TASK T: CMS at the LHC

1. Overview

In High Energy Physics, as elsewhere, "the past is prologue". The discovery and synthesis which is embodied in the Standard Model has been largely the result of exploration at the energy frontier. The construction of the Large Hadron Collider (LHC) at the CERN laboratory provides the latest extension of the frontier. In order to discover the physics beyond the standard model, which is predicted to be at the TeV scale, the UW group has elected to participate in the Compact Muon Solenoid (CMS) collaboration at the LHC at a center of mass energy of $\sqrt{s}$ = 14 TeV. The central design concept is a high-field superconducting solenoid (4T) about which are arrayed detectors to efficiently record the muons, photons and electrons which are expected to signal the new physics. The complexity of this undertaking challenges the collaboration to design and economically construct apparatus which can conclusively isolate the new features despite the extraordinarily difficult experimental environment --- but at a scale (financial, physical, temporal and demographic) seldom encountered in the field. The completion of construction and installation of the detector is scheduled for 2004 and at least a decade of intense experimentation is to follow. Using the experience obtained from participation in the design of the SDC detector, the UW group is participating in the effort to build two components: the trigger system, including the calorimeter first level trigger, and the endcap muon system. The UW group has leading management roles in both of these systems.

We have led the design of the CMS calorimeter trigger incorporating many of the successful concepts used at the ZEUS detector at HERA. Based on extensive simulations of trigger rates and efficiencies for detection of electrons, photons, jets and neutrinos, we have produced a prototype adder ASIC, high-speed backplane, Receiver Card, Electron ID Card, Clock Card and Crate that are integral parts of this design. We propose to complete the work to design, prototype, build, install and commission the level 1 calorimeter trigger including the hardware evaluation and tests required.

The collaboration has delegated to us responsibility for the engineering and procurement of the endcap iron structure, which in part returns the magnetic flux. We have completed and validated the design of a bolted block solution for this structure and have placed a $6.1M contract for the fabrication with a Japanese firm. Other components of the structure are to be constructed by our collaborating countries to a UW design and under the supervision of the UW group. The UW group has also proposed to take an important role in the cathode strip chamber production, by the design of the alignment system and the integration of the utilities in the system.

Because the goal is to do physics at the TeV scale, we will actively participate in the development of the computing strategy and programming. These facets of the experiment are not part of the construction project, but must be supported as a part of the base at the participating institutions. We are responsible for the calorimeter trigger simulation and propose to apply our simulation expertise to the much needed areas of calorimeter jet reconstruction, higher level triggers and muon chamber reconstruction with an initial focus on the requirements on chamber design and alignment. The construction and commissioning of the trigger carries with it the obligation to maintain and monitor it. This will require a significant fraction of the future base program of this task.

2. Introduction & Background

2.1 Wisconsin SSC Activities

D. Carlsmith, R. Loveless, D. D. Reeder and W. H. Smith had been active in the SDC design since the inception of the collaboration. W. H. Smith was scientific spokesman of the SDC trigger group, chaired the SDC trigger technical board, and served on the SDC technical board and SDC electronics technical board. D. Reeder and D. Carlsmith were project leaders for the SDC Intermediate Angle Muon System and members of the SDC muon technical board. D. Reeder also served on the SSCL Board of Overseers. Also working on this task were Assistant Scientist S. Dasu, Postdoctoral Research Associate S. Lusin, Electronics Engineers J. Lackey, M. Jaworski, T. Gorski (PSL), and mechanical engineers A. Pitas (Pitas Instruments), F. Feyzi (PSL), J. Cherwinka (PSL), L. Greenler (PSL) and G. Emmel (PSL).

2.2 Wisconsin LHC Activities

Shortly after the termination of the SSC project, we began discussions with the ATLAS and CMS collaborations at the LHC. The CMS collaboration indicated areas of need that closely matched the interests and capabilities of the Wisconsin group and we were formally accepted by the CMS Collaboration in February 1994 with responsibilities in the areas of the trigger and the endcap muons detector. The successful negotiation of the protocols defining the agreement between CERN and the US was accomplished in part by the LHC Detector Working Group on which D. Reeder served *ex officio* as Chair of the US CMS Collaboration Board and W. Smith as a consultant. W. Smith was appointed by CERN to serve as the only representative from a CERN non-member state on the LHC Electronics Review Board (LERB) and was selected by CMS as one of three CMS representatives to serve on the successor to this organization, the LHC Electronics Board (LEB). In 1999, W. Smith is chairing the annual LEB conference.

2.3 Wisconsin Role in CMS Management

Wisconsin is unusual in the US University program in the extent of its management responsibilities. W. Smith is the CMS Trigger Project Manager and the US-CMS Trigger Level-2 (WBS) Manager. As such he serves on the CMS Management Board and CMS Steering Committee. D. Reeder has served as the Spokesman and *ex officio* chair of the US CMS Executive Board and the US CMS Collaboration Board and the US representative on the CMS Management Board. At present D. Reeder has been elected the co-chair of the CMS Muon Institutional Board. W. Smith is one of the three internal CMS referees charged by CMS management to periodically review all CMS electronics systems. R. Loveless is the US CMS Level-2 manager for US Common Projects, primarily relating to the design and acquisition of the end cap iron disks and serves on the CMS Magnet Board. He is also the CMS Endcap Muon Technical Coordinator and serves on the CMS Technical Board.

Recognition of the important Wisconsin contributions to the effective management of USCMS is afforded by the comments of the February 1999 DOE/NSF US CMS Review Committee chaired by D. Lehman:

“The Common Project Group under Richard Loveless has made outstanding progress since the last review. The placement of the End Cap Iron Yoke contract for $6.1M, which is $2.7M under estimate, is commended. …..”

“ The EndCap Muon Group appears professional and well managed, and communication within the group and with CMS occurs frequently and in an effective manner.”

“ The trigger and data acquisition groups have shown good progress since the last review. … Significant changes in calorimeter and muon trigger electronics have been made since the last review with net benefits in system robustness and accessibility. … Both groups are well managed, with good communication and delineation of responsibilities both internally and with international CMS. Good attention to comprehensive design and interface documentation. “

3. The CMS Experiment

3.1 Physics Goals

The CMS detector [22] is designed to study high p_T physics in 14 TeV center of mass proton-proton collisions at the LHC. In order to accomplish this study and to extend the mass range of Higgs searches, it is necessary to operate the LHC at a luminosity of $10^{34}cm^{-2}s^{-1}$. The goals of the physics program include the study of electroweak symmetry breaking, the investigation of the properties of the top quark, the search for new heavy gauge bosons, probing for quark and lepton substructure, looking for supersymmetry and exploring for other new phenomena. Models of electroweak symmetry breaking generally include a scalar field whose interactions give mass to the W and Z bosons, as well as to the charged fermions. The dynamical component of this scalar field, the Higgs boson, is expected to decay into WW and ZZ pairs if its mass exceeds 180 GeV. Other theories predict new particle states that decay to ZZ, WW, WZ or γZ. Thus, the study of such boson pairs is an important avenue for understanding origin of electroweak symmetry breaking. The efficient detection of these new particles requires the identification and precise measurement of their decay electrons and muons over as large a solid angle as possible.

Detection of the top quark and measurement of its mass will provide important information about the fermion mass spectrum and the Standard Model. The millions of t-quark events expected per LHC year present an opportunity to make precision measurements of their properties. The top decay to W^+W^- may also represent a significant background to the Higgs boson search, and, therefore, needs careful study. The observation of one or two isolated leptons that have resulted from the semileptonic t-quark decay will serve to identify events with t-quarks. The identification of the b-quark jets (jets with a secondary vertex) can be used to reduce the backgrounds in the t-quark event sample, which come from multi-jet production in association with a W.

It is possible that new forces may manifest themselves at LHC energies by the production of massive bosons similar to the W and Z. Heavy charged bosons can be found by looking for events with isolated high-p_t leptons and large missing E_T. Another intriguing possibility is that quarks consist of other particles bound by some new force. At high energy this compositeness would appear as a deviation of the scattering cross section of quarks from the predictions of QCD. Another indication might be an excess of hadronic jet events at high transverse momenta. Evidence for lepton substructure might be seen in a deviation of the lepton pair mass spectrum from that expected by Drell-Yan calculation.

Supersymmetry proposes a relationship between fermions and bosons that forecasts each to have a partner of the opposite spin (*i.e.* boson (fermion) → fermion (boson)). An example is the gluino, the supersymmetric partner of the gluon which is a fermion. This particle might be produced in large numbers and is expected subsequently to decay to at least one stable neutral particle which is not observed. Therefore, gluino production would be characterized by a large imbalance in the observed total transverse momentum. Gluino decays may also produce like-sign dileptons.

3.2 CMS Detector Overview

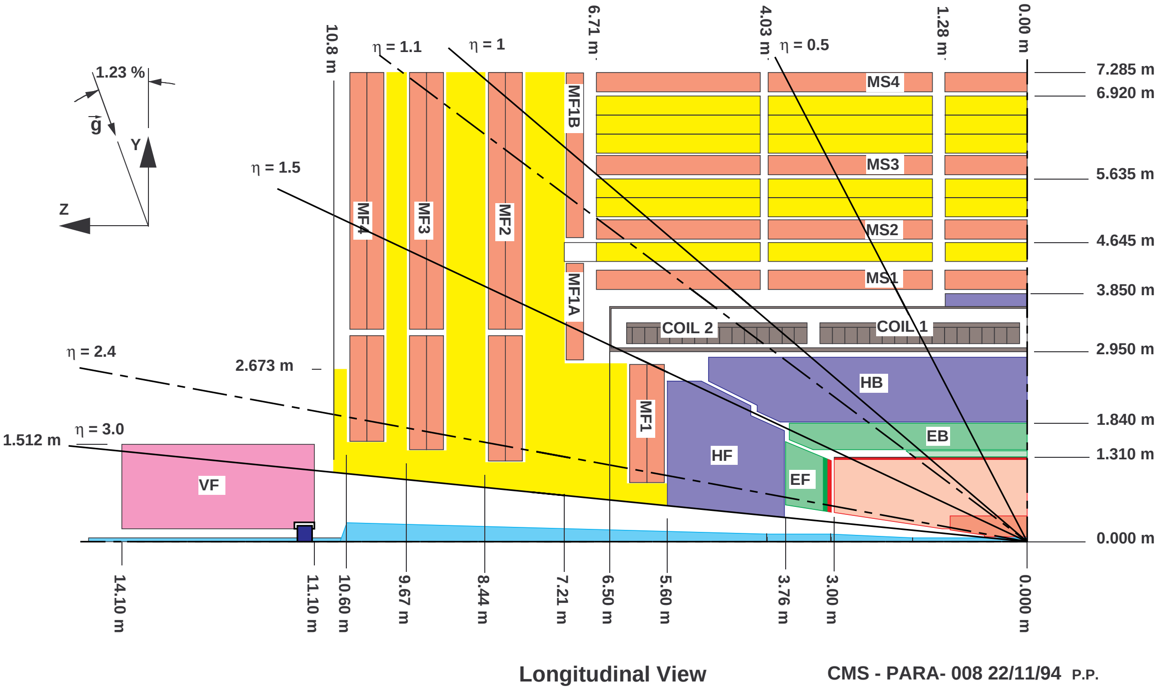


Figure 1. Longitudinal view of the CMS detector.

To achieve the physics goals described above, we must construct a detector that can identify and measure electrons and muons (together with their charges), decays of B mesons and hadron jets with good efficiency and resolution over as much of the solid angle as possible. The longitudinal view of the CMS detector is shown in Figure 1 and a transverse view is shown in Figure 2. The detector employs a 4 T magnetic field produced by a large superconducting solenoid to preserve a ~1% momentum resolution (muons < 100 GeV) over a range of rapidities -2.5 < η < 2.5. More specifically, the inner tracking system will use silicon and gas microstrip detectors to measure charged tracks with a momentum precision of $\Delta p/p \cong 0.1\, p_T$ (TeV) over the same rapidity range |η| < 2.5. A high-resolution crystal calorimeter is located inside the coil and will accurately detect the two-photon decay of an intermediate mass Higgs. Nearly hermetic hadron calorimeters surround the interaction region to pseudo-rapidities (η) of |4.7| and are used to tag forward jets and to measure missing energy.

