SPECAL: SPaghetti Electromagnetic CALorimeter for CMS endcaps

1. Introduction:

We propose a calorimeter, made of a passive absorber and fibres as active medium, to replace the endcap electromagnetic calorimeter of CMS for the HL-LHC phase. This calorimeter provides, in the energy range relevant for the physics program at the HL-LHC, energy resolution and transverse granularity comparable to the current ECAL endcap and any of the proposed alternatives. The readout is organized in towers, facilitating the integration in the existing CMS trigger and reconstruction frameworks.

The choice of fibres as active medium provides flexibility in the design and a lower cost than crystal or silicon based calorimeters. A baseline design matching the requirements for the HL-LHC phase is in the reach of the existing fibre and photodetector technologies. Additional improvement in the performance is possible after specific R&Ds aimed at improving the fibre quality and the readout photodetectors.

2. Design goals:

A new electromagnetic calorimeter in the endcap region of CMS for the HL-LHC phase is necessitated by the impact of the radiation damage on the current PbWO4 calorimeter. The new electromagnetic calorimeter must stand radiation levels up to XXX, and particle fluences up to XXX. Moreover, we aim at retaining the electromagnetic energy resolution of the current detector, with improved immunity to pileup and improved background rejection capabilities, through a finer transverse granularity. Jet reconstruction will be made in combination with the HCAL (in the “HE rebuild option”). No specific optimization of the electromagnetic compartment to improve on the jet reconstruction is attempted in this document. However, pileup rejection and jet reconstruction considerations call for a high transverse granularity accompanied by a small Moliere radius. The Moliere radius defines the transverse separation between electromagnetic showers. A fast response of the calorimeter, to minimize the pileup from interactions occurred at different beam crossing is also requested.

A fibre calorimeter can fulfill the above requirements. Scintillating-fibre calorimeters have been long investigated, and successfully operated in past experiments, with energy resolutions in the range of the desired performance for HL-LHC [1]. Quartz-fibre calorimeters, despite the limited light output from Cherenkov emission, have long been known to be very radiation tolerant [2], and for this reason have been adopted for the forward region of CMS [3]. Fibre calorimeters, arranged in a projective or quasi-projective geometry have a virtually a very high transverse granularity, defined by the readout pitch (provided the fibre packing fraction is sufficiently high) and no longitudinal sampling. This geometry can be easily shaped into a tower-like structure similar to the current ECAL PbWO4 endcap, facilitating the integration in the CMS reconstruction and trigger.
3. Baseline design considerations:

The energy resolution, the Moliere radius and the total length of the calorimeter depend on the properties of the absorber, of the fibre and on the relative packing fraction.

In order to achieve an energy resolution of about 2% for photons of $E_T=65$ GeV at a pseudorapidity $\eta=1.6$ (comparable to the resolution of the ECAL endcap during the LHC Run I), a stochastic term of about $15%/\sqrt{E}$, a constant term of order 1% and a noise term of order 600 MeV would be needed. The stochastic term is dominated by the sampling fluctuations and by the statistical fluctuation in the number of photoelectrons, which can be approximately estimated from:

1) $\sigma_E/E(\text{samp}) \sim 2.7% \sqrt{(d/f_{\text{samp}})}$  \[4\]
2) $\sigma_E/E(\text{pe}) \sim 100% / \sqrt{N_{\text{p.e.}}}$

where $d$ is the fibre diameter in millimeters, $f_{\text{samp}}$ is the sampling fraction for minimum ionizing particles, and $N_{\text{p.e.}}$ is the number of photoelectrons per 1 GeV of energy deposited in the calorimeter. Using for reference a fibre with $d=0.8$ mm, one must have $f_{\text{samp}} \sim 5\%$ for the sampling term to be around 10%. A light output of 100 p.e./GeV would give a similar contribution from the photoelectron statistics. A larger light output is desirable to limit the noise term of the energy resolution and to make the impact of spurious signals from minimum ionizing particles (mip) crossing the photodetectors (of order 1-10 p.e./mip, depending on the photodetector type) negligible.

Additional contributions to the resolution will come from the longitudinal and transverse uniformity of the response, that depend on the transverse non-uniformity of the material and on the (stability of the) light attenuation in the fibre. These aspects will be addressed in Section 5, and should be optimized to have a constant term to the resolution of order 1%.

