Mitigation of Anomalous APD signals in the CMS Electromagnetic Calorimeter

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Abstract. Anomalous large signals are observed in the CMS Electromagnetic Calorimeter during proton-proton collisions at the Large Hadron Collider. They are ascribed to direct energy deposition by particles in the Avalanche Photodiodes (APDs) used for the light readout. Laboratory and test beam studies, as well as Monte Carlo simulations, have been used to understand their origin. The methods that have been employed to reject these signals in the online trigger of CMS and in the reconstruction of physics data are also presented.

1. The CMS Electromagnetic calorimeter

The Compact Muon Solenoid (CMS) [1] is a large general-purpose detector operating at the Large Hadron Collider (LHC) [2] at CERN. The principal goal of CMS is to search for Physics beyond the Standard Model at the TeV energy scale.

The main component of CMS to detect and measure the energies of electrons and photons is the Electromagnetic Calorimeter (ECAL) [3, 4]. The CMS ECAL consists of 75848 lead tungstate (PbWO4) crystals, organised into a barrel and two endcap detectors and providing coverage in the pseudorapidity range $-3.0 < \eta < 3.0$. Two silicon preshower detectors are placed in front of the endcaps, covering the pseudorapidity range $1.65 < |\eta| < 2.6$.

Scintillation light emitted by the lead tungstate crystals is converted to electrical signals by photodetectors glued to the rear face of the crystals. Avalanche Photodiodes (APDs) are used in the ECAL Barrel, and Vacuum Phototriodes (VPTs) are used in the ECAL Endcaps.

The APD photodetectors are Hamamatsu type S8148 reverse structure avalanche photodiodes specially developed for the CMS ECAL [5]. The internal structure of the APD may be represented for the purpose of this discussion as having a 5 $\mu$m thick high-gain silicon layer (gain=50) and a 45 $\mu$m thick low-gain silicon layer (gain=1.4). Each APD has an active area of $5 \times 5$ mm$^2$ and a pair is mounted on each crystal and read out in parallel. A protective epoxy layer of about 400 $\mu$m thickness covers the front of the APD. Each pair is mounted in a capsule, a moulded receptacle (see Figure 1), which is then glued to the rear face of each crystal. The main properties of the APDs at gain 50 and 18°C are listed in [1].

2. Anomalous signals: ECAL spikes

Anomalous signals, consisting of isolated large signals with equivalent energies that can exceed 100 GeV in CMS, have been observed in the ECAL Barrel during LHC proton-proton (pp) collisions. An example event is shown in Figure 2. The isolated deposit in the top-right of this figure corresponds to an equivalent transverse energy of 690 GeV in the ECAL. These deposits,
termed ECAL “spikes”, are observed to occur at a rate that is proportional to the collision rate of the proton beams. As a consequence, they present issues for triggering CMS at high luminosity and must be eliminated from physics analyses in order to prevent large biases in the energies of reconstructed electrons, photons and jets and in the computation of missing transverse energy (MET).

The spikes discussed in this note are understood to be associated with particles (produced in pp collisions) striking the APDs and very occasionally interacting to produce secondaries

1 On average, one spike is observed per 370 minimum-bias triggers in CMS at $\sqrt{s} = 7$ TeV.
that cause large anomalous signals through direct ionization of the silicon. This hypothesis has been checked by studying the APD response via laboratory and test beam studies, and the development of Monte Carlo simulations where the APDs are treated as active volumes.

A model of the APD structure has been implemented in the CMS Monte Carlo simulation [6]. This simulation, which uses the GEANT 4 [7] package for particle transport, is employed to further understand the origin of spikes and their rates in CMS. The simulations show that direct ionization of the APD by protons/ions produced in pp collisions can produce large apparent energy signals after amplification (direct ionization produces $\sim 2.8 \times 10^5 \text{e}/\text{MeV}$, c.f. $\sim 4.5 \text{p.e.}/\text{MeV}$ for scintillation light in PbWO$_4$). The simulation results and laboratory measurements [8] indicate that a significant fraction of the anomalous signals are produced by np scattering in the protective epoxy coating of the APD, and the resulting proton directly ionizing the APD active volume.

