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 Combined Forward Calorimetry Option for Phase II CMS Endcap Upgrade

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Abstract. Traditionally, EM and HAD compartments are thought to be separate and are often optimized individually. However, it is possible to optimize a robust and economical combined calorimeter system for myriad physics objectives. By employing event-by-event compensation afforded by the dual-readout technique, we have shown that excellent jet performance can be attained with a longitudinally un-segmented calorimeter that is calibrated only with electrons. In addition, the linear hadronic energy scale renders complex off-line correction schemes unnecessary. The proposed replacement of the CMS EE and HE calorimeters with a single Combined Forward Calorimeter (CFC) shows excellent jet performance complemented by good EM object detection. In this paper, we give brief snapshots on basic design criteria, timing characteristics of Cherenkov and scintillation pulses, trigger generation criteria and performance under high radiation fields. Although CMS has recently chosen different technologies for its endcap calorimetry in Phase II, the concepts developed here are likely to remain valuable for some time to come.

1. Introduction

The Combined Forward Calorimeter (CFC) can be thought of as two independent calorimeters occupying the same volume (the clear and scintillator fibers as two active media in a single absorber) that provide complementary information. The Cherenkov ($Q$) part originating in the clear fibers provides information on the EM content as well as the fast timing signal, whereas the scintillation ($S$) part predominantly gives information on ionization ($dE/dx$) losses. The ratio of the two signals enables us to measure the EM fraction ($f_{em}$) of a shower event-by-event and to remove the source of one of the larger fluctuations in energy measurement. The proposed calorimeter gives excellent energy measurement and it is likely to help mitigate pile-up effects because of its fast (Cherenkov) response and fine transverse granularity.

It is possible to optimize a robust and economical combined calorimeter (ECAL+HCAL) system for myriad physics objectives. We have shown that excellent performance can be attained with a longitudinally un-segmented calorimeter that is calibrated only with electrons in beam tests [1, 2, 3, 4] and in standalone simulations [5]. In addition, the linear hadronic energy scale renders complex off-line correction schemes unnecessary. Our studies targeted optimization of crucial design aspects: the absorber (tungsten vs brass), tower orientation

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(quasi-pointing vs non-pointing), fiber spacing (packing fraction), cerium-doped fused-silica (SiO2:Ce3+) fiber structures (LY, decay time, core/clad/buffer sizes) for rad-hard scintillation light, detailed photon propagation in fibers, pulse formation using variety of photodetectors, effective longitudinal segmentation using timing information and pulse shape.

Fine transverse segmentation is one of the key features that contributes strongly to efficient particle ID and background suppression at the high luminosity LHC. The measurement of \( f_{\text{em}} \) on an event-by-event basis is also a powerful discriminant: \( f_{\text{em}} \approx 1 \) for electromagnetically interacting particles, and \( < 1 \) for hadronically interacting ones. Precise pulse shape information on the other hand, reveals space-time structure of the shower profile inside the calorimeter. Finely sampled pulse shape opens up new possibilities in object reconstruction because appropriate treatment of the pulse shape effectively segments the calorimeter into many sections in depth [5].

2. Physical Design

The baseline absorber material is cartridge brass (70% Cu and 30% Zn). The angular coverage extends from \( \sim 25^\circ \) to \( \sim 2^\circ \) corresponding to \( 1.5 \leq |\eta| \leq 4.0 \). The span of \( 23^\circ \) can be either covered by a non-pointing or by a quasi-pointing geometry (Figure 1).

![Figure 1.](image)

Figure 1. Two options are considered for all brass absorber: a) non-pointing tower geometry where the fibers are positioned parallel to the beam axis (Option I), and b) quasi-pointing geometry where the geometric axis of the towers nearly points toward the interaction point (Option II).