To fix some numbers, in the following table, we indicate possible choices of the absorber assuming a fibre with the quartz density (2.6 g/cm$^3$), a packing fraction of 20% in volume (i.e. in cross area), and a fibre diameter $d=0.8$ mm.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$f_{\text{samp}}$ (*)</th>
<th>$\sigma_{E(\text{samp})}/E$ (%)</th>
<th>$X_0$ (cm)</th>
<th>$R_M$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>7.64</td>
<td>0.068</td>
<td>9.26</td>
<td>1.87</td>
<td>2.0</td>
</tr>
<tr>
<td>Pb</td>
<td>9.56</td>
<td>0.054</td>
<td>10.35</td>
<td>0.71</td>
<td>2.2</td>
</tr>
<tr>
<td>W:Cu (70:30)</td>
<td>13.48</td>
<td>0.039</td>
<td>12.30</td>
<td>0.55</td>
<td>1.7</td>
</tr>
<tr>
<td>W</td>
<td>15.96</td>
<td>0.033</td>
<td>13.38</td>
<td>0.45</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 1. Expectations for a quartz-fibre calorimeter; the sampling fraction (*) is given by the fibre to total mass ratio.
While the optimization of the geometry will come after detailed simulations (Sect. 5), Table 1 can be used to identify reference configurations with packing fraction and properties that provide the desired resolution and calorimeter compactness. For example, a W:Cu (70:30) alloy would result in a compact calorimeter with a total length of approximately 15 cm for 25 radiation lengths ($X_0$), and a sampling term of about 12%/√E. With this geometry, we estimate a total of about 400 fibres in a square area of Molière radius size. About 8 million fibres (for a total of ~2500 km) would be needed to instrument the entire ECAL endcap region from $|\eta|\sim 1.5$ to $|\eta|\sim 3$ (an extension to $|\eta|\sim 4$ is conceivable).

For constant packing fraction, the number of fibres scales with the square of the fibre diameter. Therefore, fibres with diameters much smaller than 0.8 mm are unpractical to assemble. Larger diameters may be difficult for production reasons. If the packing fraction were reduced to 1% - 50% less fibres $\sim$, the sampling term would degrade to 18%/√E. [The packing fraction could be varied with $\eta$: there is no need for extreme resolution at low energy at high $\eta$, but rather for thin showers].

The optical signals from the fibres will be read out in photodetectors, with fibres grouped to form detector units of transverse size matched to the Molière radius. A readout granularity of 1.8x1.8 cm$^2$ would require about 40000 readout channels (20000 in each endcap). Finer granularities may be easily obtained, if proven useful and cost effective.

4. Fibres:

The total volume of the fibres would be of about 2 m$^3$ (pay attention to this number: in the LYSO it is about 1 m$^3$ if I'm not wrong, ... thus if fibres are drawn from crystals, the cost would not be low). The following options are under consideration:

Cherenkov fibres

The promptness of Cherenkov emission makes clear fibres very interesting for application at the HL-LHC. Quartz fibres are sufficiently radiation tolerant to stand HL-LHC operation, and are commercially available. The major limitation stems from the low light output of these fibres in projective geometries, due to the directional nature of Cherenkov emission. Denser fibres are under study (e.g. YAG, ...). They look promising in terms of radiation tolerance (costs and mass production?) and have core index of refractions that may result in higher light output efficiencies.

To fix some numbers, the total number of Cherenkov photons emitted in a quartz fibre (n=1.45) can be estimated from $N_{ph} \sim (200 \text{ cm}^{-1}\text{eV}^{-1}) L \Delta E$, where $L$ is the track length, and $\Delta E$ the spectral acceptance of the fibre/photodetector. For a shower of energy $E$, the track length in the fibre is given by $L \sim [f_{\text{samp}} E/\rho_{\text{fibre}}]/<dE/d\rho>$. Neglecting threshold effects, and assuming a spectral acceptance $\Delta E=2$ eV, a light yield of order 4000 photons/GeV is estimated for the configurations of Table 1. However, the light output of fibres in quasi-pointing geometry is small. The light output measured with quartz fibres
in the CMS HF (0.25 p.e./GeV [3]) would result in about 5 p.e./GeV with the sampling fractions of the configurations given in Table 1. This figure would spoil completely the energy resolution.

