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GEANT4 simulation of energy resolution of the SPACAL electromagnetic calorimeter

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Abstract. Geant4 based simulation study of energy resolution is performed for Spaghetti electromagnetic calorimeter module (SPACAL). Several configurations of SPACAL module, with different fiber pitch and scintillation material, were simulated. For each configuration, the energy and angular dependencies of energy resolution were determined. The sampling fraction for electromagnetic showers for the selected SPACAL configuration was also determined

1. Introduction

In modern high-energy physics experiments calorimeters play increasingly important role. These devices are necessary for energy measurement and identification of final state particles. There exist electromagnetic and hadron calorimeters: the former are intended for measurement of energy of electrons (positrons) and photons, while the latter measure energy of hadrons. Structurally, calorimeters are subdivided to homogeneous, where one active material is both absorber and active medium, and heterogeneous (sampling) detectors, where the absorber and detector functions are performed by different materials [1].

Spaghetti calorimeter (SPACAL) is a type of calorimeters consisting of scintillating fibers inserted into the absorber material [2]. SPACAL type calorimeter with fibers oriented parallel to the beam direction is considered for the inner part of the future Electromagnetic Calorimeter (ECAL) for the LHCb Upgrade-II [3]. The present LHCb ECAL is built by Shashlik technology, with Lead absorber, Polystyrene-based scintillator and Kuraray Y11 as wavelength shifting fibers [4]. Because of significant increase of radiation load, it is necessary to use a radiation hard scintillator material, such as Y₃Al₅O₁₂ (YAG:Ce) and Gd₃Al₂Ga₃O₁₂ (GAGG:Ce) crystals [5, 6]. The increased occupancy of events at the LHCb Upgrade II dictates using of a more dense material for the absorber, in order to obtain narrower showers and reduce the shower overlap. The best candidates for the absorber could be Tungsten or various Tungsten-based alloys. The advantage of SPACAL technology, compared to Shashlik, is that the light is transported to photodetectors by the scintillator itself, without using wavelength shifting fibers, which allows to obtain higher light yield.

The energy resolution of the LHCb ECAL has to be about $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1\%$. One of the goals of this simulation study was to identify the parameters of a SPACAL structure which fulfils this requirement. The SPACAL energy resolution was determined as function of the absorber and scintillator geometry and incident angle of the incoming particle.

2. Energy resolution simulation



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Three main items were studied:

- Dependence of energy resolution on incident angle of primary particle;
- Dependence of energy resolution on SPACAL geometry parameters, such as fiber size and distance between fibers;
- Shower width and sampling fraction.

All the simulation results presented below are obtained on the basis of the energy deposited in the scintillator, without taking into account the light absorption in the scintillating material and are performed using toolkit GEANT4 with FTFP_BERT_EMV physics list.

2.1. Dependence of energy resolution on entrance angle of primary particles

From general consideration, the energy resolution of SPACAL type calorimeters should deteriorate for particles coming at low angles to the direction of the fibers.

In order to quantitatively study this effect, a SPACAL module with 1 mm² square fibers and distance between centers of fibers 1.8 mm was simulated. The absorber material is Tungsten-Copper alloy (75:25% mass fraction), scintillator – GAGG:Ce. The reason for this is that this is the structure of existing SPACAL prototype, which is going to be studied at the test beam. The primary particles were electrons of different energies, entering the prototype at angles of 3°, 6° and 9° with respect to the fiber direction both in (zx) and (zy) planes (the z axis is parallel to the fiber direction). The beam spot size for all the simulation runs of this paper was 3x3 mm². The energy dependence of the SPACAL resolution for these three angles is shown in Figure 1. The results of the fit with the formula $\sigma(E)/E = A/\sqrt{E} \oplus B$ is superimposed at the graphs. One can see that the energy resolutions for 6° and 9° are similar, whereas at 3° it is a bit worse.

