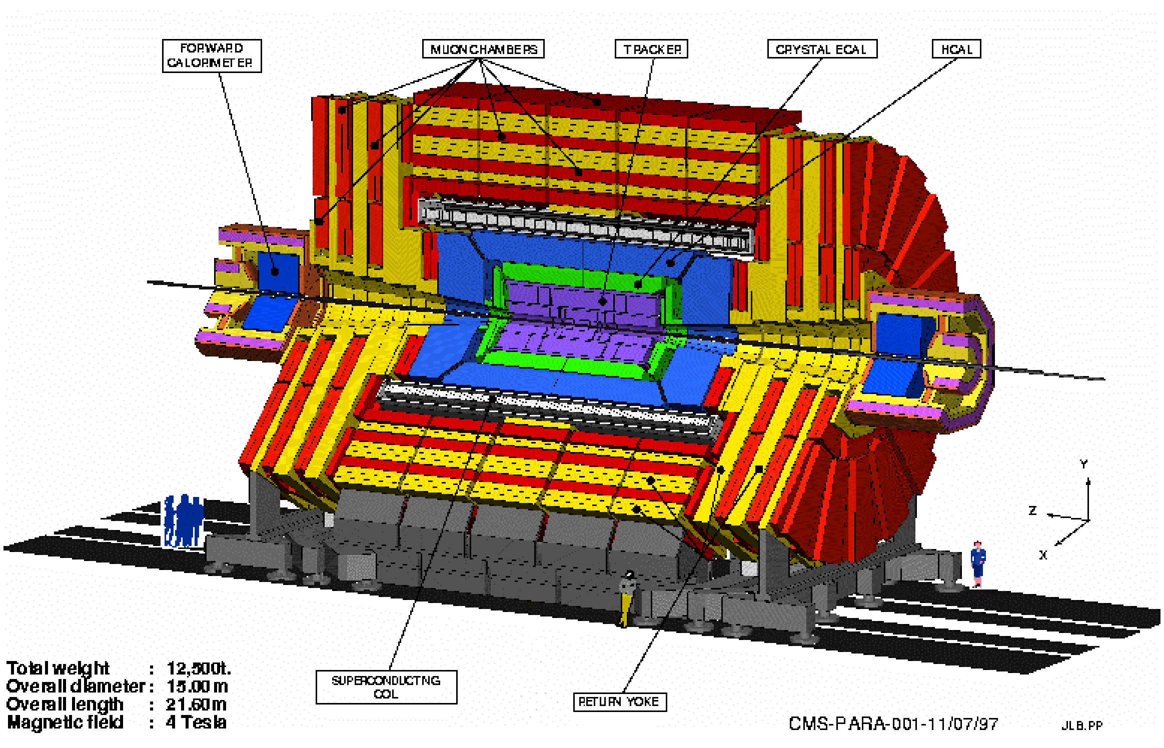
US CMS
Parameters Book

Technical Description of the Baseline Subsystems of the US CMS Project

December, 1998



1.0 Introduction

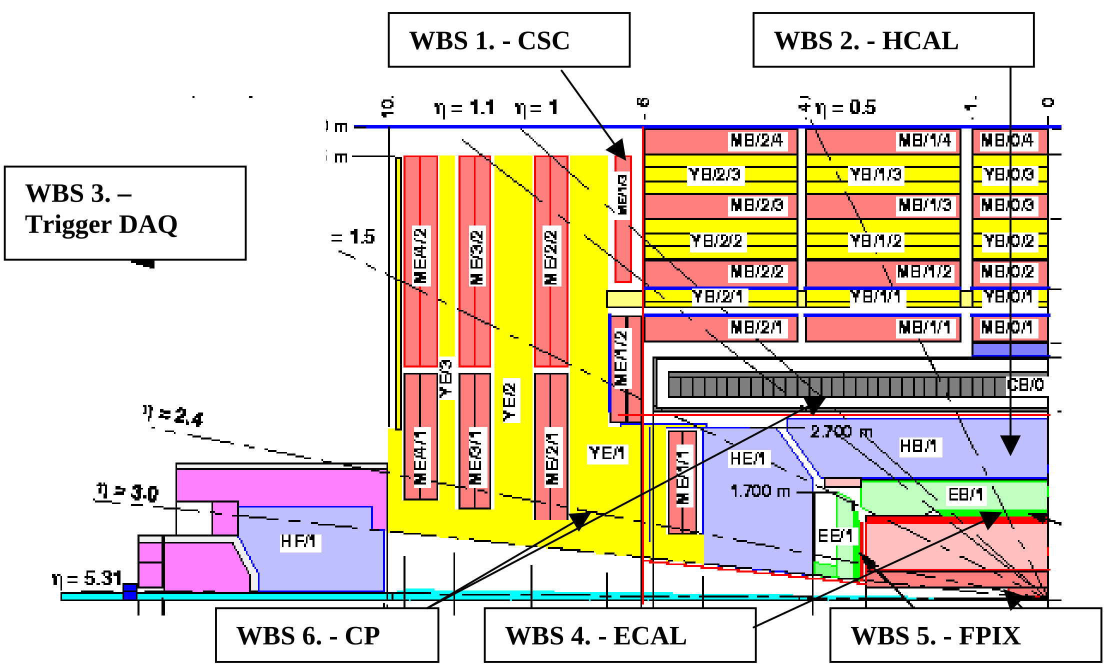
The US CMS project was baselined in a review by DOE and NSF in May of 1998. That review concentrated on the cost and schedule of the subsystems of US CMS. During that review a brief technical description of the baseline scope of the project was submitted to DOE/NSF and was subsequently put as an Appendix to the US CMS Project Management Plan.

An expanded definition of the technical baseline scope appears in the Memorandum of Understanding between CERN and CMS. The deliverables are defined to level 4 of the Work Breakdown Structure (WBS). The focus of that document is on the estimated cost of those deliverables.

This document represents the next level of technical definition of the subsystems of the US CMS Project. This technical description is complementary to that given in the CMS MOU which is primarily fiscal. Each subsystem of the WBS is defined and discussed in some detail in the subsequent sections. A brief overview is given in this introduction.

The US CMS Collaboration has agreed to take leadership responsibility in the CMS experiment for the endcap muon system, all the hadron calorimetry, and associated aspects of the trigger and data acquisition system. The Collaboration also plans to contribute to important areas of the electromagnetic calorimetry, tracking, and common projects. The general layout of the CMS Detector is shown in Figure 1.

A summary description of the US CMS baseline scope is provided below. The details at the lowest work breakdown structure level are available in the US CMS work breakdown structure dictionary dated May 19, 1998. Level 2 WBS numbers associated with the various subdetector or subsystems efforts are identified in Figure 1.



1. Endcap Muon – cathode strip chambers
2. Hadron Calorimeter – full HB, HOB, He, and HF transducers and readout – HE scint, HF QP fibers
3. Endcap Muon and Calorimeter Trigger. DAQ filter
4. Electromagnetic Calorimeter – barrel transducers, front end electronics, and laser monitor
5. Forward Pixels
6. Common Projects – endcap yoke and barrel cryostat
7. Project Office

Figure 1

WBS 1.1 – Endcap Muon System (EMU):

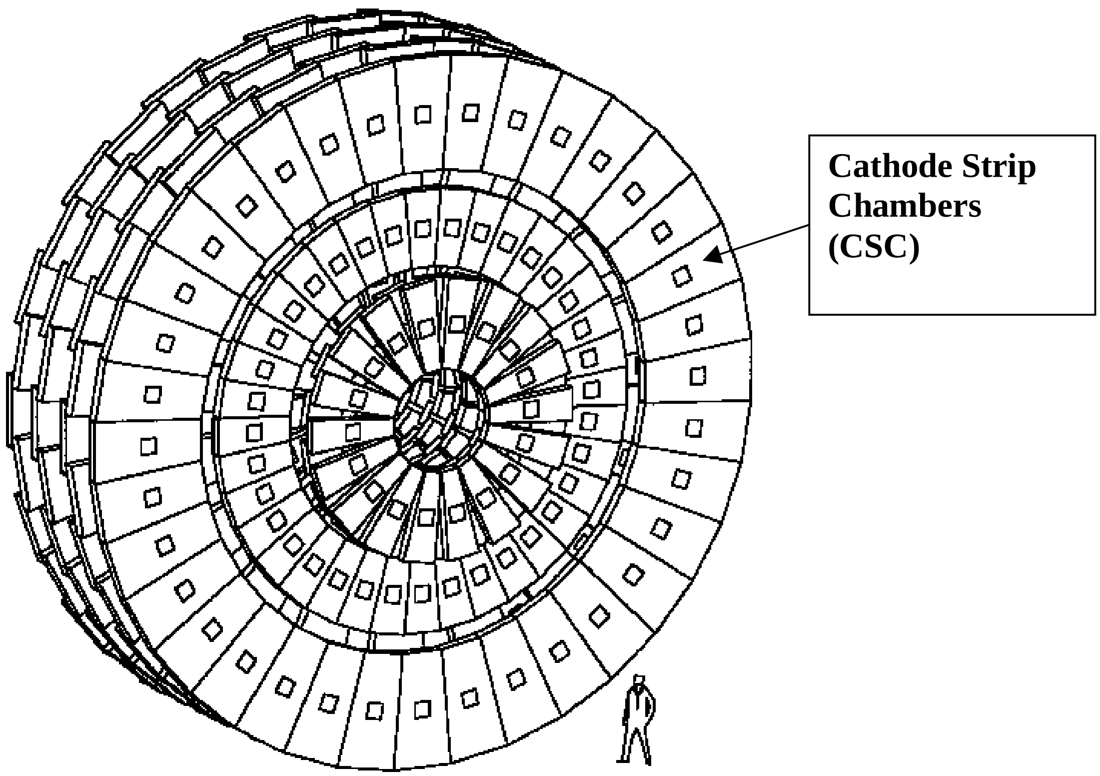


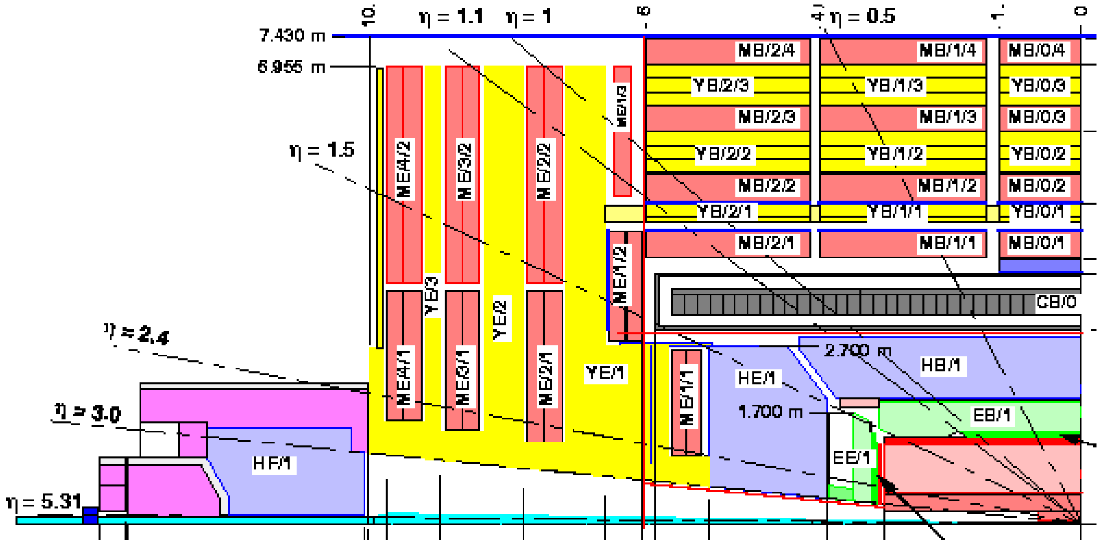
Figure 2

The CMS Endcap Muon System consists of three muon stations (four stations are shown in Figure 2; the fourth station was eliminated as part of the US CMS rescoping exercise) interleaved with three iron disks. The angular region covered is $0.9 < \eta < 2.4$. Here η is the pseudorapidity, that is $-\ln[\tan(\vartheta/2)]$, where ϑ is the angle to the beam axis. Muon stations are six-plane trapezoidal cathode strip chambers. A precise coordinate measurement in cathode strip chambers comes from interpolating charges induced by cathode strips.

The total number of chambers in the endcap system for the US CMS baseline is 360 (372), where the number in parentheses includes spares. The largest cathode strip chambers are 3.4 x 1.5 m^2 in size. Each chamber consists of six trapezoidal planes. Strips run radially to provide a precise measurement of the ϕ coordinate, while wires run azimuthally and define the radial coordinate of the track. The overall area covered by the chambers is more than 950 m^2 and the total number of wires exceeds 1.7 million.

The US will manufacture, instrument, and install 148 large chambers, and will make parts kits for the assembly of 148 smaller chambers by China, and 76 smaller chambers by Russia. The US is responsible for all parts, critical tooling, the on-chamber electronics, and the level 1 trigger.

There are 5 types of chambers shown schematically in Figure 3.



ME23/2 – largest chambers, 10-degree in ϕ, outer ring of stations 2, 3
ME2/1 - inner ring of station 2, 20-degrees in ϕ
ME3/1 - inner ring of station 3, 20-degrees in ϕ
ME1/2 - intermediate ring of station 1, 10-degrees in ϕ (high resolution CSC)
ME1/3 - outer ring of station 1, 10-degrees in ϕ

Figure 3

The ME23/2 are entirely the responsibility of the US.

For ME234/1 the US provides parts and critical assembly tooling. PNPI (Russia) is responsible for assembly, testing, shipping, and commissioning. For ME1/23 the US provides parts and critical assembly tooling. IHEP (China) is responsible for assembly, testing, shipping, and commissioning.