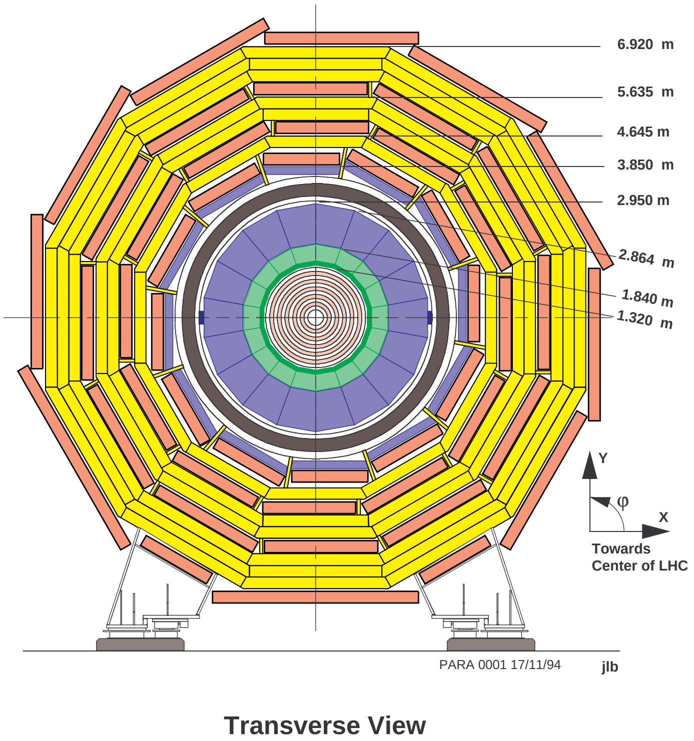


Figure 2: Transverse view of the CMS detector.

3.3 CMS EndCap Iron Flux Return

The organization of CMS is similar to most recently constructed detectors, in that the design and construction of the various components of the detector are proposed and accomplished by international consortia of groups. Some items, however, are too technical, industrial or expensive to fit this paradigm. At CMS these are the solenoidal magnet and the ancillary iron flux return, which represent about a quarter of the total materials and supplies budget and are designated the common responsibility of all collaborators. The overall management of this common effort is done by CERN, but the design and procurement of the endcap iron disks was delegated to the University of Wisconsin as an “in-kind” contribution representing a part of the US obligation to the common fund. The design is completed and approved and the cost of procurement is significantly below the initial estimate, due in part to the UW effort.

3.4 CMS Muon System

Muons are measured in the central tracking systems and again in the external muon identifier, which uses the magnetic flux returned in the external iron to make another, albeit crude, measurement of the momentum (figure 3). The external muon subsystem is comprised of three layers of iron interleaved with three tracking/trigger layers of chambers. The barrel flux return is composed of five axial rings. The central ring supports the solenoid coil and internal detectors. Two endcap systems support the endcap muon detectors, the endcap calorimeter systems and the required shielding. These endcap systems must be mobile in order to provide access to the central detectors.

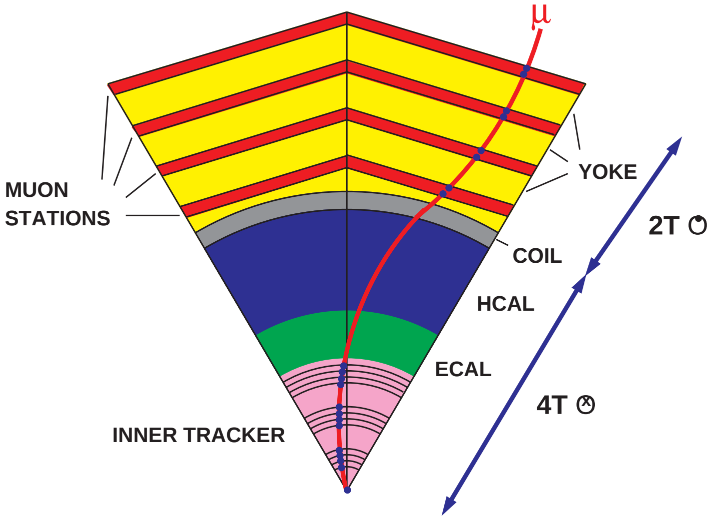


Figure 3: A profile view of the CMS Endcap Muon System.

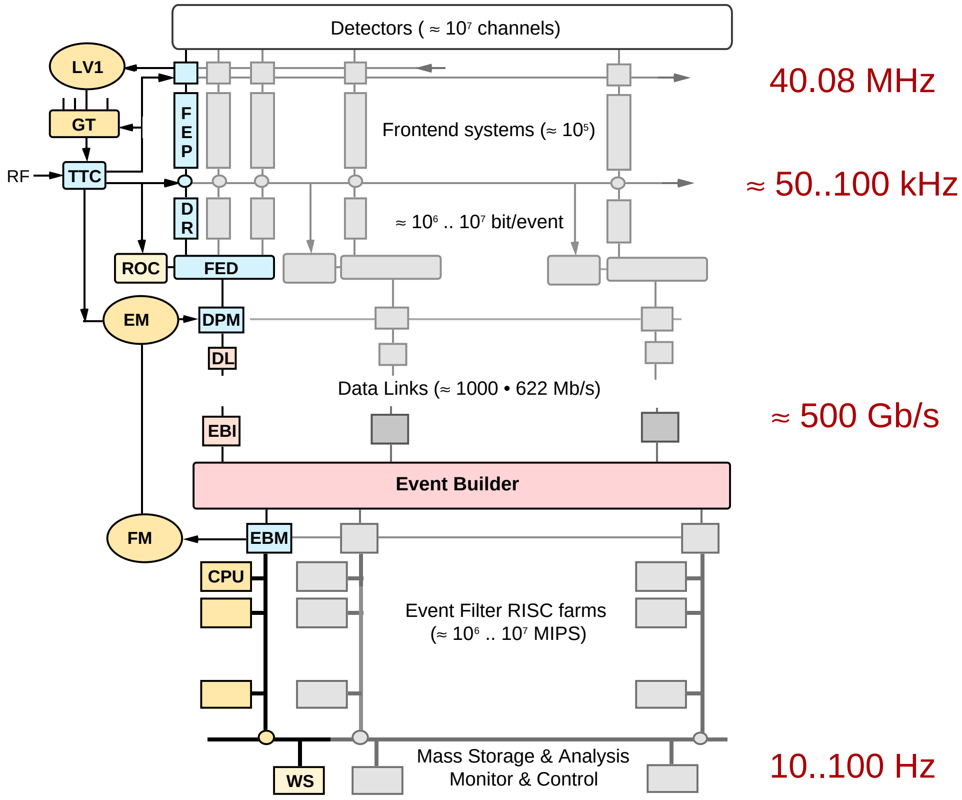
In the barrel region, the muon tracking chambers are Drift Tube Chambers with Bunch Crossing Identification Capability (DTBX) arranged in staggered layers. A station is composed of two substations each containing four layers of wires to measure azimuth and two layers of orthogonal wires measuring polar angle. Mean-timing techniques are used to associate the hits with the bunch crossing in which the parent event occurred.

In the endcap region, Cathode Strip Chambers (CSC) are used to measure the azimuthal coordinate (the direction of the magnetic deflection). In figure 5 the endcap region is shown together with the large iron disks and the cathode strip chambers (CSC). These endcap CSCs are generally overlapped in ϕ to ensure the maximal acceptance as well as to validate the alignment of adjacent chambers. The identification of a muon to its bunch crossing is made using the fast anode signals, while the pattern of cathode hits is used to trigger the read out of the system.

In the region $|\eta| < 2.1$, Resistive Plate Chambers (RPC) will be used to provide redundancy for both the muon pattern trigger and the bunch crossing identification. For $|\eta| > 2.1$, we will rely on the crossing identification and trigger from the CSC system alone. A major challenge to the design is to smoothly integrate the two technologies (drift tubes and CSCs) in the region of η in which they overlap.

3.5 CMS Trigger

Triggering is another of the extraordinary challenges facing detector designers at the high luminosity LHC collider. For the nominal LHC design luminosity of 10^{34}, an average of 25 events occurs at the beam crossing frequency of 25 nsec. 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. As described in Figure 4, CMS has chosen to reduce this rate in two steps. At the first level all data is stored for 3 μsec, after which no more than 75 kHz of the stored events are forwarded to the second level. This must be done for all channels without dead time. The second level is provided by a subset of the on-line processor farm which, in turn, passes a fraction of these events to the remainder of the on-line farm for more complete processing. During the 3 μsec level 1 trigger processing time, decisions must be developed that discard a large fraction of the data while retaining the small portion coming from interactions of interest. The large physical size of the detector and the short decision time present a series of technical and system problems. Inasmuch as the design of an LHC detector trigger system strongly impacts the design of the detector, an LHC detector cannot be designed without addressing how it is to be triggered.



LV1	Level 1 Trigger	DPM	Dual Port Memory
GT	Global Trigger	DL	Data Link
TTC	Timing, Trigger and Control	EBI	Event Builder Interface
FEP	FrontEnd Pipeline	EBM	Event Buffer Memory
DR	DeRandomizer	EM	Event Manager
ROC	ReadOut Controller	FM	Filter Manager
FED	FrontEnd Drivers	WS	Work Station Cluster

Figure 4: The CMS trigger and data acquisition system.

3.6 Computing and Software

The ability to study physics with CMS crucially depends upon a reliable and high performance implementation of its computing and software system. This task is especially crucial for the CMS experiment because it intends to use generic computing hardware and software even at level-2 trigger. The event reconstruction software and data taking are tightly coupled together, for instance in providing intelligent filters in the reconstruction to minimize the volume of data read out for background events, that will be rejected by various higher level software triggers. Our group brings extensive experience in the design and implementation of both computing hardware and software. Our group members bring in the experience from ZEUS and BaBar experiments. The physics analysis and trigger systems experience is particularly useful in this effort. We have taken on roles in both muon reconstruction and higher level trigger software projects which naturally evolve from our hardware responsibilities and will eventually lead to physics analysis. We are also expect to help in designing and implementing the core software required to support physics analysis with CMS. Sridhara Dasu has recently been nominated to sit on the CMS Software and Computing Technical Board which coordinates this CMS subproject.

Another critical area of software development is that of system diagnostics and test. Wisconsin Scientist W. Badgett has assembled a new test setup for the purpose of testing Calorimeter Trigger Cards and evaluating online diagnostic software. We have received a grant from Wind River for a 5-user license for VxWorks, the real-time software adopted by CMS for the Motorola VME Crate processors. This system is in use in the test beams and is also supported by Fermilab and used by CDF. We received funding from the University of Wisconsin for a new test crate including a new processor, all other hardware and a Sun Workstation for support. The setup is operational and will be used for online software development.

The final area of software critical for our CMS trigger project is our suite of electronics design tools. We have received a grant from Mentor Graphics under their Academic software program that provides us with the full suite of Mentor Graphics electronics design tools. We also receive the necessary design tools from Vitesse interfaced to this system for the ASIC designs. In addition, for the precision work needed for the high-speed (160 MHz) printed circuit board designs, we received funding from the University of Wisconsin for the top of the line Zuken-Redac Visula design suite, which we used to build the Receiver and Electron Isolation Cards.

