WBS Dictionary/Basis of Estimate

Documentation

US CMS Calorimeter

Regional Trigger System

WBS 3.1.2

1. INTRODUCTION

1.1 The CMS Calorimeter Trigger System

The CMS trigger and data acquisition system is designed to operate at the nominal LHC design luminosity of 10^{34} cm^{-2} s^{-1}, where an average of 20 inelastic events occur at the beam crossing frequency of 40 MHz. This input rate of 10^9 interactions every second must be reduced by a factor of at least 10^7 to 100 Hz, the maximum rate that can be archived by the on-line computer farm. CMS has chosen to reduce this rate in two steps. The first level stores all data for approximately 3 μs, after which no more than a 100 kHz rate of the stored events is forwarded to the second level. During the 3 μs of the level 1 trigger processing time, trigger decisions must be made to discard a large fraction of the data while retaining the small portion coming from interactions of interest. The calorimeter trigger system plays a crucial role in the trigger system providing triggers based upon the energy profiles left in the CMS calorimeter by electrons, photons, jets and non-interacting particles in the interesting events. It also provides additional information for the muon trigger system for isolation and minimum ionization signal identification.

1.1.1 Requirements

The CMS calorimeter trigger system should be capable of selecting events with electrons, photons, jets and large missing transverse energy with high efficiency and good geometric acceptance. At high luminosity, 10^{34} cm^{-2} s^{-1}, the single electron/photon trigger is required to be fully efficient in the pseudo-rapidity range $|\eta|<2.5$ for a threshold of $E_t>40$ GeV. For the di-electron/di-photon trigger the threshold should be $E_t>20$ GeV for each particle in the same η-range. Single and multiple jet triggers are also required, having a well known efficiency in order to allow reconstruction of the jet spectrum. Finally, a missing transverse energy trigger with a threshold of 150 GeV is also required. At low luminosity, 10^{33} cm^{-2} s^{-1}, in addition to the above requirements, the system is required to trigger on single and double electrons in the pseudo-rapidity range $|\eta|<1.6$ with transverse momenta above 10 and 5 GeV respectively, with an efficiency greater than 50%. The system is also required to select hadronic tau-jets in the pseudo-rapidity range $|\eta|<2$ with jet $E_t>40$ GeV with an efficiency above 50%. The total calorimeter trigger rate should not exceed approximately 15 kHz at all luminosities. The trigger E_t cutoffs should be sufficiently low such that full efficiency is realized at the specified physics thresholds while keeping the background rates within the requirements of the data acquisition system. All triggers should also run at prescaled level with lower thresholds.

1.1.2 Input Data

For most of the CMS ECAL, a 5 × 5 array of PbWO4 crystals is mapped into trigger towers. In the rest of the ECAL there is somewhat lower granularity of crystals within a trigger tower. There is a 1:1 correspondence between the HCAL and ECAL trigger towers. The trigger tower size is equivalent to the HCAL physical towers, .087 × .087 in $\eta \times \phi$. The ϕ size remains constant in $\Delta\phi$ and the η size remains constant in $\Delta\eta$ out to an η of 2.1, beyond which the η size doubles. There are 3888 total ECAL and 3888 total HCAL trigger towers from η = -2.6 to η = 2.6 (54 × 72 η–ϕ divisions).

For each trigger tower the front-end electronics sums the constituent ECAL crystal energies or HCAL longitudinal segments and converts it to transverse energy in a compressed 8-bit non-linear scale using a programmable lookup table. In addition, the energy profile within the trigger tower is used to set a bit to indicate fine-grain identification of electromagnetic deposit in ECAL or muon identification bit in HCAL. The fine-grain EM isolation bit is set if the maximum energy found in a pair of strips of six crystals represents a large fraction of the total energy found in the 25 crystals in the trigger tower (See Figure 1).