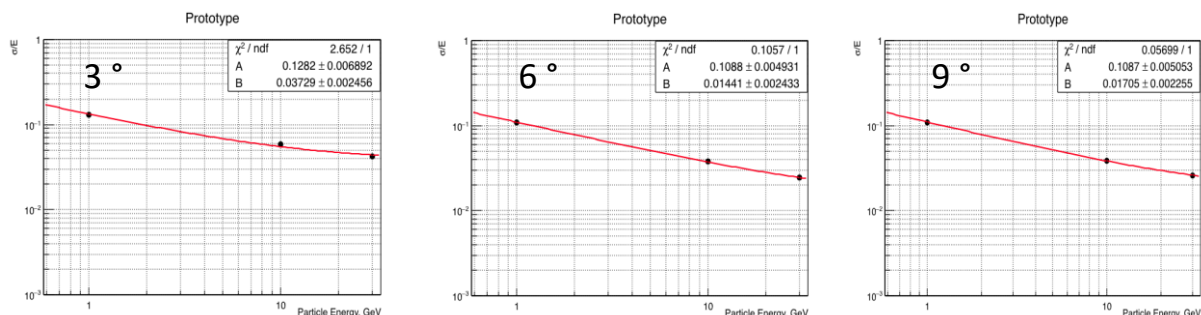


Figure 1. Energy resolution of SPACAL module for 3° (left), 6° (centre) and 9° (right) angles of primary particles.

2.2. Dependence of the energy resolution on detector structure. Shower's profile

The sampling term of energy resolution as a function of the particle incident angle for different SPACAL configurations is shown in Figure 2. The observed deterioration of the resolution at low angles can be explained by increasing the sampling fluctuation for a narrow shower crossing only a few fibers. The effect is significantly smaller for configurations where the shower is broader and occupies more fibers (Lead absorber, 1.6 and 1.7 fiber distance).

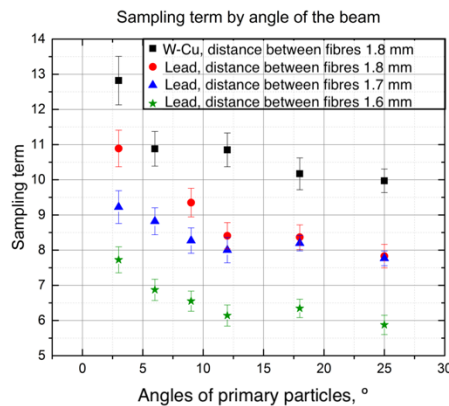


Figure 2. Sampling term of energy resolution as a function of the incident angle of primary particles for different SPACAL configurations: square 1x1 mm² GAGG:Ce fibers, Tungsten:Copper (75:25) and Lead absorbers with distance between centres of fibers 1.8 mm (squares and filled circles), Lead absorber with distance between centres of fibers 1.7 and 1.6 mm (triangles and stars).

The shower maps for 1 GeV electrons at 3° incident angle for the Tungsten:Copper (75:25) and Lead absorbers with distance between centers fibers 1.8 mm are shown in Figure 3. The somewhat broader shower in case of the Lead absorber explains a better energy resolution.

