HF Status

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**Abstract.** We report the performance of HF calorimeter and some details about the PMT window hit events. The new 4-anode PMTs will be installed during the 2013 shutdown period. We have developed HF GFlash, a very fast simulation of electromagnetic showers using parameterizations of the profiles in Hadronic Forward Calorimeter. HF GFlash has good agreement to 7 TeV Collision Data and previous Test Beam results. In addition to good agreement with Data and previous Test Beam results, HF GFlash can simulate about 10000 times faster than Geant4.

1. Introduction
CMS has two Hadron Forward (HF) calorimeters on both sides of the interaction point (IP), at about 11 m distance, cover the very forward angles of CMS, in the pseudorapidity range 3 < |\(\eta|\) < 5. Such detectors will optimize the detection of those processes that produce forward jets, especially processes involving heavy Higgs and SUSY particles. An added benefit is to improve the determination of the missing transverse energy. The two cylindrical HF units are placed at each end of the detector at the beam height. They are sampling calorimeters with plastic clad quartz fibers embedded into the iron absorber. It has an active radius of 1.4 m. Each unit is 1.65 m long and composed of 18 slices of 20-degree sections. Long (1.65 m) and short fibers (1.43 m) in the calorimeter sample the energy in hadronic and electromagnetic showers, respectively. 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.
2. PMT Upgrade
During 2010, the anomalous events that had been seen in the HF calorimeter earlier continued to be a problem. These events were mostly due to the particles hitting the PMT window and producing Cherenkov radiation, thereby creating large false energy signals. One of the suggestions to eliminate these false signals is to discard the data that do not show any correlation in the long and short fibers. In principle, long and short fibers should measure similar energies. However, using the correlations in the long and short fibers eliminates some of the anomalous events after the data acquisition; it does not prevent the signals to be produced in the first place.

Even though the correlations between the long and short fibers seem to give us a good way of eliminating most of the anomalous signals, this is not enough because it is not complete and it does not eliminate the erroneous trigger signals. The solution has to reduce these signals at the source such as replacing all the PMTs with thinner window 4-anode PMTs. Thinner window will produce less Cherenkov scintillation in the window and using the correlation between different anodes will eliminate the remaining signals coming from the windows. The real Cherenkov light coming from the calorimeter towers will produce similar signals in all four anodes but not the Cherenkov light produced in the window.

Hamamatsu 4-anode PMTs (R7600) are chosen to be the replacement PMTs for the HF. Initial tests done with these PMTs in the test beam at Fermilab and CERN show that the Cherenkov light produced by particles hitting the PMT windows could be distinguished easily and clearly from the real signals. During the 2013 shutdown, new thin-window high-efficiency 4-anode PMTs will be installed instead of the current PMTs to reduce the anomalous signals to negligible levels. These new PMTs are being tested prior to the installation, as they are delivered by Hamamatsu.

3. HF Simulation
Previous HF simulation (based on Shower Library) in CMS Collaboration has no ability to simulate PMT Window Noise and other noises. The worst part of the previous simulation that it was created using only discrete energy bins (10 GeV, 20 GeV, 30 GeV, 40 GeV, 50 GeV, etc. not continuous) that limit its precision significantly. The HF Shower Library has another problem because it deletes particles that enter HF Detector immediately and replace them with Shower Library that has very limited statistics. Fortunately, we have developed HF GFlash, a fast simulation of electromagnetic showers using parameterizations of the profiles in Hadronic Forward Calorimeter. HF GFlash solves almost all problems that previous HF simulation has.

HF will experience unprecedented particle fluxes because on average, 760 GeV per proton proton interaction is deposited into the two forward calorimeters, compared to only 100 GeV for the rest of the detector. Due to this condition, CMS has changed the HF geometry for simulation because it will need very long computing time if we use full HF geometry for huge number of high energy particles. The new HF geometry does not include detail description of sensitive detectors in HF, but only general description of HF.

HF GFlash has been optimized to the latest HF geometry and condition. In fact, since we have collision data available, our understanding about our detector and physics at 7 TeV improved significantly and we have modified HF GFlash in such a way that it has good agreement to Data and previous Test Beam results. In addition to good agreement to Data and previous Test Beam results [1], we also have improve the speed of HF GFlash significantly. The new HF GFlash can process electron particle guns 2 times faster than previous HF GFlash.
4. Theory
For physics analysis and feasibility studies large number of Monte Carlo events may have to
be produced. Using individual particle tracking, the computing time needed for such kind of
simulations increases linearly with the energy absorbed in the detector and can easily become
prohibitive. Using parameterizations for electromagnetic showers can speed up the simulations
considerably, without sacrificing precision. The high particle multiplicity in electromagnetic
showers as well as their compactness and the good understanding of the underlying physics
makes their parameterization advantageous.