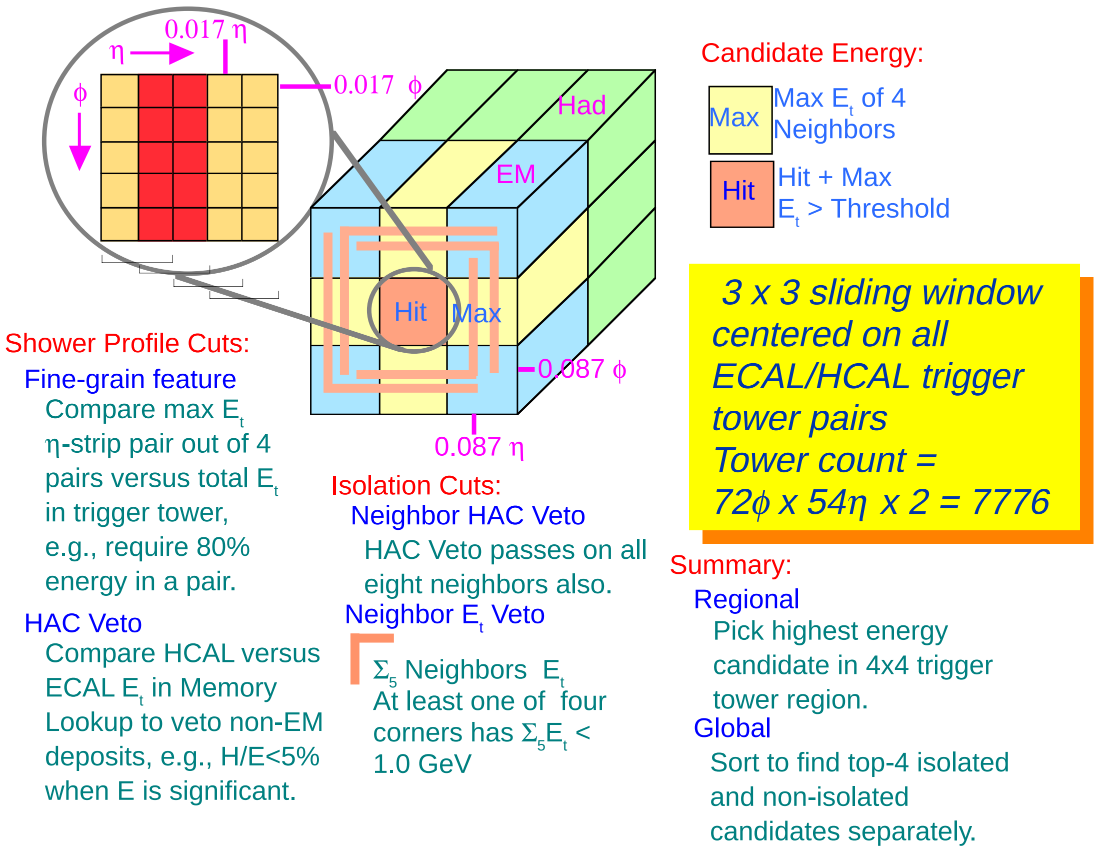

Figure 1. Level 1 Electron Trigger Algorithm.

1.1.3 Algorithms

The electron/photon trigger is based on the recognition of a large and isolated energy deposit in the electromagnetic calorimeter by asking for a small hadronic energy deposit in the HCAL in the cluster region. There are different thresholds for inclusive electrons/photons, dileptons, and for very high E_t electrons. The isolation cuts are relaxed and finally eliminated for triggers with increasing E_t thresholds. As shown in Figure 1, the basic 3x3 sliding window electron algorithm implemented in the hardware design involves multiple cuts on the longitudinal and transverse isolation of the ECAL energy deposit. The first cut involves a favorable comparison of the hit tower HCAL to ECAL energy ratio, i.e. H/E < 0.05. The second cut involves requiring fine-grain EM ID described above. These two cuts alone are used at low luminosity to provide a “non-isolated” electron trigger. A third cut requires a favorable H vs. E comparison in all eight nearest neighbors. A fourth cut requires transverse isolation of the electron/photon energy deposit by considering all four 5- tower corners of the 3x3 window and requiring that at least one of them is below a programmable cutoff $\Sigma_5 E < 1$ GeV. The act of checking all four 5-tower corners ensures that the candidates depositing energy in any corner of the central tower do not self-veto due to leakage energy The jet triggers are based on sums of ECAL and HCAL transverse energy in non-overlapping 4x4 trigger tower (0.35 η x 0.35 ϕ) regions. The jet trigger region sums have a 10-bit dynamic range covering energies up to about 1000 GeV. The jet trigger region sums are sorted based on their transverse energy to obtain top ranking jets. Tests of single, double, triple and quadruple jet region sums against progressively lower programmable thresholds, possibly in combination with electron and muon candidates, enables making level-1 trigger decision.

