New crystal technologies for novel calorimeter concepts

Paul Lecoq
CERN, Geneva, Switzerland
paul.lecoq@cern.ch

Abstract. Present calorimetric systems give a global information on the total energy deposit at a given time in large detector cells but provide no details on the cascade mechanism of this energy deposition in space and time, as well as on the physics of the signal generation.

In the domain of High Energy Physics (HEP) high-precision measurement of hadrons and jets is one of the detector challenges at future high energy colliders. It has been shown that higher segmentation of the calorimeter and/or the simultaneous recording of the scintillation light produced in an active medium, which is proportional to the total energy deposited by the shower particles, and the Cherenkov light, which is only produced by the charged, relativistic shower particles, can significantly improve the performance of present hadron calorimeters.

At low energy, for instance for medical imaging devices, the detailed recording of the whole Compton-photoelectric interaction chain would have a strong impact on the spatial resolution, energy resolution and sensitivity of the imaging cameras.

Recent progress in heavy scintillating crystal production methods as well as in nanotechnologies applied to diffractive optics introduce interesting perspectives for the development of innovative strategies for an homogeneous but finely structured calorimeter. It is shown here how a new class of metamaterials based on these technologies can open the way to new calorimeter concepts allowing to simultaneously record with high precision the maximum of information on the shower such as its direction, the spatial distribution of the energy deposition and its composition in terms of electromagnetic, charged and neutral hadron contents.

1. Introduction
The present paper proposes to take advantage of new scintillator production processes and of recent advances in nanotechnologies, applied in particular to the domain of photonic crystals and diffractive optics, to develop novel detector concepts capable of delivering much richer information than usual in a X- or Gamma - ray detector and more generally in a calorimeter.

Homogeneous crystal calorimeter are well known to give excellent electromagnetic energy resolution at low energy, as was first demonstrated by the spectacular charmonium spectroscopy study
at SPEAR with the NaI(Tl) Crystal Ball in the seventies (Figure 1a). Large crystal based calorimeters build in the last 25 years (L3 with BGO, Babar and Belle with CsI, CMS with PWO) have demonstrated that systematics can be controlled with high precision on several thousands or even tens of thousands of crystals to give excellent energy resolution also at high energy (Figure 1b).

However scintillating crystals are considered to have poor performance, when associated to hadron calorimeters for hadron and jet calorimetry. This is due to the fact that homogeneous calorimeters are by nature non compensating. Moreover quenching mechanisms limit the scintillation efficiency in high ionizing density regions, giving rise to different responses for minimum ionizing and heavily ionizing particles. As a result the e/h ratio is generally much larger than 1 limiting therefore the hadronic energy resolution, as long as corrections on an event to event basis cannot be made to take into account the fluctuations of the electromagnetic fraction in hadronic showers.

Indeed in the domain of High Energy Physics (HEP) high-precision measurement of hadrons and jets is one of the detector challenges at future high energy colliders. A global (integral) approach for jet calorimetry cannot achieve a better jet resolution than 60-70%/√E. Whatever the technical approach, the requested jet resolution of 30%/√E requires high granularity analysis of jet showers and/or a precise determination of the different shower components (electromagnetic, charged hadronic, neutral).

The present paradigm with associated intense R&D in Europe and US is the one of particle flow, which amounts to develop tracking calorimeters with extremely high granularity such as silicon tungsten sandwiches aiming at the identification of all particles in jets and the tracking of individual showers This implies a highly segmented calorimeter with a huge number of channels and complex engineering problems to extract the signals.

An alternative approach, much less explored at the level of R&D, is to integrate over the shower development and aim to measure independently the scintillation light produced in an active medium, which is proportional to the total energy deposited by the shower particles, and the Cherenkov light, which is only produced by the charged, relativistic shower particles. Since the latter are almost exclusively found in the electromagnetic (em) shower component (dominated by π’s produced in hadronic showers), a comparison of the two signals makes it possible to measure the energy fraction carried by this component, f_em, event by event. As a result, the effects of fluctuations in this component, which limit the performance of non-compensating calorimeters (non-linearity, poor energy resolution, non-Gaussian response function), could be eliminated or at least reduced to improve
substantially the energy resolution of hadronic showers in general and of jets in particular. This would lead to an important improvement in the hadronic calorimeter performance.