The Gflash package allows the parameterization of electron and positron showers in
homogeneous (for the time being) calorimeters and is based on the parameterization described
by G. Grindhammer [2]. The spatial energy distribution of electromagnetic showers is given by
three probability density functions (pdf),

\[ dE(r) = E f(t) dt f(r) dr f(\phi) d\phi, \]

describing the longitudinal, radial, and azimuthal energy distributions. Here \( t \) denotes the
longitudinal shower depth in units of radiation length, \( r \) measures the radial distance from
the shower axis in Moliere units, and \( \phi \) is the azimuthal angle. A gamma distribution is used
for the parameterization of the longitudinal shower profile, \( f(t) \). The radial distribution \( f(r) \),
is described by a two-component ansatz. In \( \phi \), it is assumed that the energy is distributed
uniformly: \( f(\phi) = 1/2\pi \).

The center of gravity, \( \langle t \rangle \) and the depth of the maximum, \( T \), can be calculated from the shape
parameter \( \alpha \) and the scaling parameter \( \beta \) according to

\[ \langle t \rangle = \frac{\alpha}{\beta} \]

\[ T = \frac{\alpha - 1}{\beta}. \]

In the parameterization all lengths are measured in units of radiation length \( (X_0) \), and energy
in units of the critical energy \( E_c \) defined as

\[ E_c = 2.66 \left( \frac{X_0 Z}{A} \right)^{1.1} \]

This allows material independence, since the longitudinal shower moments are equal in different
materials. The following equations are used for the energy dependence of \( T_{\text{hom}} \) and \( (\alpha_{\text{hom}}) \), with

\[ y = \frac{E}{E_c} \]

and

\[ t = \frac{x}{X_0} \]

where we define \( x \) as the longitudinal shower depth:

\[ T_{\text{hom}} = \ln y + t_1 \]

\[ \alpha_{\text{hom}} = a_1 + (a_2 + a_3/Z) \ln y. \]
5. Performance of HF GFlash

We simulated the computing time for 10,000 20 GeV electrons and Table 1 shows that HF GFlash can perform simulation faster than Shower Library.

|                        | Shower Library (previous MC) | HF GFlash |
|------------------------|------------------------------|-----------|
| Minimum Computing Time | 0.0095                       | 0.0059    |
| Maximum Computing Time | 3.01                         | 2.81      |
| Average Computing Time | 0.62                         | 0.53      |

Table 1. Comparison of computing time between HF GFlash and Shower Library for 10000 20-GeV electrons.

We also check the longitudinal shower profiles produced using HF GFlash and compare them to the longitudinal shower profiles produced using Shower Library. In Fig.1, we can see that longitudinal profiles produced by HF GFlash(CMSSW 3_11_0) and Shower Library(CMSSW 3_10_0_pre3).

Using the results of energy response ratio from Team Beam data as the reference, we can check the performance of energy response ratio of HF GFlash compared to Shower Library. From Table 2, we found that HF GFlash has better agreement to Test Beam data compared to Shower Library.

|                  | HF GFlash | Test Beam | Shower Library |
|------------------|-----------|-----------|----------------|
| $S e_{50}/L e_{50}$ | 0.24      | 0.24      | 0.20           |
| $L p_{50}/L e_{50}$ | 0.67      | 0.66      | 0.63           |
| $S p_{50}/L e_{50}$ | 0.51      | 0.50      | 0.51           |
| $S p_{50}/L p_{50}$ | 0.76      | 0.76      | 0.80           |

$L e_{50}$ = Energy deposited in Long Fiber from 10000 50-GeV electrons
$S e_{50}$ = Energy deposited in Short Fiber from 10000 50-GeV electrons
$L p_{50}$ = Energy deposited in Long Fiber from 10000 50-GeV charged pions
$S p_{50}$ = Energy deposited in Short Fiber from 10000 50-GeV charged pions

Table 2. Comparison of energy response ratio between HF GFlash, Test Beam (reference) and Shower Library using electrons and pions at 50 GeV.
Table 3. Comparison of energy response ratio between HF GFlash, Test Beam (reference) and Shower Library using electrons and pions at 100 GeV.

|                | HF GFlash | Test Beam | Shower Library |
|----------------|-----------|-----------|----------------|
| $S_{e100}/L_{e100}$ | 0.30      | 0.30      | 0.25           |
| $L_{p100}/L_{e100}$ | 0.70      | 0.69      | 0.67           |
| $S_{p100}/L_{e100}$ | 0.57      | 0.55      | 0.56           |
| $S_{p100}/L_{p100}$ | 0.82      | 0.80      | 0.84           |

$L_{e100}$ = Energy deposited in Long Fiber from 10000 100-GeV electrons
$S_{e100}$ = Energy deposited in Short Fiber from 10000 100-GeV electrons
$L_{p100}$ = Energy deposited in Long Fiber from 10000 100-GeV charged pions
$S_{p100}$ = Energy deposited in Short Fiber from 10000 100-GeV charged pions