4. CMS Endcap Muon Activity

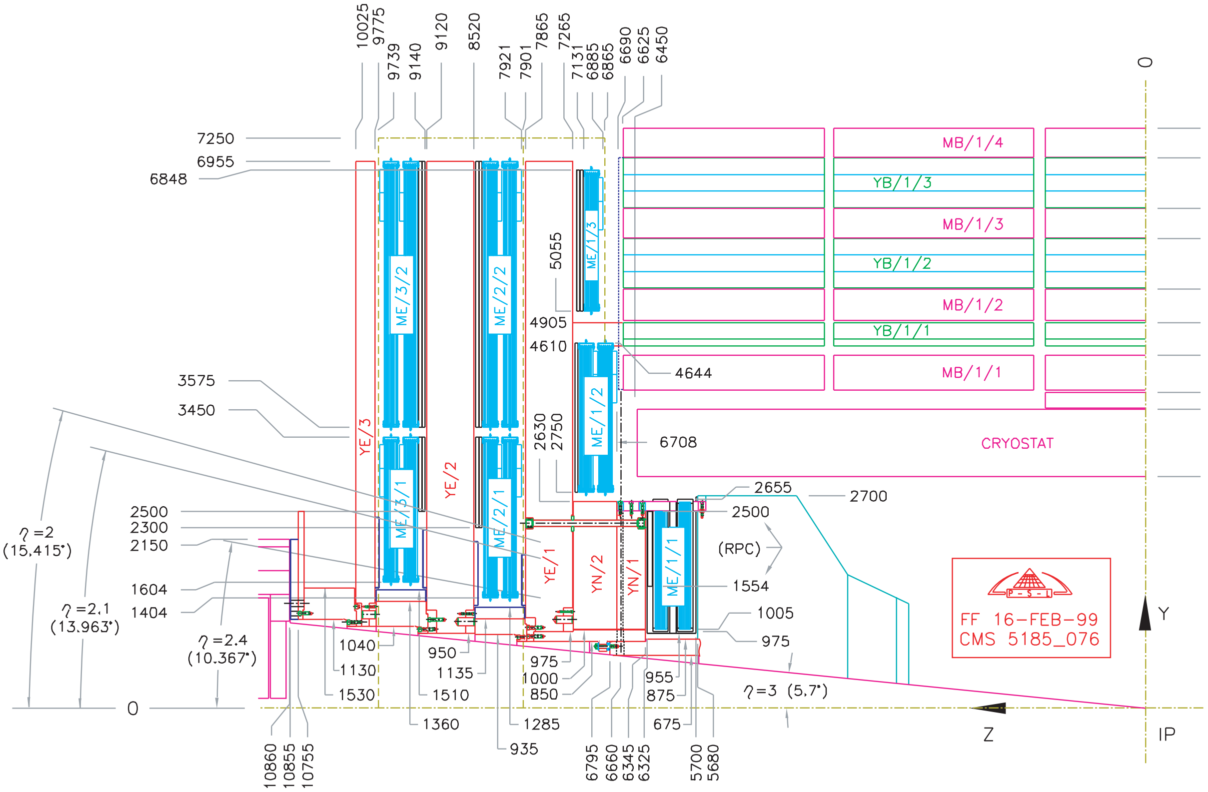


Figure 5: Profile view of the CMS endcap muon system.

The CMS Collaboration has agreed that the US group will be primarily responsible for the design and fabrication of the components in the endcap region (*i.e.* both the flux return iron and the CSC chambers). Groups from PNPI (Russia) and IHEP (China) have agreed to participate in the assembly of the CSC chambers. According to the plan all materials would be manufactured or purchased within the USA, but some chambers would then be wound, assembled, and tested in Russia and China. The project manager for this effort is G. Mitselmakher of U. Florida and the Technical Coordinator is R. Loveless of Wisconsin.

4.1 Iron Flux Return

The CMS endcaps, located at each end of the detector, consist of three large disks (YE1, YE2, and YE3) and one small (nose) disk mounted axially along the beam line as shown in Figure 5. Their primary function is to return the magnetic flux from the 4 tesla solenoidal field. These large iron disks also act as an absorber to reduce background due to hadronic debris. The disks YE1, YE2, and YE3 are connected both at the outside edge and at the inner edge. The nose is attached directly to RF1. The entire endcap is constrained by the 'z' supports that are located on the inner most ring of barrel iron plates.

The Wisconsin group has been delegated the responsibility for the design and procurement of the endcap iron. We have designed similar large iron structures in the past, *e.g.* the ZEUS iron yoke and the SDC yoke, and the CDF forward toroids. Several independent finite element calculations have been made of the magnetic field [21], the forces resulting from it and the consequent deflection of the disks (14 mm maximum). Using the results of these calculations we have prepared a detailed design of the disks and the disk supports, which incorporates a bolted assembly plan for uniformity and quality assurance.

In order to provide access to the CMS detector each endcap must be movable. The solution adopted by CERN is to use an air pad system. CERN has now tested a custom set of 4 air pads each of which must carry 350 tonnes per pad and has been tested to more than 420 tonnes. A smaller test was done successfully on a slope of 1.2% (the slope on which the CMS detector is deployed).

Since the endcap access may need to occur quickly on relatively short notice, cabling and piping for the elements supported by the endcap must either travel with the endcap or be able to be disconnected quickly and easily. Furthermore, to provide access to the muon chambers and to the on-chamber electronics which are mounted between the disks, the large disks must be moveable with respect to each other, again imposing constraints on the type of connection. We expect the need for access to the muon chambers will be relatively less frequent, since the time and effort necessary for chamber access will be considerably longer than for inner detector access.

An axisymmetric model of the CMS detector is shown in Figure 6. This model includes the coils, the endcap disks (labeled RF1, RF2, RF3, and nose), and the barrel steel rings (RY1, RY2, and RY3). The solenoidal coils generate a 4 Tesla magnetic field at the center of the CMS detector with 4 layers of current-carrying superconductor (20 kA each).

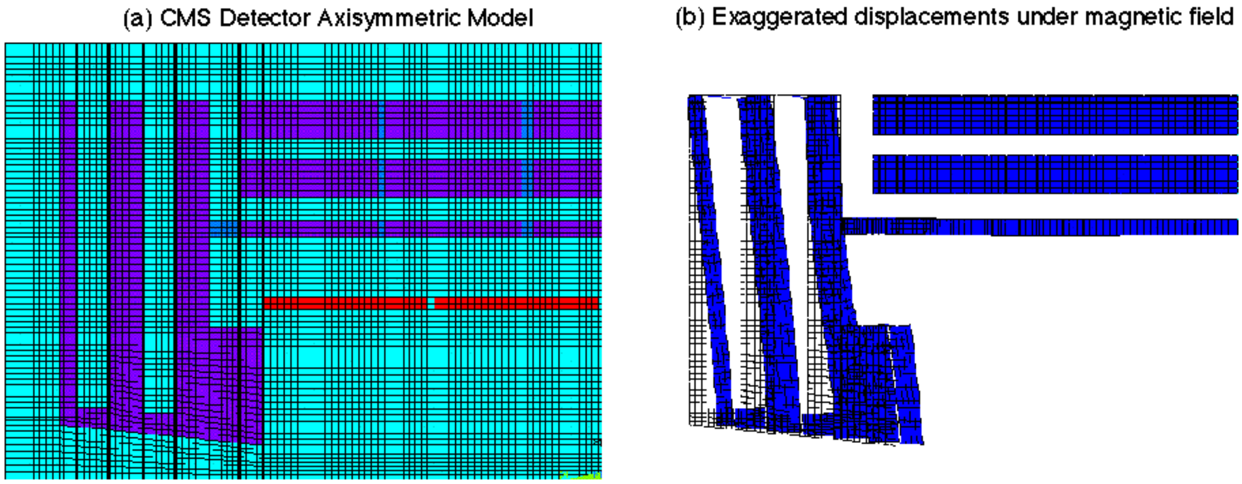


Figure 6: (a) Model of the CMS detector showing the coils, the barrel plates, and the endcap disks used to calculate the magnetic field. (b) Exaggerated displacements of the endcap disks due to the magnetic field.

The results of the calculation of the magnetic field are shown in Figure 7. Within the coil the field is approximately uniform with magnitude 4 tesla. In the return plates of the barrel ring it is about 1.7 tesla. In the endcap region the field changes direction and the radial component becomes significant in the outer rings RF1 and RF2. The effect on the field due to the gaps between the barrel ring segments (20 cm in the inner gap, 12 cm in the outer) can be clearly seen. The maximum stress typically occurs at the inner edges of YE1 and YE2 where the deflections are largest. However, the maximum value, 83 MPa, is well within the strength of hot rolled, low carbon steel (yield strength ~ 200 MPa).

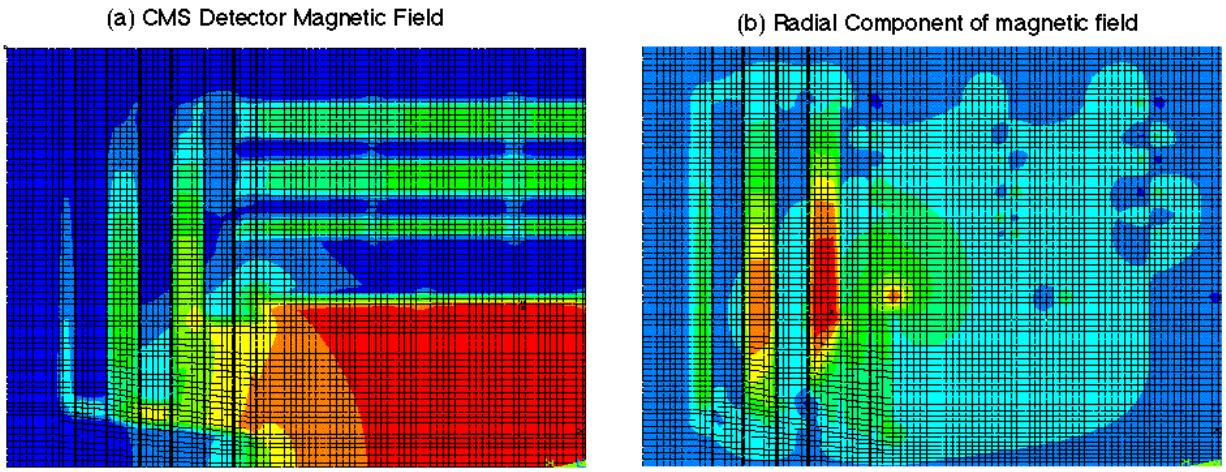


Figure 7: (a) The magnetic field (tesla) for the CMS detector geometry of Fig. 6a. (b) The radial component of the field.

The large magnetic forces cause the disks to deflect toward the IP at the inside edge, despite the 60 cm thickness. Even though the total force on YE2 is smaller than YE1, it deflects more since it is supported only at the outer edge. We have designed a shielding ring of 15cm radial thickness between the disks to divert the magnetic flux to disks YE2 and YE3. The calculations show that with the installation of the shielding ring connection between disks will always be in compression. If less flux were carried by YE2 and YE3, the deflection of these disks would be less than that of YE1 and the connection might open.

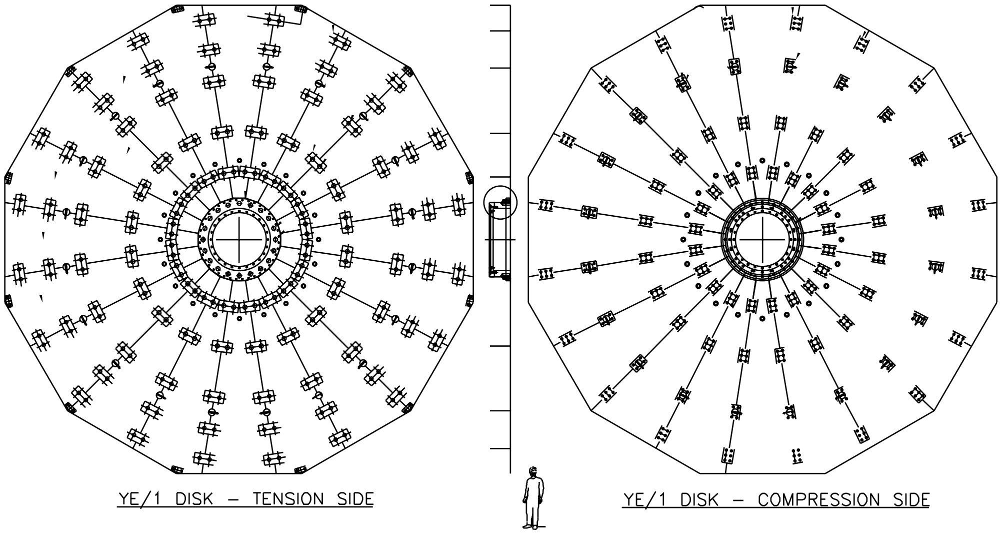


Figure 8: Typical disk construction from 20 pie-shaped sectors.