Neutrino identification consists of calculating the event missing E_t vector and testing it against a threshold. The calorimeter trigger calculates both sums of E_t and missing E_t. The transverse energy vector components are calculated from each 10-bit jet trigger region by multiplying with entries in corresponding lookup tables with angular coordinates. The sum of the scalar E_t and the vector components over the entire detector span made using digital summing networks provides sum E_t and the missing E_t. When pre-scaled by factors of 1000 or more the unbiased sum Et trigger enables checking other trigger efficiencies and measuring the E_t spectrum.

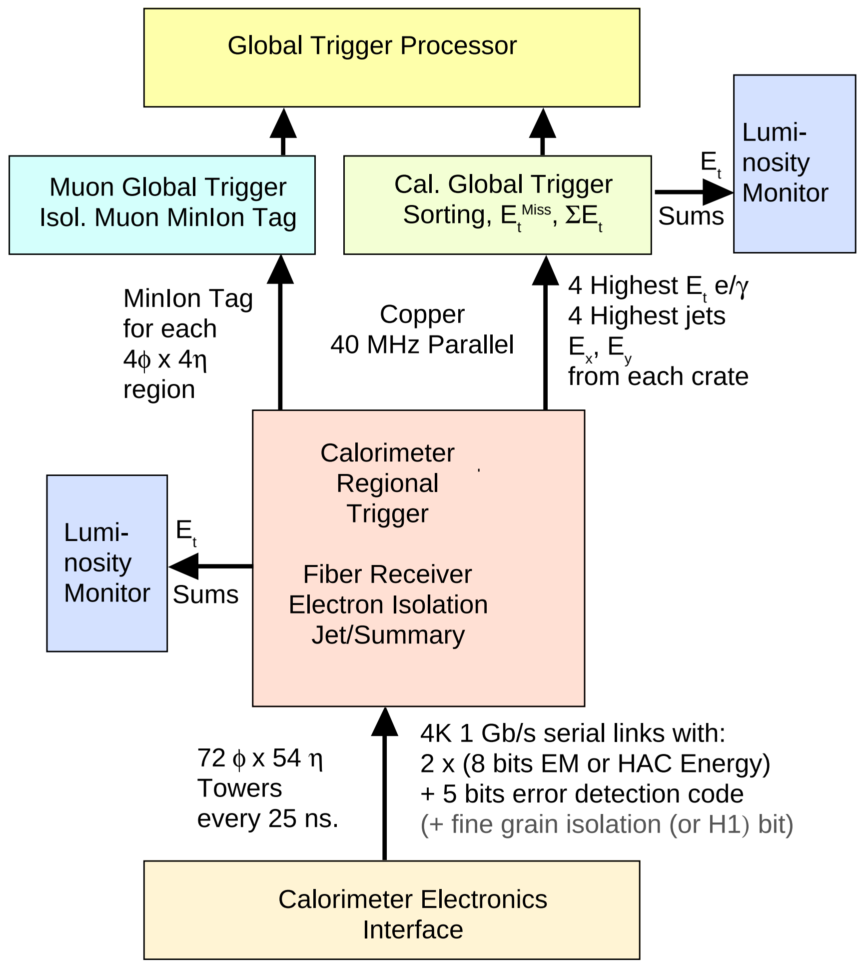

Figure 2. Overview of Level 1 Calorimeter Trigger.

2. SYSTEM OVERVIEW

2.1 Design Criteria:

The main design criteria for the system are:

The design is implemented using off the shelf technology where possible.
ASIC's are used only where fully justified.

The design emphasizes flexibility and programmability:
Digital logic built around memory lookup tables.
All trigger cutoffs are programmable.

The design minimizes hardware on the detector:
Reduce power, space, and cooling requirements
Maximize access
Reduces coupling between trigger and detector geometry

Boards and crates:
Designed using realistic power consumption, circuit density and cooling considerations.
I/O connections, serial data, backplane traffic and timing, DAQ and clock and control interfaces can be implemented with present day technology

Copper cables:
Designed to minimize the interconnects between crates.
1.2 Gbaud serial data on copper cables fibers carry trigger primitives from the detector front end electronics in the barracks to the nearby calorimeter trigger electronics.
Could be produced with currently available hardware.