WBS 1.2 – Hadron Calorimeter (HCAL):

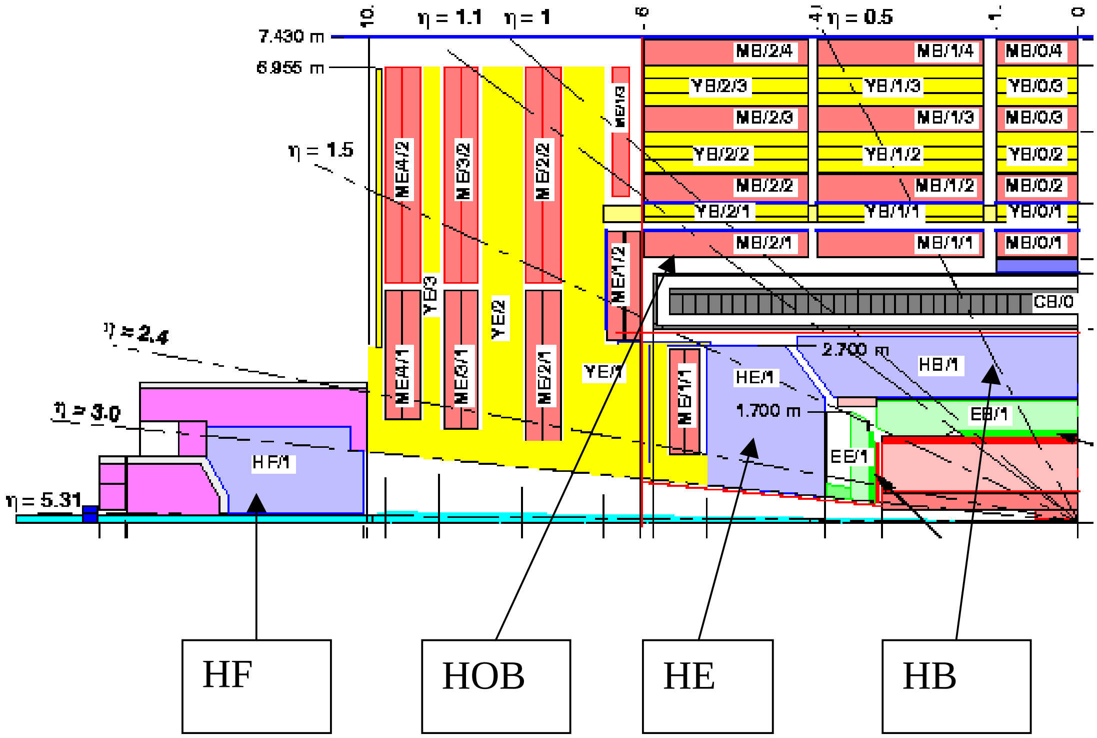


Figure 4

The hadron calorimeter, shown schematically in Figure 4, in CMS is organized geographically. There are five mechanically distinct structures: the barrel (HB, $0. < \eta < 1.3$), 2 endcaps (HE, $1.3 < \eta < 3$), and the 2 forward (HF, $3 < \eta < 5$) calorimeters. The US CMS hadron calorimeter group responsibilities are to produce the barrel absorber and the barrel scintillator tile/wave length shifter optics. In HF the US will supply none of the absorber, but a fraction of the quartz fiber sampling medium. In addition, the US will produce the barrel, outer barrel, endcap, and forward transducers and front end electronics.

The hadron calorimeter is organized into towers of size $\Delta\eta\Delta\phi = 0.087 \times 0.087$ for the barrel and endcap and $\Delta\eta\Delta\phi = 0.174 \times 0.174$ for the forward calorimeter. There are 3 longitudinal depth segments H1, H2, and HO in HB. In HE there are two depth segments, while HF has three; HFE, HFH, and HFT.

The work breakdown structure 1.2 items include all the effort to design, produce, assemble, install, and commission the hadron calorimeter for the CMS detector. The HB calorimeter is constructed of 36 wedges, each weighing ~ 26 tonnes. The absorber is copper for HB and HE. The minimum HCAL depth is 5.8 interaction lengths inside the CMS coil. The HE is built as a single unit, but the optical system is packaged as 18 distinct 20-degree "pie" wedges, thus matching the HB segmentation.

There are distinct calorimeter towers in $\Delta\eta\Delta\phi$ and in longitudinal depth. These are supplied with electronics channels, which amplify and digitize the signals produced by the HPD (HB, HOB, HE), and read out the PMT (HF). The channel count (excluding spares) is 5184 in HB, 2160 in HOB, 3774 in HE, and 1728 (1920) in HF. The resulting digital signals are stored in a pipeline and sent to the trigger/DAQ system by means of multiplexed fiber optic communication systems. The received data is sent to the trigger and DAQ systems separately. The system is calibrated using LEDs, radioactive sources, and lasers.

WBS 1.3 – Trigger/Data Acquisition (TRIDAS):

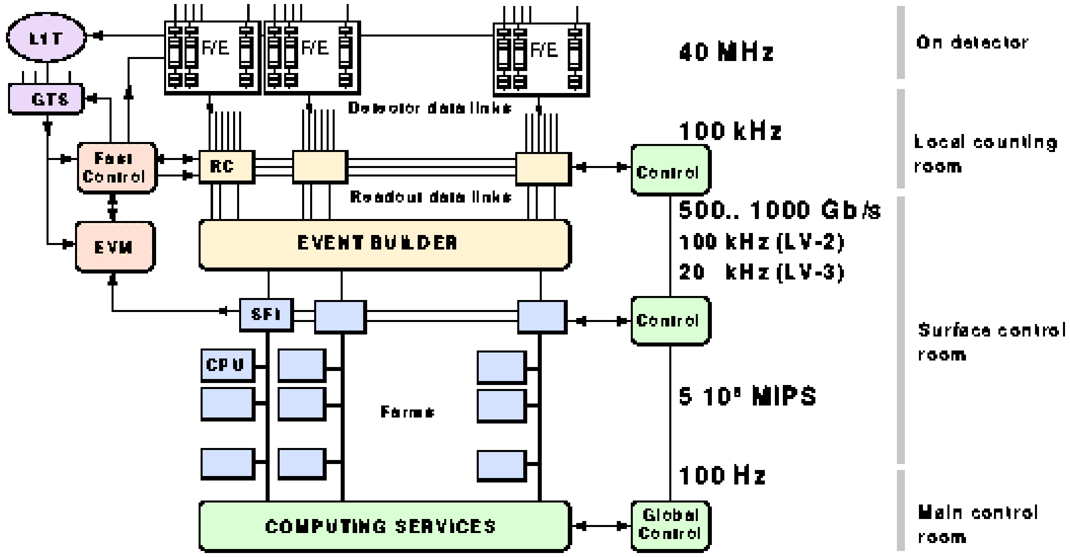


Figure 5

US CMS is responsible for elements of the first level muon trigger and the level 1 calorimeter trigger. In addition, US CMS takes responsibility for the data acquisition filter units (FU), and the event manager (the layout of the data acquisition system is shown in Figure 5).

WBS element 1.3.1.1 includes all the effort to develop, produce, assemble, install, and commission the Regional Muon Trigger. The system is designed with 3 muon stations; however, the design allows easy expansion to a 4-station system. The US will provide Port Cards (55), Sector Receiver Cards (56), and Sector Processor cards (30) for the level 1 CMS Muon Trigger.

Work breakdown structure element 1.3.1.2 includes all the effort to develop, produce, assemble, install, and commission the Regional Calorimeter Trigger. This system processes the electromagnetic and hadronic trigger tower sums from the calorimeter front end electronics and delivers regional information on electrons, photons, jets, and partial energy sums to the global calorimeter level 1 trigger system. The system begins after the data from the front end electronics is received on optical fibers and translated to signals on copper and ends with cables that transmit the results to the calorimeter global level 1 trigger system. The trigger is based on a 54 x 72 (η x ϕ) array of ECAL and HCAL trigger towers. The towers supply 8 bits of energy information. The US provides 22 VME crates with custom backplanes.

Work breakdown structure element 1.3.2 includes all the effort to develop, produce, and assemble the parts of the CMS Data Acquisition system for which the US CMS groups are responsible. The US has undertaken the responsibility to provide the full Filter Unit system and the complete Event Manager system. In the R&D phase, US groups will also participate in the design and testing of prototyping modules that can be used both on the Readout Units and the 432 Filter Units. The complete DAQ system will perform at 75 kHz, and the system is scalable.

WBS 1.4 – Electromagnetic Calorimeter (ECAL):

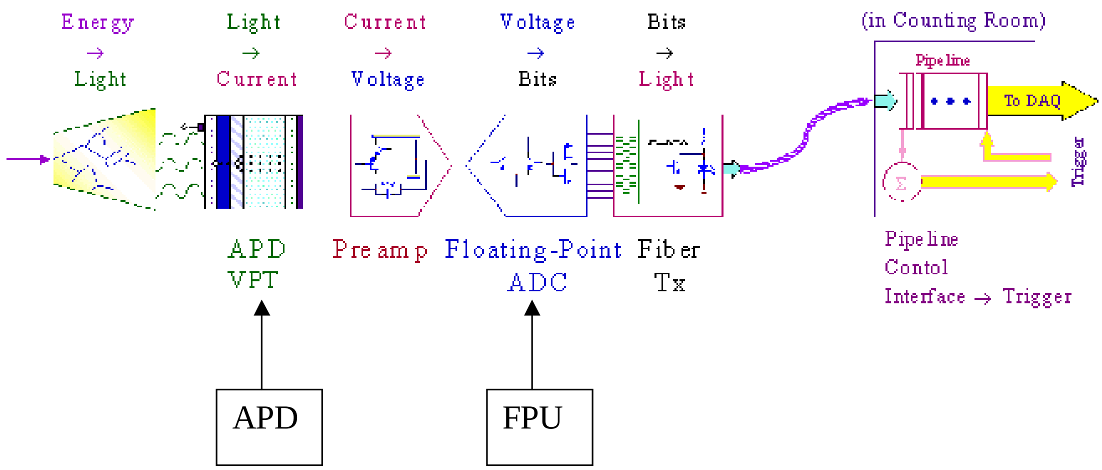


Figure 6

US CMS is responsible for elements (identified in Figure 6) of the electromagnetic calorimeter. This device utilizes $PbWO_4$ crystals to detect electromagnetic showers. The US is responsible for partial procurement, 36000, of the light transducer Avalanche Photodiode (APD), the floating point unit (FPU), 60200, which converts a voltage to a digital number, the bit serializer which converts that number into a serial bit stream for transmission off the detector, and elements of the laser monitor/calibration system.

There are 61,200 crystals in the barrel ECAL, or EB. Each has a pair of APDs with 25 mm^2 sensitive area. The US is responsible for ~50% of the APD prototypes and ~30% of the procurement of the production APDs.

The US is responsible for the design and procurement of all the EB front-end multi-ranging floating point units (FPU), and CHFET bit-serializers.

The US is responsible for elements of the laser monitor system. These include the laser, cooling, collimators, shutters, mirrors, and other optical mounts.

WBS 1.5 – Forward Pixel Tracking (FPIX):

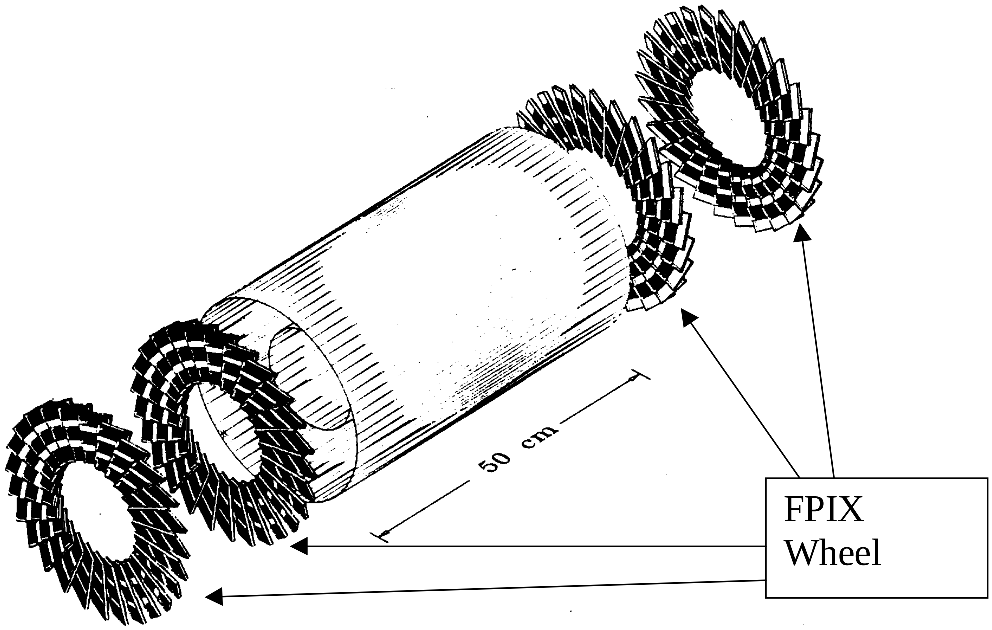


Figure 7

US CMS is responsible for the delivery of the forward silicon pixel (FPIX) detector system. This system consists of 4 assemblies, or wheels, (shown in Figure 7) of silicon pixels. These wheels are made from subassemblies, which are arranged as “turbine blades”. This unique arrangement allows for Lorentz force charge sharing among pixels, thus enabling the devices to have good impact point resolution in 2 dimensions.

The FPIX system covers the angular range $1.4 < \eta < 2.6$. The US will design, assemble, deliver, install, and commission the entire system. This system consists of 4 disks containing 96 “blades”. Each blade has 7 silicon sensor arrays comprising 45 readout chips. There are 4320 total readout chips and 672 Si sensors. The total system has ~12 million pixels, each 150 μm x 150 μm. The system consists of sensors, readout, mechanical support, and ancillary services.

WBS 1.6 – Common Projects:

Common Projects in CMS are the magnet and the common software and computing. The US pays a representative share of the Common Projects as defined to be a fixed fraction of the contribution of the US to CMS. The US contribution will be defined to be the M&S items of the baseline scope of the US CMS project. The fraction is currently assessed to be 31.5 percent. This currently agreed upon US contribution to Common Projects is $23M.