The disks are assembled by bolting together 20 pie-shaped sectors as shown in Figure 8. We require a trial assembly at the factory before shipping to CERN in order to ensure all sectors fit and meet the size specification. The sector bolting design uses tie plates located in pockets machined in the iron and 100mm dowel pins. At the inner edge of the disk the stresses are highest because this is where the maximum deflection occurs under magnetic loading. A special high-alloy central ring will tie the sector ends together on the inner edge and provide block positioning during assembly.

We have chosen preloaded bolts (superbolts) to provide for precision tensioning and, thus, load sharing to minimize these deflections.

A challenge to the design of the alignment system for the muon chambers is to accommodate the large deflections which occur after the magnetic field is energized. The system must incorporate a semi-automatic readout.

A design of the nose region has been made and validated by 3D FEA calculations. The endcap calorimeter has been designed by Dubna and its interface to the first disk YE1 has been specified and agreed to by all parties. The decision by CMS has been to use a large endcap calorimeter (300-tonne). This requires that the cart be modified to add large struts to stabilize the load (see figure 9). The forward calorimeter is located behind the endcap system at a greater distance from the IP and, together with the backs-splash from interactions at the face of the low β quad, produces a large background radiation field in the muon chambers which must be protected. Along the $\eta=3$ cone we will need at least 150mm of iron shielding and some polyethylene shielding for neutrons. The iron shielding in this area carries sufficient magnetic flux to ensure that the disk connections remain in compression under magnetic loads.

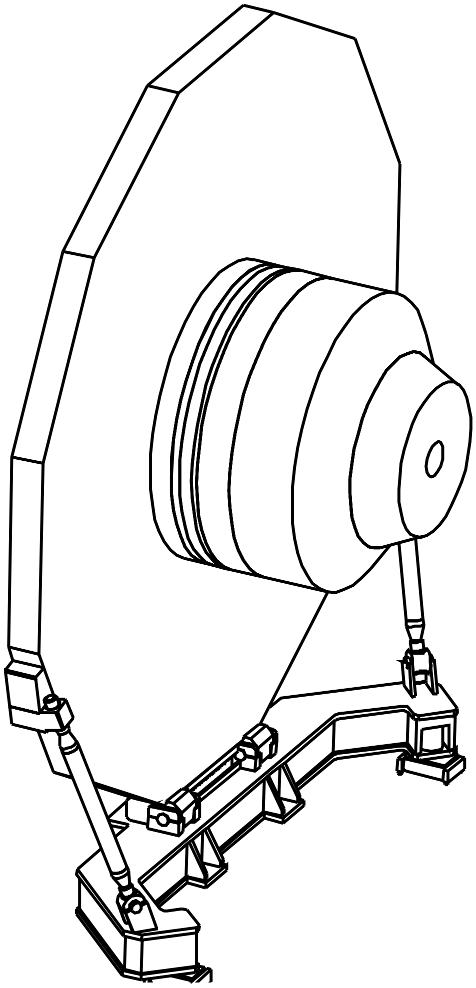


Figure 9: The cart support for YE1 showing the large cantilevered load and the strut support.

4.2 Flux Return Accomplishments and Future Tasks

The schedule for installation of the CMS detector requires the early completion of the solenoid magnet. In order to test the solenoid, the iron flux return must have been delivered and installed. Thus, a “critical” path item is the procurement and installation of the iron flux return which is, as noted a UW responsibility. We have completed and validated a ‘reference’ design to illustrate feasibility. The calculation of the magnetic field and associated forces was done and documented [CMS note 94-293 (Dec 1994)]. Various manufacturing techniques were tested before the bolted design was adopted; *e.g.* the electroslag welding tests which were conducted in Germany during 1994-6. The design work culminated with the completion of the Technical Design Report [41] for the magnet (including flux return) which was reviewed and approved by the LHCC in May 1997.

Having received approval to proceed, we circulated the reference design in 1997 to about 100 potential vendors for review and comments. Incorporating the new information, we generated a request for proposal to the vendors. Seventeen companies returned bids in April 1998. Based on the evaluation of the bids by an expert committee, the three most likely bidders were visited to clear up the remaining questions. In December 1998, we received approval by the safety committee at CERN and placed the contract with Kawasaki Heavy Industries at a signing ceremony in Madison. The production of the support carts were selected to be done at the Hudong Shipyards in Shanghai as a common fund contribution by China. The design was done at the UW was approved by CERN Safety in April 1999. By March 1999 we approved the shop drawings for the disks and material was ordered. Also in April 1999, a test of the joints using the "Superbolt" connection was done in Japan by UW and Kawasaki engineers.

Among the tasks to be addressed in the future are:

- The responsibility for oversight and supervision of the vendors remains with the UW until completion of the assembly at CERN.
- In 1999 we will acquire the necessary Superbolts at a cost expected to be roughly 590K$.
- In April 1999 the contract between IHEP-Beijing and Hudong Heavy Machinery for the endcap support carts was signed and work will begin on final shop drawings. We expect to approve the drawings in early summer with fabrication starting in Aug 1999. We expect delivery in the middle of 2000.
- During June 1999 we will complete the design of the connection pieces at the outer edge of the disks.
- In November 1999 we will assemble the first endcap disk at Kawasaki. Other disks are scheduled for trial assembly in three or four month intervals thereafter.
- We expect the assembly process to begin in Jan 2001 and to be complete by Dec. 2001, in time for the completed magnet to be tested in Sep 2003.
- After the completion of the acceptance tests, the magnet and its associated iron will be lowered into the experimental hall. It is anticipated that the muon chambers will be installed at ground level and lowered together with the disks.

4.3 Cathode Strip Chambers

The cathode strip chambers are trapezoidal in shape. Most chambers cover roughly 10 degrees (some cover 20 degrees) and are completely overlapped in azimuth. In η there are two layers of chambers (see Fig. 5). The overlap region not only provides greater angular acceptance, but also allows us to align adjacent chambers using the muons that pass through both chambers. Each chamber will have six planes of wires (and strips) to provide good timing information as well as a redundant measurement of muon tracks. The redundancy is necessary to be robust against backgrounds, particularly neutrons.

A major advantage of cathode strip chambers is that the accuracy of the track measurement is derived from the geometry of the strips and not from the drift velocity or wire position. We simply form a centroid of the charge induced on a cluster of strips. We need a resolution of 75 microns per station for the first (innermost) layer where the maximum sagitta is found. For the other stations the resolution requirement is somewhat less stringent. The design has been successfully tested using full scale prototypes together with their associated readout electronics in a beam at CERN both with and without the expected background radiation (γ).

The six-layer chamber structure is built from seven Cu-clad FR4 honeycomb (polycarbonate) panels. Strips are milled into the sides of the panels. Wires are wound with 3.2mm spacing and glued to FR4 bars fastened to the panels. The identification of the parent beam bunch crossing is made using the wire (anode) signals and the track measurement is done using the strip (cathode) readout. Both cathode and anode electronics front-end boards are mounted on the face of each chamber. The signals are then routed to crates located in the periphery of the disks.

4.4 CMS Muon Chamber Accomplishments and Future Tasks

Much of the management documentation of the production of the Endcap Muon detector has been done at Wisconsin. The WBS spreadsheets have been produced at Wisconsin for both the DOE and CERN costing [39]. R. Loveless has developed the resource-loaded cost and schedule for the endcap muon system as a part of the overall US CMS Management Plan. This will provide for the tracking of the cost and schedule required by DOE.

The design of the chambers is essentially complete. The planning for the primary production site at FNAL has been done and tested by the industrial production of prototypes. The tooling required has undergone several iterations and is quite satisfactory. The major task delegated to the UW group is to integrate the chambers, electronics, services *etc.* in to a complete system. As part of this effort we have completed the documentation of the mechanical design of the system to be used to align the muon chambers to the overall detector coordinates. An important issue still not completely resolved is the construction and integration of the RPCs (resistive plate chambers) which are used as a redundant trigger in high radiation areas. These are the responsibility of other groups, Chinese and/or Korean. The specification and acquisition of the services, electric power, gas, cabling, as well as provision for the "slow" control monitoring of the system, is the remainder of the UW integration task.

Future activities related to our responsibilities to the chamber design and construction are:

- The management of the production of the chambers and associated services will be done in part by R.J. Loveless who is the Technical Coordinator of the US endcap muon project.
- The UW design for the mounting of the chambers to the iron disks uses steel posts with minimal kinematic constraints. The posts are sized so that the maximum deflection will be less than 1mm. Mechanical tests of the mounting of prototype chambers have validated the design goals.
- Based on the results of the mechanical tests of the first prototype, the chamber design was modified to include a rigid external frame. The UW group has design and will construct these frames using aluminum extrusions appropriately machined. The standardization of the design will accommodate the various sizes of chambers.
- In summer 1999 we expect to complete an integrated test of the production chamber and associated electronics. Based on information gained in this test, the integration of services and cabling will be completed.
- A general requirement at CMS is that all heat generated be removed as close to the source as possible. This means that the electronics mounted on the CSCs must be water-cooled. The UW design provides that each electronics board is to be mounted on a cooled copper/brass pad. A similar system was developed at Wisconsin for the ZEUS calorimeter with good success.
- The simulation of the procedures necessary to determine the alignment database for the muon chambers will be done at UW, in order to validate the specified tolerances. Clearly, this is related to the problem of reconstruction of the muon tracks and we will participate in the development of these programs.

5. CMS Trigger Activity

5.1 Level 1 Calorimeter Trigger Design

After establishing requirements for the performance of the trigger system [1], [2], [3] that fulfill the physics goals of the CMS experiment, we have produced a conceptual design [19,47] of the level 1 calorimeter trigger system. General considerations that were emphasized in this design include access to components, requirements of power, space and cooling, information for diagnostics, efficiency, performance monitoring, traffic on the backplane, timing and synchronization, feasibility of I/O connections, and interface to DAQ and clock/control. The design is implemented using off-the-shelf technology whenever feasible. ASICs are used only where fully justified. The logic design maximizes flexibility and programmability by using memory lookup tables and other programmable devices.

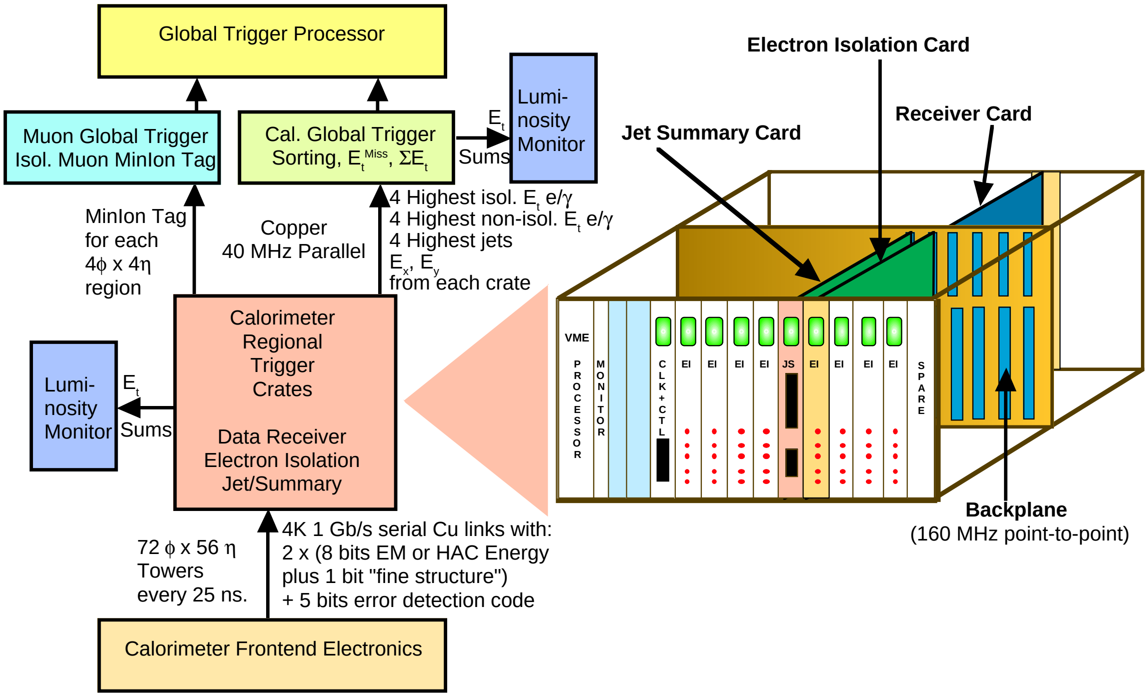


Figure 10: CMS level 1 calorimeter trigger overview and details of one crate.

