The CMS-HF quartz fiber calorimeters.

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Abstract: Two hadronic forward (HF) calorimeters extend the acceptance of CMS at large rapidities and are built with radiation-hard components (steel absorbers and quartz fibers) to resist the severe radiation levels in the forward regions. Very high energy jets can be measured in HF, by detecting Cherenkov light emitted by shower particles in the quartz fibers. The HF calorimeters are now installed in the underground CMS cavern; after commissioning, the detectors are being prepared for beam. Progress in calibration work and current plans for the HF calorimeters during the initial LHC runs are summarized.

Keywords: Quartz, Cherenkov, calorimeter, radiation.

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1. Introduction

The Large Hadron Collider (LHC) will reach unprecedented high energies ($\sqrt{s} = 14$ TeV) and luminosities ($L = 10^{34}$ cm$^{-2}$ s$^{-1}$), opening vast new opportunities for particle physics research and discoveries, but producing extreme radiation conditions for experiments in the underground caverns. Each LHC apparatus needs to resist high radiation levels, without compromising its excellent performance. For the CMS detector, among many other crucial issues, an almost hermetic calorimetry coverage is required to measure missing $E_T$ and forward high-energy jets, potential key signals of new physics [1].

Two hadron forward (HF$^+$) calorimeters on both sides of the CMS interaction point (IP), at about ±11 m, cover the very forward angles of CMS, in the pseudorapidity range (3.0 < $\eta$ < 5.0), leaving only clearance for the beam pipes (Fig.1). To resist the high LHC radiation levels in this region, they are built with radiation hard components: steel absorbers with longitudinal quartz fibers, which should survive very high doses (of the order of Grad). About 1000 km of quartz fiber have been used for the two HF modules, which weight about 250 tons each. These devices can measure hadronic jets up to few TeV energies, detecting the Cherenkov light, emitted by the shower particles in the quartz fibers, and transported through the same fibers to photomultiplier tubes (PMT), located on the downstream side of the calorimeter modules (Fig. 1). These detectors have become a benchmark reference for large-scale applications of quartz fiber calorimeters [2].

The two modules have been assembled at CERN in Building 186, where both were also calibrated with radioactive sources. Some HF wedges had been earlier tested and calibrated with electrons and hadrons in the SPS H2 beam line. The two modules were
then transported from Building 186 to the CMS assembly hall SX5 at LHC Point 5 [3] and subsequently lowered in the underground UXC5 cavern [4].

![Forward CMS Region](image)

Fig. 1 – The forward region on one side of the IP in CMS: the quartz calorimeters HF (fibers) and Castor (plates) cover respectively pseudorapidity ranges $(3.0 < |\eta| < 5.0)$ and $(5.0 < |\eta| < 7.0)$; at 140 m further from IP, the ZDC (fibers) calorimeter measures high-energy forward neutrals.

2. Quartz Fiber Cherenkov Calorimetry

Cherenkov radiation has been frequently used to measure the energy of electromagnetic showers, for instance in lead-glass calorimeters [5]: now it becomes increasingly useful for hadronic calorimetry as well, thanks to quartz fibers, a new type of active material for calorimeters, providing very high radiation hardness, excellent optical quality and fine granularity. Valuable properties of Cherenkov calorimeters [6] are well recognized:

- Cherenkov light is strongly correlated with the showering particles' trajectories, providing directional information;
- Cherenkov radiation emission is essentially instantaneous, thus giving a fast response, useful for high rate applications;
- Cherenkov radiation is produced by charged particles with velocity above a certain threshold: these detectors are essentially blind to low energy particles and neutrons, and preferentially sensitive to the large amount of $e^{\pm}$ produced in EM processes, and emitting Cherenkov radiation in quartz down to $E \geq 190$ keV;
- A sizable fraction of hadronic cascades in an absorber is transformed into $\gamma$ rays (mainly through $\pi^0$ decays), giving $e^{\pm}$ as final products; in a Cherenkov calorimeter, hadronic showers are essentially visible through their EM components, with lateral width much narrower than for real hadron cascades (as appearing in ionizing or scintillating calorimeters) and concentrated near the core of the shower, thus making jet isolation easier;
- Quartz fibers maintain good transparency to visible light up to Grad doses [7].
Quartz fibers for calorimetry were introduced by P. Gorodetzky and co-workers [8], for detectors exposed to very high radiation levels, typically Grads ($10^9$ rad = 10 MGy): for instance "Zero Degrees Calorimeters" (ZDC) at very forward angles in fixed-target heavy-ion scattering experiments [9]. A number of detectors based on quartz fibers have been constructed in order to profit from the above listed merits [10]. There are however also some shortcomings:

- The light output of this type of calorimeters is quite low due to several reasons:
  - The energy of showering particles is mainly dissipated through ionization losses; only a minute fraction is released in the form of Cherenkov radiation;
  - The fraction of quartz fibers in the calorimeter is rather low (about 1%) to keep the overall cost of the calorimeter at an affordable level;
  - Only a small fraction of produced photons is trapped in the fibers and transported to photodetectors;
- As, contrary to visible light, fibers' transparency to UV deteriorates under high radiation at LHC, there is no advantage in using UV-sensitive photodetectors;
- This type of calorimeters is highly non-compensating, i.e. the detector is essentially sensitive only to the electromagnetic shower core and the so-called e/h ratio is quite large ($e/h \approx 5$), implying that the signal for high-energy hadrons (for instance pions), is considerably lower (by a factor of about 1.5) than the signal for electrons (or photons) of the same energy.

3. Structure of the HF Calorimeters
The forward calorimeter is essentially a cylindrical steel structure with outer radius 130 cm, inner radius 12.5 cm (to accommodate the beam pipe) and length 165 cm ($\approx 10 \lambda_I$). The absorber of each HF module weights 108 t and is azimuthally subdivided in 20-degree modular Fe wedges assembled in 2 half-cylinders; thirty-six such wedges (18 on either side of the interaction point) make up the HF calorimeters. Each absorber wedge has a matrix of longitudinal grooves spaced by 5 mm horizontally and vertically; in each groove, quartz fibers are inserted. The fibers have a 600 $\mu$m diameter fused-silica core, 630 $\mu$m with the polymer hard-clad, and 800 $\mu$m with protective acrylate buffer. Half of the fibers run over the full depth of the absorber while the other half starts at a depth of 22 cm from the front of the detector. These two sets of fibers are read out separately. This arrangement makes it possible to distinguish showers generated by electrons and photons, which deposit a large fraction of their energy in the first 22 cm, from those generated by hadrons, which produce signals in both calorimeter segments. We refer to the long fiber section as L (it measures the total signal), and the short fiber section as S (it measures the energy deposition after 22 cm of steel). Long and short fibers alternate in nearby grooves spaced by 5 mm inside the absorber. The packing fraction by volume (fiber/total) in the first 22 cm is 0.57% and it is twice as large beyond that depth.

The fibers extend behind the back face of the absorber (Fig. 2), and are grouped in bundles separately for L and S fibers, corresponding to towers in $(\eta - \phi)$, with a typical segmentation of 0.175 x 0.175 ($\Delta \eta \times \Delta \phi$); the fiber bundles are routed from the back of the calorimeter to air-core light guides which penetrate through a steel-lead-polyethylene shielding matrix, protecting the PMTs housed in the readout boxes. Each wedge has 2
readout boxes (RBX), each housing 24 PMTs (8-stage, with bialkali photocathode and borosilicate glass window; the field of the CMS magnet at the HF position is sufficiently low to have negligible effect on the HF PMTs, which are individually shielded.

Fig. 2: HF wedges during assembly and fiber stuffing in the steel absorber, in Build. 186

Each HF module is divided into 36 segments in azimuth and 12 segments in pseudo-rapidity, resulting in 432 towers per side, each of them corresponding to a physical channel, and sampled by fibers of 2 different lengths, (L) and (S) readout by separate PMTs. The L fibers are sensitive both to photons/electrons and hadrons, while the S fibers miss most of the EM showers (developing and dissipating most of their energy in the front part of the absorber) and are therefore preferentially sensitive to hadrons.

Fig. 3: The development of EM and HAD showers in one HF wedge
Using this longitudinal segmentation of the calorimeter, where the sampling fraction in the front (EM) section is lower with respect to the rear (HAD) section it is possible to achieve a partial equalization of the HF response to electrons/photons and hadrons, despite the strong non-compensating nature of this type of calorimeter.

Signals from the PMT are digitized on a bunch by bunch basis using a dedicated chip, and then routed to a set of 36 Trigger and Readout (HTR) boards each servicing 24 HF physical towers.