Full Trigger system carries sufficient information for diagnostics, efficiency studies, and understanding trigger behavior.

2.2 Baseline design

The calorimeter level 1 trigger system baseline design, shown in Figure 2, receives digital trigger sums via copper links from the front end electronics system in the electronics counting house. The data includes energy on an eight bit compressed non-linear scale and the fine grain ID. The data for two HCAL or ECAL trigger towers for the same crossing will be sent on a single copper serial link in eighteen total bits accompanied by five bits of error detection. One additional bit is used to set the link into either control or data modes.

The calorimeter regional crate system uses 19 calorimeter processor crates covering the full detector. Eighteen crates are dedicated to the barrel and two endcaps. These crates are filled out to an η of 2.6, with partial utilization between 2.6 and 3.0. The remaining crate covers both Very Forward Calorimeters.

Each calorimeter regional crate transmits to the calorimeter global trigger processor its sum E_t, E_x and E_y. It also sends its 4 highest-ranked electrons and 4 highest energy jets along with information about their location. The global calorimeter trigger then sums the energies and sorts the electrons and jets and forwards the top four calorimeter-wide electrons and jets, as well as the total calorimeter missing and sum E_t to the CMS global trigger.

The regional calorimeter trigger crate, shown schematically in Figure 3, has a height of 9U and a depth approximately of 700mm. The front section of the crate is designed to accommodate 280mm deep cards, leaving the major portion of the volume for 400mm deep rear mounted cards.

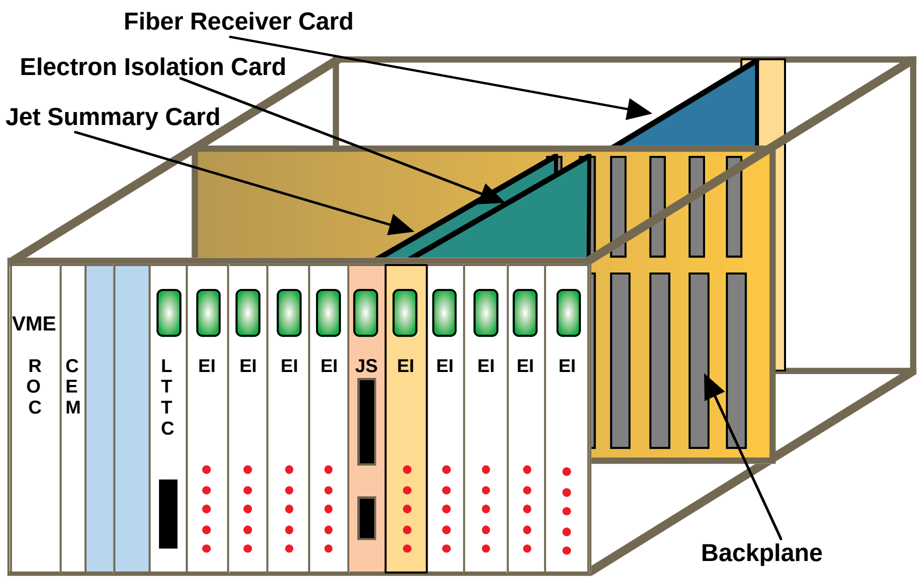

Figure 3. Schematic view of a typical Calorimeter Level 1 Regional crate.

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The majority of cards in the Calorimeter Level 1 Regional Processor Crates, encompassing three custom board designs, are dedicated to receiving and processing data from the calorimeter. There are eight rear mounted Receiver cards, eight front mounted Electron Isolation cards, and one front mounted Jet Summary card for a total of 17 cards per crate. The high density high-speed 160 MHz data flow is achieved by plugging all cards into a custom “backplane” with about 1400 point-to-point differential links in addition to full VME bus.

The Receiver card is the largest board in the crate. It is 9U by 400mm. The rear side of the card receives the calorimeter data from optical fibers, translates from fiber to copper, and converts from serial to parallel format. The front side of the card contains circuitry to synchronize the incoming data with the local clock, and check for data transmission errors. There are also lookup tables and adder blocks on the front. The lookup tables translate the incoming information to transverse energy on several scales. The energy summation tree begins on these cards in order to reduce the amount of data forwarded on the backplane to the Jet Summary card. Separate cable connectors and buffering are also provided for intercrate sharing.