This concept, developed by R. Wigmans and others with the DREAM calorimeter \cite{1} suffers however some limitations depending on the way it is implemented. In its original design the basic element of this calorimeter is an extruded copper rod, which acts as the absorber. This 4x4mm$^2$ rod is hollow, the central cylinder has a diameter of 2.5 mm. In this hole is inserted the active material made of several plastic scintillating fibers acting as ionizing detectors, mixed with undoped fibers, intended for detecting Cherenkov light. This is therefore a sampling calorimeter with a resolution limited by sampling fluctuations inherent to this kind of calorimeter.

Another approach, promoted by the same group is based on the separation of the scintillation and Cherenkov signal produced in homogeneous detector blocks made of scintillating crystals such as Bismuth Germanate (BGO), Lead Tungstate (PWO) or others. This solution is of course free of sampling fluctuations. There is however a non negligible coupling between the Cherenkov and scintillating signals in a bulk scintillating crystal. Indeed there is a strong overlap between the continuous Cherenkov emission spectrum (varying as $1/\lambda^2$) and the scintillation excitation spectrum, usually in the high frequency part of the optical window of the crystal, where the Cherenkov emission is the highest. Cherenkov emission is one of the channels of scintillation excitation mechanism because of the high UV photo-absorption cross-section in the scintillation excitation region. In other words it means that part of the Cherenkov light is absorbed by the luminescent centers of the crystal and reemitted at longer wavelength as scintillation light, as shown in Figure 1 for Lutetium Orthosilicate crystals (LSO).

We propose an alternative to these approaches, combining their relative merits and limiting their drawbacks. It relies on recent impressive development in the domain of crystal growth and nano-photonics opening the way to homogeneous calorimeter designs with high granularity 3D imaging as well as particle identification capability.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Excitation (left) and emission spectra (right) of the two LSO scintillation centres. The Cerenkov spectrum is superimposed and shows the strong overlap with the excitation spectrum.}
\end{figure}

2. The micro-pulling-down crystal fiber production technology

The analysis of the potential of different crystal growth techniques from the melt shows that pulling-down technology from a shape-controlled capillary die gives the possibility to produce elongated crystals with dimensions that are not accessible using traditional cutting and polishing of bulk crystals grown by the more standard Czochralski or Bridgeman methods. The size of the melting zone in the pulling-down technique is up to one order of magnitude smaller than that observed in the Czochralski method. Therefore, it is believed that the pulling-down process can be considered as a good way to achieve stationary pulling conditions and can facilitate the growth process, allowing for instance much
faster growth and higher concentration of doping ions, even for those with high segregation coefficient.

A group of institutes and companies closely linked to the Crystal Clear collaboration [2] (CERN, VUB Brussels, University Claude Bernard LPCML, company Fibercryst Lyon, company Cyberstar, Grenoble) is presently involved in the development of this new crystal growth technology, which allows the fast and cheap production of heavy crystal scintillating fibers. High quality fibers of LuAG (Lutetium Aluminum Garnet) have been grown in collaboration with the company Fibercryst (Lyon) and the Laboratoire de Physico-Chimie des Matériaux Luminescents (LPCML) from University Claude Bernard (Lyon). Other well known heavy scintillating crystals such as BGO, LSO, LYSO [3], YAP and LuAP have also been grown in fibers of different sizes and PWO is under study. These high quality scintillating fibers are characterized at CERN and LPCML and can open attractive possibilities for the design of future detectors for HEP or other applications. The most relevant parameters of these crystals are summarized in Table 1.

| Properties Crystal | Light yield (ph/Mev) | Decay time (ns) | Density (g/cm3) | Luminosity wave-length (nm) | Experience of fiber pulling | Easy to grow crystal | Easy handling and polishing | Other remarks |
|---------------------|---------------------|----------------|----------------|--------------------------|--------------------------|---------------------|---------------------------|----------------|
| YAG:Ce              | 20 000              | 70             | 4.57           | 550                      | Strong                   | YES                 | YES                       | up to 2m        |
| LYSO:Ce             | 25 000              | 40             | 7.40           | 420                      | Strong                   | NO                  | YES                       | 30cm up to now |
| BGO                 | 8 000               | 300            | 7.10           | 480                      | Strong                   | NO                  | YES                       | up to 2m        |
| LuAG:Ce             | 20 000              | 40-70          | 6.73           | 535                      | Medium                   | YES expected        | YES                       | 1 to 2m        |
| LuAG:Pr             | 20 000              | 20             | 6.73           | 290-350                  | Medium                   | YES expected        | YES                       | Should behave as a garnet (like YAG) |
| GSO:Ce              | 14 000              | 60             | 6.71           | 460                      | Weak                     | Medium               | NO                        | Brittle and tends to cleave at polishing |
| YSO:Ce              | 14 000              | 37 and 82      | 4.45           | 420                      | Weak                     | YES expected        | YES                       | A few cm       |