Variations on the two options are possible and depend on the overall goals of the experiment, such as the upgrades of muon systems, forward calorimeters, forward pixel detectors, and the beam pipe. For example, the inner annulus (\( \sim 2.4 \leq |\eta| \leq 4 \)) can be constructed out of (replaceable) tungsten in order to accommodate an additional muon chamber in the back (Option III). This approach will potentially provide better performance in resolving overlapping jets (tungsten) and flexibility (replaceable). As this replaceable insert is compact, the impact
on cost is relatively small. The fourth possibility is to entirely replace brass with a tungsten alloy (Option IV). The clear advantage in this case is the shorter overall length in \( z \)-direction (\( \sim 120 \text{ cm in tungsten} \) vs. \( \sim 200 \text{ cm in brass} \)). Unless explicitly noted, all results given here are based on Option I.

Two different kinds of fibers scintillating (\( S \)) and clear (\( Q \)) are embedded in the absorber and they are nominally spaced 2.0 mm apart, alternating in a square-grid pattern. The fiber dimensions are assumed to be identical for both types: 600 \( \mu \text{m} \) diameter core, 50 \( \mu \text{m} \) thick cladding, and 50 \( \mu \text{m} \) thick buffer. In the case of clear (Cherenkov) fiber, the core is high-OH\(^-\) fused-silica, the clad is hard-polymer and the buffer is made out of acrylate. The numerical aperture is 0.33. The scintillating fibers are made of rad-hard SiO\(_2\):Ce\(^{3+}\) core and are surrounded by similar cladding and buffer materials. The packing fraction of active materials by volume is 3.5% of each type. The clad plus buffer materials and air take up 5.4% and 3.3% of the calorimeter volume, respectively. The effective Molière radius and radiation length are 2.0 and 1.82 cm, respectively.

The brass absorber is 200 cm long (10.2 \( \lambda^\text{eff}_I \)) in the beam direction. In the back of the absorber, 23 cm is reserved for the readout and services. Steel plates provide mechanical strength and match the existing support brackets in CMS, thereby minimizing integration issues (Figure 2). The transverse tower size is \( 2 \times 2 \text{ cm}^2 \) and \( 4 \times 4 \text{ cm}^2 \) at larger radius (\( r \geq 180 \text{ cm} \)). The transverse segmentation is the same throughout the calorimeter, i.e. HAD tower size is the same as the EM tower size. The smaller towers contain 50 fibers per channel (either \( S \) or \( Q \)) and read out separately. The total number of channels is 65,196 for \( S \) and 65,196 for \( Q \) for the entire calorimeter (see Table 1).

The absorber fine structure (grooves or holes) can be made in several different ways:

- As in CMS forward calorimeters multiple grooved (cold rolled) plates are stacked and (diffusion) welded together to form large blocks of the absorber [6]. The grooved plates may also be produced by stamping, etching or machining.
- Thin precision punched (perforated) plates can be stacked together to form large absorber blocks.
Table 1. The nominal parameters of the brass absorber option.

| Parameter                                  | Value                                      |
|--------------------------------------------|--------------------------------------------|
| Absorber                                   | Brass (70% Cu + 30% Zn)                   |
| Total Weight (kg)                          | 235.376                                    |
| Nominal Fiber-to-fiber Spacing (mm)        | 2.0                                        |
| Fiber Core dia. (mm)                       | 0.6                                        |
| Fiber Core+Clad dia. (mm)                  | 0.7                                        |
| Fiber Total dia. (mm)                      | 0.8                                        |
| Hole dia. (mm)                             | 0.9                                        |
| Nuclear Interaction Length, $\lambda_I$ (cm)| 19.7                                       |
| Radiation Length, $X_o$ (mm)               | 18.2                                       |
| Moliere Radius, $\rho_M$, (mm)             | 20.0                                       |
| Transverse Segmentation ($r < 180$ cm)     | $2 \times 2$ cm$^2$                       |
| Transverse Segmentation ($r \geq 180$ cm)  | $4 \times 4$ cm$^2$                       |
| Longitudinal Segmentation                  | by timing on $Q$-channel (200 ps)          |
| Number of channels                         | 130,392                                    |
| Total Fiber Length ($Q$ or $S$) (km)       | 9.955                                      |

- Emerging 3D metal printing technologies are now capable of “printing” stainless steel, brass and tungsten. The bond jetting technique, for example, is able to print relatively large blocks albeit with reduced density (60% of metal). The selective laser sintering technique produces higher density blocks with good precision.