The transverse energy for each of the two 4 x 4 trigger tower regions is independently summed and forwarded to the Jet Summary card. On the Jet Summary card these E_t sums are used to continue the energy summation tree and also compared against a threshold to determine whether any sub-region contained jets. The Et sums are applied to a set of lookup tables to generate E_x and E_y for each 4 x 4 region. A separate adder tree is used to sum up E_x and E_y from the regional values.

In the present baseline design, the Receiver card also has separate lookup tables to provide linearized 7-bit ECAL transverse energy, and H versus E comparison bits, for the electron/photon algorithm. These data are staged to both the cards within the crate at 160 MHz on the backplane, and to the neighboring crates on cables at 40 MHz. The Electron Isolation card receives the data staged to it from the Receiver cards and implements the algorithm discussed above in custom ASIC's. The E_t and isolation bits of the highest E_t electron/photon candidate from each of the two 4×4 trigger tower regions handled by the Electron Isolation cards are passed to the Jet/Summary card. The Jet/Summary card separately sorts these data from all eight Electron Isolation cards in the crate to obtain top four "non-isolated" and "isolated" electron/photon candidates, and passes them on to the global trigger on cables at 40 MHz.

2.3 References

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3. COST

A summary of the cost of the CMS Regional Calorimeter Trigger is contained in Table 1. The unit costs are detailed in Table 2. The costing methodology and WBS definitions are explained in the following sections. The funding profile based on the schedule described in section 4 is shown in Figure 4.

WBS Number	Description	EDIA (k$)	M&S (k$)	Base (k$)	Cont (%)	Total (k$)
3.1.2	Calorimeter Regional Trigger	1,247	3,141	4,388	50	6,581
3.1.2.1	Prototypes	301	140	441	46	643
3.1.2.2	Preproduction ASICs	243	310	553	47	811
3.1.2.3	Test Facilities	18	60	78	50	117
3.1.2.4	Power Supplies	3	79	82	30	106
3.1.2.5	Crates	21	13	35	30	45
3.1.2.6	Backplane	64	130	194	54	299
3.1.2.7	Clock & Control Card	67	65	132	40	185
3.1.2.8	Receiver Card	109	1,561	1,670	54	2,571
3.1.2.9	Electron Identification Card	95	649	744	50	1,116
3.1.2.10	Jet Summary Card	67	103	170	50	254
3.1.2.11	Cables		7	7	30	9
3.1.2.13	Crate Monitor Card					
3.1.2.14	Trigger Tests	260	22	282	50	423
3.1.2.15	Trigger Project Management					

Table 1. Summary of costs of the CMS Calorimeter Trigger.

WBS	Item	Unit Cost	Units	M&S
3.1.2	Calorimeter Trigger	-	-	3,140,520
3.1.2.1	Prototypes	-	-	140,380
3.1.2.2	Preproduction ASICs	-	-	310,000
3.1.2.3	Test Facilities	-	-	60,000
3.1.2.4	Power Supplies	3,600	22	79,200
3.1.2.5	Crates	600	22	13,200
3.1.2.6	Backplane	5,910	22	130,020
3.1.2.7	Clock & Control Card	2,960	22	65,120
3.1.2.8	Receiver Card	8,870	176	1,561,120
3.1.2.9	Electron Isolation Card	3,690	176	649,440
3.1.2.10	Jet Summary Card	4,670	22	102,740
3.1.2.11	Cables	7,300	1	7,300
3.1.2.12	DAQ Processor	-	22	-
3.1.2.13	Crate Monitor Card	-	22	-
3.1.2.14	Trigger Tests	-	-	22,000
3.1.2.15	Trigger Project Managemen	-	-	-

Table 2. Summary of unit costs of CMS Calorimeter Trigger.