3. Online rejection of ECAL spikes
Since the characteristics of ECAL spikes are localised high energy signals, they will often satisfy the conditions for triggering electrons and photons in CMS. A detailed description of the trigger algorithm can be found elsewhere [9]. If untreated, the rate of spikes would be a dominant component of the 100 kHz CMS Level-1 trigger rate bandwidth. Eliminating the spikes online is vital to maintain the lowest possible unprescaled electron and photon triggers that are required for CMS physics measurements.

Spike-like energy deposits are prevented from triggering CMS by exploiting additional functionality of the ECAL front-end electronics. The amplitude recorded in each channel in a “strip” (5×1 crystal array) is compared to a configurable threshold. The resulting 5-bit word, which records how many channels in the strip are above threshold, is used as the index in a lookup table, which outputs one bit per strip. It is configured to return zero if only one channel in the strip is above threshold (spike-like) and one if more than one channel is above threshold (corresponding to a typical electromagnetic (EM) shower). The resulting five “strip bits” for a given trigger tower (5x5 crystal array, corresponding to a single readout unit of the ECAL front-end electronics) are then ORed together to give a single bit per tower, the strip Fine-Grained Veto Bit (sFGVB). This will return zero for an isolated energy deposit (a single channel above threshold) or one for an EM-like energy deposit (multiple channels above threshold). Figure 3 shows the operation of the sFGVB on typical EM and spike-like energy deposits.

![Figure 3](image)

**Figure 3.** Operation of the strip Fine-Grained Veto Bit (sFGVB) on an electromagnetic shower (left) and a spike-like energy deposit (right).

If the sFGVB is set to zero, and the trigger tower transverse energy is greater than 8 GeV (12 GeV in 2012), the energy deposition is considered spike-like. The trigger tower energy is set to zero and the tower will not contribute to the triggering of CMS for the corresponding event.
The sFGVB is now implemented in CMS and has been operational since April 2011. It has been measured using data to reject > 95% of spikes with transverse energy greater than 8 GeV, with only a small (0.4%) effect on the efficiency for triggering well-identified electrons with transverse energy greater than 20 GeV. In 2012, the sFGVB was re-optimised for conditions with high event pile-up (mean of 20-30 interactions per LHC bunch crossing), achieving the same performance as for 2011 data.

4. Offline rejection of ECAL spikes

Spikes, which generally deposit energy in a single channel, have an anomalous pattern of energy sharing between crystals. A discriminating variable is constructed (see Figure 4), based on the ratio of the energy deposited in the central (highest energy) crystal in an ECAL energy deposit, $E_1$, to the summed energy in the four adjacent crystals, $E_4$. An EM shower, well-centered on an ECAL crystal, will typically contain $\sim 80\%$ of its energy in the central crystal and $\sim 20\%$ of its energy in the neighbouring crystals. Figure 5 shows the distribution of the “Swiss-cross” variable, $(1 - E_4/E_1)$, for CMS data and Monte Carlo (simulating EM energy deposits only). There is a clear additional peak around 1.0 in the data, due to the presence of ECAL spikes. A cut of $(1 - E_4/E_1) > 0.95$ rejects more than 99% of spikes with transverse energy greater than 10 GeV, with a negligible impact on the efficiency of selecting EM showers \[10\].

![Swiss-cross variable](image)

**Figure 4.** Definition of the “Swiss-Cross” topological variable $(1 - E_4/E_1)$.

![Swiss-cross distribution](image)

**Figure 5.** Distribution of the Swiss-Cross variable for the highest energy deposit in each event, for data (points) and simulation ($\sqrt{s} = 7$ TeV, filled histogram). Only events with an energy deposit with transverse energy $> 3$ GeV are plotted. The two distributions are normalized to the same total number of minimum-bias events with $(1 - E_4/E_1) < 0.9$.