The CMS barrel and endcap calorimeter trigger system is implemented in 18 crates, as illustrated in Figure 10, each handling 256 trigger towers mostly covering 0.087 ϕ x 0.087 η apiece, arranged in 8 ϕ x 28η regions. The very forward calorimeter trigger will be serviced by a separate 19th crate and is not discussed further. The mapping of the barrel and endcap calorimeter towers onto trigger crates is shown in Figure 12. Full performance electron finding is carried out to $\eta=2.6$. Continuous coverage for energy sums and jets is provided out to $\eta=3$ in the barrel and endcap crates with the coverage extended to the very forward calorimeter in the 19th crate. Each regional processor crate contains 8 Receiver cards, 8 Electron Identification Cards, a Jet/Summary card, a crate processor card and a system monitor card.

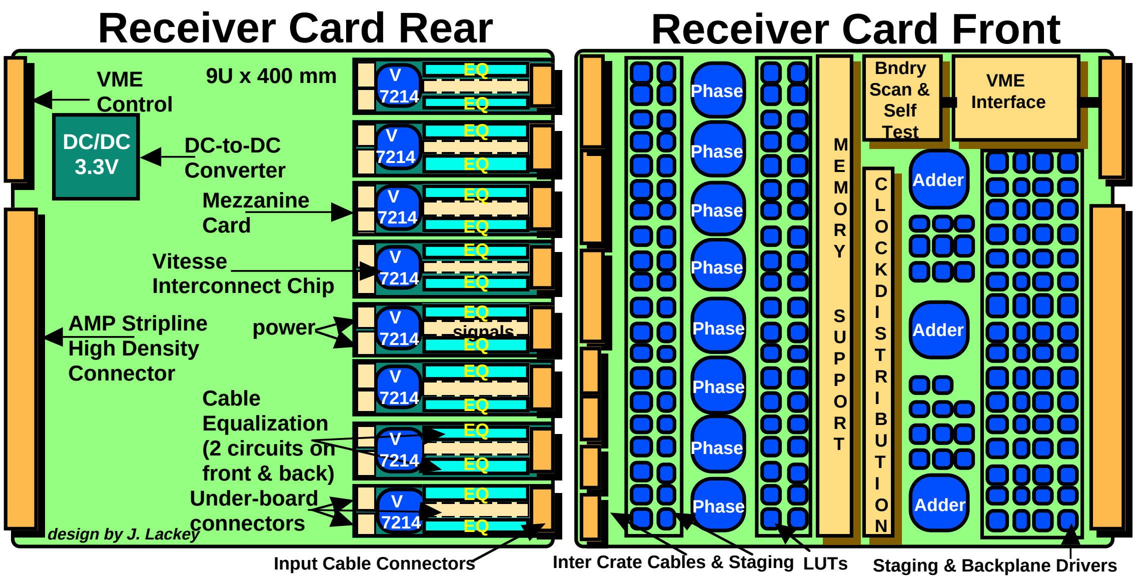


Figure 11: Trigger Receiver Card rear (left) and front (right) sides.

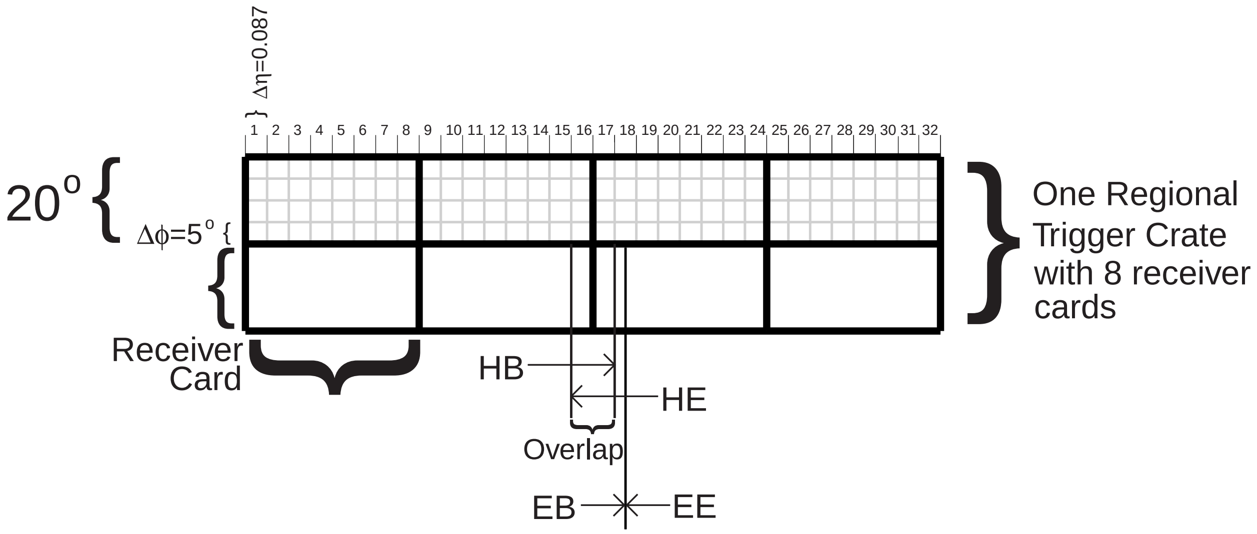


Figure 12: Mapping of barrel and endcap calorimeter towers onto trigger crates.

Data from ECAL and HCAL trigger towers arrives serially on copper cable at 1.2 Gbaud to the back of the 8 Receiver cards in the crate, as shown in Figure 11. Each receiver card covers 4ϕ x 8η towers or an area of 0.35 ϕ x 0.7 η as shown in Figure 12. After the serial-to-parallel conversion and error checking the data are transferred through the card to the front side of the Receiver card. Data are synchronized and passed through look-up tables to separately linearize the energies into the precision needed for electron and energy triggers. Data in parallel form are shared at 40 MHz with the neighboring crates after synchronization. The entire system operates in lock step thereafter at 160 MHz. The energies are then summed to 4 x 4 trigger tower regions using custom Adder ASICs on the Receiver card. This ASIC has been built and is discussed below. The heart of the crate is a central "backplane" which provides data sharing at 160 MHz. Data for the electron identification logic are transferred first to the Electron Identification cards shown in Figure 13 and then the 4 x 4 sums are transferred to the Jet/Summary card.

The Jet/Summary card is also shown in Figure 13, It receives two 4ϕ x 4η jet sums from each of the eight Receiver cards and computes total E_T, E_x and E_y for the 256-tower region within the crate. The Electron Identification Card receives data at 160 MHz and performs the electron identification algorithm in a custom ASIC. The best quality candidate from each of two 16-tower regions is transferred to the Jet/Summary card. A prototype Receiver Card, Backplane and Electron Isolation Card have been built and successfully tested as described below.

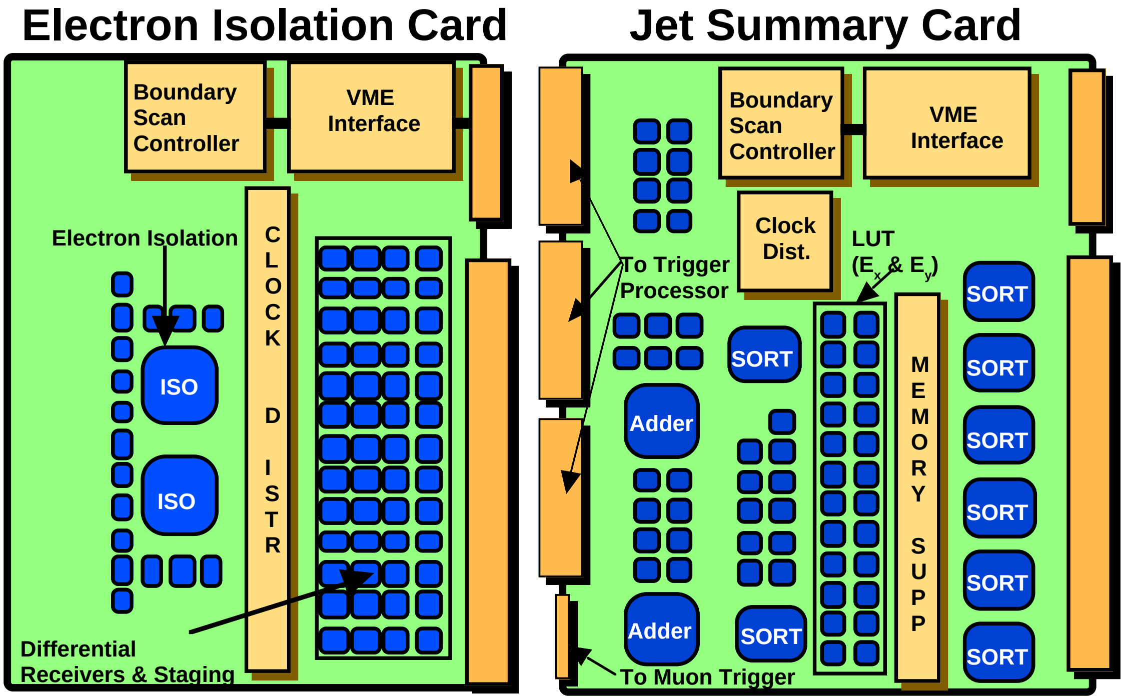


Figure 13: Electron Identification and Jet/Summary Cards.

We have produced a conceptual design of the Phase ASIC used on the Receiver Board to receive and synchronize/align four channels of parallel data from the serial/ parallel converters. In order to achieve maximum utilization of board space, all the logic following the Phase ASIC is run at 160 MHz. Significant savings are realized by placing the multiplexing circuitry, necessary to convert the 40 MHz data flow into 160 MHz, at the output stage of the ASIC.

We have produced a conceptual design for the Electron Isolation ASIC. An entire 4 x 8 region can be processed by two of these ASICs in four 160 MHz cycles. We have also produced a conceptual design for the Sort ASIC. It sorts 32 candidates in one crossing and appends 5 bits of location information to each input. The 5-bit location follows each datum through the Sort ASIC and uniquely identifies the four largest 2- tower sums.

5.2 Hardware Development & Prototyping

As a test of the technology proposed here, we have built an integrated circuit that adds 8 13-bit numbers. This was developed in cooperation with Vitesse Corporation in GaAs technology. The logic design is shown in Figure 14. High speed GaAs technology was chosen because it has an ECL I/O capability and it can provide an opportunity to run sections of the trigger logic at four times the LHC clock frequency. This results in a considerable reduction of circuitry in the trigger data path.