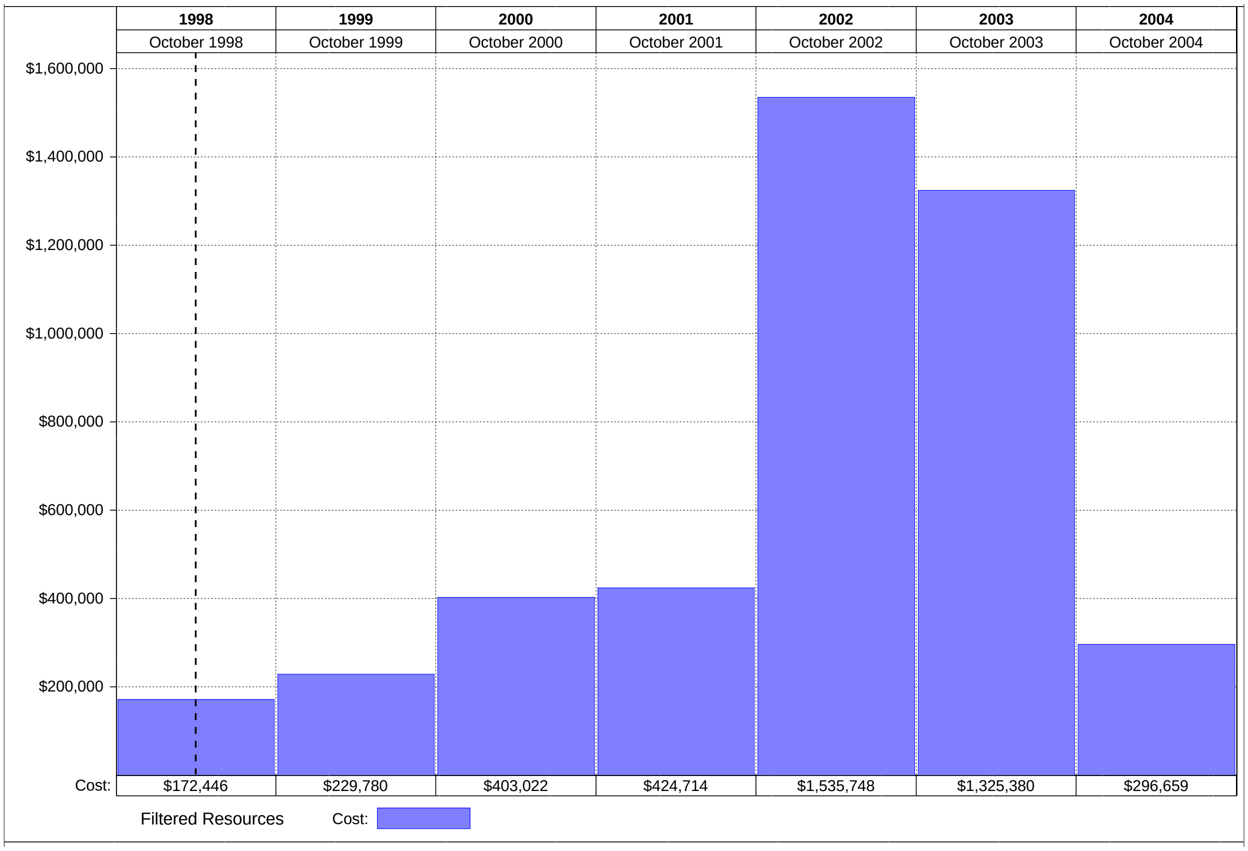

Figure 4. Funding profile for the Regional Calorimeter Trigger Project.

4. SCHEDULE

We foresee the development of the Regional Calorimeter Trigger System in four phases. The prototype design and production phase will continue until the end of 1999. The final design of the various system components will continue until 2003. Production will begin in 2002 and end in 2004. Installation and commissioning will take place in 2004. The schedule, at its highest level, is shown in Figure 5 and the schedule milestones are summarized in Figure 6.