Table 1: Some parameters of crystalline fibers grown by Fibercryst

In the present state of the art the pulling down technique allows to grow fiber (rod) shaped crystals with a controlled diameter between 0.3 and 3.0mm and up to 2 m in length. By modifying the shape of
the capillary die it is also possible to produce elongated crystalline materials with more complex non-cylindrical cross-section (square, rectangular, hexagonal) for easier integration of the crystal in complex detectors. The procedure based on pulling-down technology was recently improved at the LPCM Laboratory and Fibercryst Company in Lyon to grow both single crystal fibers and shaped bulk crystals. The crystals are produced from the melt obtained at the capillary die positioned at the centre bottom of a cylindrical Iridium crucible as illustrated in Figure 3. Once the melt drop is formed, the growth process is initiated after connection of the seed with the drop at the bottom of the crucible (capillary die). Then the seed is pulled down continuously with a pulling rate ranging from 0.1 to 0.5 mm/min (about 10 times faster than Czochralski and 50 times faster than Bridgeman). Ongoing developments are going along a multiple capillary die crucible allowing to grow several fibers in parallel. The industrial optimization and cost effectiveness study of this process still needs to be made but this should lead to comparable costs per unit volume of grown crystal than with standard crystal growth approaches.

3. The metamaterial concept

The basic concept of this proposal is to structure the standard detector block or pixel used so far in such a way as to extract more information than the total energy deposit in the block. In electromagnetic calorimeters the dimensions are typically 1 Moliere radius in the lateral and 25 radiation lengths in the longitudinal directions.

With the proposed approach it is possible to conceive detector blocks made of trunks of "cables" constructed from crystal fibers. Various scintillators can be selected to build these cables, having different emission wavelength, different scintillation yield and decay time, so that a direct encoding of the light is made as a function of the point of emission. A single photodetector can then decode this complex signal and derive a much more complete information about the shower process. For high energy calorimeters materials with different UV transmission cut-off can be selected so that the part of the Cerenkov emission in the detected light can be determined. Another approach is to choose scintillating materials activated by a doping ion instead of self activated scintillators (BGO, PWO).
Crystals such as Cerium doped LSO or LYSO for instance (Lutetium-Yttrium orthosilicate), both very fast (40nsec decay time) and dense (7.4g/cc) or LuAG (Lutetium Aluminum garnet, 70ns decay time and 6.73 g/cc density), or LuAP (Lutetium Aluminum Perovskite, 17nsec decay time and 8.34 g/cc density) are excellent candidates for mixing Cerium doped fibers, which would then behave as scintillators, with undoped fibers of the same material, which would only produce Cerenkov light. One could then obtain a very homogeneous, dense and compact system capable of disentangling the electromagnetic from the hadronic part in a shower in a calorimeter with a uniform radiation length, Moliere radius and interaction length in the whole volume of the detector. Moreover the assembly of the fibers can be organized in a flexible way, allowing a multitude of detector geometries.

If the detection of neutrons proves to substantially improve the overall jet energy resolution (requires simulation work) neutron sensitive scintillation fibers can also be inserted in the cables. No attempts have been made yet to grow such fibers but scintillators like Lithium Tetraborate LBO (Li₂B₄O₆), Lithium fluoride based materials like LiCAF (LiCaAlF₆) or more generally the Cerium doped elpasolite family (Cs₂₋ₓRbxLiMX₆, where X=Sc, Y, La, Lu and X=Cl, Br, I) are very attractive candidates because of the presence of high neutron capture cross section Lithium and Boron and of their low density (2.42 for LBO), which makes them rather insensitive to gamma conversions.

It must be noticed that, although monocrystalline, the fibres are flexible enough to be assembled and twisted as in a cable in order to avoid straight gaps aligned with the particle trajectory. The exact number and distribution of the different type of fibers (Cerenkov, scintillating, neutron sensitive) as well as their diameter will be optimized by Monte Carlo.

