Calorimetry with meta-crystals

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Abstract. We present the meta-crystals concept, an approach that consists of using both undoped and properly doped heavy crystal fibers of identical material as the active medium of a calorimeter. The undoped fibers behave as Cherenkov radiators while the doped ones behave as scintillators. A dual readout calorimeter can be built with its sensitive volume composed of a mixture of both types of crystals. In addition if the calorimeter is adequately finely segmented it can also function as a particle flow calorimeter at the same time. In this way one could possibly combine the advantages of both the particle flow concept and the dual-readout scheme. We discuss the approach of dual readout calorimetry with meta-crystals made of Lutetium Aluminium Garnet (LuAG) and present studies on the material development, first testbeam activities and results based on simulation for understanding the performance trends. We close with a brief outlook on open issues and further R&D needed to proceed from an ideal conceptual case to the design of a realistic detector.

1. Introduction
An experiment at a future lepton collider sets strict requirements for vertex, tracking and calorimetric detectors. The R&D effort on the design of the calorimeters is directed mainly into two fronts, the particle flow approach [1] and the dual-readout scheme [2]. Within the former both the electromagnetic and the hadronic calorimeters are very finely segmented in order to allow very efficient pattern recognition and thus identify and track all particles in a jet. In the dual readout approach one would like to have a calorimeter that is capable of measuring both the ionisation/scintillation and the Cherenkov signals generated by a hadronic shower. By doing so it is possible to determine on an event by event basis the electromagnetic fraction of the shower in order to cancel/correct for this source of fluctuation that degrades the energy resolution of the calorimeter. In the following we discuss a dual readout approach that is based on meta-crystals [3].

2. Calorimetry with meta-crystals
The meta-crystals concept consists of using both undoped and properly doped heavy crystal fibers of identical material for the generation of the signal of the detector. The undoped fibers behave as Cherenkov radiators while the doped ones behave as scintillators. A dual readout calorimeter can be built with its sensitive volume composed of a mixture of both types of crystals. In addition if the readout volume is adequately finely segmented longitudinally and transversely it can also function as a particle flow calorimeter at the same time. The conceptual design of a readout unit of such a calorimeter is illustrated in figure 1. The unit consists of a structured distribution of different types of fibers. Typical dimensions of a unit are of the...
order of $1 - 1.5 \ R_M$ and $20 - 25 \ X_0$ in the transverse and longitudinal direction respectively. In addition to Cherenkov and scintillating fibers one could also have fibers that would be sensitive to neutrons and so to have a triple readout calorimeter. Candidate materials are those based on lithium or boron which have high neutron capture cross-section. As shown in the figure the light from the different types of fibers is directed to different silicon photomultipliers or other solid state photodetectors by using diffractive optics light concentrators (micro-lenses). The diffractive optics plate is patterned so to match the structure of fibers and can be attached to both ends of the unit. The development of such a concept requires a comprehensive program of R&D studies in various fronts, from material development and crystal fiber production to simulation studies, testbeam activities and prototyping. Recent progress on these topics is discussed below.

2.1. Material development and related studies

A candidate material under study to be used for this concept is the Lutetium Aluminium Garnet Lu$_3$Al$_5$O$_{12}$ (LuAG) crystal. Its properties are summarised in table 1. This crystal material combines a high density of $6.73 \ \text{gr/cm}^3$ and relatively short radiation and interaction lengths of 1.41 cm and 23.3 cm respectively sufficient to build a dense and compact detector. Its high refractive index of 1.842 at 633 nm and low energy threshold for Cherenkov radiation at 97 keV for electrons makes it a good Cherenkov radiator (to be compared with 1.55 and 190 keV respectively for quartz). Furthermore when LuAG is doped with cerium (Ce) it shows excellent scintillating performance with high light yield of more than 25000 photons per deposited MeV, emission peaked at 520 nm and decay time of about 60 nsec. A faster scintillation signal can be achieved if LuAG is doped with praseodymium (Pr), then the scintillation signal is characterized by UV emissions peaked at 320 nm and 370 nm and decay time of 20 nsec (see figure 4 and [5]).

Table 1. Physical and optical properties of Lutetium Aluminium Garnet (LuAG) crystal.