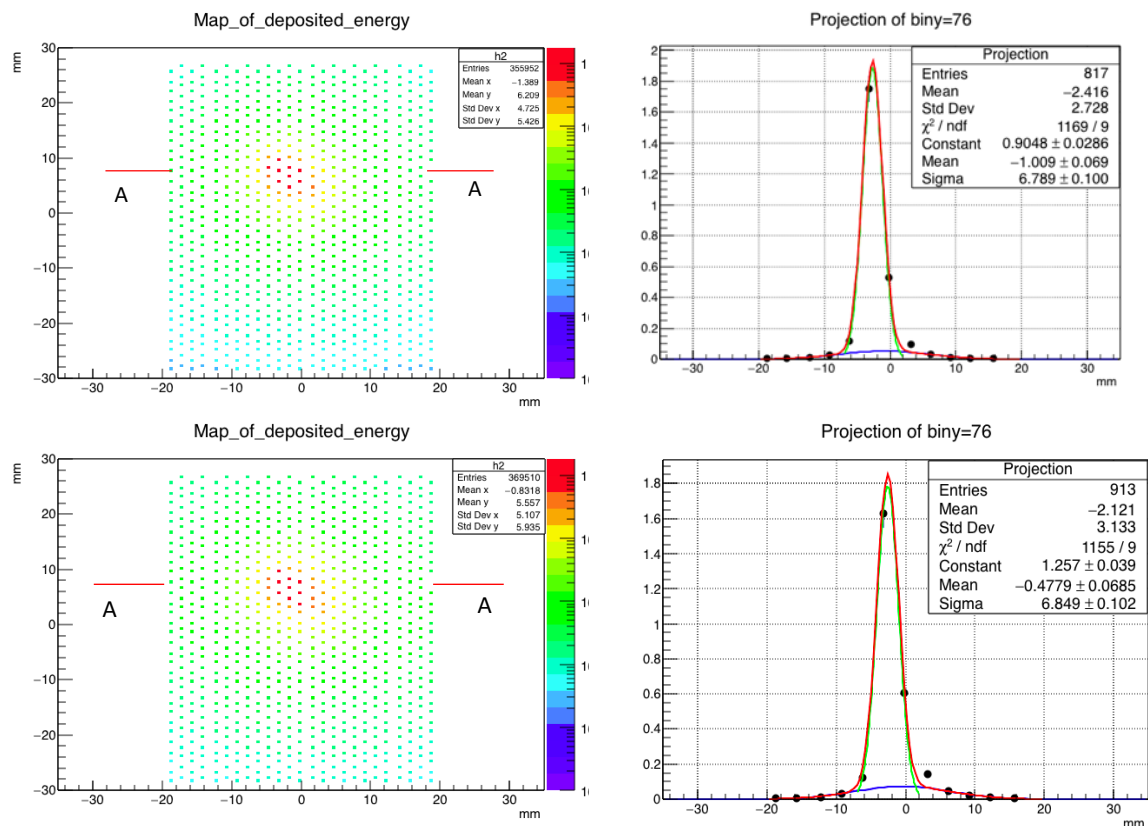


Figure 3. Map of deposited energy in fibers of SPACAL module with absorber from W-Cu alloy (top left) and lead (bottom left) and its projections onto X axis (top right and bottom right respectively).

The energy resolution of electromagnetic calorimeters is defined by the statistical fluctuations of particles in electromagnetic shower and sampling fluctuation significantly. The energy resolution of SPACAL module is mostly affected by sampling fluctuations. For detailed study of this dependence, a SPACAL module with absorber from Tungsten-Copper alloy (75:25% mass fraction) with total density equal 15.7 g/cm^3 was simulated. The width of the fibers, distance between them and scintillating material (YAG:Ce or GAGG:Ce) were varied. Figure 4 shows the energy resolution for different SPACAL configurations with YAG:Ce and GAGG:Ce scintillator at 1 GeV primary particles energy and 3° incident angle.

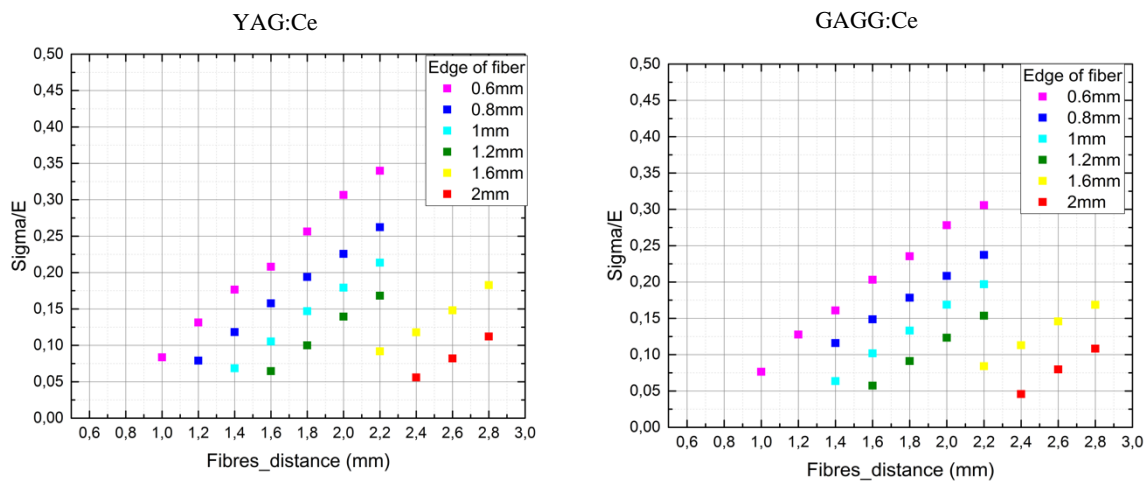


Figure 4. Energy resolution as a function of fiber width and distance between their centres for 1 GeV particles, 3° . Left: YAG:Ce; right: GAGG:Ce.

The Molière radii for each of these configuration are presented in Figure 5.