4. Performance of the HF Calorimeters

The HF calorimeter is based on quartz fibers where Cherenkov radiation forms the basis of signal generation. Thus, the detector is essentially sensitive only to the electromagnetic shower core and is highly non-compensating (e/h ≈ 5). This feature is also manifest in narrow (and relatively short) showers compared to similar calorimeters based on ionization. The choice of fused-silica optical fibers as active material is dictated by its exceptional radiation hardness. The electromagnetic energy resolution is dominated by photoelectron statistics and can be expressed as \( \Delta E/E = A/\sqrt{E} + B \). For electrons the stochastic term \( A \approx 198\% \) and the constant term \( B \approx 9\% \). The hadronic energy resolution is largely determined by the fluctuations in neutral pion production in the shower development: when expressed as in the electromagnetic case, \( A \approx 280\% \) and \( B \approx 11\% \).

The light yield of the HF calorimeters is approximately 0.25 phe/GeV for electrons in L fibers, thus 1 phe corresponds to about 4 GeV; high energy muons traversing the absorber module, give approximately a similar value (~ 3.5 GeV in average); if a muon impacts a PMT, it generates on average a signal equivalent to 30 phe (~ 120 GeV).

The transverse width of the shower seen via Cherenkov light is rather narrow: in the case of electrons, ~ 98% of the visible energy is contained in 5 cm around the shower axis (~ 85% within 1 cm). In the case of hadron showers, the transverse shower profile is wider: 70% within 1 cm (90% within 5 cm).

5. Commissioning and Calibration of the HF calorimeters

The two HF modules have been assembled at CERN in Building 186, where both were also calibrated with radioactive sources and with LED in 2006. Some HF wedges had been earlier tested and calibrated with electrons and hadrons in the SPS H2 beam line. The two modules were then transported to the CMS assembly hall SX5 at LHC Point 5 [2] (Fig.4a). The HF calorimeters are now installed in the underground CMS cavern; most of installation and commissioning was done in 2007 and beginning of 2008; soon the calorimeters will be prepared for beam (Fig. 4b).

The HF modules were the first CMS pieces to be lowered into the experimental hall UXC5, at the end of 2006; in the beginning 2007 HF+ was the first detector to be connected through the cable chains to the read-out electronics situated in USC5 cavern and have the front-end electronics powered-up: therefore HF+ commissioning started underground, obtaining, after intensive work, to have all channels functional and properly mapped into the readout. HF+ was the first active detector included in the Global Runs (GR), a series of monthly week-long integration exercises [12]. Since the end of May 2007 (GREM), HF+ was in regular use for electronic checks, and also for software development and testing, giving an excellent opportunity for debugging electronics and software in realistic conditions [13] (Fig. 5).
It was soon followed by the other CMS subsystems (Fig. 6) and joined early in 2008 by HF. With the approaching of beams in LHC, the activities around HF are focusing on precision tuning and calibration of the detectors, as well as preparation for initial operations with beams.

The calibration of the HF is based on three independent hardware systems: Laser Gain Monitor, Light Emitting Diodes, and Moving Radioactive Source. These systems should deliver the required calibration resulting in an overall energy scale uncertainty of approximately 3%. The chain of calibration steps starts from the detailed studies of the PMT properties performed at reception of the 2000 R7525HA PMTs from Hamamatsu: the gains (G) of all PMTs have been determined and subdivided in groups of sufficiently close values [14].
In 2004, during test beam studies, several slices of the HF were tested with electron, pion, and muon beams at energies varying from 30 to 300 GeV. The response to these different particles and energies were compared with results of simultaneous runs with a Co\textsuperscript{60} wire-source [15]. A systematic source scan of all HF wedges was performed in Bldg 186 on fully HF assembled modules, before transport to SX5. During these tests, data were separately taken with the wire-source remote and inserted into the detector. The charge collected as a function of the source position inside the absorber provides information on the energy calibration of the detector (Fig. 7). There is a clear difference in the number of counts between the wire-source positions inside the detector and at remote park position. This sourcing campaign was planned in order to transfer the beam energy calibration (100 GeV electrons) from the few wedges tested on the beam to the totality of the wedges in both HFs.

Additionally LED runs have been taken at different levels in order to estimate the gains G of PMTs (from SPE spectra [16]) and the dependence of G on the HV of the PMTs. Using these measurements it was found that the relative gains measured at the University of Iowa test station and the gains obtained from the SPE data are highly correlated [17]. These relative gain values were used to group the PMTs going to different tower positions (the lower gains closer to the beam). It also confirms the reliability of using the SPE peaks in monitoring the gains with the LED system.