3. Readout Geometry, Signal Formation, and Electronics

Figure 3 shows the transverse granularity of the CFC as implemented in simulation. The fiber bundles are formed using Optical Guiding Unit (OGU) which guides the fibers to either scintillating or clear fiber bundle. The diameter of the small bundles is $\sim 6.5$ mm and the larger ones measure $\sim 13$ mm.

![Figure 3](image-url)

Figure 3. The transverse segmentation for a 20-degree wedge results in 1368 channels of small ($2 \times 2$ cm$^2$) and 443 channels of larger ($4 \times 4$ cm$^2$) towers. In a wedge, total number of towers is 1811.
A typical SiPM is taken as a benchmark photodetector, however others such as multi-channel VPT and GaInP sensors need also to be considered. Figure 4 shows the pulse shape for 1 GeV electrons impinging brass absorber with fiber-to-fiber distance set at 2.4 mm, as an example. The pulse is sampled at 5 GHz and the amplitude is shown in units of fC/200 ps. The light yield is \( \sim 30 \) photons/GeV resulting in 10 pe/GeV. The SiPM gain is assumed to be 250,000 (\( \sim 15 \) fC/pe). The QIE noise is \( \sim 2 \) fC. The timing features of the pulse include SiPM and the “3 ns preamp/electronics” time constants. The response is 150 fC/GeV.

The Cherenkov photon light yield smoothly varies as a function of the impact point: the EM showers generate 30 photons/GeV at \( \eta = 1.5 \) and 25 photons at \( \eta = 3.5 \). The scintillating fiber model consists of fused-silica core with parametrized scintillation properties. The photon yield per unit energy is constant within 2% (\( \sim 1820 \) photons/GeV for EM showers).

Figure 4. The simulated SiPM pulse shape for the Cherenkov pulse for 1-GeV electrons.

Figure 5 shows the conceptual CFC readout. The signal from the Cherenkov photodetector (\( Q \)-channel) is split into two paths. The first path is a conventional chain as in the CMS HCAL Phase I upgrade. The signal is digitized on detector and sent to the counting room for trigger generation. The digital pipeline holds data for the HLT up to 20 \( \mu s \). The second path is for a detailed analysis of the Cherenkov signal using a multi-GHz pulse-shape sampler. The analog pipeline holds the signal up to 20 \( \mu s \). When the CFC receives an L1A, the analog signal is extracted from the pipeline and digitized in a narrow time window of interest (5-10 ns). The digitized signal is then sent to the HLT.

The first path is very similar to the CMS HCAL Phase I electronics. The QIE can be upgraded from non-linear 8 bits to non-linear 10 bits for a larger dynamic range (15-16 bits equivalent) with a resolution better than one percent. The sampling frequency is also to be increased from 40 to 80 MHz to allow a crude pulse shape analysis for L1.

A 5 GHz pulse shape sampler is already commercially available: the Domino Ring Sampler (DRS4) series is one example. The DREAM/RD52 collaboration used DRS4 in beam tests and successfully measured the longitudinal shower shape utilizing timing information [7]. The next generation sampler, DRS5, is under development at PSI and will be ready for production in 2015. It provides up to 10 GHz sampling, up to 3 \( \mu s \) latency, and dead-time-free readout.

We considered the 40 MHz QIE10 as a benchmark system and assumed 10 fC/pe and 30% PDE for the SiPMs. QIE10 consists of 8 bits (6 mantissa and 2 exponent) and is non-linear, extending from 3 fC to 330 pC (10^5 dynamic range). The LSB is 3.2 fC, and at high energies, the QIE10 digitization error is 1%. The CFC EM energy resolution at high energies is below
Figure 5. While a part of the CFC readout system is based on existing (CMS HCAL) readout technology, a multi-GHz sampler on the Cherenkov side brings additional capabilities such as effective longitudinal segmentation and precision timing for the front-end. The back-end is on the right.

2%. There is insufficient headroom, a situation that can be remedied with an additional bit in exponent (see Figure 6).