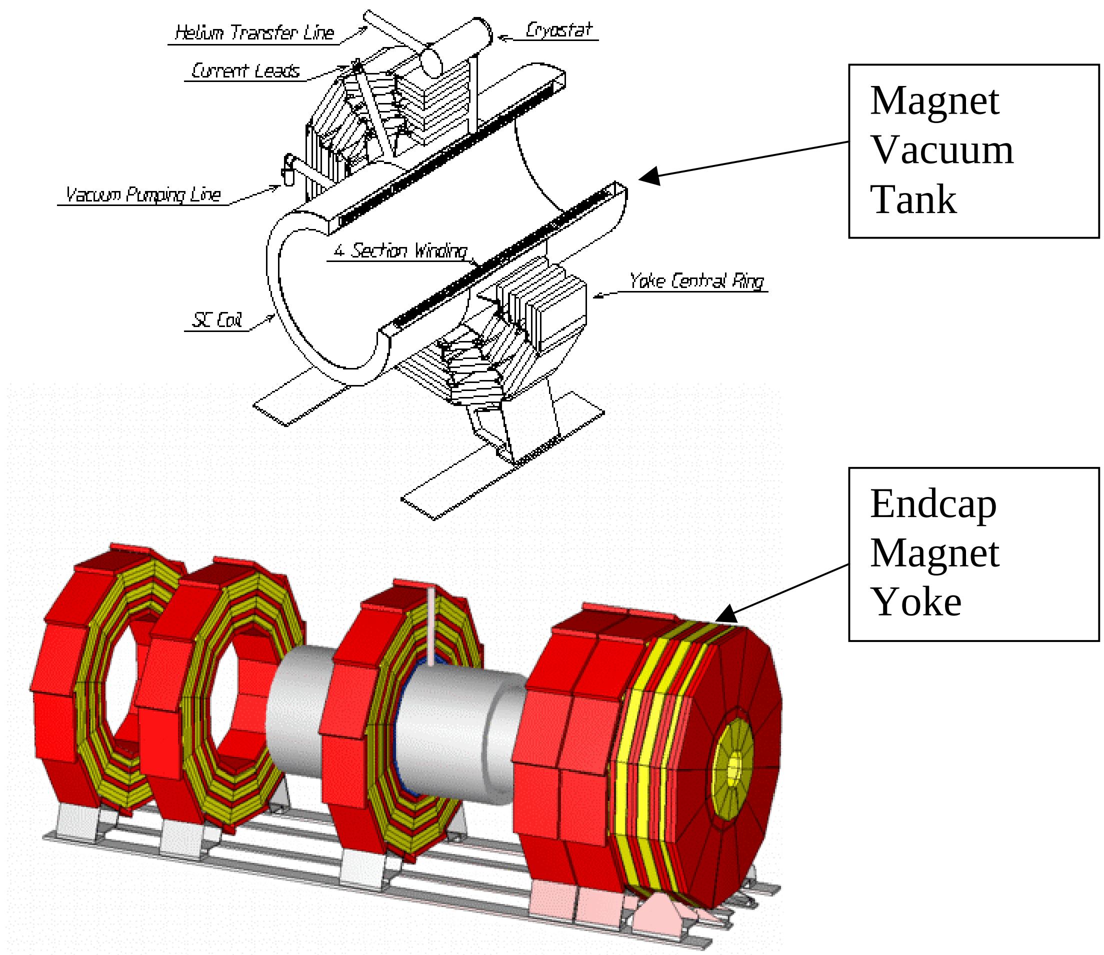


Figure 8

The US CMS contribution is made by material acquisitions rather than by cash payments. The two major efforts in US CMS are related to the US CMS interests in the hadron calorimeter and the forward muon system. This may evolve, as the cost experience with CMS Common Projects becomes clearer (i.e., we may be able to provide more or less than currently planned in the way of material acquisitions based on real cost experience.)

The US takes full responsibility for the design and procurement of the endcap steel yoke (shown as the yellow toroids in Figure 8 bottom). The US also takes partial responsibility for the barrel yoke and the coil vacuum tank (shown in Figure 8 Top). These two projects have already been bid and the contract for the endcap will be awarded within a few months. The contract for the barrel is already in place.

WBS 1.7 – Project Office:

This work breakdown structure element includes all the effort needed to exercise Project Management in CMS. The tasks include:

Baseline Development

The first phase of the US CMS Project is to construct a baseline cost estimate, have it reviewed, and accepted by the DOE and NSF as an acceptable estimate of the set of deliverables which can be supplied with high confidence for the total funding available to the project.

Tracking

A major function of the US CMS project office is tracking the progress of the project. That function includes the overall level 1 schedule, the level 2 linked schedules, and the derived annual Statement of Work. The actual costs are to be reported at the lowest work breakdown structure level by means of invoices to the Fermilab general ledger.

Reporting

The US CMS project office will report to the Fermilab Project Management Group, the DOE/NSF Project Manager, and the Joint Oversight Group in a manner specified by those entities.

Northeastern University Administration

The NSF funds will be sent from NSF to Northeastern University. They will be divided then as per instruction of the technical director/construction project manager and sent to the NSF supported groups of US CMS. In order to perform these functions, Northeastern University requires the services of an Administrative Assistant.

Support for Education/Outreach

The education liaison function includes the development of educational proposals of US CMS. In support of these and other educational activities, the US CMS project office supplies funds for programmatic travel and for M&S supplies.

1.1 Endcap Muon (EMU)

An overall view of the CMS Endcap Muon (EMU) system was shown in the introduction. There are 432 endcap chambers of trapezoidal shape placed between the iron disks, which return the magnetic flux of the central solenoid and also shield the chambers. The chambers are arranged to form three disks, called stations ME1, ME2, and ME3. The station ME1 has three rings of chambers: ME1/1, ME1/2, and ME1/3, while the other three stations are composed from two rings of chambers: ME2/1 and ME2/2, ME3/1 and ME3/2. All but the ME1/3 chambers overlap in φ. There are 18 or 36 chambers in every ring.

The performance requirements for the system of are as follows:
- 75 μm off-line spatial resolution in φ for ME1/1 and ME1/2 chambers and 150 μm for the others;
- 1-2 mm resolution in φ at the Level-1 trigger;
- 1-2 cm resolution in R both at Level-1 trigger and in off-line;
- >92% probability of identifying correct bunch crossings, occurring at LHC every 25 ns;
- reliable performance at 1 kHz/cm^2 rates with no drastic aging effects during the 10 years operation.

US responsibilities (deliverables) include:

- Overall EMU project co-ordination and integration.
- Design of ME1/2, ME1/3, ME2/1, ME2/2, ME3/1, ME3/2 chambers. Production of all parts for all these 360 (+12 spares) chambers: 72 (+2) ME1/2, 72 (+2) ME1/3, 36 (+2) ME2/1, 72 (+2) ME2/2, 36 (+2) ME3/1, and 72 (+2) ME3/2.
- Design and production of assembly tooling and testing equipment for three US sites: Fermilab, University of California (UC), and University of Florida (UF). Production of critical tooling and equipment for two foreign sites: PNPI (St.Petersburg) and IHEP (Beijing).
- Assembly and complete system tests (chambers with all on-chamber electronics) of 72 (+2) ME2/2 and 72 (+2) ME3/2 chambers[1]. Installation and commissioning of these chambers at CERN.
- Design and Production of all on-chamber DAQ and Level-1 Trigger electronics for all 360 chambers (plus 10% of spares).
- Design and Production of services for the system of 360 chambers (High Voltage, Low Voltage, Electronics Cooling, and Local Gas Distribution Systems).
- Design and Production of the Alignment System for the 360 chambers.

1.1.1 Cathode Strip Chambers (WBS 1.1)

EMU Cathode Strip Chambers: general description and mechanical parameters

Endcap muon chambers are so-called Cathode Strip Chambers, or CSCs, of a trapezoidal shape. Seven panels stacked together form six gas gaps, each of which contains a plane of anode wires (positive high voltage is applied to the wires). One of the two cathode surfaces in each of the gaps is milled lengthwise to form a fan-shaped set of strips (each strip has a constant Δφ width). A charged particle passing through each of the gaps makes an avalanche on a wire. By reading out a direct signal from the wires and an induced signal from the strips one can localize the track in both directions. Wires grouped in

[1] The rest 216 (+8) smaller chambers will be assembled at PNPI (St.Petersburg) and IHEP (Beijing). Chamber parts and electronics (full assembly kits) and critical tooling are provided by the US. Standard assembly and testing procedures developed in the US will be used to assure the quality control. Assembly labor for these chambers is paid by Russia and China as their contribution to CMS.

bunches provide a coarse measurement of a radial coordinate, while an interpolation of charges induced on strips provides a precise measurement of a φ-coordinate. Small wire spacing allows for an efficient bunch crossing tagging. CSCs have a few important features: they combine both the precision and trigger functions in one device; can operate in high rates, in large and non-uniform magnetic fields; do not require tight gas, temperature or pressure control; and easily allow for a variety of strip patterns (e.g. fan-shaped).
There are 5 different chamber types in the system with the total number of chambers of 360 (plus 12 spares). The overall area covered by the chambers is about 950 m^2, and the total number of wires about 1.6 million. Table 1 summarizes all chamber parameters. The only difference between different chamber types is their size, strip and wire channel count, while the basic underlying design is identical.

Table 1. Chamber parameters.

	ME1/2	ME1/3	ME2/1	ME3/1	ME23/2
Overall chamber parameters					
Number of chambers	72	72	36	36	144
Additional spares	2	2	2	2	4
Planes per chamber	6				
φ-coverage, degrees	10°	10°	20°	20°	10°
φ-overlap, # strips	5	none	5	5	5
η-coverage	1.2-1.6	0.9-1.1	1.6-2.4	1.75-2.4	Varies
η-overlap	none				
Length, mm	1800	1900	2065	1845	3380
Width (top), mm	1078	1192	1534	1534	1530
Width (bottom), mm	740	859	751	835	895
Chamber thickness, mm	250				
Basic single plane parameters					
full gas gap (2h), mm	9.5				
wire diameter, μm	50				
wire spacing, mm	3.16	3.16	3.12	3.12	3.16
Width of dead area along chamber edges					
width at the top, mm	94				
width at the bottom, mm	68				
width along long sides , mm	120				
Wires					
wires per plane	528	560	620	550	1028
wires per wire group	7-11	16,17	5, 6	5, 6	16
wire group width, mm	22-35	51, 54	16, 19	16, 19	51
wire group cap., pF	30-70	70-110	20-60	20-60	80-150
wire groups per plane	64	32	112	96	64
Strips					
Δφ(single strip), mrad	2.33	2.16	4.65	4.65	2.33
strip pitch (top), mm	10.4	14.9	15.6	15.6	16.0
strip pitch (bottom), mm	6.6	11.1	6.8	7.8	8.5
gap between strips, mm	0.5				
strip capacitance, pF	110	145	145	130	250
strips per plane	80	64	80	80	80
HV					
Operating HV, kV	4.1				
HV segments per plane	2	3	3	3	5

EMU Cathode Strip Chambers: detailed design description

The exploded schematic view of the chamber is shown in Fig.1. Seven 16 mm thick panels form the basis of the chamber mechanical structure. They are made of 1.6 mm copper clad FR4 skins[2] commercially glued on 3.2 mm cell size, 12.7 mm thick polycarbonate honeycomb core[3]. The gap bars are glued along the perimeter of each other panel and form six gas gaps of 9.53 mm when all seven panels are stacked together. There are 2 to 4 buttons in each plane placed along the chamber center line and the entire stack of panels is tighten down in these points. Thus, the panels have no more than 60 cm of unsupported length. Measurements showed that most of the panels are flat within required ±0.2 mm on such spans.

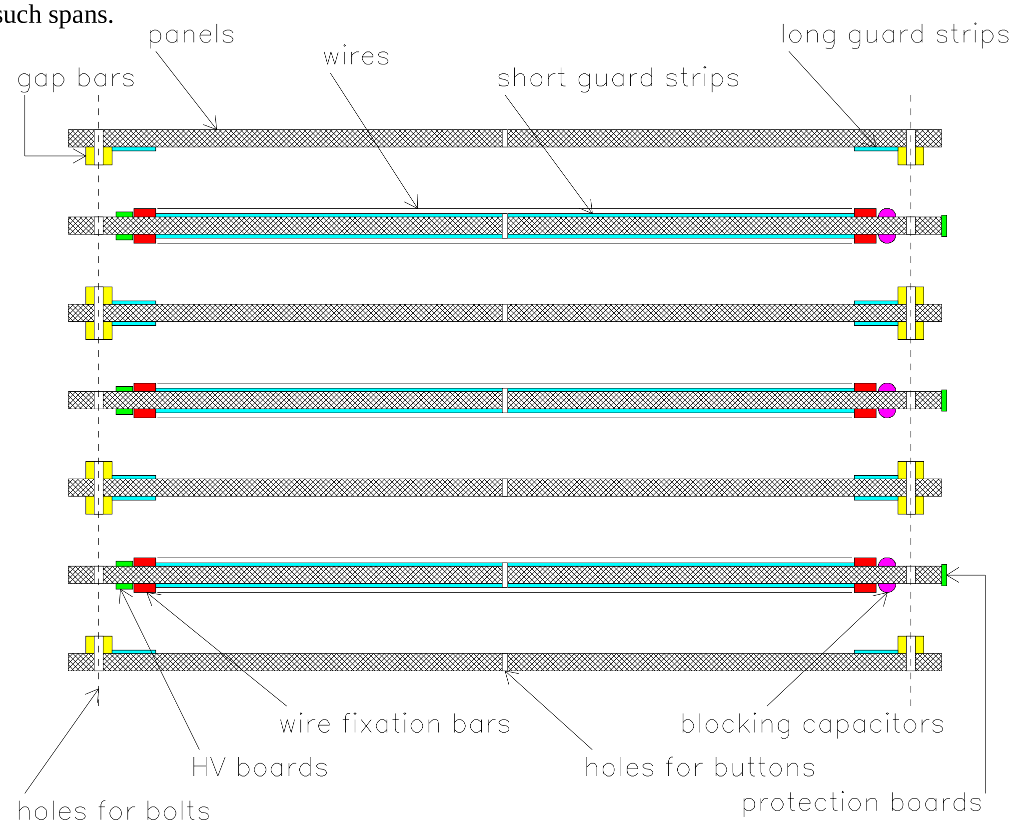


Fig. 1. An exploded view of a EMU Cathode Strip Chamber.

The panels also serve the role of cathodes. One side of six panels has a pattern of 64 or 80 strips milled by a CNC machine. Strip pitch has constant • • • in azimuth coordinates and, thus, varies from the bottom to the top of a chamber; also, it is different for different types of chambers, the full range being from 6.6 to 16.0 mm. The gap between strips is about 0.5 mm. Milling is done with a 45° cutter to make cut edges smooth. The position of strip centers was measured to have a spread of 32 µm (rms), and strip straightness---20 µm.