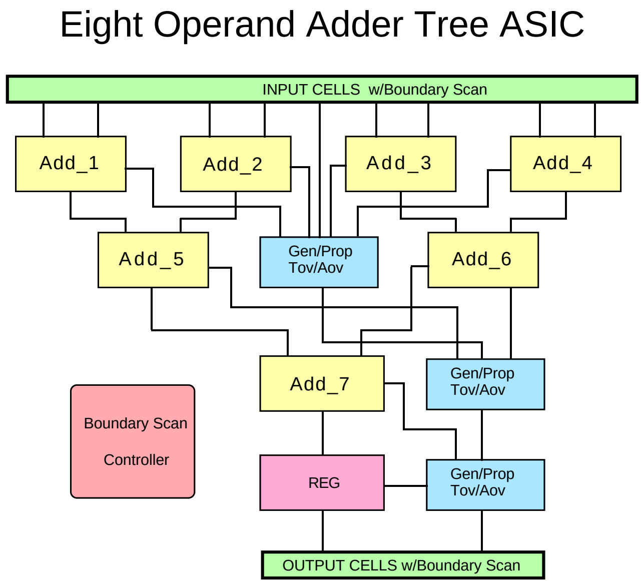


Figure 14. Design of GaAs 8 x 13 bit Adder ASIC.

The Adder ASIC consists of a 4-stage pipeline with eight input operands and 1 output operand. Each operand has 10 bits of value, one bit of sign, one bit of input value overflow (tower overflow) and one bit of arithmetic overflow for a total of 13 bits. There are three adders in sequence with registers at the output of each stage and a set of registers at the input. It has full implementation of J-Tag/ Boundary Scan. The circuit has been evaluated by Vitesse who confirm its operation at 240 MHz.The functionality of this Adder ASIC circuit which was installed on the prototype Receiver Card has been verified in tests.

As another test of the implementation of our trigger system design we have constructed a backplane, shown in the front and the rear of the prototype crate in Figure 15 and Figure 16.

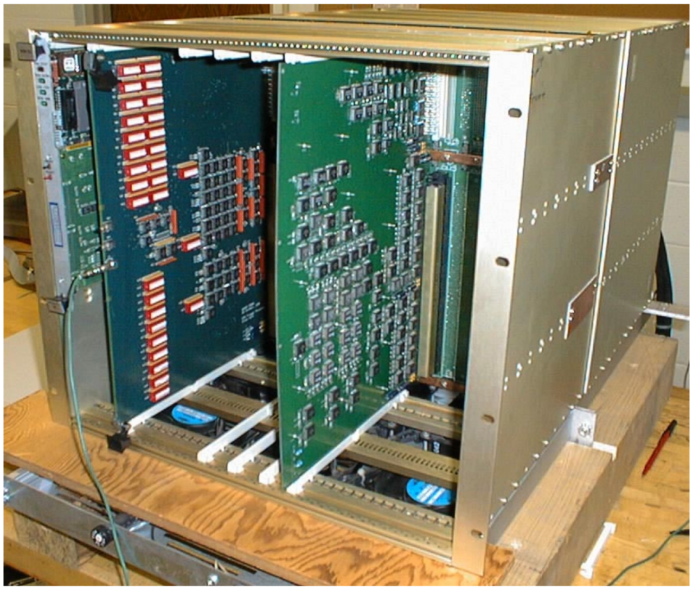


Figure 15: Front of Prototype Crate.

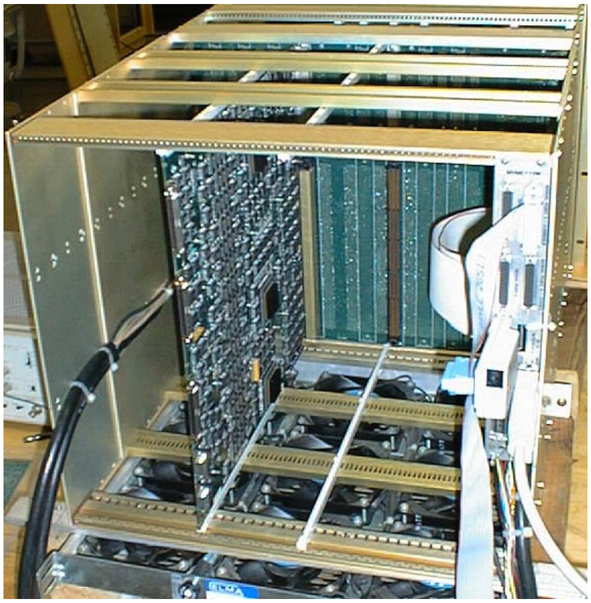


Figure 16. Rear of Prototype Crate with Receiver Card Installed

The backplane has a right side trigger processing area with rear and front-mounted cards that exchange trigger data on 340-pin connectors. The left front-facing region is standard VME on 2 96-pin connectors, which is then carried to the other cards in the custom trigger data-processing section on single 128 pin connectors. We built a custom clock board to test the operation of the backplane. This test of the point-to-point differential ECL transmission indicated far end rise and fall times of 0.8 ns. We also constructed the prototype Receiver Card shown in Figure 17. The board is designed to receive data from the input 1.2 Gbaud copper links and transmit trigger data over the backplane to the prototype Electron Identification Card shown in Figure 18, as well as providing a full functional test of the Adder ASIC.

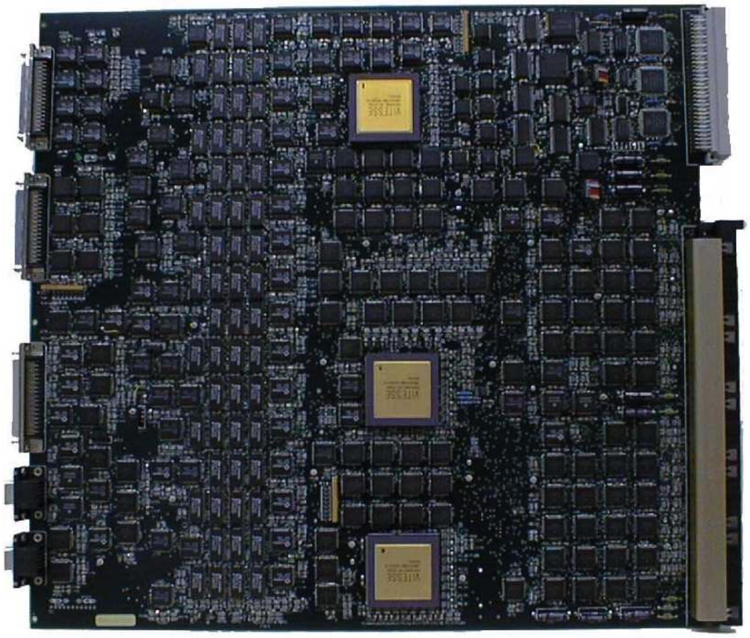


Figure 17: Prototype Receiver Card with 3 Adder ASICs installed.

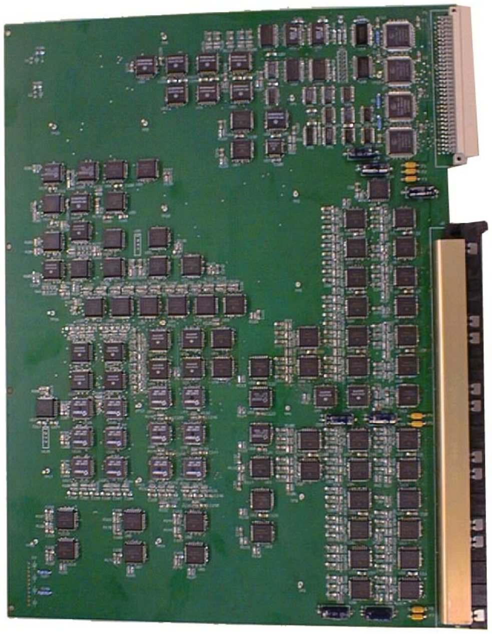


Figure 18. Electron Identification Card Prototype

5.3 Simulation Program - Design developments

The calorimeter trigger hardware described above implements the electron/photon, jet, missing transverse energy and total transverse energy trigger algorithms shown in Figure 19. The electron/photon trigger algorithm is based on a sliding window technique, which uses the addition of leakage energy to sharpen the efficiency turn-on curve and vetoes on hit and neighbor tower H/E, fine-grain EM energy profile and neighbor tower EM energy deposits. Together, these vetoes reject contamination from profusely produced jets which sometimes produce large EM energy deposits. The algorithms used in the determination of jet and missing transverse energy are based on transverse energy sums over a 4x4 trigger tower region.

This trigger system has been simulated extensively by a program which uses parameterized functionality to increase its speed [20], [27], [35], [30]. This program was developed by our group. Based on the results obtained, the trigger system was determined to meet the rate constraints imposed by the data acquisition system while providing high efficiency for the physics processes studied in the CMS Technical Proposal [22]. These studies have also suggested minor modifications to either improve the performance or simplify the baseline design [19].

The use of fine-grain $PbWO_4$ crystal electro-magnetic calorimetry provides the capability to analyze electron showers within a trigger tower and to provide an EM cluster identification bit [28]. A simple peak-finding algorithm applied to strips of crystals in η can be implemented with a modest increase in the complexity of the trigger primitive generation stage of the FERMI front-end electronics for ECAL. Simulation results [28] indicate that the background can be reduced 2-4-fold, while maintaining the signal efficiency > 95%. These new algorithms are now incorporated into the specification of the calorimeter trigger system [33]. Our simulation efforts [36] have resulted in variations on the theme that involve relatively minor hardware changes, but allow implementation of both the fine-grain electron/photon identification and an additional neighbor tower EM isolation.

Last year, we have made an extensive study of the trigger algorithms with the detailed simulation of CMS (CMSIM program incorporating GEANT simulation of the detector). These results compare favorably to those from our fast simulation program [38].

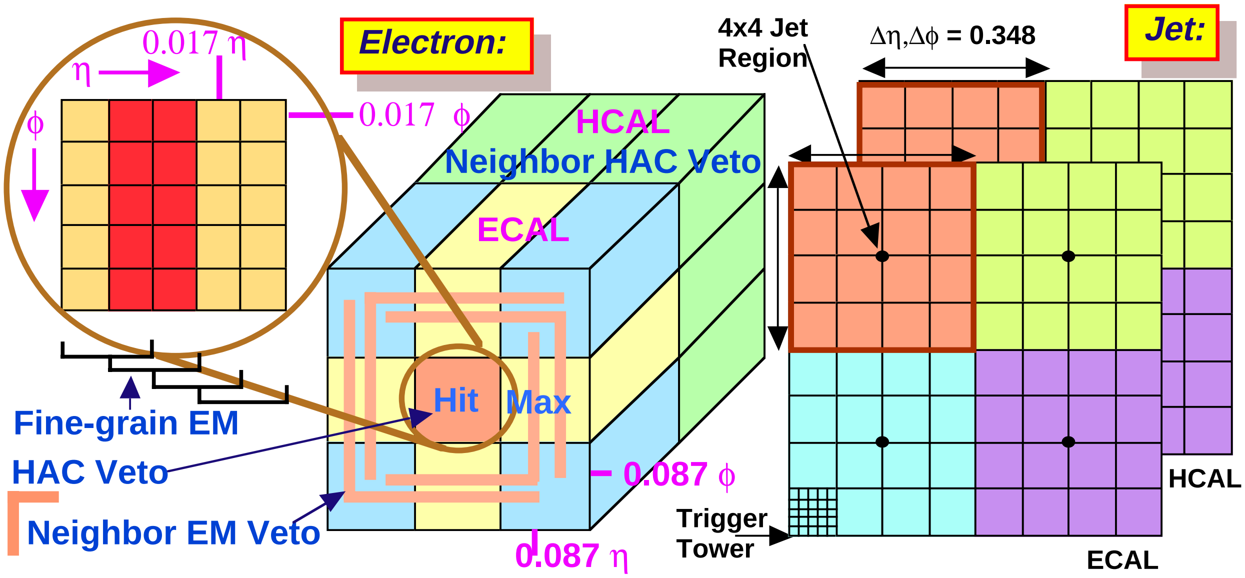


Figure 19. Electron and Jet Trigger Algorithms.

This year we have focussed primarily on improving the algorithm further, to perform better in triggering on semi-leptonic B decays during the initial low luminosity phase of LHC. The main improvement is in the more complete use of fine-grain information in both hit and neighbor towers. We have also implemented separate sorting trees for non-isolated and isolated electron/photon candidates. We have verified that the algorithm can be implemented within the hardware design described above and it performs well [62].