Table 4. Comparison of energy response ratio between HF GFlash, Test Beam (reference) and Shower Library using electrons and pions at 150 GeV.

|                | HF GFlash | Test Beam | Shower Library |
|----------------|-----------|-----------|----------------|
| $S_{e150}/L_{e150}$ | 0.33      | 0.34      | 0.28           |
| $L_{p150}/L_{e150}$ | 0.71      | 0.73      | 0.70           |
| $S_{p150}/L_{e150}$ | 0.59      | 0.60      | 0.56           |
| $S_{p150}/L_{p150}$ | 0.83      | 0.82      | 0.80           |

$L_{e150}$ = Energy deposited in Long Fiber from 10000 150-GeV electrons
$S_{e150}$ = Energy deposited in Short Fiber from 10000 150-GeV electrons
$L_{p150}$ = Energy deposited in Long Fiber from 10000 150-GeV charged pions
$S_{p150}$ = Energy deposited in Short Fiber from 10000 150-GeV charged pions

For energy resolution, we found that HF GFlash can improve the resolution by 50%. In this case, we define energy resolution as the difference of energy resolution observed in Test Beam data and simulation. For simulation we use HF GFlash or Shower Library, and we found HF GFlash has better resolution compared to Shower Library.

Electromagnetic energy response of electrons is predicted to be linear and Test Beam data has shown that it is linear (within stat. error) up to 150 GeV. We have tuned HF GFlash so that it has linear energy response up to 14 TeV.

Previous MC simulation based on Shower Library can not simulate high energy particle for example, electrons with energy higher than 2 TeV. Fortunately HF GFlash can handle not only low energy particles but also high energy particles. We can prove that HF GFlash can produce nice longitudinal profiles correctly for 1 TeV, 7 TeV and 14 TeV (see Figure 1)

One major breakthrough is the ability of HF GFlash to simulate PMT Window hits for the first time and previous MC simulation can not simulate PMT Window Hits. This achievement, encourage us to simulate other noises such as Fibre Bundle in HF. The early results show that inclusion of PMT Window Hits, Fibre Bundle and Jungle improve the agreement between HF GFlash Data and 7 TeV Collision Data.

We have used HF GFlash to produce some sample datasets, for example: ttbar, $Z\rightarrow ee$ and MinBias. The internal memory size is very crucial and we have checked and confirmed that HF GFlash used reasonable computer memory size for physics simulation. We use the correct geometry and we have done validation of HF GFlash using CMSSW_3_10_0_pre9 (a standard CMS software combination used for analysis at the end of 2010) when HF GFlash was chosen.
**Figure 1.** Longitudinal Shower Profile produced by HF GFlash for electron with energy 100 GeV (blue), 1 TeV (red) and 14 TeV (black). This plot shows the capability of HF GFlash to handle very high energy particle simulation.

**Figure 2.** HF GFlash has linear energy response for electron with energy from 50 GeV to 14 TeV.
as the default of HF simulation.

We reconstruct SimHit produced by HF GFlash to produce RecHit (reconstructed hits) that will be used for physics analysis in CMS Collaboration. We should be very careful about timing in RecHit and we see that HF GFlash gives reasonable timing information compared to certified Collision Data.

By the end of November 2010 we have collected about 36 pb⁻¹ certified Collision Data that can be used to study RecHit (reconstructed hits) energy distribution in HF towers for Long and Short Fibres. Using MinBias generator we can simulate HF RecHit for every tower. We have made 52 comparison plots for every HF tower and we found the HF GFlash has good agreement with 36 pb⁻¹ Certified Collision Data and we can see HF GFlash can perform better than previous MC based on Shower Library.

The crucial part of tuning is coming the next few months when we have 100 fb⁻¹ Collision Data from CMS Detector. At that time, we will have reasonable number of events to use Z→ee to tune HF GFlash with real physics process. In this analysis we will require one electron in central region as the tag and the other as the probe to check the performance of HF GFlash.

![Figure 3. Recontructed hit energy at towers 31, 33 and 39 collected using HF GFlash (Blue), Shower Library (Red) and 2010 Collision Data (Black).](image-url)
6. Summary
In summary, The HF detectors performed very well during the 2011 run period. Prior to the run, relative timing of the HF channels were improved and light guide sleeves were replaced. Operating parameters of the HF detectors were further optimized. In 2013, all the existing PMTs will be replaced with the 4-anode PMTs.

We have developed the most powerful simulation on earth that can handle very high energetic particles with better performance. HF GFlash has been compared and tested

(i) Test Beam data
(ii) Shower Library
(iii) 36 fb$^{-1}$ Certified Collision Data

Due to its better performance, CMS Collaboration has chosen HF GFlash as the standard HF Detector simulation since 2011. HF GFlash has been tested and the tests showed that it is faster and more accurate so that HF GFlash will be a very useful simulation not only for CMS Detector but also for other physics experiments, such as International Linear Collider, Muon Collider, etc.

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