Figure 6. A case study: 2 bits exponent and 6 bits mantissa in a QIE10 system (a). When an additional bit is added to the exponent (3 bits or 8 ranges), the digitization precision improves (b). The EM energy resolution curves are for comparison purposes only.

The baseline approach for effective longitudinal segmentation is accomplished by the analyses of the signal shapes. Figure 7.(a) shows the level of timing precision that was achieved in a test beam using a DREAM module: the distribution of the time difference between the PMT signals from 80 GeV electrons measured in the calorimeter and the trigger counters upstream. This difference was obtained by measuring the start of the calorimeter signals with the DRS chip (a simple threshold), where the domino wave was started by the trigger signal. We see that a time resolution of 0.55 ns is achieved in this way. The same measurement for 180 GeV pions yielded a very different time distribution, Figure 7.(b). The slope of 0.8 ns reflects the fact that the light is produced at a depth $z$ which varies like $\exp(-z/\lambda_{\text{int}})$. Since the interaction length is $\sim25$ cm in this detector, the time resolution of 0.55 ns means that the depth at which the light is produced can be determined with a precision better than 20 cm. The starting time
of the DRS signals indeed measures the depth at which the light is produced in the fibers, by comparing the DRS information with the depth measured in two other ways, namely from the longitudinal profile measured in the leakage counters (Figure 8.(a)) and from the lateral displacement of the center-of-gravity of the calorimeter signals with respect to the coordinates measured in the upstream wire chambers (Figure 8.(b)) [8]. Experimental data clearly show that timing information provides sufficiently precise determination of “center of light” inside the calorimeter.

Figure 7. The starting time of signals from 80 GeV electron (left) and 180 GeV pion (right) showers in a DREAM module, measured with the DRS readout. The readout was triggered by the passage of a beam particle through the upstream trigger counters.

Figure 8. The depth of the light production in the unsegmented fiber module versus the depth measured from the leakage profile (a) or from the displacement of the center-of-gravity with respect to the coordinates measured in the upstream wire chambers (b).

The detailed time structure of each event makes it possible to obtain crucial information about the depth at which the light is produced. By using the fact that light travels at a speed of $c/n$ in the fibers, while the particles producing the light travel at $c$, the starting time of the
signals makes it possible to measure the depth at which the light is produced, as illustrated in Figure 9.

![Light Propagation in a 2-\text{m Calorimeter}

**Figure 9.** The dependence of the starting time of the signals on the depth \( z \) inside the calorimeter at which the light is produced. Also shown are the time traveled by the beam particles from the front face of a 2-m long brass calorimeter to this depth \( z \) and the dependence of the time traveled by the light through the fibers from \( z \) to the photodetector.

There is a significant (measured) difference between the distribution of the starting time of pion and electron induced showers as shown in Figure 7. Since the depth distribution pattern of the light produced by the latter is very similar for all showers, the of the starting time distribution of the electron showers is a good measure for the precision in the depth of the light production that can be obtained for individual showers. Note that the timing precision that is derived from the EM showers was 0.55 ns and was not optimized to achieve maximal longitudinal segmentation. In addition to the effective longitudinal segmentation, this timing information also makes it possible to measure, and correct for, the attenuation (intrinsic and radiation induced) characteristics of the fibers.

4. Performance

The CFC calorimeter builds on the experience gained working with several operating calorimeters and the R&D prototypes in the last decades. More specifically, the “spaghetti” calorimeters, such as SPACAL, HF, and DREAM/RD52, have given us increasingly wider and deeper perspectives in calorimetry. We studied various tungsten alloys in detail but only the results for the brass absorber are given here. Although the dual-readout technique provides hadronic response linearity with excellent energy resolution, it might be possible to construct CFC naturally compensating as some results presented here may suggest. In order to make realistic progress on this issue, appropriate prototypes need to be tested in high energy beams to verify the simulation results.