Secondly, budgetary considerations resulted in reduction of the total output rate of the level-1 trigger system. We have tuned trigger cutoffs in our simulations to reduce the output rate and have verified that the physics output of the experiment is not compromised [60].

The efficiency of the electron/photon algorithm, for top and bottom events that decay to electrons, as they vary with electron momentum are shown in Figure 20 and Figure 21. The efficiency is shown separately for the full algorithm and for the various sub-algorithms. The top events efficiency plot includes the minimum bias events appropriate to the high luminosity LHC running, i.e., $L = 10^{34}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The asymptotic efficiency for both cases is reached at about 10 GeV above the trigger E_T cutoff. The E_T cutoffs chosen at various luminosities, i.e., 27 GeV at $10^{34}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 16 GeV at $10^{33}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and 8 GeV at $10^{32}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$can be sustained within the rate requirement [62].

In order to study the physics performance of the calorimeter trigger we follow our earlier procedure [30] of selecting representative E_T cutoffs for various sub-triggers satisfying the target total rate of 12.5 kHz. We then explore the efficiencies of triggering on various high p_T physics processes. The CMS data acquisition system is now expected to handle a 75 kHz-input rate. However, the calculated baseline trigger rates may be uncertain by an unknown amount due to the poorly measured gluon distribution in the proton, which contributes the bulk of the QCD background that dominates the calorimeter triggers. In order to provide a margin of safety we require that the total calculated trigger rate be < 25 kHz and the calorimeter portion < 12.5 kHz.

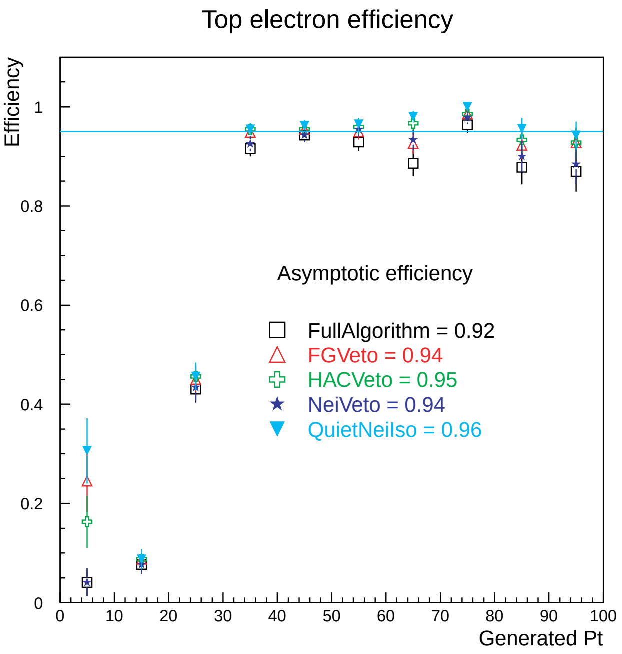


Figure 20: The electron/photon algorithm efficiency is plotted versus the p_T of the top decay electron for various cuts

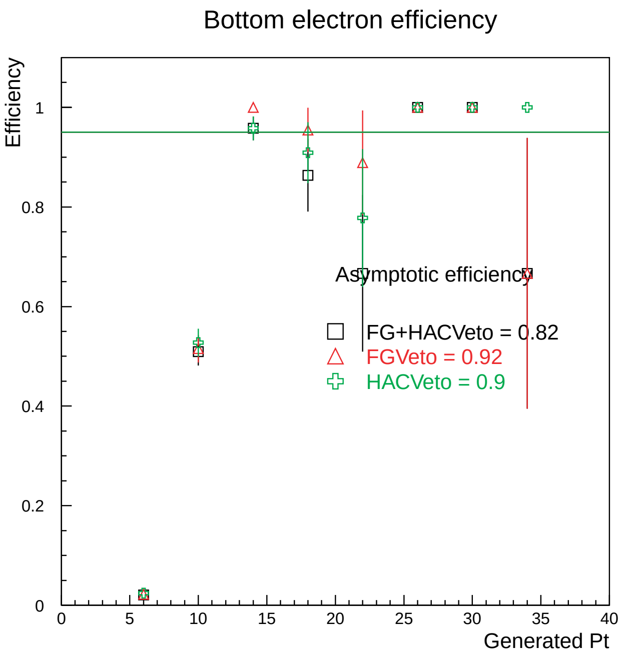


Figure 21: The electron/photon algorithm efficiency is plotted versus the p_T of the bottom decay electron for various cuts.

The trigger rate breakdown and the selected E_T cutoffs for various sub-triggers, at high and low luminosities are shown in Table 1. The E_T cutoff selection is, of course, arbitrary, but we select these specific values to emphasize the electron/photon triggers that enable the exploration of high p_T physics with the best signal to noise ratio. However, we ensure that sufficient bandwidth is reserved for total E_T, missing E_T and jet triggers to study SUSY and QCD physics.

Trigger Type	**High Luminosity**		**Low Luminosity**	
	Trigger ET Cutoff (GeV)	**Incremental Rate (kHz)**	**Trigger ET Cutoff (GeV)**	**Incremental Rate (kHz)**
Sum E_T	400	0.3	150	1.0
Missing E_T	80	0.9	50	0.7
Electron	27	5.3	16	7.3
Dielectron	14	1.3	8	3.0
Single jet	100	1.0	50	0.3
Dijet	60	0.7	35	0.1
Trijet	30	1.3	20	0.2
Quadjet	20	1.0	15	0.04
Jet+Electron	50 & 14	0.3	30 & 10	0.2
Total Rate (kHz)	**12.1**		**12.8**	

Table 1. High and low luminosity background rates, increments over previous row and total for all triggers, for a representative set of trigger E_T cutoffs.

For these efficiency studies, we select from the physics processes considered in the CMS Technical Proposal [22] only those that place the most stringent requirements on the trigger system. Because we do not include effects of offline reconstruction inefficiencies or cuts when evaluating efficiencies, these results are conservative. We have performed these studies for both high and low luminosity, L = 10^{34}cm^{-2} s^{-1} and 10^{33}cm^{-2} s^{-1}, and have summarized them in Table 2.

Luminosity	Physics Process	Efficiency (%)
High 10^{34} cm^{-2} s^{-1}	$H(80\ \mathrm{GeV}) \rightarrow \gamma\gamma$	91
	$H(120\ \mathrm{GeV}) \rightarrow Z\ Z^{*} \rightarrow e\ e\ \mu\ \mu$	73
	$H(200\ \mathrm{GeV}) \rightarrow Z\ Z \rightarrow e\ e\ q\ q$	95
	$p\ p \rightarrow t\ t \rightarrow e\ X$	82
	$p\ p \rightarrow t\ t \rightarrow e\ H^{+}\ X \rightarrow e\ \tau\ X$	76
Low 10^{33} cm^{-2} s^{-1}	$p\ p \rightarrow t\ t \rightarrow e\ X$	97
	$p\ p \rightarrow t\ t \rightarrow e\ H^{+}\ X \rightarrow e\ \tau\ X$	94
	SUSY squark & gluino production M_{LSP} = 45 GeV, $M_{sparticle}$=300 GeV	77
	5.3.1 SUSY Neutral Higgs $10 < \tan\beta < 30$, $100 < M_{A,H} < 400$ GeV	38 - 96

Table 2. High and low luminosity physics processes efficiency for the representative set of trigger E_T cutoffs selected. (*Note this efficiency does not include the muon trigger).

For the efficiency studies several physics processes are selected. The generic Standard model physics processes of importance are $t \rightarrow e + X$ (sets the most stringent requirement on the single electron trigger), $W \rightarrow e + \nu$, and $Z \rightarrow ee$. The Standard Model Higgs processes selected are H (80 GeV) $\rightarrow \gamma\gamma$, H (120 GeV) $\rightarrow Z\ Z^{*} \rightarrow e\ e\ \mu\ \mu$, and H (200 GeV) $\rightarrow Z\ Z \rightarrow e\ e\ q\ q$.

The efficiencies for the above physics channels studied at the high and luminosity LHC running are listed in the Table 2. The selected trigger E_T cutoffs yield high efficiency for these representative physics processes while satisfying the bandwidth requirement.

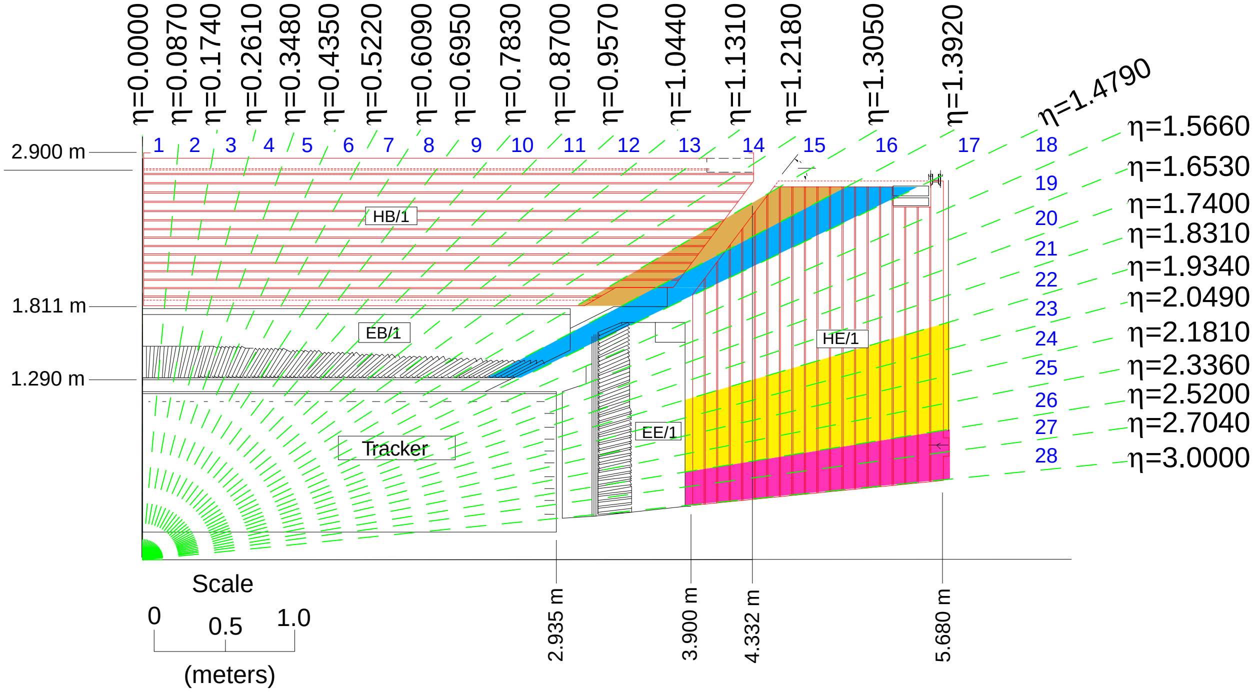


Figure 22. Mapping of calorimeter cells into trigger towers.

Another major simulation effort has been to determine the trigger tower geometry for the Barrel and Endcap Electromagnetic and Hadronic Calorimeters. We have been collaborating closely with the mechanical design and electronic readout teams to produce detailed and complete calorimeter trigger tower assignments for every calorimeter readout cell. We have been running simulation studies to determine the consequences of various tower mappings. This determination is important since the HCAL scintillator towers must be compatible with the ECAL trigger towers. A side view of the mapping we have developed is shown in Figure 22.

5.4 Plans for CMS Trigger R&D

The focus of our hardware development efforts in FY2000 is to complete the initial design and prototyping of the trigger to meet the milestone of issuing the Trigger Technical Design Report (TDR) at the end of 2000. Therefore, we plan to prototype and to make an engineering evaluation of hardware proposed in order to determine its capability, feasibility, and cost. The goal of the hardware evaluation is to provide the information required for the final design of the calorimeter trigger system and for the specification of interfaces to the Front End, Trigger and DAQ systems.

