Calorimeter trigger electronics for CMS detector at LHC

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We present the level-1 calorimeter trigger system algorithms, electronics design, prototype evaluation and simulation results for the CMS detector at LHC.

1 Introduction

The CMS detector for the Large Hadron Collider (LHC) presents an extraordinary challenge for its trigger and data acquisition system. At the LHC crossing frequency of 40 MHz and design luminosity of 10^{34} cm^{-2} s^{-1} about 25 minimum bias interactions occur per crossing. However, interesting hard interactions resulting in leptons or photons occur only at about 100 Hz, matching the expected archival capacity. Therefore, the trigger system must carefully sift the 40 MHz data to retain interesting physics signals while discarding the background. The CMS solution to this problem is implemented in two physical levels, one based on custom electronics and the other relying upon commercial processors. The level-1 system uses only coarsely segmented data from calorimeter and muon detectors, while holding all the high resolution data in pipeline memories in the front-end electronics, to produce a trigger decision in 3 μs. Level-1 triggered events at 100 kHz rate are sifted further in higher levels of triggers implemented as software filters. We discuss here the level-1 calorimeter trigger [1] electronics, which is designed to use high-speed data paths to collect and share nearest neighbor information and perform simple algorithms in custom integrated circuits to identify signatures for high energy electrons, photons, neutrinos and jets.

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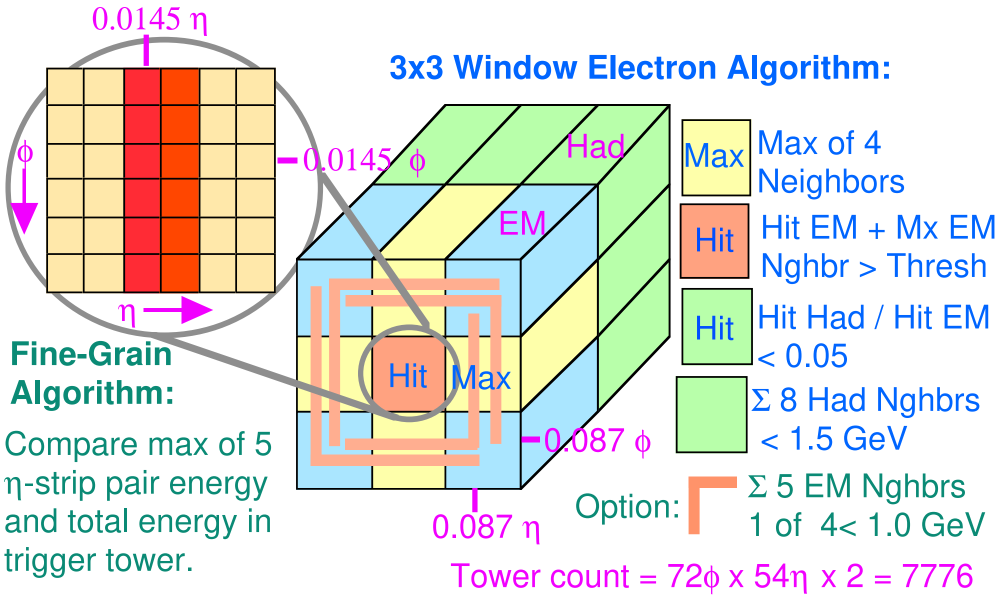

Fig. 1. The electron/photon trigger algorithm.

2 Algorithms

The CMS calorimeter consists of a fine-grain (e.g., $0.0145\phi \times 0.0145\eta$ in the barrel) 25 radiation length section of $PbWO_4$ crystals (ECAL) to measure electro-magnetic showers and a more coarse-grain $(0.087\phi \times 0.087\eta) \approx 7$ interaction length section of Cu-Scintillating tile sandwich towers to measure hadronic showers. The calorimeters cover the full azimuthal angle (ϕ) and large pseudo-rapidity (η $-2.6 \leq \eta \leq 2.6$) ranges with the ECAL crystal boundaries matching the HCAL towers. About 90% of the energy in EM showers is contained within two ECAL crystals in η but may be spread in several ϕ crystals due to the bending of charged particles in the 4 Tesla CMS magnetic field. Most of the energy for jets is contained within these two sections of the calorimeter and the hadronic shower tail catcher is not needed for the trigger purpose.