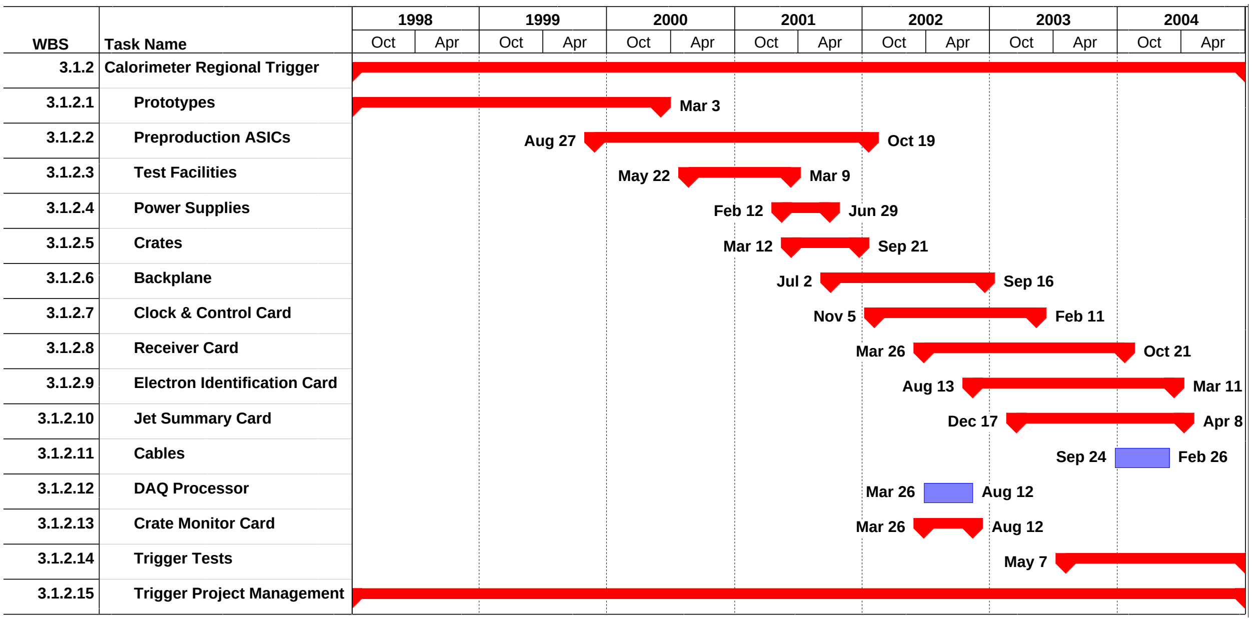

Figure 5. Summary of Calorimeter Trigger Schedule.

