Operation and Performance of the CDF Calorimeters

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Abstract. All electromagnetic and hadronic components of the The CDF run II calorimeter system are scintillator - based sampling calorimeters employing both older (Run I) and newer fiber - based techniques for light extraction. The system has now been operating successfully for several years and is presently taking data at high luminosity thanks to its design characteristics and the upgrade of its frontend daq and trigger electronics. The composition and operation of the calorimeter system is described with due consideration for calibration and maintenance techniques required for the preservation of data quality and stability and its performance will be summarized with reference to design expectations.

1. The CDF calorimeters: design characteristics

All CDF calorimeters (fig. 1a) are scintillator-based sampling calorimeters. The central region which extends to a pseudorapidity (η) of about 1 is spanned by an 18 - radiation length (Xo) lead ( 1/8 inch) - scintillator (5 mm polystyrene) em calorimeter (CEM) [1] followed by a 4.7 - interaction length (λ) iron ( 2.5 cm ) - scintillator (1cm PMMA) hadron calorimeter (CHA)[2]. The basic structural units of both calorimeters are 15° wedges (fig. 1b) which are subdivided in 10 projective towers, each subtending 0.1 units of pseudorapidity and 15° of azimuth. Light from all active scintillator elements of each tower is collected on each side of the wedge by wavelength-shifter (wls) and transported to the photomultipliers (PMTs) by means of plexiglass guides which are routed through the “cracks” between wedges which end up spanning ~5% of the azimuth. Strip chambers, located at 5.9 Xo (see fig. 1b), measure transverse shower development at shower maximum with orthogonal strips and wires.

CEM light-output is ~100 photoelectrons (p.e.) per GeV per PMT and design energy resolution $\sigma(E)/E$ for electrons is 13.5%/ $\sqrt{E \sin \theta}$ (E in GeV). The large sampling fraction of the CHA was chosen for good resolution (33%/ $\sqrt{E \sin \theta}$ with a 4% constant term) for 50 GeV pions but this design performance was compromised at higher energies because of the limited thickness due to financial and structural limitations.

The CHA is complemented by the Wall Hadron Calorimeter (WHA) [2] (see fig. 2a) which extends its η-range to ~1.1. This is also an iron (5 cm) – scintillator (1 cm PMMA) but the sampling fraction is smaller than for the CHA because higher forward energies require more absorber and its resolution is correspondingly worse. Preliminary studies [2] indicated that light output from both Hadron calorimeters might be expected to decrease because of the adverse effects of radiation on the...
scintillator attenuation length. On the other hand the magnetic field has been observed to increase scintillator output by ~4% [2].

Figure 1 (a) A quadrant of the CDF detector showing the positions of the calorimeters. (b) A central calorimeter wedge showing the light-collection system for the inner CEM. An analogous wls – acrylic light pipe system (not shown) collects a routes light for the CHA.

In anticipation of the Run II luminosity upgrade, the configuration of the Run I forward calorimeters was modified to accommodate the shorter bunch spacing. The resulting Plug configuration is shown in fig.2a. It includes a lead-scintillator em calorimeter (PEM) [3] followed by an iron-scintillator hadron calorimeter (PHA) [4]. These calorimeters span the range 64.3 < |η| < 3.1. A “miniplug” calorimeter [5] for forward diffraction studies will not be described here. The design of the plug calorimeters is shown in more detail in fig. 2. The plug calorimeters were the first large-scale application of the “scintillator tile” + wls fiber configuration. It is illustrated in fig. 2b. The PEM alternates 4 mm polystyrene (Kuraray SCSN 38) scintillator with 4.5 mm lead plate lined with 0.5 mm stainless steel in 22 layers for a total of 21 X0 (corresponding to 1 λ). The PHA uses thicker (6mm) tiles of the same scintillator which it alternates with the 5.08 cm slabs of iron inherited from the Run I Plug calorimeter, for a total of 7 λ. This iron was incremented (darker shading in fig. 2b) so as to extend the polar angle covered by the calorimeter to smaller angles as a substitute for forward gas-based calorimeters used in Run I. A stack of tiles alternated by absorber constitutes a projective tower and the light collected from all tiles in a tower is routed to the photocathode of a single PMT (Hamamatsu R4125) for each calorimeter. The PEM is preceded by a pre-radiator (PPR) comprising a single layer of 10 mm PVC scintillator (BC408) [6] subdivided into the same tower-based tile structure but viewed separately by dedicated PMTs.