The electron/photon trigger algorithm, illustrated in Figure 1, is composed of two portions, one based on the fine granularity of the ECAL crystals and the other based on sliding windows of ECAL and HCAL trigger towers. The fine-grain portion of the algorithm involves four steps. Firstly, E_t in each of the five $6\phi \times 2\eta$ crystal groups, i.e., η-strips, are added. Secondly, the maximum of the five η-strip pairs is found. Thirdly, the sum of all the crystals in the trigger tower is determined. Finally, the maximum η-strip pair is required to contain most (e.g., 90%) of the total E_t for the trigger tower to set the fine-grain EM ID bit. The sliding window portion of the algorithm operates on $3\phi \times 3\eta$ trigger tower windows centered around each of the trigger towers and involves four steps. Firstly, the electron/photon candidate energy is obtained by summing the energy from the center tower and the highest energy tower of its four neighbors. Care is taken to avoid double counting contiguous energy deposits as multiple electrons. Secondly, hadronic background is vetoed by requiring that the energy leakage fraction into the hadronic section behind the center tower is below a programmable level ($H/E < 0.05$). Thirdly, the hadronic isolation flag is set by requiring that the sum of the surrounding hadronic energy in the 3x3 region is below a programmable cut. Finally, the electromagnetic isolation flag is set by requiring that at least one of the four five-tower L-shaped corners is below a programmable cut. This multi-step algorithm allows efficient tuning of the cuts depending upon the physics interest at the time of data taking.

The jet trigger is provided by summing ECAL and HCAL trigger tower data in non-overlapping 4×4 trigger towers covering a $0.35\phi \times 0.35\eta$ region. This small effective jet "cone size" is chosen so that the higher energy jet centers provide the trigger while preserving the ability to resolve multi-jet events which are important to discover SUSY. The missing transverse energy is calculated by converting E_t from the jet regions into E_x and E_y and summing them over the entire detector to provide a neutrino or other non-interacting particle trigger.

The energy in the two longitudinal segments of HCAL is required to be consistent with minimum ionizing particle deposition to provide a muon ID bit for each trigger tower. These bits in each of the $4\phi \times 4\eta$ jet regions are ORed to indicate the potential for a minimum ionizing particle within the region. This bit is then appended with the quiet bit, which is set by requiring that the jet energy in that region is below a programmable cutoff. This information is used along with the stand-alone muon trigger data to provide an "isolated muon" trigger.

3 Trigger system

The level-1 calorimeter trigger system consists of three stages, namely the trigger primitive generation and transmission on the detector, the regional trigger and the global trigger in the electronics room off the detector.

The ECAL trigger primitive data (i.e., trigger tower transverse energy and the fine-grain EM ID bit) generation is implemented as a part of the front-end electronics in a dedicated trigger board using custom ASICs. Reduced resolution 10-bit data from each crystal are used to obtain the trigger E_t and the fine-grain EM ID bit. The trigger tower E_t is coded into 7-bits using a programmable look-up-table. The resultant 8-bit data from pairs of channels and 5-bit error detection Hamming code are converted from parallel-to-serial and transmitted on 1 GB/s fiber optic links to the regional system. The HCAL