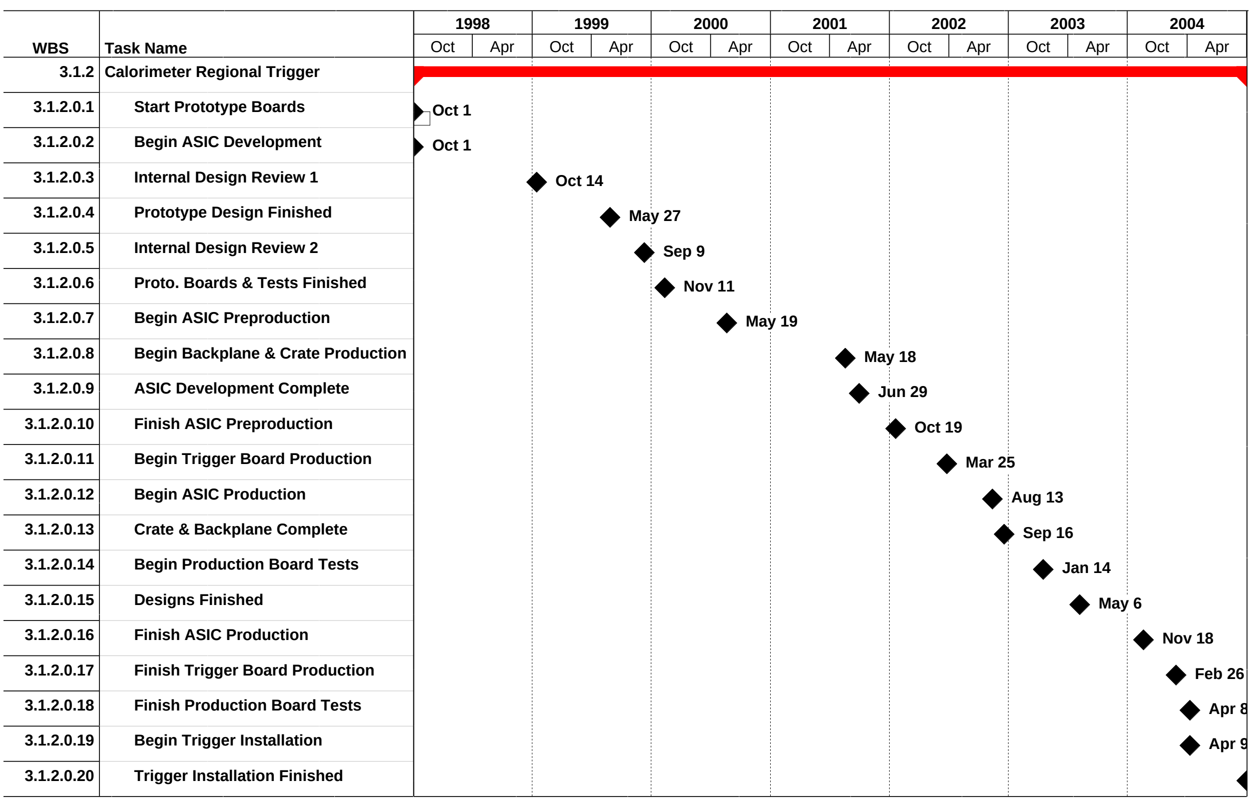

Figure 6. Calorimeter Trigger Major Milestones.

5. US RESPONSIBILITY

The US institutions participating in CMS have undertaken the design and building of the Regional Calorimeter Trigger System. This system begins after the serial data from the front end electronics is received on 1.2 Gbaud Copper cables and ends with cables that transmit the results to the calorimeter global level 1 trigger system. Responsibilities for the front end electronics trigger sums, front end trigger primitive data transmission system, global calorimeter trigger and trigger interface to DAQ are assigned to the US HCAL and non-US CMS groups.

US Institutions participating in the Regional Calorimeter Trigger:

Institute	Contact Person
University of Wisconsin, Madison	W. Smith
Fermilab	J. Elias

6. COSTING METHODOLOGY

6.1 Base Cost

The M&S cost for the trigger system was calculated by determining the cost of ASIC's, parts, boards, crates, and cables. The numbers of ASIC's, parts, boards, crates, and cables were determined from the design described above and in the references. The cost for the electronics boards was based on actual cost for manufacture and assembly of over 300 9U x 400 mm deep 12-layer 83 MHz VME Calorimeter Trigger Boards and their accompanying crates and infrastructure built for the Zeus experiment over the period 1991 through 1995. The board costs were increased to account for the stricter impedance control necessary at the higher speed of 160 MHz. They were also based on the prototype CMS trigger Backplane and Clock & Control boards already manufactured and the Receiver Card submitted for manufacture. The parts costs were determined from scaling of Zeus Trigger Cards and checked against the prototype logic built for the Clock & Control board, the prototype Receiver Card and the designs of the individual cards. The ASIC costs are based on the 160 MHz 8 x13-bit Adder ASIC manufactured by Vitesse for the CMS calorimeter trigger. Each ASIC design was carried to a the extent necessary to determine number of pins, approximate floor area and a target package used in consultation with Vitesse to determine the cost.

The EDIA cost for the trigger system was calculated from the EDIA costs for the Zeus Calorimeter Trigger System and checked against the costs already experienced for the design, manufacture and test of the CMS Trigger Adder ASIC, Backplane and Clock & Control prototypes and the engineering design and parts costs for Receiver Card. Production EDIA effort was calculated from the Zeus Calorimeter Trigger system production manufacture, test, and installation. The engineering and technical team charged with producing the CMS calorimeter trigger is the same as the Zeus calorimeter trigger project.

6.2 Contingency

The costs listed in the budget estimate are the base costs of producing each item correctly the first time. There are also explicit costs listed for prototyping where required. The cost contingency is the cost required beyond the base cost to ensure successful completion. The calculation of contingency has been done for each individual WBS item. The determination of contingency was informed by an analysis of the Zeus trigger electronics. M&S and Labor costs also took into account the actual experience on these projects before any contingency was determined. In addition, the prototyping experience on CMS trigger electronics was also used as input.

The calculation of contingency was done for each individual WBS item according to the methodology established by US CMS Project Management. Each item is first assigned a contingency factor composed of the product of maturity of design and a judgment factor. The maturity of design is assigned as 1.5 for a conceptual design, 1.4 for a design which has been partially engineered, 1.3 for a full engineering design, 1.2 where a bid package has gone out, and 1.1 for an item that is ordered from a catalog. The judgment factor is set to 1.0 for most tasks and is increased to 1.1 for the most difficult tasks. The total cost is multiplied by the contingency factor to produce the total cost plus contingency.

The WBS and Basis of Estimate that summarize these costs, the source of the cost estimates, and the justification of the contingency assignment are given in Appendix A.

APPENDIX A:

WBS DICTIONARY AND

BASIS OF ESTIMATE