Figure 10 shows the EM energy resolutions for the scintillating part as a function of the fiber spacing. The resolution is computed from signal distributions (\( \text{rms} \) divided by the mean) at five different energies. If we are to take 2-mm fiber-to-fiber spacing as a reference, the stochastic term is better than 20% while the constant term is below 2%. The same set of plots are shown in Figure 11 for clear (Cherenkov) fibers. In the case of the Cherenkov part, the dominating factor is the photo-statistics whereas in the case of the scintillator part, the sampling fluctuations dominate over photo-statistics.
Figure 10. The EM energy resolutions, stochastic (left) and constant terms (right), for scintillating fibers are shown for brass absorber at three pseudorapidity regions as a function of fiber-to-fiber spacing. The red markers indicate the resolutions achieved if scintillation and Cherenkov signals are summed. The DREAM data point (blue) is included as a reference point.

Figure 11. The EM energy resolutions, stochastic (left) and constant terms (right), for clear Cherenkov fibers are shown for brass absorber at three pseudorapidity regions as a function of fiber-to-fiber spacing. The DREAM data point (blue) is included as a reference point.

The scintillator part gives excellent (raw) hadronic energy resolution, better than $40\%/\sqrt{E}$ for 2-mm fiber-to-fiber spacing (Figure 12). As expected, the energy resolutions for jets are not significantly different than that of the single hadrons. The response to hadrons (signal/GeV) is easily linearized and the resolution is further improved using the dual-readout technique as shown in Figure 13.

Figure 14 displays the energy-weighted Cherenkov photon arrival times for electrons and pions as well as the $rms$ spread of these distributions as a function of particle energies. It is evident that signals from hadron showers arrive $\sim 0.5$ ns earlier compared to that of electron initiated showers for all configurations. The $rms$ distributions are also distinctly different between the two types of showers: EM showers are tightly distributed in time ($\sim 50$ ps) whereas due to stochastic nature of neutral pion production in hadronic showers, the $rms$ distributions are wider ($\sim 400$ ps) for pion initiated showers. Figure 15 illustrates how the timing information from a non-pointing geometry contributes in sharpening the $E_T$ definition. Using a simple correction scheme, we are able to improve the $E_T/E$ distributions to narrow gaussian distributions. For more details, see
Figure 12. The HAD energy resolutions for both quartz (left) and scintillating fibers (right) are shown at different pseudorapidity regions as a function of fiber-to-fiber spacing. The DREAM data point is shown in blue as a reference.

Figure 13. Before (a) and after (b) dual-readout corrections are applied to the scintillation and Cherenkov signals for the case of fiber-to-fiber 2.4 mm in brass for 200 GeV charged pions at $\eta = 2.0$.

5. Trigger Design
The CMS L1 trigger is able to perform identification of muons, electrons, photons, jets and missing transverse energy and the CFC will contribute to the identification of photons/electrons and jets. At L1, we consider the transverse shower shape, $f_{\text{em}}$ and potentially the timing information. An example of energy distributions in X-Y plane for electrons and pions are shown in Figure 16. The fine granularity is used to construct a variable sensitive to the transverse shower size, utilizing a ratio of energy deposition in two rectangular areas with different sizes $E(X\times Y)/E(X'\times Y')$, where $E(X\times Y)$ is the energy deposition in area of $X\times Y$ cells.

We studied a simplified L1 electron/photon particle identification. We used two variables:
Figure 14. The Cherenkov photon timing characteristics for electron and pion initiated showers in brass are shown: mean arrival times for EM showers (a) and for HAD showers (b). The rms spread of these arrival times are displayed in (c) for electrons and (d) for hadrons. The markers represent the $\eta$ location: circle $|\eta|=3.5$, square $|\eta|=2.0$, and triangle $|\eta|=1.5$, and the colors symbolize the fiber-to-fiber spacing: black 1.2 mm, green 1.8 mm, blue 2.4 mm and red 3.0 mm.