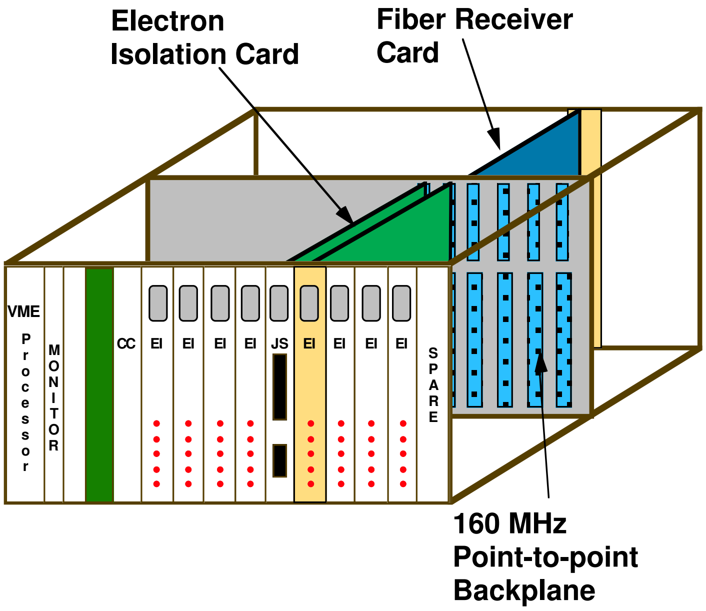

Fig. 2. CMS level-1 calorimeter regional trigger crate.

trigger primitives, i.e., trigger tower E_t and minimum ionization particle ID bit, with an $\eta - \phi$ mapping identical to the ECAL trigger towers, are similarly transferred to the regional trigger system.

The barrel and end-cap calorimeter regional trigger system is implemented in 18 crates spanning the $\eta - \phi$ plane. The regional trigger crate which handles 256 trigger towers is illustrated in Figure 2. The very forward calorimeter trigger will be implemented in a separate 19th crate and is not discussed here. Data from 32 ECAL and HCAL trigger towers arrives on fiber optic cables in serial form at 1 GBaud to the back side of the eight Receiver cards plugged into the rear of the crate. After optical-to-electrical and serial-to-parallel conversion the data are transferred through the card to the front side of the Receiver cards. Data is synchronized and verified to be valid using the error detection Hamming code. Data in parallel form is shared at 40 MHz with the neighboring crates after this synchronization step. Data are then passed through look-up tables to separately linearize the energies into the number of bits needed for electron isolation and energy triggers. The entire system operates in lock-step after this stage at 160 MHz. The energies are then summed to 4×4 trigger tower regions using custom Adder ASICs on the Receiver card. The heart of the crate is a central "backplane" which provides data sharing at 160 MHz. Data for the electron isolation logic which includes both the data received on the fiber and that received on inter-crate cables are transferred to the Electron Isolation cards plugged into the front-side of the "backplane". The 4×4 sums are transferred to the Jet/Summary card plugged into the center of the backplane on the front-side of the crate. The Electron Isolation card implements its algorithm in a custom integrated circuit. The candidate electrons are ranked and top candidates are passed to the Jet/Summary card.

Table 1
Calorimeter trigger background rates for a sample set of E_t cutoffs selected to optimize physics gains at two LHC luminosities.

Calorimeter Trigger Type	High Luminosity E_t Cutoff (GeV)	High Luminosity Rate (kHz)	Low Luminosity E_t Cutoff (GeV)	Low Luminosity Rate (kHz)
Single Electron	25	6.84	12	10.3
Double Electron	12	1.45	7	1.54
Single Jet	100	2.06	50	1.98
Double Jet	60	2.17	30	1.63
Triple Jet	30	3.16	20	1.02
Quadruple Jet	20	2.96	15	0.68
Jet + Electron	50,12	1.35	15,9	5.98
Missing E_t	80	1.29	40	2.11
Sum E_t	400	0.48	150	1.04
Total		14.9		15.2

The Jet/Summary card sorts the electron and jet candidates in the crate to output the top four candidates of each kind on a cable to the global trigger. It also calculates sums of E_x, E_y and E_t in the crate using Adder ASICs.

The global trigger system is also implemented using a custom crate with a point-to-point backplane for data sharing. The cards in this crate further sort or sum their input to obtain the final output of the calorimeter trigger which is used together with the muon trigger data to provide the final trigger decision.

4 Simulation results

A Monte Carlo program of the CMS detector, simulating a simplified geometry with parameterized detector response, is used to study the performance of the trigger system. Effects such as those due to detector resolutions, digitization scales, trigger scale limitations and multiple interactions per crossing are included. Several hundred thousand simulated QCD jet events have been used to determine the background rates shown in Table 1. Specific physics signals of interest which challenge the trigger system are chosen to study the efficiencies and are listed in Table 2.

Table 2
Efficiencies for physics processes placing most stringent trigger requirements, with cutoffs listed in Table 1. The Standard model Higgs at high luminosity and the SUSY MSSM model CP-odd Higgs (A) at low luminosity are considered.