Transverse shower development is measured by a shower max counter (PES) located behind the 4th layer of the PEM, at ~ 6 X0 (see fig 2a). The PES [7] comprises 2 layers of 5mm by 6mm PVC (BC404) scintillator strips of varying length, read out by 0.83 mm wls fiber (Kuraray Y11) embedded longitudinally in the strip. The strips are are arranged in 8 U/V planes, each spanning 45° of azimuth.

Design performance was 16% / √E ⊕ 1% for the PEM with 5 p.e./ minimally-ionizing particle (mip)/ tile corresponding to a total light output of 400 p.e./GeV. For the PHA, it was 70% / √E ⊕ 4% with 5 p.e./mip/tile, corresponding to a total light output of 40 p.e./GeV.
Figure 2. (a) Plan of a CDF plug calorimeters showing their coverage in polar angle and the location of the shower max (PES) detector. (b) A 15-degree azimuthal section (a “megatile”) of PEM showing how it is subdivided into “tiles” together with an enlargement of one of these tiles showing how light is collected by wls fiber embedded in the tile.

All calorimeters were read out by the same frontend (f.e.) electronics [8] based on the QIE (Q Integrator and Encoder) custom-built 8-range (I/2-I/256) current-splitter/integrator/encoder developed to accommodate the run II requirement for increased dynamic range. The f.e. CAFÉ cards, containing the QIE chip, a 10-bit FADC, Q-injection circuitry and FRAM are mounted on the f.e. VME boards known as the ADMEMs (ADC + MEMory) which provide the Level 1 trigger with transverse energy sums for each tower, obtained using Xilinx FPGA’s.

Calibration and monitoring instrumentation [1-4,9,10] is an essential part of the CDF calorimeter system. It is needed both to transfer test-beam calibrations and to monitor stability and functionality at run time. There are two essential elements: (1) lasers or flashers which inject pulsed light at the PMT photocathode and (2) radiation sources which are used to stimulate the scintillator. The first element is used to monitor the signal collection and amplification chain, beginning with the PMT, whereas the radiation sources test the entire chain, including the light generation and transmission process in the scintillator. Together, they enable one to disentangle problems and instabilities originating in the light generation and transmission system from those originating in the chain beginning with the PMTs. (e.g. magnetic field effects on scintillator response [2] and deterioration in plug PMT response discussed later). The light-injection systems also incorporate LEDs for injection of low-level continuous light at the photocathode in order to reduce rate-dependent gain fluctuations. The charge-injection circuitry incorporated in the f.e. CAFÉ cards also allow for monitoring of the signal digitization stability by the QIEs.

All CDF calorimeter are equipped with a radioactive source calibration system [11] employing either Cs$^{137}$ or Co$^{60}$ sources, the former being preferred because less penetrating radiation produces more localized effects. The CEM calorimeter is equipped with a Xenon flasher system and LEDs [9] whereas the CHA and WHA rely on a Nitrogen UV laser for light injection [2]. A Nitrogen laser system is also used to distribute light pulses to both plug calorimeters.
2. Measuring the calibrations

In this section we outline the procedure whereby the energy scale of the calorimeters was determined and transferred.