A special machine has been designed to wind wires directly on panels. Gold plated tungsten wires, 50 µm in diameter, are spaced by about 3.2 mm and stretched at 250 g tension (60% of the elastic limit). They have maximum length of 1.2 m and run from end to end without any intermediate supports. The wire tension does not deviate from the nominal by more than ±5%, while wire spacing are within ±150 µm. After winding wires are first glued and then soldered on an automated soldering machine. Groups of contiguous wires are connected to make one readout channel. The wire signals are read out via 1 nF blocking capacitors and HV is distributed to wires at their other end (one fully controllable HV channel is provided to each plane).

Each wire plane is sub-divided in 3-5 independent HV segments. In places where buttons had to be inserted two wires are removed and on one of the two panels forming the gas gap 3.2 mm thick and 16 mm wide FR4 strips running along wires are glued. By virtue of charging up, they substantially

[2] *General Electric Co.*, Coshocton, Ohio 43812, USA

[3] *Plascore, Inc.*, Zeeland, Michigan 49464, USA

reduced electric field on the four wires stretching over them. Thus formed boundary allows for independently turning HV on/off on any of the five wire plane sections, should the need arise.

After stacking the panels and tightening perimeter bolts, continuous beads of RTV are applied along perimeters of each of the planes. An external frame formed by 3.2 mm thick Al side plates is attached along the chamber perimeter. It stiffens the chamber and, also, interconnects top and bottom copper skins to form a complete Faraday cage. Each chamber has three mounting points, one at the middle of bottom side and two in the corners at the top of the chamber.

EMU Cathode Strip Chambers: High Voltage system

Each plane of the 360 chambers will have one computer controlled HV channel (each channel is capable of providing current up to 200 • A at the maximum HV of 6 kV). The HV system will be based on a commercial multi-channel HV main frame (CAEN, Model SY 527 with A-832P HV cards).

The all needed HV cards can be accommodated in 18 crates to be mounted in the control room. The outputs of the HV cards will be connected to the fan-out terminals located on the outer rim of the endcap disks by 12-conductor flexible about 100 m long cables. Each terminal serves a 40• sector of a muon station. At the fan-out terminals each channel, which corresponds to a single plane of one of the CSC chambers, is fanned out into 3-5 chamber HV segments. At these easily accessible fan-out terminals it is possible to disconnect manually any of the segments of a single plane if that segment is drawing excessive current (current monitoring for each of the segments will be available at the fan-out terminals). Several multi-conductor cables (depending on chamber size) connect the fan-out terminal to each chamber. Table 2 summarizes the number of different elements in the CSC HV system.

Table 2. Elements of the CSC HV system.

	needed	spares
Independently computer controlled HV channels (one per CSC plane)	2,160	
Total number of chamber HV segments	8,208	
HV cards (12 channels per card)	180	8
HV crates (10 cards per crate)	18	2
100 m long 12-lead HV cables	180	6
HV fan-out terminals (1 per 40• sector of each station) with local HV cables	54	4

EMU Cathode Strip Chambers: Deliverables

This section summarizes in explicit form all deliverables associated with EMU CSC sub-project.

WBS 1.1.1.1 CSC and Tooling: R&D, Design, and Tests

- complete design and prototyping of all five types of chambers (ME1/2, ME1/3, ME2/1, ME3/1, ME23/2);
- development of the chamber assembly procedures; design and prototyping of the assembly tooling;
- chamber tests not associated with the chamber production per se (e.g., tests of prototypes in cosmic rays and in the beam, chamber aging tests, gas optimization studies, etc.)

WBS 1.1.1.2 Overall CSC Production Management

- the chief chamber production engineer,
- the chamber cost and schedule engineer,
- miscellaneous expenses associated with management and technical coordination of chamber production spread over three US and two foreign sites.

WBS 1.1.1.3 Fermilab Site Task

- procurement of all materials for all 360 (+12 spares) chambers;

- setting up facilities with appropriate dedicated tooling for panel production;
- panel production for all 360 (+12 spares) chambers;
- setting up facilities with appropriate dedicated tooling for chamber assembly;
- assembly of 72 (+2) ME2/2 and 72 (+2) ME3/2 chambers;
- crating and shipping of the assembled chambers to UC and UF sites;
- procurement of the critical tooling for the two foreign sites, PNPI and IHEP;
- shipping of 72 (+2) ME1/2 and 72 (+2) ME1/3 chamber assembly kits to IHEP;
- shipping of 36 (+2) ME2/1and 36 (+2) ME3/1chamber assembly kits to PNPI.

WBS 1.1.1.4 UCLA Site Task

- setting up facilities with appropriate dedicated tooling and equipment for final chamber assembly and system tests;
- long term high voltage training of 36 (+1) ME2/2 and 36 (+1) ME3/2 chambers
- final assembly of chambers with all on-chamber electronics and services
- system performance tests of 36 (+1) ME2/2 and 36 (+1) ME3/2 chambers; repairs if the test results do not meet specifications
- shipping of the tested chambers to CERN

WBS 1.1.1.5 UF Site Task

- setting up facilities with appropriate dedicated tooling and equipment for final chamber assembly and system tests;
- long term high voltage training of 36 (+1) ME2/2 and 36 (+1) ME3/2 chambers
- final assembly of chambers with all on-chamber electronics and services
- system performance tests of 36 (+1) ME2/2 and 36 (+1) ME3/2 chambers; repairs if the test results do not meet specifications
- shipping of the tested chambers to CERN

WBS 1.1.1.6 Installation and Commissioning

- installation and commissioning of 72 (+2) ME1/2 and 72 (+2) ME1/3 chamber at CERN

WBS 1.1.1.7 High Voltage system

- design and tests of the high voltage system for the entire system of 360 chambers
- procurement of 20 HV mainframes (CAEN Model SY 527) and 188 HV cards (CAEN A-832P).
- procurement of 186 100 m long 12-lead HV cables with connectors
- procurement of 58 HV fanout boxes with local HV distribution cables
- commissioning of the HV system at CERN

1.1.2 Front End Electronics

The EMU front-end electronics system consists of four types of boards: cathode front-end boards, anode front-end boards , DAQ Motherboard and Trigger Motherboard. Depending on chamber types, there are typically 4 to 5 cathode front-end boards and 3 to 7 anode front-end boards per chamber. Each cathode or anode front-end board serves 96 input channels. There is one DAQ Motherboard and one Trigger Motherboard per chamber. All the boards are mounted on the chamber. The motherboards serve as links between the front-end boards and the rest of the experiment. They send the readout and trigger data to the central DAQ and the Level-1 trigger systems. They receive trigger, timing and control (TTC) signals and distribute them to the front-end boards. The following table shows the scope of the system. The numbers of each type of boards in the EMU system , including spares, are listed below in Table 3.

Table 3 Number of Boards for EMU Front-end Electronics

Cathode Front-end Board	1901
Anode Front-end Board	1624
DAQ Motherboard	396
Trigger Motherboard	396

Cathode Front-end Boards (WBS 1.1.2.1)

Each cathode front-end board receives 96 inputs and reads out a tower consisting of 16 neighboring strips per layer by 6 layers deep. The functional diagram for the cathode front-end board is shown in Figure 2. The input signals from each of the strips are sent into 16-channel charge-sensitive preamplifier-shaper ASIC's (There are 6 such ASIC's per front-end board). Input signals are amplified and shaped into voltage pulses. The output pulse shape corresponding to an impulse charge input is semi-Gaussian and the peaking time is 100 ns . To minimize pile-up effects in high rate situations, circuits to cancel the long ion drift tail of a chamber pulse are incorporated into the shaper. Channel-by-channel calibration will be done using a set of precisely matched capacitors that couple a test pulse to each channel's input.

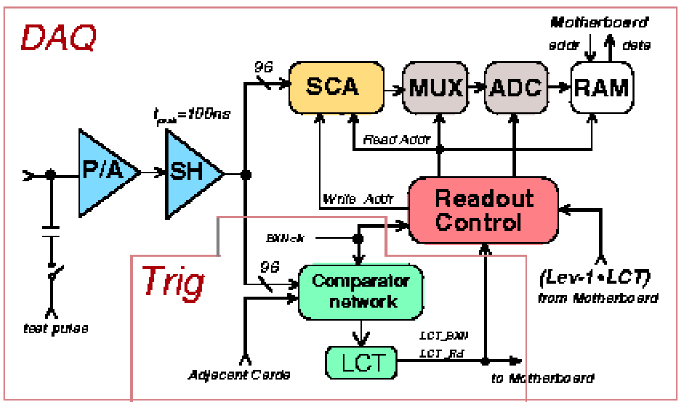


Figure 2. Functional Diagram of the Cathode Front-end Board.

One output of the shaper is connected to the trigger path whose main components are a Comparator Network and a Local Charge Track (LCT) processor. The comparator network locates the centroids of the induced strip charges in each chamber layers to an accuracy of half the strip width and marks its time. The resulting information is fed into the LCT trigger processor which look for coincidence of cluster centroids from a minimum number of chamber layers which form a ``road''. The time, location and angle of the LCT are used to determine trigger primitive parameters for the Level-1 muon trigger.

The other output of the shaper is connected to the DAQ readout path. The voltage is sampled every 50 ns and held in a Switch Capacitor Array (SCA) during the Level-1 latency. The stored voltage samples are digitized and readout when 1) an associated LCT trigger occurs, and 2) the LCT is time-correlated with a Level-1 Accept. Otherwise, the stored samples are written over. This readout strategy significantly suppresses random background hits induced by neutrons and photons. The digitized data is saved in memory and transmitted to the main DAQ system upon request by the MB. The following table lists the number and types of IC's housed on the cathode front-end board.

ASIC Type	No. Channels per ASIC	No. of ASIC's on board
Preamp-Shaper	16	6
SCA	16	6
Readout Control (FPGA)	96	1
Comparator	16	6
LCT Demux/Controller	96	2
LCT Selector	96	2
Trigger RAM (32 kByte)	6	16
ADC (12 bits, 20 MHz)	1	6

Table 4 IC's on the Cathode Front-end Board

Anode Front-end Boards (WBS 1.1.2.2)

The anode readout is similar to that of the cathode except that the emphasis is on the accuracy of timing instead of pulse height. Each input channel of the anode front-end board is a ganged group of wires (10 to 20) in a chamber layer. Figure 3 shows the functional diagram for the anode front-end board.

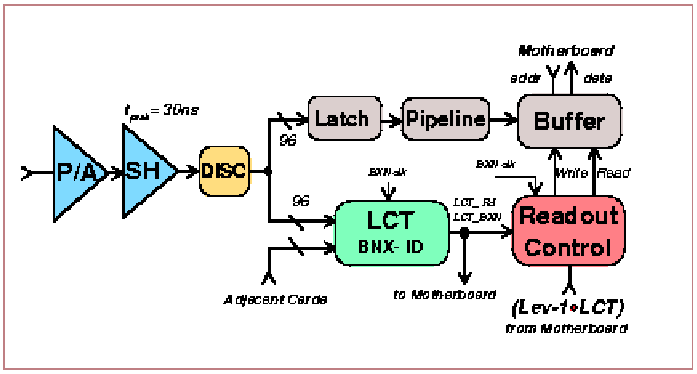


Figure 3. Functional Diagram of the Anode Front-end Board

The input signals go into 16-channel preamplifier-shaper ASIC's (6 per board). The amplifiers are similar to the ones on the cathode front-end board, but optimized for the summed anode input capacitance. The signals are shaped with shaper peaking time of 30ns and sent into discriminators. The output pulses from the discriminators are used to form the LCT and to determine the bunch crossing time of the track segment. They are also latched and pipelined for readout into the DAQ network via the motherboard, providing hit/no-hit information for each of the wire groups. Table 5 lists the IC's housed on the anode front-end board.

ASIC Type	No. Channels per ASIC	No. of ASIC's on board
Preamp-Shaper	16	6
Discriminator	16	6
Readout Control (FPGA)	96	1
LCT Pretrigger/Controller	96	2
LCT Selector	96	2
Trigger RAM (32 kByte)	6	16

Table 5 IC's on the Anode Front-end Board

The DAQ Motherboard (WBS 1.1.2.3)

The Motherboards serve as links to the level-1 muon trigger and to the central DAQ of CMS. There is one DAQ and one Trigger motherboard for each CSC module. The functionality of the trigger and DAQ Motherboards is shown in Figure 4.

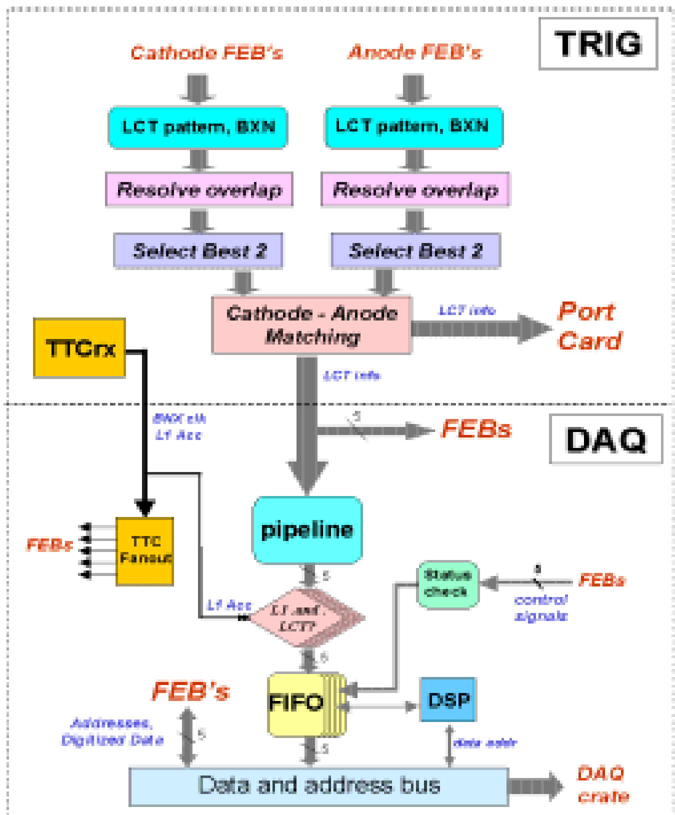


Figure 4. Functional Diagram of the Readout Motherboard.

The readout of the data from each front-end board is coordinated by the DAQ Motherboard. The digitization of the stored voltage samples on the cathode front-end boards and latching of the hits on the anode front-end boards are initiated by the arrival of a Level-1 accept which has a bunch crossing number matching that of an LCT. When this occurs, the readout controllers on the front-end boards are notified. Digitization will begin on the cathode front-end boards. Those pulse samples stored on each of the 96 channels on the front-end board within a time window of 800 are digitized. The digitized data is sent to the output buffer on the motherboard and transferred by optical link to the central DAQ.