Figure 15. The average arrival time of photons to the SiPMs vs $E_T/E$ are plotted for 500 GeV (left column), 200 GeV (middle column) and 100 GeV (right column) jets at $|\eta|=1.5$ for Option I. In the bottom row, a simple correction scheme is applied to sharpen the $E_T/E$ ratio in order to suppress possible tails.

the transverse shape and $f_{em}$. The transverse shape is defined as $E(2\times 7)/E(5\times Y)$, where $X\times Y$ is $\eta$ dependent:

- $\eta=1.5 : E(2\times 7)/E(5\times 31)$
- $\eta=2.0 : E(2\times 7)/E(5\times 21)$
- $\eta=3.5 : E(2\times 7)/E(5\times 9)$

The EM fraction is evaluated by the ratio of the quartz and scintillator fiber signals collected from the same area used in the denominator of the transverse shape variable. The performance
Figure 16. The energy distributions in X-Y plane for pions and electrons in the presence of 140PU at $|\eta| = 1.5, 2.0$ and 3.5. Left column is for Cherenkov and the middle column is for scintillation for pions. The right column is for electrons. A pixel corresponds to a physical tower in Option I.

of the particle identification is evaluated on samples with single electrons (signal) and pions (background) in the energy range of 20-500 GeV. We choose 95% signal efficiency as a reference point and evaluate the background rejection for the cases of 0 and 140 PU. The result is shown in Figure 17 as a function of the transverse energy ($E_T$) and for $\eta = 1.5, 2.0$ and 3.5.

6. Radiation Tolerance

The effects of radiation damage to clear fused-silica fibers have been well studied and it has been shown that the induced absorption depends on the wavelength and accumulated dose by the following equation:

$$\mu_{\text{IND}}(\lambda) = \frac{1}{4.343}\alpha(\lambda) \left( \frac{D}{100} \right)^{\beta(\lambda)}$$  (1)
Figure 17. The electron identification performance at the L1: charge pion rejection is shown for a fixed electron selection efficiency of 95% for 0 and 140 PU.

where $D$ is the accumulated dose in MRad and $\alpha$ and $\beta$ are functions of the wavelength $\lambda$. The numerical values $\alpha$ and $\beta$ for fused-silica fibers are taken from [9, 10].

The FLUKA simulation tool was used to estimate the expected dose and neutron fluences up to after 3000 fb$^{-1}$. The typical maximum dose inside the absorber ranges from $\sim 15$ kGy to $\sim 16$ MGy. From the dose maps available, the non-uniform $\mu_{\text{IND}}$ of the fibers is calculated along their length according to Eq. 1. The non-uniformity of radiation damage to the fibers results in the addition of a constant term to the energy resolution. Figure 18 show this constant term as a function of $\eta$ for two wavelengths. For 450 nm light at $\eta = 4$, the additional constant term is of the order of a few percent.

Figure 18. The additional constant term for two particular wavelengths is shown here as a function of $\eta$ after 3000 fb$^{-1}$. This shows at $\eta = 4$ and additional $\sim 1-2\%$ constant term for 450 nm light.

The development of rad-hard cerium-doped scintillating fibers to a level at which they can be deployed in calorimeters in Phase II started recently and some promising results have been already presented in this conference [11, 12, 13]. Based on progress in rad-hard inorganic scintillating materials [14, 15], on the CMS HF experience [9, 10], and on developments in fiber production technologies, the R&D on rad-hard scintillating fibers is likely to succeed in the coming years. Aside from calorimetry, other types of scintillating fiber detectors will also benefit from these advances.
Figure 19. The emission spectrum of SiO$_2$:Ce$^{3+}$ fiber peaks around 470 nm (left) when it is excited at 337 nm by a pulsed N$_2$ laser. The decay time is about $\sim$50 ns (right) with small contributions from faster and slower components [14].

Figure 19.(left) shows the emission spectrum of a SiO$_2$:Ce$^{3+}$ cladless fiber produced in Milan-Bicocca and characterized at TTU. The light emission peaks at around 470 nm, and the light yield (although not shown in this figure) is expected to be approximately twice that of BGO. The dominant decay time is $\sim$50 ns (Figure 19.(right)). Shorter decay times are desirable, and synthesis strategies to shorten the decay times down to $\sim$5 ns could involve tuning activator concentration along with the use of co-dopants. Another dopant, praseodymium, for example, would give $\sim$10 ns in shorter wavelengths.

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