2.1. General procedure
The following procedure was used to set the energy scale for all CDF calorimeters:

- Relative channel gains are derived from radioactive source and/or laser measurements.
- Absolute calibrations are obtained from test beam (TB) measurements of E/p. All HVs were set for the same Nominal Gain of all towers (e.g. 2 pc/GeV).
- Dimensionless correction factors, called LERs (Linear Energy Response), where \( \text{LER} = \frac{\text{Nominal Gain}}{\text{Real Gain}} \), were determined for the correction of residual differences.
- After application of the LERs a unique Scale Factor (SCL) was determined for all channels so that \( E_{\text{GeV}} = \text{count}_{i} \times \text{LER}_{i} \times \text{SCL}(\text{GeV} / \text{count}) \).
- Calibrations were transferred to the detector by repeating the radioactive source runs in situ and applying the test beam constants adjusted for the change in readout electronics, eventual differences in radioactive sources and the “brightening” effect of the CDF magnetic field on the scintillator output.

2.2. An example
Some procedural details are given here for the plug calorimeters by way of illustration (a more detailed account of the calibration procedure is given in refs [3] [4]). A replica of the real plug calorimeters, spanning 45° for the PEM and 60° for the PHA, was constructed and set up for data taking at the MT6 TB using the Run I (RABBIT) electronics. All towers of the replica module were exposed to \( e^+ \) and \( \pi^+ \) and \( \mu^+ \) beams whose momenta were varied between 5 and 230 GeV/ and tagged with a resolution of between 1.1% and 1.6% at lower and upper ends of the momentum range, respectively. LERs and SCLs were determined as a function of energy from measurements with electrons and pions while the energy deposited by muons was used to check the calibration model.

The energy resolution for the PEM is shown in Fig. 3 where the design resolution is also shown for comparison. Non-linearity for the PEM was better than 1% and non-uniformity less than 2%.

![Fig 3 (a) The PEM resolution for a tower of the PEM replica as measured at test beam. (b) The LERs for the PEM calorimeters at CDF, versus geometrical ID. Points on the left are for the west plug.](image-url)
Radioactive source runs were also taken at TB and, on the basis of the measurements of beam momentum, energy deposited in the calorimeter, current generated by the radioactive sources, calibration transfer constants (in pC/GeV/μA) were determined with the beam centered on all towers. These were then corrected for differences in the radioactive sources (Co$^{60}$ at CDF vs. Cs$^{137}$ at TB), a shorter (132ns vs 2.2 μs) charge integration gate at CDF and enhancements (“brightening”) in the scintillator light output [2] due to the CDF magnetic field. Radioactive source runs were repeated at CDF and an example of the resulting LERs, for all towers of both PEMs is shown in fig. 4b.

3. Keeping the calibrations: run-time calibration and monitoring

The response of the calorimeters can vary with time for a variety of reasons ranging from component failure to gradual deterioration and it is therefore of critical importance to monitor all channels and update calibrations as often as possible. In this section we outline the procedures employed for the CDF calorimeters

3.1. Organization

CDF data is expected to be calibrated and run through (offline) production within 2 months of being taken. This sets the overall time scale and it is the responsibility of the “Physics coordinator” to ensure that calibration updates are in the database every ~200 pb$^{-1}$ of integrated luminosity. A “calibration coordinator” oversees a “calibration group” of “system” experts, each responsible for a detector subsystem. For the calorimeter systems experts are nominated for each of the CEM, CHA, WHA, PEM, PHA, PES, HAD/EM timing. System experts are expected to update the on-line calibration database on a weekly basis.

3.2. Operations

One can distinguish between two types of calibration:

- Detector-level hardware calibrations which are initiated by the shift crew at fixed intervals (e.g. daily). These are automated to the degree that it is possible.
- Higher-level automated calibrations: a calibration executable, that runs continuously, strips out, stores (e.g. in ntuples) and processes events (e.g. di-muon/electron events, minimum bias events, jet events) for calibration purposes.

Monitoring the results of calibration runs is greatly facilitated by the calibration database and monitoring software (DBANA). Monitoring takes place at different levels: at calibration time by the shift crew; on a weekly basis by the above-mentioned system experts who are responsible for identifying and solving problems and for updating calibrations on a weekly basis; by the experts over longer periods in preparation for offline production.