A few solutions can be investigated to increase the light efficiency (option 3) most promising?:

1) **Tilted fibres**: Quartz fibres parallel to the beam axis would form an angle with the showers of about 10 degrees at $\eta \sim 2$. The exact estimate of the light output in this geometry requires a dedicated simulation. However, for typical numerical apertures of the quartz fibres (NA~0.3, i.e. $\Delta n \sim 0.03$ between the core and the caldding), a considerably enhancement of the light yield is possible only at an average angle between the fibre and the shower axes in the range from 40 to 60 degrees [2]. This would complicate event reconstruction and pileup rejection. (*Can we try a spacordion [6], angles too large??*)

2) **Quartz fibres with WLS coating** would be rad-tolerant in the core, while the WLS could help increase the collection efficiency for Cherenkov emission. Coatings of plates of Cherenkov radiator have been studied in the context of the R&D for the HE calorimeter of CMS [4]. A full qualification in terms of stability and rad-hardness in a fibre configuration would require a dedicated R&D. For numerical aperture NA~0.3 (meaning a $\Delta n \sim 0.03$ between core and caldding), about 2% of isotropic photons is captured by the fibre (see for example [2]). This would result in approximately 50 p.e./GeV. Further optimization might bring this option to the desired level for this application.

3) **Heavy fibres, with high index of refraction**: both the Cherenkov yield and the collection efficiency (namely the numerical aperture) can be increased with cores of high index of refraction (e.g. YAG, ...). For $n_{\text{core}} \sim 1.8$, and a quartz cladding (doable?) the NA of these fibres should enable a collection of well more than 100 p.e./GeV. Option to be investigated, perhaps coupled with option 2. (*Mass production? Optical matching at the fibre exit?*)

**Scintillating fibres**:

Scintillating fibres have the advantage of being brighter, although the light emission is slower, and the radiation hardness yet to be explored. Several candidates have been considered so far, with very promising scintillation properties: SiO$_2$:Ce, DBS:Ce, LuAg:Ce, quartz capillaries with liquid scintillator in the core. Plastic fibres, commonly used in past calorimeters, are not sufficiently radiation hard for this application. The required R&D should demonstrate 1) the radiation-hardness of the scintillation mechanism and of the light transmission; 2) the possibility to produce fibres with sufficiently fast scintillation components (<50 ns) and emission spectrum matched to the readout devices; 3) the capability of mass production with quality control and assurance.

1) SiO$_2$:Ce [adapt text from existing, ask A.Vedda, Nural]
2) DBS:Ce  [Misha et al.]
3) YAG:Ce, LuAg:Ce [Etiennette et al.]
5. Simulation results:

Pickup one representative fibre with reasonable packing fraction and show simulation results to confirm/modify the text above [A.Benaglia, M. Lucchini, P. Govoni et al.]

PRELIMINARY RESULTS on W/Cu 75:25 confirm the sampling term and Moliere radius from the estimates above. Simulation with cladded YAG (a fibre yet to be produced) looks promising. ~ 19%/sqrt(E) + 1% constant term (scintillation is ~ 15%/sqrt(E) + 1%)

→ ADD FIGURES

6. Absorber and mechanical assembly:

To achieve the desired electromagnetic resolution and transverse granularity the packing fraction should be high with fibres of relatively thin size. This makes the mechanical assembly challenging.

- Grooved plates (with extrusion?) → Adopted in several experiments. Available from Leadextrusion (lead only?). Amount of work? Manual assembly?
- Drilled towers / wedges + automatic fibre insertion (machining of W:Cu → Harditaly and others)
- W powder and spacordion [6]

Discussion of prototypes and tests → costs

7. Photodetectors:

VPTs (RAL? Bristol?) or PMT-MCP (anyone interested?)

- Discussion
- A minimum ionizing track generates a signal of about 4-10 p.e. in the PMT window. Thus a light yield in excess of this is necessary. Discussion of the options...

SiPM are being developed with single cell size of order 10 um. This would give more than 1 M pixel on the area of a Moliere radius

- dynamic range?
- cooled SiPM for rad-hardness (test with FBK?)

GaInP – if available from other R&Ds (Perhaps just mention this option. It does not seem the easiest way to go)

8. Readout chain and trigger

Copy and past from Shashlik/CFC?
Bibliography:


[5] Y.Onel, A. Belloni, ...