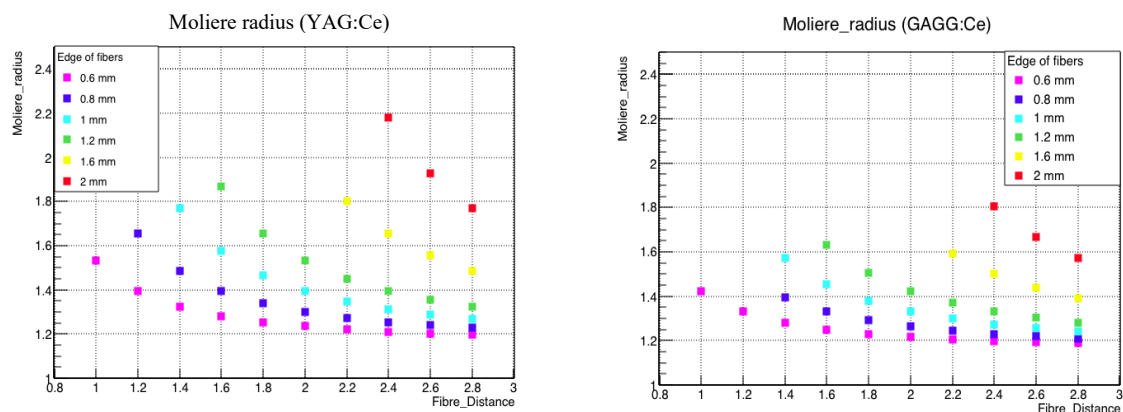


Figure 5. Molière radii for different SPACAL configurations. Scintillator YAG:Ce – left, GAGG:Ce – right.

One can see, for the SPACAL type calorimeters the requirement of good energy resolution is in contradiction with the requirement of narrow shower shape. The detector structure should be optimized for each particular application.

2.3. Study of the sampling fraction of SPACAL for electromagnetic showers

For determination of energy deposited in fibers and absorber, a SPACAL prototype with pure Tungsten absorber was simulated. The parameters of the prototype were the following: scintillator – 1 mm² square GAGG:Ce fibers with 1.6 mm distance between centers them, absorber – pure Tungsten (19.1 g/cm³). The prototype was divided longitudinally into two sections, 4 and 10 cm long. The lateral dimensions of the both sections of the simulated prototype were 50x65 mm². The incident angle of the particles was 3°, the beam spot size 3x3 mm². The results of the simulation are presented in Table 1.

Table 1. Deposited energy in SPACAL module elements.

Energy of particles	Total energy dep. In module (% of true)	Energy dep. In 1 st section (% of total)	Energy dep. In 2 nd section (% of total)	Energy dep. In Fibers (% of total)
1 GeV	0.92 GeV (93 ± 3%)	0.58 GeV (63 ± 17%)	0.34 GeV (37 ± 16%)	0.16 GeV (17 ± 3%)
2 GeV	1.83 GeV (92 ± 3%)	1.02 GeV (56 ± 17%)	0.81 GeV (44 ± 16%)	0.32 GeV (17 ± 2%)
3 GeV	2.76 GeV (92 ± 3%)	1.4 GeV (55 ± 17%)	1.36 GeV (45 ± 16%)	0.48 GeV (17 ± 2%)
4 GeV	3.67 GeV (92 ± 3%)	1.74 GeV (48 ± 15%)	1.92 GeV (52 ± 14%)	0.64 GeV (17 ± 2%)
5 GeV	4.58 GeV (92 ± 3%)	2.06 GeV (45 ± 14%)	2.51 GeV (55 ± 14%)	0.81 GeV (18 ± 2%)
10 GeV	9.07 GeV (91 ± 3%)	3.41 GeV (38 ± 14%)	5.66 GeV (62 ± 13%)	1.64 GeV (18 ± 2%)

The sampling fraction only weakly depends on energy in the range 1-10 GeV and is 17-18%. Total average leaks of energy outside the module are around 7-10%. One can also see that uncertainty of the energy sharing between the two longitudinal sections is about 15% for all energies.

3. Conclusions

Results of this work are based on a simulation of the energy deposition in SPACAL electromagnetic calorimeter module. The results have demonstrated the dependence of the energy resolution on the fiber size and distance between fibers. In dense calorimeter modules the electromagnetic shower are narrow, which leads to deterioration of energy resolution for small incident angles. Simulation of dense prototype based on pure Tungsten show that percentage of energy in GAGG:Ce fibers less than 20% of total deposited energy in the module. Longitudinal shower's fluctuations contribute to uncertainty energy deposited in sections along shower directions. These simulation results are going to be verified at the beam tests.

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