The DAQ motherboard also acts as interface to the Run Control and to Slow control. The interfaced functions include down-loading of the FPGA and DSP programs, resetting of the readout controller on the front-end board, down-loading calibration information, down-loading commands for turning off bad channels, monitoring of low voltage levels and temperature. JTAG will be used for the slow control.

Trigger Motherboard (WBS 1.1.2.4)

The information associated with LCT's generated on cathode front-end boards and anode front-end boards are sent to the Trigger Motherboard. This information includes the bunch crossing time and the location and angle of each LCT. When the timing between a cathode LCT and an anode LCT's is found to agree within +- 1 bunch crossing, the LCT is a valid one. When more than one valid LCT is found for the chamber, only the best two, as determined by quality factors, are retained and passed on to the port cards along with the (anode) LCT bunch crossing number. (Each port card spans a 30 degree sector of an endcap station.) The tasks performed by the trigger motherboard are fully pipe-lined and synchronous with the beam-crossing clock. Another function vital to the operation of the front-end electronics, receiving and fan-out of TTC signals to the front-end boards, is also located on the Trigger Motherboard.

Low Voltage Supply and Distribution System (WBS 1.1.2.5)

The voltages required to operate the various types of the electronics boards in the EMU system will be supplied by 2(3) main supplies, each capable of generating up to 1125 A at 80 volts. The generated power will be transmitted by copper conductors at 80 volts to each of the endcap muon stations where it will be distributed to the electronics system using DC-to-DC converters (960 units in total) which transform the delivered power to the desired voltages.

1.1.3 Mechanical Structure

The CSC chambers are mounted directly to the iron surface of the disks using quasi-kinematic mounts In all stations except ME1/3 the chambers are overlapped to provide full phi coverage. The quasi-kinematic mounts are formed from Al extrusions and are bolted directly to the chamber frames. These mounts are bolted onto wings mounted on posts bolted to the iron disks. Fig. ?? shows how the chambers are attached to the disks.

The quasi-kinematic mounts locate the CSC chambers and provide some compliance for mechanical tolerances or thermal expansion. One mount, • RZ, fixes the location of the chamber tightly in all dimensions: • , R, and Z. Another mount, • Z, has a slot which fixes the chambers in • and Z, but not R. The third mount, Z, has alarge hole which does not constrain the chambers in either or R, but does fix the Z location.

item	Number/chamber	Total number
Disk posts	2	720
• RZ mount bracket	1	360
• Z mount bracket	1	360
Z mount bracket	1	360

1.1.4 Cooling

The front-end electronics is atttached to the face of the CSC chambers as close as possible to the ends of the strips (cathodes) or wires (anodes). The muon trigger electronics will be located around the periphery of the iron disks in standard racks. All the electronics must be cooled, but the rack-mounted electronics will be cooled by conventional rack systems. The front-end boards must be cooled by a special system attached to the chambers. Table 5 gives an estimate of the heat loads for the front-end boards.

Table 5: Estimate of heat load for the largest chamber ME234/2.

electronic board	heat/board(w)	boards/cham	heat/chamber(w)
cathode 96-channel FE	22	5	110
anode 96-channel FE	11.0	4	44

The estimated heat load for the entire CSC systems is 54KW (ME1/1 excluded). Table 1 shows an estimate of the heat load for the largest chambers (ME2/2 and ME3/2). The most efficient method for removing this heat is to mount each of the boards on a metallic pad which has thermal contact with the heat production on the board. Then the pads are cooled using a connection to a pressurized water system. The overall height of the CMS detector is 14 m so the water pressure differential over this height will vary by roughly 1.4bar. The return pressure should be higher than this differential and the supply pressure should be at least 2bar above the return.

On the outer face of the chamber copper pads are mounted under each electronic board. All the pads on a chamber face are connected by a "continuous" 1/4" copper tube which is brazed to each pad (see Fig. ??). A flexible 1/4" hose is connected to the water inputs and outputs of each chamber. This flexible hose connects to the manifold laterals via O-ring fittings. An aluminum faraday shield (for both RF and cooling) is mounted on each copper pad to cover the electronic board.

The present plan for stations 2 and 3 is to connect three chambers in series (2 10-degree and 1 20-degree CSCs) covering a sector of 20 degrees as shown in Fig. 2. For station 1, which has no 20-degree chambers, we will connect only two 10-degree chambers in series.

The cooling manifolds, supply and return, are located on the outer edge of each disk. These manifolds are 1.25" stainless steel pipes with lateral connections to each group of CSC chambers. Each face of the 12-sided endcap disks contains one section of the manifolds; sections are connected by O-ring seals on flanged ends. In order to accommodate installation tolerances we add a short flexible section for each connection. Along the manifold holes are drilled for local connections and 1/4" stainless steel half couplings are welded. Each lateral connection has a 1/4" ball valve; the return connection also has a flow restrictor (2.8l/m or .75GPM). Flexible 1/4" hoses carry the water to the chambers. Each hose connection is made with O-ring fittings which are robust and reliable.

Fig. 3 shows a close-up view of the water manifolds and the cable trays on the outer edge of the endcap disk. A top view shows the layout of lateral connections to either side of the disk. Also shown is a cut view of the edge of the disk with manifolds for water, gas, and hydraulics.

The input water temperature will be 18-20 degrees C (about 5 degrees above the dew point). The sizing of the system has been made to insure that the temperature rise per connection remains less than 2 degrees C.

1.1.5 Alignment System

The endcap alignment system (for track matching and momentum measurement) defines positions in the endcap relative to the Central Tracker and Barrel muon systems by connecting to the Link-Barrel system. In order to trigger on and define the correct position of passing particles (after software alignment correction), mechanical chamber positions and orientations need to be known with a reasonable tolerance, especially the R coordinates and ϕ angle rotations. The typical total error budget on these measurements is around 150 • m (smaller than the baseline 200 • m chamber resolution) but smaller at the ME1 muon momentum defining ring (75 • m).

In the Endcap Muon Position Monitoring System (EMPMS) critical tracker • plane references will be transferred to each of the Endcap system detector layers at the CMS outer radial boundaries. Twelve interleaved LINK Straight Line Monitors (SLMs) through the Barrel muon system are defined by the two outer end MABs (structures holding the CCd cameras for the barrel alignment). These MABs are connected by the Link alignment system to the Central Tracker coordinate system as shown in Fig.5. The Endcap Link lines transfer six (R• , R) references to each detector CSC station. There is also an Endcap Z coordinate transfer system to all chamber layers. It consists of a concatenation of laser-detector triangulation distance measurements between the Barrel end MABs and carbon fiber tubes/reference surfaces on the outer boundary of the YEn iron between all the layers of chambers. Thus diametrically opposing (R• ,R,Z) link points around the endcap iron are defined. Two possible optical beam position sensors are under development/test: ALMY, a transparent sensor and DCOPS, an open geometry sensor using cross-hair laser lines

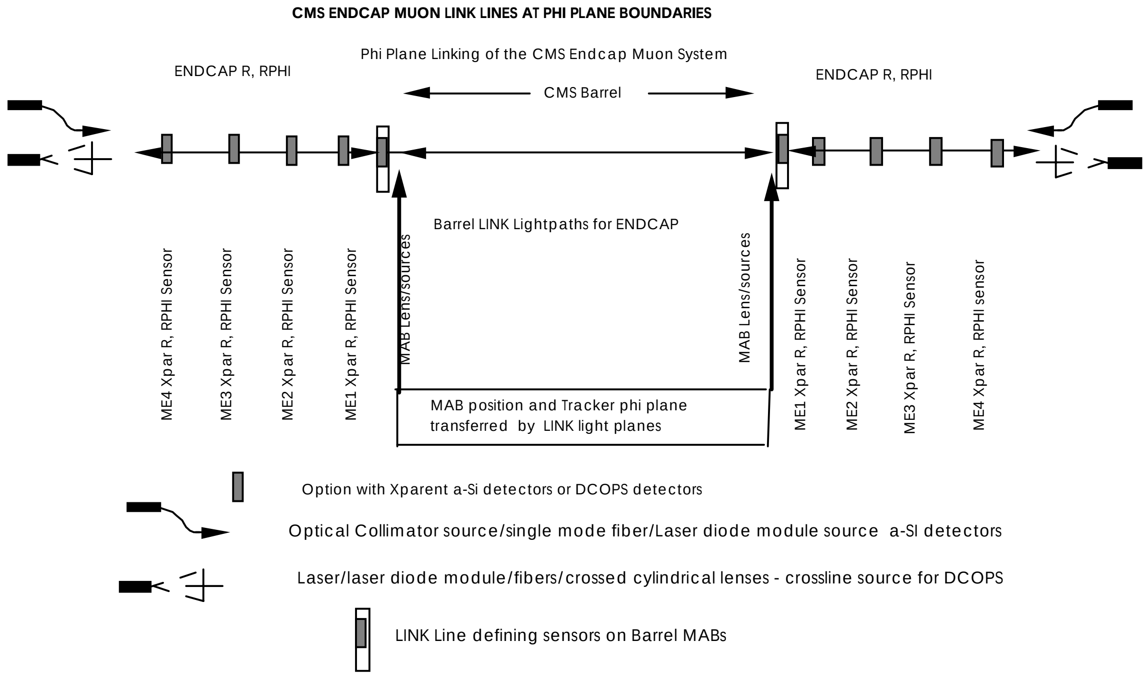


Fig. 5: Tracker • plane transfer to the Endcap Muon System by the Link system

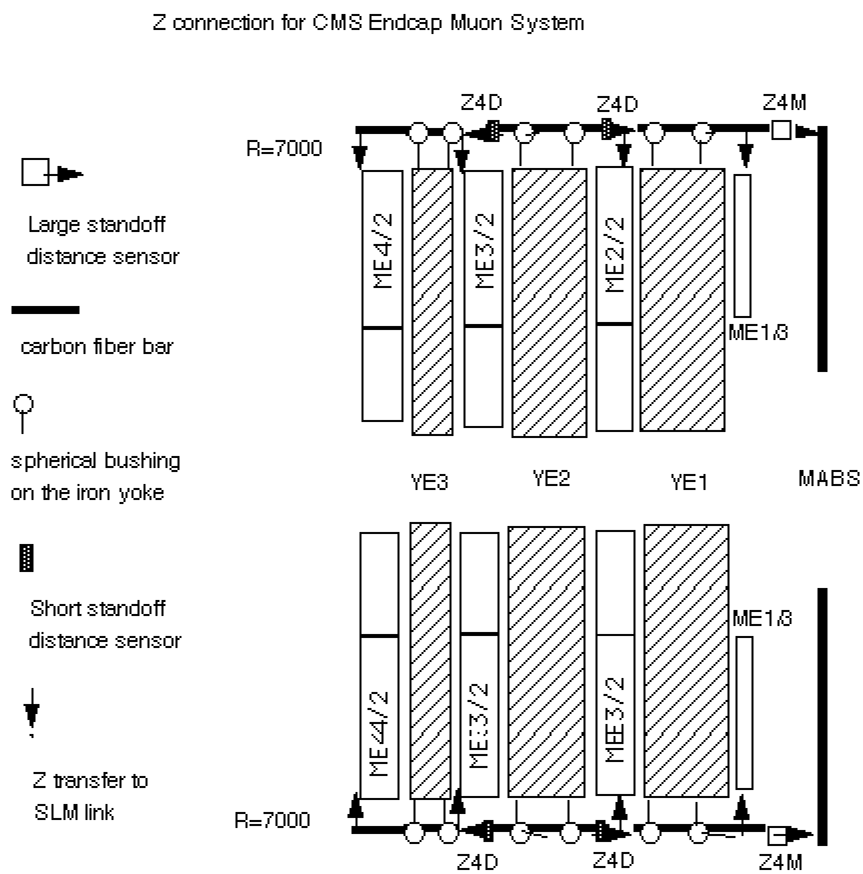


Fig. 6: Z coordinate transfer to (MEn/m) layers from references on the MABs.

The Link line SLMs consist of laser+optics sources at each end of the CMS Endcaps (ME4) projecting across CMS through a string of eight (ten if ME4) transparent optical position sensors

(ALMY or DCOPS). The two optical sensors on the end MABs of the Barrel system define the Link line in the tracker coordinate system. For ALMY, the bi-directional sensors respond to both Z+ and Z-source. A bi- directional version of DCOPS with an optical wedge has been succesfully tested. Also 20m laser sources have been prototyped. Estimated error on Link transfer at Endcap Link Sensors range 71- 108 µm.

Z transfer exists along all six Link SLM lines on each Endcap. The Z tubes are rigidly connected (referenced) to the link transfer fixtures and float (slide) in spherical bearing supports on the YEn iron. We have tested a commercial distance sensor (OMRON Z4MW40) that works on a 40 ± 10 mm stand-off with a long term resolution (3 week measurement periods) of 1-2 mm with a slow drift of less than 0.1 • m/day. This sensor has observed diurnal motions of 1 • m. It is insensitive to light backgrounds, fringe magnetic fields, and is thermally compensated. It will be used to transfer a Z reference surface on the MABs without touching them.

Between the outer boundaries of the Endcap iron discs there is a much smaller differential motion, so we have tested another low cost commercial distance sensor, the OMRON Z4DA01. It has a linear range of 2.5 mm at a 6 mm stand-off with a sensitivity of 2 • m and long term stability (2 weeks) of 10 • m at a 20% duty cycle.

Detector resolution is insensitive to the Z coordinate and we need to track only the large (several mm) magnetic iron motions across the local layers. Estimated local Z errors (148 • m) are dominated by transfer block torsion errors due the endcap iron bending (129 • m).

