Development of Sampling Modules for the Upgrade II of the LHCb ECAL

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Motivations

The LHCb experiment will run at increased luminosity up to $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

New requirements will be posed on the electromagnetic calorimeter (ECAL) in terms of radiation hardness and occupancy.

Spaghetti Calorimeter (SPACAL)

Scintillating fibres embedded in dense absorber:

- Garnet crystals and Tungsten for the 1 MGy area
- Polyethylene and Lead for the 200 kGy area
- Longitudinal segmentation and double readout front and back to increase radiation tolerance, improve reconstruction, and to allow for an optional timing layer in the shower maximum

Shashlik

Lead and plastic scintillators tiles, with wavelength-shifting (WLS) fibres:

- Employed in the current ECAL
- Old modules will be refurbished and upgraded with double readout and faster WLS fibres (e.g. Kuraray YS-4)

R&D on Scintillating Crystal Garnets

Crystal garnets are radiation hard. 

$\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ (GAGG) is a candidate for the innermost region.

- Different samples explored from various producers
- Samples spanning a factor 2 in light output and 3 in decay time
- Mg$_{2+}$ co-doping stabilises Ce$^{4+}$ speeding up scintillation and improving time resolution

Simulations

- Geant4 Monte Carlo simulation of energy deposit and parameterized ray-tracing transport of scintillation photons. Gain in computation time by factor 1000x
- Particle flux from the LHCb simulation and Upgrade II ECAL geometry available for physics studies

SPACAL Prototypes

Shashliks used now are radiation-hard up to 40 kGy. A new technology is needed for:

- the 32 innermost modules up to 1 MGy
- 144 inner modules up to 200 kGy

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Testbeam Campaigns 2020-2021

Several prototypes tested with electron beams at DESY II and CERN SPS

Energy Resolution

- SPACAL prototypes require an incidence angle different from 0° due to their pointing geometry
- Energy resolution close to $\frac{E}{\sqrt{E}} + 1\%$ with a small tilt of $3^\circ$ (vertical) $\oplus$ $3^\circ$ (horizontal)
- Good agreement between testbeam results and Monte Carlo simulations

Time Resolution

- Time resolution dominated by:
  - Scintillation of the active material
  - Photodetectors properties, e.g. time transit spread (TTS) and single photoelectron response
  - Electronics
- SPACAL modules have better time resolution at low energy (no wavelength-shifting fibres, higher light output)
- All the prototypes reach time resolution of order 15 ps at high energy

Readout

The baseline approach for the calorimeter architecture is to move the Front-End board to the ECAL platforms, an area with lower radiation dose. Tested the current 12 m long cables:

- No major degradation of time resolution observed with current cables
- Low-attenuation cables are under study