Examples of typical detector-level calibrations are the QIE and plug laser calibrations. In the QIE calibration sequence, known charge is injected into the QIE (using the charge-injection circuitry on the CAFÉ card, mentioned previously) for calibration of the electronic gain of all calorimeter channels. The procedure also identifies bad or noisy electronic channels. Calibration data are processed by online “consumer” programs which store pedestals, means, r.m.s. deviations and gains in the data base where they can be monitored using DBANA. Shift crew monitor the data right after the calibration and signal eventual deviations from reference data for inspection by the experts.

The plug laser system is used to distribute light from each laser pulse to all plug calorimeter channels and to stable PIN diodes which monitor the intensity fluctuations of each laser pulse to better that 1%. Ratios of calorimeter-to-PIN signals are therefore expected to be stable to that level and eventual deviations are indicative of malfunction or of gradual variations in the channel calibration beginning a the channel PMT. Thanks to this system, a progressive degradation of the plug PMT responses was brought to light at an early stage. Laser data are also processed on-line by a
“consumer” program which stores the results in the calibration data base where they may be monitored using DBANA and used to correct for the degradation in PMT gain.

An example of a higher-level calibration is the procedure used to track and update the CEM calibrations: 8 GeV e.m. “objects”, selected by a “calibration trigger”, are stored and subsequently used for E/p in situ calibration. This procedure evidenced a ~3% annual drop in calorimeter response due to scintillator degradation. The monitoring of variations in the Z peak also showed luminosity-dependent variations at the <1% level. Response variations are also monitored by tracking the minimum-bias rate at fixed \( \eta \).

CHA LERs are also monitored and updated using E/p measurements since problems developed in the CHA radioactive source drive mechanism: J/PSI muon momenta are compared to the muon energy measured by the calorimeter. When muon statistics are insufficient, monitoring of the minimum-bias rates at fixed \( \eta \) is used as a fall-back procedure. These procedures confirm previous observations of response degradation due to deterioration in the scintillator attenuation. The degradation rate is shown in fig. 4 (left).

![Figure 4. LER variation for the CHA and WHA calorimeters vs year.](image1)

The rate of degradation is more pronounced for the WHA as seen in fig. 4. The WHA radioactive source system continues to operate satisfactorily and periodic source runs are used to track the response variations.

Response variations in the plug calorimeters (see fig. 5) are due to PMT gain decreases, as already mentioned above.

![Figure 5. The response of a channel of the west PHA vs run number](image2)
They increase with $\eta$ and range between 1% and 8%. The source of the PMT gain degradation is not understood.

4. Jet energy scales

Calorimeter responses are major ingredients of the Jet energy scales which are needed to evaluate the energies of partons resulting from underlying physics processes. As such they are essential for most analyses and are the major source uncertainty in the top quark mass. Given their importance, they are the responsibility of a dedicated “Jet Energy Resolution group”.

The parton energy is distributed amongst all elements of the parton shower and its evaluation depends on an understanding of the shower evolution and on the “jet energy corrections” such as the those deriving from the dependence of calorimeter response on the type of particle, non linearities in the calorimeter response, energy losses due to acceptance and energy losses from the jet clustering algorithm. Amongst the major responsibilities the jet energy resolution group is the evaluation of energy corrections and the improvement of jet clustering algorithms. Tuning the calorimeter simulation MC, based on GFLASH [12], is an essential element of this work. Test beam data (for $p>20$GeV) and in situ data (for $p<20$GeV) were used to tune the MC for single particle calorimeter response. As a result, the jet scale uncertainty has recovered from the upgrade changes and is now slightly better than the final Run I estimate [13,14]

![Figure 6. Uncertainties in the absolute jet energy scale](image)

5. Conclusions

The CDF calorimeters are operating at better than design expectations and are expected to survive to the end of Run II without significant further loss of performance. Operational procedures have now settled down for the home stretch. Further improvements in the jet energy scale are expected as analysts hone their tools and exploit all the bells and whistles.
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