Physics Process	Efficiency (%)	
	High Luminosity	Low Luminosity
$t\bar{t} \to eX$	88.3	99.3
$t\bar{t} \to H^+X \to \tau X$	81.7	99.0
SUSY ($M_{LSP} = 45\text{GeV}$ $M_{spart} \approx 300\text{GeV}$)	83.0	97.8
Higgs (80 GeV) or SUSY Higgs (100 GeV) $\tan\beta = 15$	97.4	47.2
Higgs (120 GeV) or SUSY Higgs (120 GeV) $\tan\beta = 10$	76.4	58.2
Higgs (200 GeV) or SUSY Higgs (200 GeV) $\tan\beta = 15$	99.1	85.9

5 Prototypes

In order to demonstrate the crucial fetatures of this trigger system we have begun an extensive prototype construction and testing program.

Three trigger primitives generation and transmission prototype boards were built and used in a test beam experiment. The trigger primitives system board received 10-bit energy data from six strips and transferred it to the processor board. It also received the output from the processor board and communicated with the data acquisition system. On the processor board three Philips L-Neuro 2.3 ASICs [1] were used to implement the fine-grain algorithm. The algorithm included summing the strips to obtain the total energy in the trigger tower, making strip pair sums, finding the maximum strip pair sum and comparing the maximum strip pair to the total energy to set the fine-grain ID. The system operated well and the test beam results allowed experimental determination of the cut value for fine-grain ratio. Future plans include integration of various fine-grain algorithm steps into a single ASIC using the design elements from the L-Neuro. A separate optical board was used to check the data transmission using a HP G-Link operated with FINISAR optical components.

The first of the prototypes for the regional trigger involved demonstration of reasonably low cost but high-speed ASIC construction capability. Since the system size, and, therefore, the cost, depends crucially on high speed data processing, we fabricated prototype adder ASICs which sum eight 10-bit signed numbers in a total of 4 clock-steps at 160 MHz. These ASICs built by Vitesse in GaAs technology, chosen for its speed and ECL output capability, have been tested to work at 200 MHz, well above our specifications.

At the heart of the trigger system described above is the custom "backplane" which provides point-to-point links for data sharing between the various cards at 160 MHz. In order to test the feasibility of operation at high frequency we built a complete prototype backplane which can house up to eight Receiver and Electron Isolation card pairs, a Clock card and a Jet/Summary card . On one end of the backplane two standard 6U VME card slots are also provided. The backplane uses a single 128-pin DIN connector to implement the 32-bit VME and a 340-pin AMP connector to implement the point-to-point links in the custom card region of the backplane. There are 1419 differential point-to-point links on the backplane between the various cards. The backplane is constructed with five ground and power planes and five signal layers. The differential pairs are held to the same layer. Although all the positions are routed only three card positions are stuffed with connectors and the crate containing the backplane is assembled.

A simplified clock card which provides the 160 MHz clock, reset and synchronize signals has also been fabricated. This card contains adjustable delays so that the phases on all the seventeen cards can be individually adjusted to match. The clock signals on the backplane show rise and fall times below 1 ns with reasonable signal levels even when measured at the farthest card slot.

A prototype receiver card containing the memory look-up-tables, the Adder ASIC and the backplane drivers is being built. This prototype implements all the 32 EM and Had. channels but does not include the fiber receivers. The purpose of the card is to test both the signal integrity on the backplane and the Adder ASIC operation. The card implements the VME control and JTAG boundary scan capability. We are also making a prototype Electron Isolation card so that the data sharing tests can be carried out.

6 Conclusions

The conceptual design of the CMS trigger system is being evaluated with construction of prototype circuits. Simulation of the trigger system indicates good efficiencies for physics signals of interest at the LHC while limiting the background rates to the capabilities of the data acquisition system.

References

[1] CMS Documents, CERN/LHCC 94-38, CMS TN/94-284, CMS TN/94-285, CMS TN/95-027, CMS TN/95-111, CMS TN/95-112, CMS TN/95-183, CMS TN/95-197, CMS TN/96-010, CMS TN/96-021, CMS TN/96-066.