tr>
<td>30</td>
<td>800</td>
<td>56</td>
</tr>
<tr>
<td>30</td>
<td>750</td>
<td>57</td>
</tr>
</tbody>
</table>

Current ECAL modules with current PMT (R7899-20)

In order to reduce effect of shower longitudinal fluctuations, two versions of shashlik were prepared for 2019 beam test

- Split WLS fibers (7+18 X0, mirrored fiber ends)
- Continuous WLS fibers

Beam Test 2019

- Better than present ECAL modules (65-70 ps achieved at 5 GeV)
- Planning to try new KURARAY WLS fibers YS-2 (much faster than Y11)
  - Improve time resolution
  - Reduce sensitivity to spillover (shorter pulse length, hopefully < 25 ns)
- Planning to test these prototypes at higher energies (20+ GeV) at SPS, when available

![Beam Test 2019](image2.png)
Parametrized simulations for SPACAL

→ MC required for optimization of SPACAL geometry, and study of factors influencing timing resolution
→ Optical photons ray-tracing needed, but extremely CPU-consuming -> parametrization strategies developed

Analytic approach

Hybrid approach

Full energy deposition by Geant4
Analytic transport of optical photons
Photons on detectors, signal formation

Full ray-tracing for Cerenkov photons by Geant4
Map of energy deposition
Parametrized transport of Scint. photons
Photons on detectors, signal formation

Optical calibration with Geant4
Map of detection probability time PDFs

→ Analytic approach valid in approximation of perfect crystal surfaces
→ Hybrid approach allows to take into account surface imperfections
→ Both approaches result in total CPU gain of factor between x100 and x400
Hybrid-MC - preliminary results

➔ Hybrid-MC equivalent to full ray-tracing
➔ Encouraging preliminary results, work in progress
➔ Study of time resolution with different readouts/coupling
  ➢ PMTs, SiPMs etc
  ➢ Clear impact of photo-detector timing resolution
➔ Study of faster garnets from different producers

En. res. matching DESY results at 3+3 deg.
Photodetectors and readout

- Requirements for Phase-II ECAL photodetector:
  - High dynamic range
  - High timing accuracy O(20ps)
  - Radiation hardness for 300 fb⁻¹ (100 Mrad)

- Candidates under study: **APDs, SiPMs, PMTs**
  - Most mature solution so far remains PMTs (rad-hardness)

- In any case, **fast waveform sampling** only choice to achieve good timing resolution with SPACAL/Shashlik
  - A dedicated ASIC will be required

- Estimate of key parameters for **electronics readout**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels</td>
<td>15-30k</td>
</tr>
<tr>
<td>Maximum occupancy</td>
<td>~10%</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>12 bits (maybe more needed…)</td>
</tr>
<tr>
<td>Sampling</td>
<td>8 samples per event</td>
</tr>
<tr>
<td>Derandomized waveform (analog or digital)</td>
<td></td>
</tr>
<tr>
<td>Sparsified readout</td>
<td></td>
</tr>
</tbody>
</table>
Rate of data transmission crucial, needs to be taken into account

Different strategies for signal processing are also being investigated (calorimeter crates vs. online system)

FE and readout on platform
- Main concern: jitter degradation
- Feasibility depends on SNR and losses over transmission line
- Only solution if timing wanted in LS3

On-detector FE ASIC
- Needs to be rad-hard
- High density required
- Back-end digital processing on crates

Clear Fibers
- Remove photo-sensors from hot area
- Likely timing degradation
- Maximum feasible distance?
Timing plane with MCPs

Possibility to embed a timing plane based on **MCPs** in the SPACAL configuration is under investigation

**MCP-PMTs**

- Intrinsically very fast, O(10-20ps)
- High gain stacking multiple layers
- Typically small-sized, very expensive
- Not radiation-hard

→ The **photocathode** of MCP-PMTs is needed if high efficiency on single electrons is required

→ If several charged particles are available (after a few $X_0$ in an electromagnetic shower) 100% efficiency can be achieved even if photocathode is removed -> **iMCPs** (ionization-mode MCPs)

→ Good timing precision can be obtained independently of shower depth (temporal coherence)

→ Embedding a ~1 cm **i-MCP layer** in the SPACAL, placed around the shower maximum, can fit the dual readout, asymmetric configuration and provide fast timing information
Timing resolution, i-MCPs

Timing resolution of i-MCPs improves after a few radiation lengths

- In this example, timing resolution of one i-MPC layer placed after an absorber with variable radiation lengths
- Around 20 ps obtained after 5\(X_0\) on beam test with 20 GeV electrons
- With some R&D efforts, this resolution could be further improved
R&D efforts with i-MCPs

To explore feasibility of this approach, it is mandatory to **reduce costs** and **improve radiation tolerance**

- Exploring feasibility of technologies developed in recent years based on **atomic layer deposition (ALD)** of resistive and emissive layers on borosilicate glass
  - Wafer size up to 20x20 cm²
  - Enhanced secondary electron emission
  - Prolonged device lifetime is predicted

- **First tests** on ALD MPCs ongoing at INFN MiB and BO laboratories

- Keeping open mind to other production methods under development by several producers

- **Strong R&D needed** to answer many open questions
Conclusions

➔ SPACAL configuration can represent a viable solution for the innermost part of ECAL
  ➢ Allows tuning of cell size, enabling reduction of occupancy
  ➢ Can provide radiation hardness with appropriate crystal materials
  ➢ R&D effort initiated by the collaboration

➔ Beam tests on first SPACAL prototypes carried out in 2018 and 2019
  ➢ Energy resolution in the right ballpark
  ➢ Timing resolution in 2019 configuration worse than expected. Sources of degradation identified, mitigation strategies defined for next prototypes

➔ Based on the knowledge acquired in beam tests, investigation continues on different
  ➢ Crystal scintillators
  ➢ Photo-detectors
  ➢ Readout architectures

➔ The possibility of developing a timing plane based on i-MCPs is under study

➔ Strategies in place to improve timing resolution for SPACAL configuration for future beam tests

➔ For the moment, given current situation, concentrating on MC-simulation efforts
Thank you for your attention!