At the extremities of each metablock a diffractive optics plate, patterned in such way as to match the cable structure will concentrate the light emerging from all fibers of the same type to an avalanche photodiode or SiPMT. Recent developments in nanotechnologies have allowed considerable progress in the tailored design and manufacture of such systems, also called MOEMS (Micro-Opto-Electro-Mechanical-Systems), which are extensively used for adaptive optics in astronomy [4]. A sketch of this concept is shown on Figure 4.

Figure 4: Principle of the metacable with 3 types of fibers and diffractive optics light concentrators
4. Material selection and first test results
We have selected LuAG as the most adequate material to design a proof of concept detector. This is a garnet of Lutetium and Aluminum with crystallographic properties rather close to YAG, a material already developed with the micro-pulling-down technology for the growing market of fiber lasers. Indeed excellent quality LuAG fibers, up to 2m in length have been grown in a consistent way. LuAG is an excellent and versatile host for a scintillator with a density of 6.73g/cm3, a radiation length of 1.41cm and an interaction length of 23.3cm. Moreover, it can easily be doped with Cerium giving rise to a bright (20'000 photons/MeV) and fast (70ns) scintillation peaked at 535nm, matching well the quantum efficiency maximum of solid state photodetectors. Would a faster scintillation signal be needed LuAG could also be doped with Praseodynum with an emission peak around 300nm and a decay time of 20ns only.

Another advantage of LuAG is its fundamental absorption edge at 250nm in the UV combined with a very large transparent optical window. Combined with a high index of refraction (1.84, to be compared to 1.55 for quartz) This makes LuAG an excellent Cerenkov radiator with a Cerenkov energy threshold of 97KeV only, to be compared to 190KeV for quartz.

The most important physico-chemical and optical properties measured so far are summarized in table 2.

| Physico-chemical properties | Optical properties |
|-----------------------------|--------------------|
| Structure / Space group     | Light yield: Ce or Pr doped (ph/MeV) |
| Density (g/cm³)             | 20'000             |
| Zeff                        | 1/2 NaI(Tl)        |
| Radiation length X₀ (cm)    | d(LY)/dT           |
| Interaction length (cm)     | PuO, 5             |
| Hardness (Mohs)             | LuAP: 19.8         |
| Fracture toughness (Mpa.m½/cm³) | 1.1             |
| Cleavage plane / H₂O solubility | No / No         |
| Melting point (°C)          | 2260               |
| Thermal expansion @ RT (°K⁻¹) | 8.8 10⁻⁶         |
| Thermal conductivity @ RT (W/m²/K) | 31             |

Table 2: Physico-chemical and optical properties of Lutetium Aluminum garnet (LuAG) crystals

The small attached movie shows the flexibility of a 1m long, 350 micron thick LuAG:Ce fiber, as well as several 1mm diameter fibers arranged in a matrix of an alpha detector.
5. Conclusion
We are exploring the potential of recent progress in the field of crystallogenesis and photonics crystals to develop a new concept of calorimeter based on metamaterials to simultaneously record with high precision the maximum of information of the cascade conversion process such as its direction, the spatial distribution of the energy deposition and its composition in terms of electromagnetic, charged and neutral hadron contents. The main objective is to combine the merits of a finely segmented imaging calorimeter and of the dual readout approach.

References
[1] Akchurin N, Atramentov O, Carrell K, Gümüs K Z, Hauptman J, Kim H, Paar H P, Penzo A, Wigmans R, Separation of scintillation and Cherenkov light in an optical calorimeter, NIMA 550 (2005) 185–200
R. Wigmans, these proceedings
[2] R&D proposal for the study of new fast and radiation hard scintillators for calorimetry at LHC, Crystal Clear Collaboration, CERN/DRDC/P27/91-15, project RD 18
[3] Anfré P, Dujardin C, Fourmigué J M, Hautefeuille B, Lebbou K, Pedrini C, Perrodin D, Tillement O, Evaluation of Fiber-Shaped LYSO for Double Readout Gamma Photon Detection, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 2, APRIL 2007
[4] Ambs P, Sheng Y, Diffractive optics, Opt. Eng., Vol. 43, 2503 (2004); DOI:10.1117/1.1813443