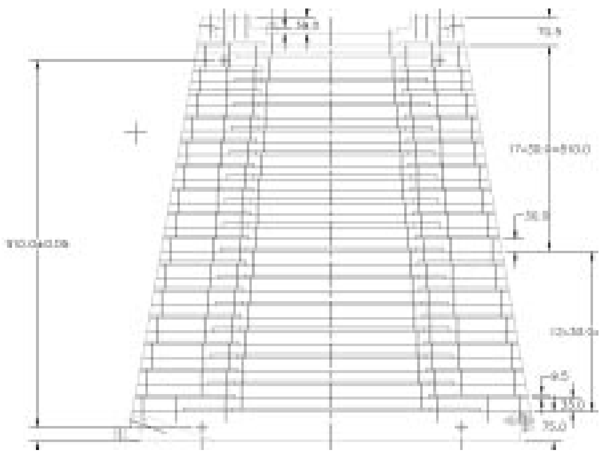
1.2 Hadron Calorimeter (HCAL)

Hadron Calorimeter - η coverage

Barrel Calorimeter (**HB**)	($0 < \eta < 1.3$)
Endcap Calorimeter (**HE**)	($1.3 < \eta < 3.0$)
Forward Calorimeter (**HF**)	($3.0 < \eta < 5.0$)

Hadron Barrel Absorber

Two half barrels (HB-1 and HB+1)
Weight: 500 Metric Tonnes
Number of wedges: 18/half barrel
Weight of wedge: 27.8 Metric Tonnes
Outer Dimensions: r= 2855.0mm (flat)
z= 4332.0mm
Inner Dimension: r= 1690.5mm (flat)
z= 3658.8mm

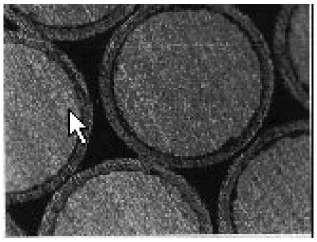


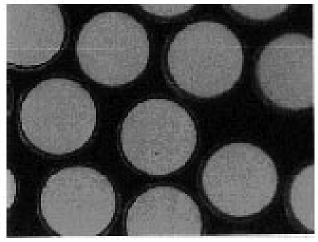
HB-1 and HB+1 Wedges

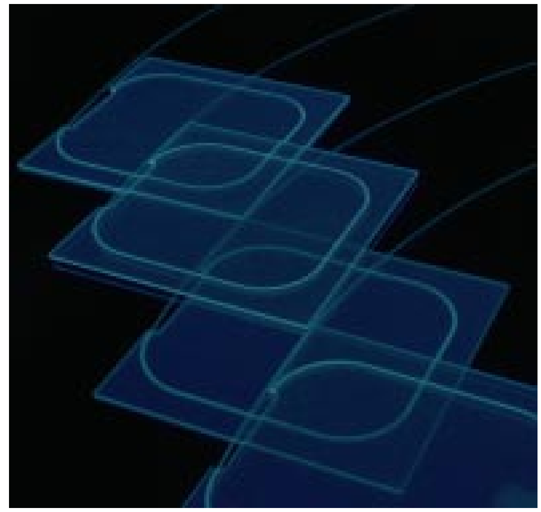
Number of wedges/half barrel: 18
Total: 36
Extra wedges: 2 (PPP1 & PPP2 -- Pre-Production Prototypes)
Wedge weight: 27.8 Metric Tonnes
Outer Dimensions: r= 2855.0mm (flat)
z= 4332.0mm
w= 997.3mm
Inner Dimension: r= 1690.5mm (flat)
z= 3658.8mm
w= 637.1mm
Phi Angle subtended: 20 degrees
Number of plates: Stainless Steel: 2
Brass: 29
Number of bolts/wedge: 2200
Total number of bolts: 76,000
spares: 8,000

Absorber Plates

Stainless Steel Plates: 2
Inner SS Plate thickness: 71mm (maximum)
weight: 1.6 Metric Tonnes
Outer SS Plate thickness: 68.5mm (maximum)
weight: 1.6 Metric Tonnes
Brass plates: 29
Brass composition: Cartridge Brass: Cu 70%
Zn 30%
Brass plate thickness: 12 plates at 33mm (nominal maximum)
weight: 0.8 Metric Tonnes
17 plates at 30mm (nominal maximum)
weight: 0.8 Metric Tonnes
Slot Gap size: 9.5mm







Hadron Barrel Megatiles

Megatiles are made of scintillator inserted into slots between wedge plates. Slots are arranged in layers - Number of layers = 17 (0:16). Megatiles consist of set of mechanically bound, but optically separated tiles. Charged particle ionazation induced light pulses will be collected by wavelength shifting (WLS) fiber from each tile. WLS fibers are
trapped inside sigma-shaped grooves machined in scintillator. WLS fibers fused to clear fibers arranged to terminate into optical connector. Signals from megatile routed via optical cable to Readout Box. Innermost layer is part of ECAL system: - Layer 0. Outermost layer attached to outer surface of HB absorber: Layer 16 Nominal Tile size: η x φ = 0.087 x 0.087 (5 degrees in phi or 1/4 wedge in phi).

Layers 0 (inter)

phi segmentation : 2x5deg megatiles + 1x10deg megatile
Central megatile: 1 per layer
length = wedge length (3165 mm)
width = 10 degrees in phi or 1/2 wedge size (320 mm)
t= 13 mm
scintillator thickness = 9.0 mm BC-448
Edge megatiles: 2 per layer
length = wedge length (3074 mm)
width = 5 degrees in phi or 1/4 wedge size (154 mm)
t= 13 mm
scintillator thickness = 9.0 mm BC-448

Layer 16 (outer)

phi segmentation :4x5deg megatiles/wedge
z= 4332 mm (half barrel)
w= 898 mm (total width)
t= 13 mm
scintillator thickness = 9.0 mm SCSN-81

Layers 1-15 (internal)

phi segmentation :2x5deg megatiles + 1x10deg megatile
Central megatile: 1 per layer
length = wedge length
width = 10 degrees in phi or 1/2 wedge size
t= 8 mm
scintillator thickness = 3.7 mm SCSN-81
Edge megatiles: 2 per layer
length = wedge length
width = 5 degrees in phi or 1/4 wedge size
t= 8 mm
scintillator thickness = 3.7 mm SCSN-81

Tile count:

layer 0 : 4 (phi) x 15 (eta)
layer 1- 2: 4 (phi) x 17 (eta)
layer 3- 8: 4 (phi) x 16 (eta)
layer 4-14: 4 (phi) x 15 (eta)
layer 15 edge : 2 (phi) x 15 (eta)
layer 15 central : 2 (phi) x 14 (eta)
layer 16 : 4 (phi) x 14 (eta)

Total number of towers/wedge: 68

with 2 readout channels: 56
with 3 readout channels: 12
Total number of readout channels/wedge: 56*2 + 12*3 = 148

Total amount of 3.7 mm scintillator/wedge: 48.7 m2
Total amount of 9.0 mm scintillator/wedge: 5.5 m2

Megatile material/wedge:

Tyvek: 108.4 m^2
Tedlar: 108.4 m^2
Plastic grooved covers (1mm on bottom and 2mm on top): 108.4 m^2

Total length of WLS fiber/wedge (0.94mm dia): 590 m
Total length of clear fiber/wedge (0.94mm dia) : 990 m

Number of optical connectors on megatiles: 4 x 17 = 68
Number of optical cables/wedge: 4 x 17 = 68
Number of optical connectors on cables/wedge: 8 x 17 = 136
Length of optical cable: 100mm to 1100mm

Tooling

Fiber polishing device: 2
Connector polishing device :1
Fiber fusing device: 2
Megatile scanner: 1
Fiber scanner: 1
Thermwood milling machines: 2
Axion milling machine: 1

Hadron Barrel Readout Box

Optical Signal mixed according to tower geometry into HPD's
HPD's turn photons into electrons with 15% efficiency and a gain of 2000
HPD signal amplified and digitized by CMS QIE electronics
QIE asics mounted 6/board on RB backplane
Calibration signals are distributed and monitored via RB
Sourcery is monitored via signal readout channels
HV/LV power distributed via RB
Cotrols communication path in/out of RB

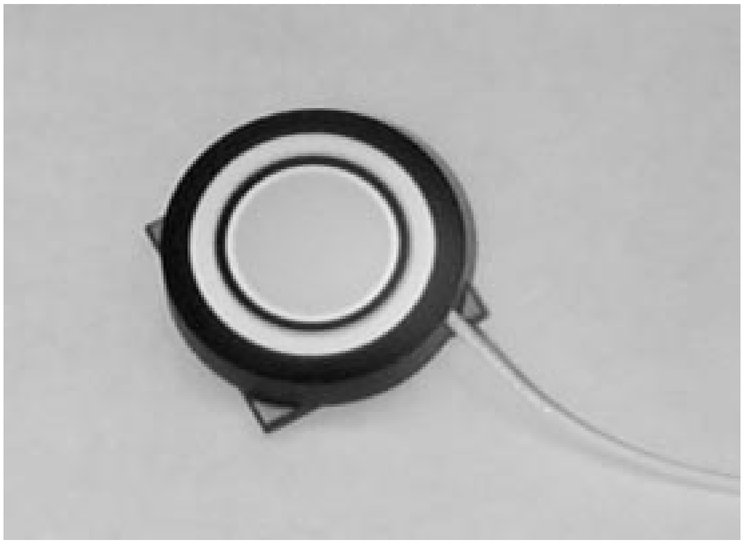
Number of Readout Boxes = 196 +spares, (36HB, 60HOB, 36HE, and 64HF)
Number of HPD's = 492 +15% spares, (36x5HB, 36x5HE, 48x2+12x3HOB)

No. of RB's/wedge: 1
No. of RB's/half-barrel: 18

No. of (input) optical connectors: 72
No. of optical bundles: 148

No. of LED's/box: 2
No. of Y11 blocks/box: 1
No. of PIN's/box: 2

No. of HPD's/box (19 pixels) : 4
No. of HPD's/box (73 pixels) ; 1
No. of HPD cookies/box: 4 + 1 = 5
No. of HPD mounts/box: 4 + 1 = 5
No. of signal channels/box: 148
No. of independent calibration channels/box: ??
No. of QIE cards/box: 25 ?
No. of optical fibers out: 50
No. of optical drivers: 50



Hadron Barrel Photodetectors

No. of HPD's/wedge (19 pixels) : 4
No. of HPD's/wedge (73 pixels) ; 1
Total No. of 19 pixel HPD's: 144
spares: ??
Total No. of 73 pixel HPD's: 36
spares: ??

Testing stations: 2
Pixel Measuring stations: 1

HB and HE Front End Electronics

Each of the 36 HB readout boxes contains:
25 six-channel boards
1 TTC/Fieldbus board
50 data links

Each of the 36 HE readout boxes contains:
36 three-channel boards
1 TTC/Fieldbus board
36 data links

Each of the 12 HOB 0 readout boxes contains:
17 three-channel boards
1 TTC/Fieldbus board
17 data links

Each of the 24 HOB +/-1 readout boxes contains:
13 three-channel boards
1 TTC/Fieldbus board
13 data links

Each of the 24 HOB +/_2 readout boxes contains:
11 three-channel boards
1 TTC/Fieldbus board
11 data links

Hadron Calorimeter Calibration System

Moving wire radioactive source of Co60.

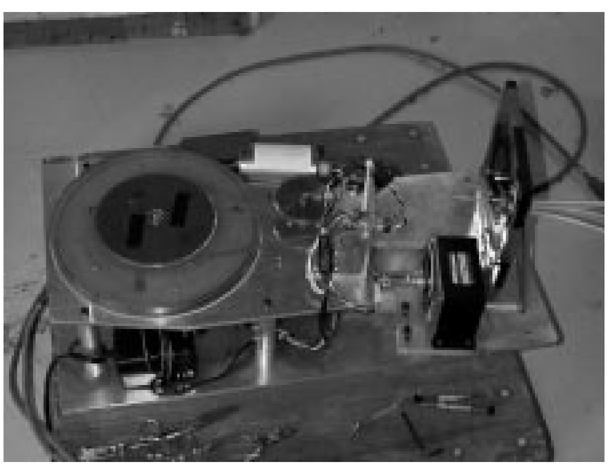
Each megatile layer will have a source tube for HB, HE and HO-B

HB 2448 source tubes
HE 2736 source tubes
HO-B 72 source tubes per ring per layer
Hence HO-B0: 144 source tubes
HO-B+/-1, HO-B+/-2 = 288 tubes

CMS closed, only 8 source tubes per wedge for HB and HE can be accessed.
None for HO-B can be accessed. CMS open, all source tubes can be accessed.
Moving wire source installed inside CMS:
HB - 4; HE - 6; HF-2.
Roving moving wire sources.
HB - 3, HE - 2; HO-B -2.

Laser Calibration system.

This includes HB, HE and HO-B.
Number of Laser(s); 1 nitrogen of about 1 mJ.
Possibly to be replaced by many blue laser (not yet on the market)
Number of Dye cells: 1 UV to blue.
Number of commutator: 1 with 16 laser pulse output SMA connectors.
Number of neutral density filters: 1
Laser control box: 1 under computer control.
Number of quartz fibers from control room to CMS each 150m long: 16
Number of primary splitter: 16
Number of quartz fibers (10 and 25 m each) from splitter to optical boxes
2 for each HB, 2 for each HE, one for each HO-B: total 204, about 4km
Number of calibration boxes attached to optical decoder boxes, one each
Number for HB 36,
Spares + PPP: 6
Number for HE 36:
Spares + PPP: 6
Number for HO-B 60
Spares + PPP: 6



In each calibration box: PPP and spares are denoted after + sign.
Number of quartz laser input 2 each for HB and HE, one for HO-B: 188+36
Number of K27 (Y11) block, one each box: 132+18
Number of LED in each box 2, total: 264+36
Number of Pin Diodes in each box 2, total: 264+36
Number of Pin Diodes in Laser Calibration box: 3
Number of output plastic (940micron) fibers, one per HPD. Total 576?+90
Number of quartz fiber output from calibration box to megatiles
8 for HB, 1 for HE and 0 for HO-B
Splitter in calibration boxes. HB - 2, HE and HO-B 1 each. Total: 168+24
Number of external splitter for HE, one each wedge, total 36+2
LED pulsers: 2 for each half barrel, total 12+2
Number of LED drivers, one per LED, total 264+36
Number of Pin diode amplifiers, one per pin diode: 267+36.
Number of quartz fibers from optical box to megatiles (8 each for HB & HE) total 576 each about 1.2 meter, about 2km.
Number of splitter inside megatiles 8 per wedge (HB+HE) 576.
Number of fibers inside megatiles 19 each, total 11,000 of about .7m ech total (100 micron fibers) 8km

Trigger/DAQ

DAQ Card = 9U VME card + Aux card for optical receivers upto 48 links
Trigger Card = 9U VME Card + Aux trigger transmitter with upto 48 1Gb links
Crates = 9U VME Crates
DCC = 9U VME card + Aux card with upto 2 1 Gb/s optical fibers
DDU = plug into DAQ card = PCI interface card with 1 Gb/s fiber input

TOTAL = HB+HOB+HE+HF:

286 DAQ cards
118 Trigger Cards
24 Crates
27 DCC Cards
27 DDU Cards

Broken down into regions as follows.