Our CMS trigger R&D program for 1999-2000 contains several major activities. The first is to test the transmission of data to the prototype Receiver Card at high speed. We will build a test card specifically for this purpose on which will be installed the mezzanine cards for the Receiver Card with their 1.2 Gbaud copper receivers of the serial data. An important ancillary result will be the verification of the scheme to transmit high-speed serial data on cables.

Since tests of our prototype crate, backplane, Receiver Card and Electron Isolation Card have proven the validity of the basic framework of data transmission and processing, we will proceed to construct and evaluate a prototype ASIC to perform the pattern finding of isolated electrons at the full speed and input data required. We need to determine whether the isolated electron algorithm can indeed be implemented in a 160 MHz ASIC. Based on our experience with the Vitesse GaAs technology used in the Adder ASIC we believe this is feasible, but a hardware demonstration is required to verify the design.

The completion of the proof of principle of the full dataflow and processing now allows us to turn our attention to the front end processing of the Receiver Card and the critical points of the input data synchronization and error detection. These functions will be performed by the Phase ASIC and we must design, build and test a prototype it.

We will then address the issue of diagnostics in order to develop a global philosophy that can be applied across trigger systems, involving both ASICs and boards. We will continue the investigation begun with the Adder ASIC by studying the J-Tag/Boundary Scan scheme at the board level. The Boundary Scan diagnostics will be incorporated into the Boundary Scan ASIC and we will construct and test it to verify the scheme.

We next plan to address the production of the summary output from the calorimeter regional trigger system and the interface to the global trigger. We will construct a prototype Jet Summary card that will process the output of the prototype Electron Identification Cards and transmit this information to the global trigger in order to test the trigger object summary logic and the interface to the Global Calorimeter Trigger system. This interface is needed to test system integration beginning in 2000; to validate the full calorimeter trigger design and to test the interfaces with the rest of the trigger system.

We will develop the software necessary to operate these prototype boards and ASICs and read them out with appropriate diagnostics. Simulation studies will be used to evaluate the design performance in order to determine the effect of design modifications and more exact specifications. The hardware and engineering parts of this R&D program include:

- Prototype Electron Isolation ASIC in Vitesse GaAs process.
- Summary Prototype Board for testing of trigger data summary generation and interface to global calorimeter trigger.
- Study of intercrate data transfer techniques.
- Design and test of input data phase adjustment and error code detection with implementation in the Phase ASIC.
- Design and test of board level JTAG/Boundary Scan diagnostics and implementation in the Boundary Scan ASIC with integrated backplane drivers.
- Design and test of Sort ASIC with integrated backplane receivers.
- Perform a full-scale crate prototype test with the crate, backplane, Receiver Card, Electron Isolation Card, Summary Card, Clock Board, and Crate Processor.
- Refine and monitor the cost and schedule.

We also plan to continue trigger system engineering. Specifically this involves power and cooling, cable requirements, physical size of electronics, location of electronics and access requirements. We intend to complete the definition of interfaces between trigger subsystems, between trigger subsystems and the global trigger system, and between the trigger system and the DAQ and front end electronics systems. The resource requirements need to be determined, including power, space and cooling. Signal specifications for communications are being finalized and monitoring requirements determined. Studies of reliability need to identify critical components and assess fault tolerance and mean time between failure for various trigger systems. Specifications will be developed for the amount of trigger system that is allowed to be taken out by a single failure. Joe Lackey serves as lead engineer on this project, assisted by M. Jaworski and PSL engineers P. Robl and D. Wahl. Board and system testing, test setup support, and operation and diagnostic software are provided by Scientist W. Badgett.

We will also continue the development of diagnostic software and online in our new test crate setup. We will develop JTAG/Boundary Scan in-situ diagnostic software to operate our on-board and on-chip JTAG/Boundary Scan chains We will develop programs to download test patterns to check the functionality of boards and ASICs. We expect that these programs will evolve into those used in integration tests with other front-end, trigger and DAQ systems as well as those used in test beams and eventually in the full experiment. We plan for the software development to take place along side with the hardware development so that the final system has fully functional software available when it is commissioned.

5.5 Plans for Simulation Program

A thorough understanding of the characteristics of the events which pass the level-1 trigger is a prerequisite to develop higher-level trigger algorithms. CMS requires three orders of magnitude reduction of rate before saving the data for offline processing. This reduction must be accomplished for the interesting high PT events using fast algorithms while retaining good efficiencies. We propose to characterize the output of the level-1 trigger and develop higher level trigger algorithms.

CMS is implementing higher level trigger algorithms in software running on a farm of generic computers. This decision eliminates the need for a dedicated data path such as those used in traditional level-2 triggers. However, the onus is upon writing intelligent software that reconstructs the events on demand and rejects those events that are unlikely to pass at later steps of the trigger algorithms early on, such that the network switch bandwidth is not wasted in reading out all the data for the event. A team of trigger, detector and reconstruction software experts have teamed up to develop an object oriented software program that allows development of these higher level trigger algorithms. We have begun participation in this effort and intend to take leading role in defining this software system that will eventually determine the physics capability of CMS.

The extraction of the final physics results from the CMS also requires a thorough understanding of how the signal and the background events pass all the way from the level-1 trigger, through the higher level triggers and the event reconstruction programs, to the analysis. So far we have been studying the efficiencies for triggering on various physics processes within the detector acceptance independent of offline reconstruction restrictions. Therefore, our quoted efficiencies are conservative. However, understanding the event reconstruction, the analysis techniques and the physics/detector background for various physics topics is necessary to determine the true physics capability of the CMS. There is an intricate interplay in the tuning between the various algorithms to efficiently extract the signal. Therefore, we also propose to develop offline analysis techniques not only to understand the physics performance but also to refine the trigger algorithms. This effort will naturally lead to the development of both the software codes and the knowledge base to exploit the physics capabilities of the CMS. Scientists Sridhara Dasu and Bill Badgett will work on this project.

5.6 Trigger Project Management

W. Smith serves as the CMS trigger project manager and the US CMS Level 2 Trigger Project Manager. As CMS trigger project manager he is responsible for the overall design and execution of the CMS trigger, including conducting the twice yearly CMS trigger reviews, as well as active participation in CMS management decisions on the Steering Committee and Management Board. Along with his two other CMS LHC Electronics Board colleagues, G. Hall and G. Stefanini, he is also responsible for conducting CMS internal electronics reviews of all systems.

As US CMS Level 2 Manager for the Trigger system, W. Smith hosts monthly video conferences with the other US CMS trigger institutions, Florida, Rice, UCLA, and Davis to review of progress, milestones, simulation activities. He also participates in meetings with FNAL and Maryland concerning integration issues for the Calorimeter Trigger and with Ohio, Florida, Rice, and UCLA for the muon trigger.

As part of these management responsibilities, we will also continue to monitor the overall CMS level 1 trigger latency. This involves the determination of the maximum total time after the beam crossing needed by each subsystem; to produce its trigger 'primitive' information, to transmit it to the trigger decision racks in the CMS electronics room, to process the information, to make a global L1 trigger decision, and to transmit the L1 accept back to detector electronics in order to send the event to the next level.

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7. Task T Budget and Narrative

7.1 Salaries and Wages

Experienced senior physicists and postdoctoral associates are absolutely necessary for the design and construction of CMS detector. To this end an appropriate operating budget must be in place to insure the accomplishment of the engineering and equipment construction. Since there is a prohibition on the spending of equipment funds for this physicist oversight function, the base program support by the HEP division is a *sine qua non*.

For the CMS Muon Activity and the CMS Common Projects Activity, we are requesting 12 months of full support for Senior Scientist Dr. R. Loveless. R. Loveless is the US CMS Level-2 manager for US Common Projects, primarily relating to the design and acquisition of the end cap iron disks and serves on the CMS Magnet Board. He is also the CMS Endcap Muon Technical Coordinator and serves on the CMS Technical Board. He is a leading scientist on US CMS and CMS. The success of the project depends on his continued leadership.

For the CMS Muon activity, we are requesting full support for 12 months for Assistant Scientist S. Lusin to work under the supervision of Profs. Carlsmith and Reeder on the construction of the prototype cathode strip chambers and services, as well as the development of the procedures needed to assure the quality of the mass-produced chambers. S. Lusin will also work on the simulation of the muon chamber performance, focussing on such issues as alignment.

For the CMS Trigger activity, we are requesting 12 months support for Assistant Scientist W. Badgett to direct the CMS calorimeter trigger testing and software effort. He will develop a hardware test environment including a test crate setup and diagnostic software. He will also work on integration of the trigger hardware with other CMS systems and he will participate in the trigger simulation effort. Dr. Badgett has been previously active and supported by Task B - Zeus (where he served as trigger coordinator), but has now turned his talents to the CMS trigger project. We are requesting 12 months of 33% support of Assistant Scientist S. Dasu to continue his leadership of the CMS calorimeter trigger simulation effort. His expertise is invaluable in the efforts to refine the first level trigger and to design the calorimeter algorithms for higher level triggers. The remainder of Dr. Dasu’s support and activities are on Babar (Task C).

For the CMS Trigger activity, we are requesting 6 months of support for Senior Engineer J. Lackey in the expectation that we will receive an additional 6 months from US CMS Project funds. J. Lackey is a leading electronics engineer with an international reputation earned by his successful design of the Zeus Calorimeter Trigger and is now responsible for the design and engineering of the CMS regional calorimeter trigger.

For both the CMS Muon and Trigger activities, we are requesting 12 months support for a technician. There is a significant amount of technical work required at U. Wisconsin for CMS in the next few years. For the Muon system, there is general infrastructure support, including tests of thermal conductivity for the cooling system, assembly and testing of low voltage power supplies, testing of magnetic shielding for the DC-DC converters, coordination of cooling system procurement and production, supervision of cooling system delivery, supervision of frame production and delivery and coordination of Low Voltage procurement and delivery. For the work on the calorimeter trigger, we need a technician to work on assembly and test of the prototype electronics, preparation of modifications of printed circuit boards with surface mount devices, general assembly of electronic components, mechanical assembly of electronic chassis and crates, cabling, inventory of parts and maintaining supply cabinets, parts ordering, maintenance and repair of test setups, soldering and desoldering, assembly of cooling, and testing of power supplies.

Although the challenge of CMS physics is very attractive to graduate students, the time scale to completion is impracticably long. A solution to this dilemma can be achieved by combining the CMS hardware experience with the analysis opportunities available through the ZEUS and CDF activities. We will be recruiting students in the future, in greater numbers as we reallocate our base resources to LHC in the post construction era.

7.2 Travel

We monitor the travel budget very seriously, in part because it is one of the few controllable items in the task. In order to meet his responsibilities as CMS trigger project manager, a member of the CMS Steering Committee and Management Board, the US CMS Data Acquisition and Trigger Level 2 Project Manager and a member of the LHC Electronics Board, W. Smith must attend numerous meetings at CERN each year. As US CMS Endcap Muon Technical coordinator and US CMS Common Projects Level 2 Project Manager, R. Loveless must also make a number of overseas trips each year as part of his duties. Although travel for engineering personnel can be defrayed as a project expense, physicist travel cannot. Significant travel support is necessary in order for a University group to sustain these leadership responsibilities. Despite continuing efforts to contain travel costs, inflation in lodging and airfare costs cause uncertainties. Nevertheless, we do our best to contain the inflationary costs and have incorporated this intent into the budget. Although we also make extensive use of videoconferencing, there remains an irreducible number of reviews and critical meetings at CERN where our presence is required. The other researchers on Task T must attend collaboration meetings and meetings at which of the planning of the Trigger and Muon System is coordinated.

7.3 Computing

The complex electronics being designed for the CMS calorimeter trigger operates at very high speed (160 MHz). This requires specialized computer-aided design software for high speed routing, placement for time delays, thermal analysis and line impedance control. The University of Wisconsin provided $50K in FY97 to upgrade and enhance our CAD electronics design software and we request support for the maintenance of this software in our base program.