![Fig. 6](image)

Fig. 6. Fraction of CMS detectors active in the Global Runs.

![Fig. 7](image)

Fig. 7: The spectra from an L fiber, for source outside or inside HF absorber.
The energy calibration in terms of the amount of charge collected per unit energy of a particle is done with the help of the wire sourcing and the measured value is about 0.21 and 0.34 GeV/fC for L and S fibers respectively [18]. These studies help to understand the operation of the QIE elements, pedestals, and the noise in the system. The three calibration factors: fC/phe, GeV/fC and phe/GeV should be consistent with 1, when multiplied together: a value of 0.25 phe/GeV means a consistency within 10%.

6. Initial operation with beams and first results

The basic role of the HF calorimeters at high luminosity [1] will consist in improving missing-energy ($E_T$) determination and tag vector-fusion events with forward jets (Fig. 8) for physics and luminosity monitoring as a service to LHC and CMS.

Fig. 8 – The VBF diagram for Higgs production, and the distribution of reaction and Higgs decay products, showing the tagging role of high energy forward jets.

During initial operation of LHC (at low luminosities) the HF calorimeters will be crucial for start-up luminosity studies, and may collect some data on forward physics. For instance HF will be able to measure forward jets for studies of QCD and diffractive processes, as well as dijets with large $\Delta\eta$ gaps ($\Delta\eta > 6$), coming from processes, where forward energetic “spectator” jets in high cross section hadronic interactions mimic somehow the role of “tagging” jets in the EW VBF process. For Mueller-Navelet dijets [19], the statistics in a low luminosity pp run ($L \sim 1 \text{ pb}^{-1}$) may reach $10^4$, enough to start studies of low-x QCD [20].

Fig. 9 – The Mueller-Navelet diagram for dijets production process [19, 20].

The online luminosity measurement [21] in CMS is based on HF, which is sensitive to a large fraction of the inelastic cross section. The design goal for the real time measurement is to determine the average luminosity $<L>$ in less than one second. Possible techniques for extracting the real time luminosity signal have been studied:
Zero-counting, based on the probability $p(0)$ of beam-crossings (BX) without interactions: $\mu = -\ln p(0)$ ($\mu$ is the average number of interactions per BX);

Hit counting, based on the number of towers above threshold for each BX; this quantity is linearly related to $<L>$, if multiple hits are negligible;

Total transverse energy $E_T$ measurements, adapted to the highest luminosity: both $N_{ch}$ and $E_T$ should be proportional to $\mu$ (hence to $<L>$).

In order to extract the luminosity signal from the HTR an additional mezzanine board (HLX) is mounted on each HTR board. Two identical servers collect data from all 36 HLX and transfer the data to a server interfacing to various clients.

7. Conclusions: the fate of HF calorimeters

In ten years of LHC operation at nominal luminosity, the parts of HF closest to the beampipe ($4.5 < \eta < 5$), will experience radiation doses close to 1 Grad ($10^7$ Gy) and large neutron fluxes leading to the activation of the absorber, at levels of $\sim 10$ mSv/h in the inner parts (1-10 $\mu$Sv/h on the periphery). Soon after extensive LHC operation, the HF modules will become off-limits and access, maintenance and repair may become almost impossible. It is expected however that active elements of HF (quartz fibers + PMTs) survive these levels of radiation with limited deterioration: fibers’ optical transmission is expected to be degraded by $\leq 50\%$ after 10 years of LHC operation and quartz fibers are practically insensitive to neutrons and to low energy particles from decays of activated radionuclides (no Cherenkov light). The PMTs are properly shielded against radiation emerging from the absorber region and maintenance of read-out boxes will be performed with the help of semi-robotic extractor tools. HF is equipped with radiation monitors located at the periphery of the detector, and with a system (Raddam) to measure the transmission properties of few reference quartz fibers embedded in the absorber, as a function of the absorbed doses [22]. Such a monitoring system will be extremely useful to follow-up the degradation of the calorimeter response and provide the appropriate corrections, to maintain the quality of the HF calibration. In conclusion, with increasing integrated LHC luminosities, the body of HF will become inaccessible, thus making maintenance problematic, but the detector should maintain its design functionality, and provide high quality data for many years of LHC operation.

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