HB: (~5400 channels)	HOB: (~2340channels)	HE: (~3888 channels)	HF: (~1848 channels)
114 DAQ cards	50 DAQ cards	82 DAQ cards	40 DAQ cards
57 Trigger Cards	0 Trigger Cards	41 Trigger Cards	20 Trigger Cards
10 Crates	3 Crates	7 Crates	4 Crates
10 DCC Cards	6 DCC Cards	7 DCC Cards	4 DCC Cards
10 DDU Cards	6 DDU Cards	7 DDU Cards	4 DDU Cards

HV/LV PS

1 LV & 1 HV PS/RBX
Total number of HV PS's= 132 (+spares)
Total number of LV PS's= 132 (+spares)

Hadron Endcap

Scintillator:

Megatiles range in size from 1.8m x 0.56m to 2.3m x 0.66m
Thickness 3.7mm
There are 36 megatiles per layer per end (10 degrees in phi)
There are 20 layers per end
Number of megatiles = 36x20 x2 = 1440
There are 2 optical connectors per megatile (total = 2x36x20 x2= 2880)
There are 2880 optical cables (2 connectors/cable + optical fiber)

Calibration Source:

Source tubes (wire source): one every 5 degrees in Phi, per megatile
= 4 per wedge layer
length: full Z-length of megatile
stainless steel, diameter 1.27 mm
antifriction paint inside 60cm of high-Z end
Source tube couplers: one per tube, brass, at high-Z edge of megatile

Endcap RBX's

No of RBX's/wedge = 1
No of RBX/s/endcap = 18
Total number of RBX's = 36

Hadron Endcap Photodetectors

No. of HPD's/wedge (19 pixels) : 4
No. of HPD's/wedge (73 pixels) ; 1
Total No. of 19 pixel HPD's: 144
Total No. of 73 pixel HPD's: 36

Endcap FEE

Each of the 36 HE readout boxes contains:
36 three-channel boards
1 TTC/Fieldbus board
36 data links

Hadron Forward HF

ABSORBER:

Eta coverage : 3 to 5
Delta eta x Delta phi : 0.175 x 0.175
Total weight : 200 tonnes
No of large modules : 176
No of smaller modules : 24
Large brick dimensions : 24 cm x 24 cm x 165 cm
Small brick dimensions : 12 cm x 24 cm x 165 cm
No of replaceble modules: 4
Z_front : 11130 mm
Z_back : 12780 mm
R_in : 140 mm
R_out (active) : 1300 mm
No of grooved plate/mod : 48
No of ungrooved plat/mod: 48
Thick. of grooved plate : 3 mm
Thick. of ungr'd plate : 2 mm
No of grooves/plate : 96 on each side
Groove x-sec : 0.5+0.150 mm by 0.5+0.15 mm square
Material : Steel (08YUGOST 9045-80)
Lifting fixtures : 2 min vacuum.

READOUT BOXES:

No of RBX's : 72
Type of boxes : 2 (Type-A and Type-B)
No of Type-A Box : 36
No of Type-B Box : 36
No of PMT in Type-A : 31
No of PMT in Type-B : 24
Optical coupling : Air-core light guides
No of ROBox/10 degrees : 1
No of cal units/box : 1
No of laser fib in : 1
No of LEDs/Box : 2
No of PIN PD/Box : 2
No of multipin HV/box : 1
No of multipin sig/box : 1
Temp control : +/- 1 C
Gas flow : Nitrogen
Material : Al
: Quick connect/disconnect mechanism
: Light tight

OPTICS:

QQ fiber dimensions : 300 micron core
315 micron clad
345 micron buffer
QQ fiber material : core : pure sythetic silica
clad : fluorine-doped synthetic silica
buffer : polyimide
QP fiber dimensions : 300 micron core
320 micron clad
345 micron buffer
QP fiber material : core : pure sythetic silica
clad : hard polymer
buffer : polymer
QQ/QP HF boundary : 400 mm at front (eta=4)
Quartz by volume : 0.85%
QQ quantity : 335 km
QP quantity : 3500 km

Long fiber length (EM) : 165 cm
Med. fiber length (HAD) : 143 cm
Short fiber length (TC) : 30 cm

Fiber-to-fiber dist : 2.5 mm in a square grid
No Long fib in a grid : 2
No Med. fib in a grid : 1
No Short fib in a grid : 1

QC Transmission tests : <0.2 dB/m (350 nm to 700 nm)
Dimension tests : +/- 2% during drawing
Proof test : 100 kpsi
OH content (bulk) : <1200 ppm
Metal impurities : <0.05 ppm
Polyimide concent. : +/- 3 microns
Numerical Aperture : 0.22 QQ
0.37 QP
Ref index @588 nm : 1.458
@400 nm : 1.470
Tensile strength : 5 x 10^7 N/m^2

Light guides : Air-core
No of light guides : 1980
Length : 25 cm
Reflection : >96%
Cross-section : Hexagonal
Flat-to-flat : <PMT_photocathode

HIGH VOLTAGE:

No of Channels : 1980
Grouping reduction : 303 (=

PHOTODETECTORS:

No of PMTs : 1980
No of diff dia PMTs : 2 (1 1/8" and 1/2")
No of PMT/tower : 2 (1 EM + 1 HAD)
No of tower/TC PMT : 2-4-4-4-4-4-1
PMT glass : Borosilicate
PMT window thickness : <2 mm
PMT windown transmiss. : >90% 380-520 nm
Photocathode : Bialkiline
QE : >15% 350-520 nm
: >20% 380-450 nm
Pulse t_transit : <25 ns
t_rise : <3 ns
t_FWHM : <10 ns
linearity : +/-2%, 1-3000 pe
Gain : ~10^5 (8-10 stages)
Current I_peak : 25 mA +/-2% lin.
I_ave : 70 microamp
Single pe resol : rms/mean < 50%
Tube-to-tube uniformity : QE*g within 2% by HV
Lifetime : >10 mC, QE*g > 80% of initial
Test centers : 3

CALIBRATION:

Radioactive Source:
Source type : Co^60
Activity : 10 mCi min
Dimensions : point source on a wire
No of Source tubes : 112 total (56 per side)
: 45 degree line with 7 tubes per line
No of Drivers : 2 (1/side)
Laser:
Laser source : Nitrogen (337 nm or similar)
Wavelength range 337-500 nm
Rate : 10 Hz max
Pulse-to-pulse var : < 5%
No of photons at PMT : 10^5 min
No of input/box : 1 with SMA connector

Split to each PMT with a fiber in ROBox

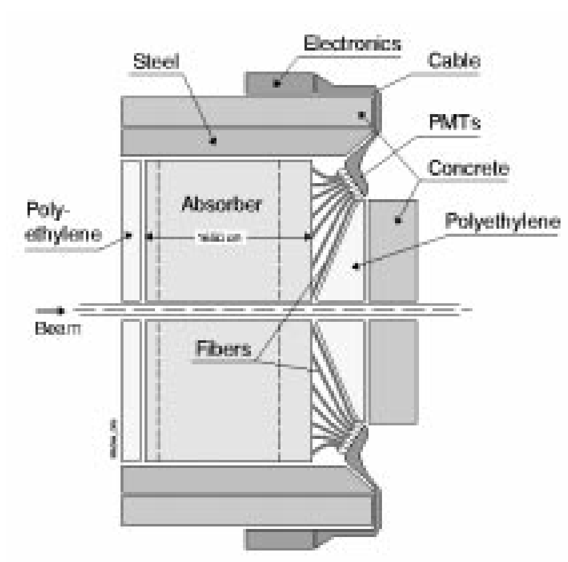
LED
Color : Blue
Rate : up to 40 MHz
No of LED/Box : 2

PIN Diode
Sensitivity : 10^5 min
No of PIN/Box : 2
Bias : +/- 5V

Front End Electronics:

9 RBX's are connected to one VME crate

Each of the 8 HF readout VME crates contains:
7 thirty-three-channel 9U VME modules
1 TTC/Fieldbus VME transition module
77 data links



1.3 TRIDAS

The CMS Trigger and Data Acquisition System (TriDAS) 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 should be archived for off-line analysis. CMS has chosen to reduce this rate in two steps. The first step (Level-1 Trigger, WBS 1.3.1) stores all data for approximately 3 μs, after which no more than a 75 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. In the second step (data acquisition and high-level Trigger, WBS 1.3.2) the data are read out of the Front-End electronics and stored in ~ 400 deep dual-ported memories (DPMs) for up to a second. The DPMs feed their data via a large switching fabric to ~ 400 farms of commercial CPUs. The latter run physics selection algorithms in order to reduce the maximum input event rate from 75 kHz to no more than 100 Hz.

The architecture described above is very similar to those of current collider experiments. The one major difference is the absence of a dedicated Level-2 trigger that provides an intermediate rate reduction of roughly another factor of 100, before events are forwarded to the processor farm. As an example, in the CDF system, the Level-2 trigger is expected to provide a reduction of events sent to the computer farm (which runs the Level-3 filter). In the CMS design, such a reduction is going to be provided by the processor farm which will filter events in two steps, a Level-2 and a Level-3 step. These two steps are referred to as the "High Level Trigger" (HLT).

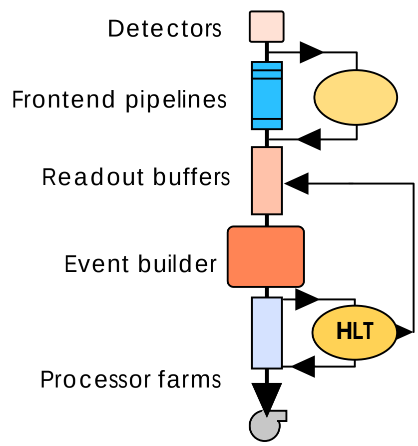


Figure 1.3.1: Block diagram of the CMS TriDAS

The main parameters of the CMS Trigger/DAQ System are listed in Fig. 1.3.2. With respect to the parameters listed in the CMS Technical Proposal (and also assumed at the 1997 DOE review of CMS) one major change is the decrease in the assumed maximum Level-1 trigger rate from 100 kHz to 75 kHz. This change was the result of a rescope of the TriDAS system following a series of internal reviews by the CMS management. The new baseline design for CMS is therefore a system capable of reading events with an average data size of 1 MB at a rate of 75 kHz. To maintain the future scalability of the system, each subsystem will be designed to be capabale of handling a maximum rate of 100 kHz.

Collision rate		**40 MHz**
Level-1 Maximum trigger rate		**75 kHz**
Average event size	**-**	**1 Mbyte**
No. of In-Out units (200-5000 byte/event)		**400**
Event builder (400+400 switch) bandwidth	**-**	**400 Gbit/s**
Event filter computing power	**-**	**5 10^6 MIPS**
Data production	**-**	**Tbyte/day**
No. of electronics boards	**-**	**10000**

Figure 1.3.2: Main parameters of the CMS TriDAS

1.3.1 Trigger

The endcap muon trigger system finds high-momentum muons consistent with coming from the primary interaction region, allowing identification of Higgs particles, W and Z bosons, etc. In addition, under low luminosity conditions, the muon trigger can identify muons down to the cutoff momentum imposed by range-out in the steel of the magnet flux return, allowing interesting studies of rare B-particle decays.

The calorimeter trigger system provides 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.

1.3.1.1 Endcap CSC Muon Trigger

The baseline CMS muon system currently consists of 4 stations of chambers in the barrel region and 3 stations in the endcap region. In the barrel detector, these are drift chambers, whereas in the endcap detector, they are Cathode Strip Chambers (CSC's). The layout of these systems is shown in profile in Figure 1. Each station of CSC contains overlapping 10 or 20-degree wide chambers, and each chamber contains 6 measurement layers. In each measurement layer, anode wires are read out to measure the non-bend (imprecise) coordinate and radial cathode strips are read out to measure the bend (precision) coordinate. A muon produces a "stub" in each dimension. All of the on-chamber electronics for muon identification, including trigger, is considered and is budgeted as part of the Endcap Muon system. The off-chamber trigger electronics which collects muon stubs from the chambers, sends the stub information "upstairs" on optical fibers, and links the muon stubs into a muon track of known momentum and direction is known as the Muon Regional Trigger System (WBS item 3.1.1) portion of the US-CMS Trigger/Data Acquisition (TRIDAS) system, WBS item 3.

The on-chamber Cathode and Anode cards, which find projections of muon stubs in strip and wire views, respectively, are mounted on the surfaces of the CSC chambers. In the 3-station endcap muon system, there are 2016 cathode strip cards and 1800 anode wire cards, mounted on 432 CSC chambers. There is one on-chamber card per CSC chamber, called the Motherboard, which does the time correlation of the two views and sends the stub information on via copper to a Muon Port Card (MPC). The on-chamber circuitry up to the cables going from Motherboards to Muon Port Cards is considered as part of the Endcap Muon system - from there on, the circuitry is part of the TRIDAS system. The Muon Port Cards assemble muon trigger data from a 60-degree ϕ swath and pass it on via Gbaud optical links to the Track Finder crates. The Track Finder crates link together the muon stubs into tracks and determine the muon momentum vectors for use in the CMS Global Muon trigger. The drift tube muon trigger, the global muon logic, and the global Level 1 trigger electronics are responsibilities of European groups. A block diagram showing the overall structure of the CSC muon trigger electronics is shown in Fig. 1.3.3.

The major portions of the off-chamber muon trigger electronics contained in WBS 3.1.1 are therefore Muon Port Cards (MPC), optical data and clock links, and track finder crates containing Sector Receiver (SR) cards, Sector Processor (SP) cards, Clock and Control Cards (CCC), and ancillary logic and cabling.