Spikes and electromagnetic (EM) energy deposits have different signal pulse shapes. Since a spike is produced by a particle directly hitting the APD, the resulting signal does not include the response time of the scintillation light. Figure 6 shows representative pulse shapes from spikes and EM energy deposits measured from CMS data. When the pulse is fitted to extract the timing of the signal, the spikes generally appear “early”, due to the faster rise time of the spike pulse. Figure 7 shows the reconstructed timing distribution for ECAL energy deposits with $E_T > 3$ GeV in both data and simulation$^2$. The timing distribution from simulation

$^2$ The timing calibration is defined such that a relativistic particle originating from the nominal collisions vertex
(which does not include the anomalous signals) is centered at zero. The timing distribution from data shows a significant component of out-of-time signals, due to spikes. A cut on the signal timing of ±3 ns is > 90% efficient at removing spike pulses, with a negligible impact on EM energy deposits. By combining the topological and timing cuts, which rely on independent variables, a spike rejection factor of significantly better than $10^2$ is achieved.

![Figure 6. Average pulse shape (normalised signal amplitude versus time) for spike (solid line) and electromagnetic (dashed line) energy deposits, measured from CMS data.](image1)

![Figure 7. Distribution of the reconstructed time of ECAL signals for the highest energy deposit in each event for data and simulation ($\sqrt{s} = 7$ TeV). Only events with an energy deposit with transverse energy $> 3$ GeV are plotted. The two distributions are normalized to the same total number of minimum-bias events with $(1 - E4/E1) < 0.9$.](image2)

### 5. Effect of spikes on CMS physics signatures

Events with large missing transverse energy (MET) are a sensitive tool to search for many sources of new physics at the LHC. ECAL spikes are one of the instrumental causes of anomalous MET measurements in CMS. If undetected, they contribute significantly to the tail of the MET distribution, degrading the performance of these physics searches.

An anomalous hit in an ECAL crystal is excluded from the reconstruction of jets and MET in CMS, using both the timing and topological cuts described in Section 4. This provides a reconstruction of jets and MET that are consistently cleaned of anomalous detector effects.

The calorimetric MET distribution (sum of the missing transverse energy in both the ECAL and the hadronic calorimeter, HCAL) for minimum-bias data and simulation at $\sqrt{s} = 7$ TeV is shown in Figure 8. Data are shown before (filled circles) and after (open circles) removal of the anomalous signals in the ECAL and HCAL has been performed. Comparison of the “cleaned” data with simulation, which does not include anomalous energies, shows good agreement. Studies using simulations indicate a negligible probability of “over-cleaning” (energy due to bona fide particles produced in pp scattering removed by the cleaning).

will be reconstructed with a mean time of 0 ns.

3 The long tail in this distribution is believed to be due to neutron-induced spikes, which propagate through the detector volume before interacting close to the APDs.

4 The timing resolution for EM signals with energy $> 1$ GeV is less than 1 ns.

5 A description of the removal of HCAL anomalous signals can be found in [11].
Figure 8. Missing transverse energy measured in the CMS calorimeters for minimum-bias data and MC pp collision events at $\sqrt{s} = 7$ TeV. Taken from [12].

6. Summary
The existence of large isolated signals in the CMS ECAL Barrel has been observed in pp collisions at the LHC. The origin of these signals due to direct ionization of the active silicon layers of the CMS APDs is supported by laboratory tests and Monte Carlo simulations.

The rate of anomalous signals in CMS is proportional to the minimum-bias collision rate, and to the number of charged tracks per event. Algorithms to efficiently remove these deposits in the online trigger and in the offline reconstruction of physics data have been developed and deployed in CMS. These algorithms have proved effective in rejecting spikes for LHC instantaneous luminosity above $10^{33}$ cm$^{-2}$s$^{-1}$, and remain efficient for the high event pile-up conditions experienced in 2012.

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