| Physical properties       | Optical properties                  |
|--------------------------|-------------------------------------|
| Density                  | Light yield (Ce doped) > 25000 ph/MeV |
| Zeff                     | Emission wavelength 520 nm (Ce doped) |
| Radiation length $X_0$   | Decay time 60 nsec (Ce doped)       |
| Interaction length $\lambda_I$ | Refractive index 1.842 at 633 nm |
| Melting point            | Cherenkov threshold 97 keV          |
| Thermal expansion        | Max Cherenkov angle 57 °             |
| Thermal conductivity     | Total reflection angle 33 °          |
Bulk LuAG crystals can be produced with traditional growth methods like the Czochralski or Bridgman-Stockbarger technique. The ingot produced then undergoes cutting and polishing procedures to the desired shape and dimensions. With these methods it is very difficult to produce fibers or in general elongated crystals with large aspect ratio. A technology that can be used for this purpose is the micro-pulling down method, a schematic of which is shown in figure 2. The University of Lyon1 in collaboration with Fibercryst-Lyon and Cyberstar-Grenoble have improved the method and applied it successfully to the production of fibers made of LuAG and other crystal materials [4]. With this method crystal fibers with diameter between 0.3 and 3 mm and length up to 2 m can be produced. The pulling rate is ranging from 0.1 to 0.5 mm/min and is considerably faster than the traditional methods, about a factor 10 and 50 times faster than Czochralski and Bridgman-Stockbarger method respectively. Another advantage of this technique is the fact that the capillary die can be non-cylindrical e.g. square, hexagonal etc, and so fibers with these shapes in cross-section can be produced as well. The method is yet to be optimised further for industrial application and it is expected that its overall cost per unit volume of production will be comparable to that of standard crystal growth methods. Samples of Ce doped and undoped LuAG crystal fibers, 2 mm in diameter and 30 cm in length, produced with this method are shown in figure 3. Figure 4 shows a typical example of the series of measurements we perform on a sample to study its properties with respect to light transmission, excitation-emission, attenuation, diffusion etc for optical characterisation and further development of the crystal material [5].

2.2. Testbeam activities and simulation studies

Bundles of undoped and Ce doped LuAG crystal fibers have been exposed to electron beam at CERN SPS during short periods in 2009 and 2010. The fibers were read-out from both ends with photomultiplier tubes. The setup was temperature controlled and could be rotated so that the beam particles can transverse the fibers at given angle. A bundle of 20 fibers, with dimensions of 2 mm in diameter and 80 mm in length each, wrapped in teflon box can be seen in figure 5. The corresponding signal pulses recorded are also shown. They are typical Cherenkov and scintillation light pulses as expected respectively. Some results of the data analysis are presented in figure 6. Figure 6(a) shows the left-right asymmetry of the recorded signal for different angles of orientation of the fibers with respect to the axis of the incident beam and for different setup configurations and samples. The undoped LuAG fibers show strong asymmetry...
as expected from a Cherenkov based detector due to the directionality of the signal generation mechanism. While the Ce doped fibers show less or no asymmetry since the scintillation light is isotropically emitted. The full-width at half maximum of the average pulses, of the order of 100 nsec for scintillating fibers and 7 nsec for the Cherenkov ones, and the rise time, about 20 nsec and 5 nsec respectively, can be seen in figure 6(b) and (c). Further studies included the temperature dependence of the behavior of the fibers [6]. Similar studies are also done at a testbench using cosmic muons. So far we have performed small scale tests equivalent to the level of a single calorimetric channel, our plans in the near future include the construction and study of a multichannel module.

In the simulation front we are performing systematic scanning of the parametric space with design parameters under study such as transverse and longitudinal granularity, sampling frequency/readout fraction, total length of calorimeter, mixture of conventional and dual readout components, corresponding composition etc. Figure 7(a) summarises the results from a set of case studies with a \(4.3 \times 4.3 \times 8.6 \, \text{m}^3\) \(\text{LuAG}\) calorimetric volume and for different readout/sampling fractions of the scintillation/ionisation and Cherenkov signals. The studies are with single pions in the energy range up to 50 GeV. The figure shows the performance in terms of the stochastic term of the energy resolution after the dual readout technique is applied. The left most series of points represent the resolution performance of a conventional detector i.e. without any readout of the Cherenkov signal and so where the dual readout correction scheme is not applied. Various sampling configurations of scintillation and Cherenkov signal readout are studied, covering the range of readout fraction from 100% down to 6.25%. We observe an improvement in the energy resolution achieved with the dual readout technique compared to conventional single signal readout and with a trend of improvement being more significant as we approach cases with smaller sampling readout fractions. The influence of the total length of the calorimeter is shown in figure 7(b) and (c) for two cases of scintillation sampling readout 100% and 12.5% respectively. Similar systematic studies combined with very preliminary cost considerations and technical challenges to be addressed help us to evaluate the performance trends, to understand any showstoppers and to proceed from an ideal case to a realistic detector.

3. Summary and outlook
We discussed the meta-crystals concept an approach that consists of using undoped and Ce doped LuAG crystal fibers as the active medium to build a dual readout calorimeter. We presented some aspects of the comprehensive R&D effort that has been established in our group with respect to material development and characterisation, fiber crystal production, first small scale testbeam activities and simulation studies for systematic scanning of the design parameters.
Figure 5. Bundles of Ce doped (top left) and undoped (top right) LuAG fibers and corresponding typical signal pulses recorded (bottom row).

Figure 6. Normalised left-right asymmetry of recorded signal with bundles of Ce doped (solid symbols) and undoped (open symbols) LuAG fibers for different orientation angle with respect to the incoming electron beam (a). Full-width at half-maximum (b) and risetime (c) of average signal pulses recorded.
of a calorimeter. We are at an early stage of development of such a concept with many design issues that should be studied further and which need rigorous R&D and prototyping. Open questions and challenges include among others the optimisation of crystal fibre production in large quantities and related cost drivers, development of a readout scheme based on micro lenses, construction challenges and scale-up problems. These can only be answered through the usual phase of prototype development, test and study of 1 permille to 1 percent and 10 percent modules of the final detector. We continue our effort and plan to study further some of the open issues in the near future.

References
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