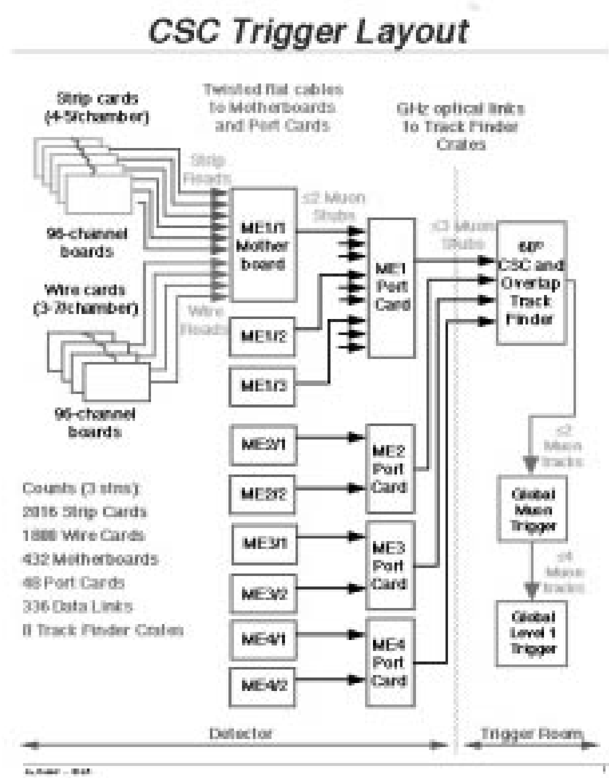


Figure 1.3.3. Block diagram of the CSC Muon Trigger System

A Muon Port Card (MPC) receives data from nine Motherboards within a CSC station. In the first station, this is a ϕ interval of 30 degrees, while in the other stations this is a ϕ interval of 60 degrees. The Muon Port Card sends the data “upstairs” via fast optical links to a CSC Track Finder crate. The MPC's are located near the outer periphery of the CSC chambers to keep copper cabling distances acceptably short. There are 12 Muon Port Cards in CSC station ME1 in each endcap, and 6 Muon Port Cards in each of the later stations, for a total of 48 MPC. It takes 7 Gbaud optical links per MPC to send the information from up to 3 muon stubs to the Track Finder. The front-end electronics is designed to present a priority-ordered set of muon stubs to the Muon Port Cards, where the priority is determined by number of layers hit, a rough measure of momentum (local bending), and consistency with arrival from the primary vertex. Within the MPC, priority-encoding circuitry is included to select the best muon stubs in the case that more than three stubs arrive simultaneously. The MPC also handle the function of receiving master clock signals via TTC interface and fanning them out to the front-end CSC chamber electronics.

The layout of the muon Track Finder contains separate racks for barrel (DT), endcap-only (CSC), and overlap processor regions. Within the barrel system, the Track Finders are organized by wheel. Each VME crate handles 180 degrees in phi of track finding. Signals from the CSC system come to the Track Finder on optical links, and are received in the CSC-only section. A conception of the system, shown below, contains 9 racks, each of which contains 2 VME crates. The CSC-only and overlap Track Finders (U.S. responsibilities) are contained in 4 racks/8 crates.

Data comes from the Muon Port Cards (MPC) on optical fibers to the CSC-only Track Finder crates. Each MPC sends data representing 60 degrees in phi of one muon station (with the exception of station 1, which sends data in 30-degree sub-sectors. The card that receives these signals is called the Sector Receiver (SR).

The Sector Receiver card does 2D to 3D muon stub conversion, alignment corrections, and data reformatting. It then sends muon stub data to the Sector Processor (SP) module on the crate backplane. If the Sector Receiver is being used in the CSC-only crate, it must also replicate the data and send it on to the Overlap crate on copper. If the Sector Receiver is being used in the Overlap crate, it must receive its input data over copper. After the data is received by the Sector Receiver cards, it can be reformatted by look-up tables into whatever format is convenient for the Sector Processor track finding.

There are three Sector Processors per crate, each handling 60 degrees in phi. In the baseline design, up to three muon stubs are transmitted from each MPC on six optical fibers. The Sector Receivers are designed to receive 15 optical fibers carrying 270 data bits. Depending on whether we have three or four endcap muon stations, two or three MPC's are connected to each Sector Receiver. The Sector Receiver, which is connected to the two ME1 MPC's in the 60 degree sector, combines the information before transmission to the Sector Processor. Two Sector Receivers send data to each Sector Processor.

1.3.1.2 Regional Calorimeter Trigger

The calorimeter level 1 trigger system baseline design 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 a fine grain ID bit determined from the data used to make the energy sums. 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 (WBS 3.1.2) portion of the US-CMS Trigger/Data Acquisition (TRIDAS) system, WBS item 3 consists of 19 calorimeter processor crates covering the full calorimeter. 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 Fig. 1.3.4, 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 400 mm deep rear mounted cards.

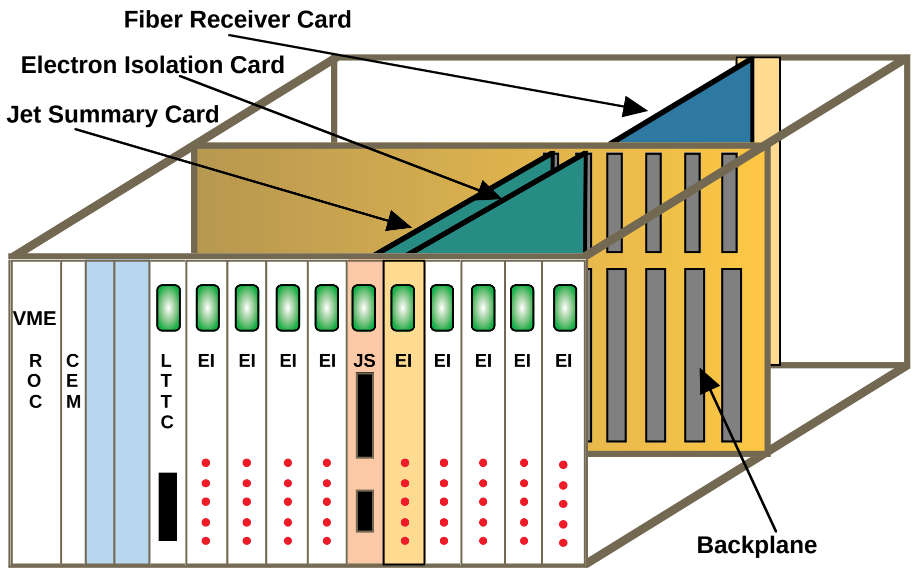


Figure 1.3.4. Schematic view of a typical Calorimeter Level 1 Regional crate.

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 inter-crate 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.

Trigger Parameters Tables

Table 1 shows the input data to the US CMS part of the Level 1 trigger processors, the CSC Track Finder and the Calorimeter Regional Trigger, Table 2 shows the output of these systems to the Global Muon and Global Calorimeter Level 1 Trigger Processors.

System	Input Level 1 Segmentation per half	Input Level 1 Data
Muon Drift Tubes	2457 ϕ x 80 η x 4 R	8 bend bits
Muon CSC	2457 ϕ x 2048 η x 3 Z	6 bend bits
ECAL ($0 < \lvert\eta\rvert < 1.479$)	72 ϕ x 17 η	8 bits energy 1 bit fine grain
HCAL ($0 < \lvert\eta\rvert < 1.479$)	72 ϕ x 17 η	8 bits energy 1 bit depth profile
ECAL ($1.479 < \lvert\eta\rvert < 2.16$)	72 ϕ x 4 η	8 bits energy 1 bit fine grain
HCAL ($1.479 < \lvert\eta\rvert < 2.16$)	72 ϕ x 4 η	8 bits energy 1 bit depth profile
ECAL ($2.16 < \lvert\eta\rvert < 2.60$)	72 ϕ x 2 η	8 bits energy 1 bit fine grain
HCAL ($2.16 < \lvert\eta\rvert < 2.60$)	36 ϕ x 2 η (ϕ data doubled)	8 bits energy 1 bit depth profile
ECAL ($2.60 < \lvert\eta\rvert < 3.0$)	72 ϕ x 1 η	8 bits energy
HCAL ($2.60 < \lvert\eta\rvert < 3.0$)	36 ϕ x 1 η (ϕ data doubled)	8 bits energy 1 bit depth profile
VFCAL ($3.0 < \lvert\eta\rvert < 5.0$)	12 ϕ x 12 η	8 bits energy 1 bit jet tag

Table 1. Input Data to the US CMS Level 1 Trigger Processors[4].

System	Output Level 1 Segmentation per half	Output Level 1 Data
Muon Drift Tubes	256 ϕ x 32 η	5 p_T bits (nonlinear)
Muon CSC	256 ϕ x 32 η	5 p_T bits (nonlinear)
ECAL & HCAL	18 ϕ x 6 η	4 highest E_T electrons, jets 10 bits energy
ECAL & HCAL	9 ϕ	E_T, E_x, E_y in 10 bits
VFCAL ($3.0 < \lvert\eta\rvert < 5.0$)	One Region for both halves	E_T, E_x, E_y in 10 bits, jet tag

Table 2. Output Data from the US CMS Level 1 Trigger Processors.

[4] The CSC Sector Receiver delivers 12 bits of ϕ information per 60° derived from the LCT bit pattern, which corresponds to 24576 bins in ϕ. It also delivers 11 bits of η information, or 2048 bins. The DT trigger server delivers 11 bits of ϕ information per 30°, giving 24576 bins in ϕ. It also delivers 5 bits of η information per wheel, which is 80 bins in η for half of the barrel.

1.3.2 Data Acquisition

The architecture of the CMS DAQ System is shown in Fig. 1.3.2.1. Upon the reception of a Level-1 accept signal, the front-end electronics are read out by a set of ~ 400 modules (Readout Units, RU) which buffer the event during the Event Building process. The RUs are connected to a number of Filter Units (FUs) which contain processors that analyze the events received from the RUs. The RUs are connected to the FUs via a high-bandwidth switch. A central intelligence, the Event Flow Control (EFC) system, synchronizes the RUs and FUs by allocating each event accepted by the Level-1 Trigger to the next available Filter Unit. Another subsystem, “Controls” is responsible for all configuration setting, monitoring and user interface.

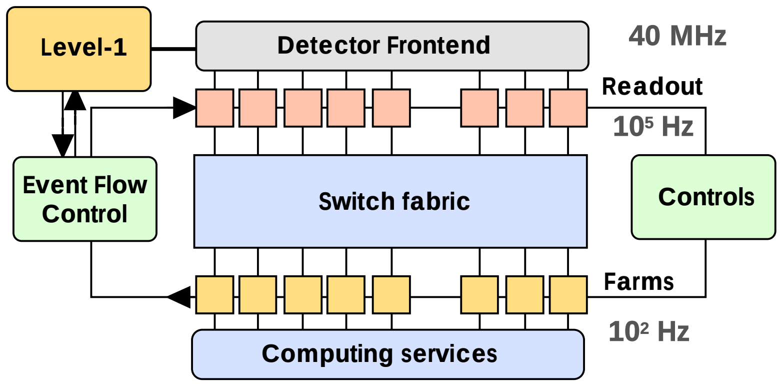


Figure 1.3.2.1: Schematic of the architecture of the CMS TriDAS.

As explained in the overview of the TriDAS (section 1.3) the processor farm executes both the “Level-2” and the “Level-3” triggering steps. The Level-2 step is executed based on only a reduced amount of data from the event in question. If the event is rejected in this step, then the EFC is told to delete the rest of the data belonging to the event from the remaining RUs. This process is shown schematically in Fig. 1.3.2.2.

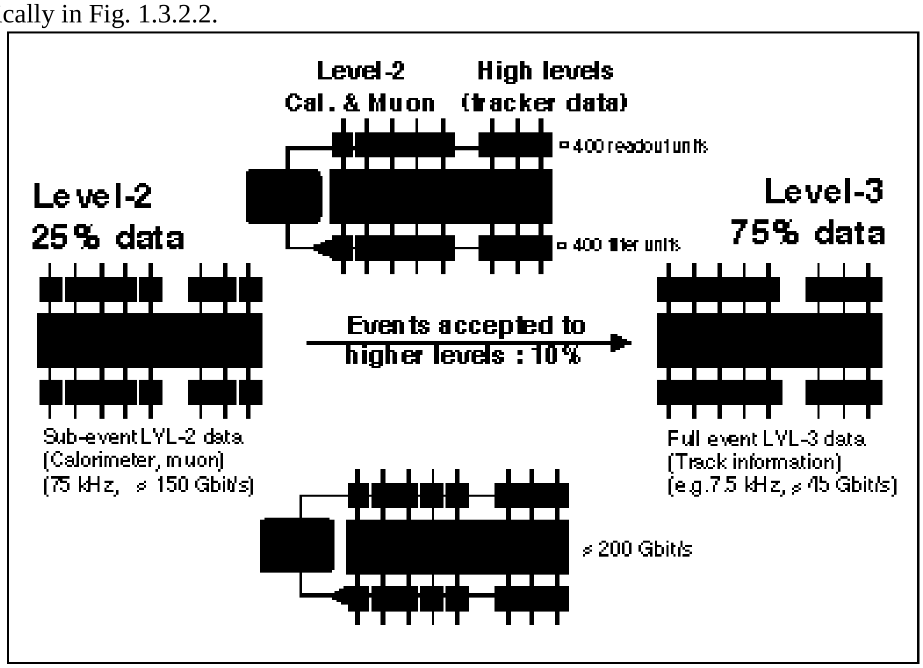


Figure 1.3.2.2: Schematic of the principle of the CMS High Level Trigger system.

The overall effect of this two-step process is to reduce the total required switch bandwidth. As an example, assuming a Level-2 rejection factor of 10, and an average fraction of data required by the Level-2 step of 25% of the total event size, the switch bandwidth required to send events to the Filter Units (assuming 100 kHz of Level-1 events) is reduced from 600 Gb/s to 200 Gb/s.

As an example, given an event that has been accepted by the Level-1 trigger system based on the inclusive electron criteria, the Filter Unit allocated by the EFC to process this event will be provided with the calorimeter data corresponding to this event. Data from the tracking detectors (whose data size is roughly three times larger than the data size from the calorimetry) will not be sent to the FU in question. The Filter Unit, in turn, will pass the event to one of the processors (Filter Nodes, FN) attached to it. The FN allocated to process the event, proceeds to analyze the information received by running an algorithm which first confirms the Level-1 trigger decision. The data provided to the processor correspond to the full detector granularity and resolution. Therefore, even a simple re-application of the Level-1 trigger algorithm can result in sharper thresholds at Level-2. More elaborate algorithms based only on calorimeter data are also foreseen. The Level-2 filter is expected to provide at least a factor 10 in rate reduction.

If an event does not pass the Level-2 filter, then the FU processing it will instruct the Event Flow Control System to erase the rest of the data corresponding to this event from the remaining RUs. If the event passes the Level-2 filter, then the FU processing it will request the rest of the data belonging to the event in question from the Event Flow Control.

US Responsibility

The US is responsible for providing the Event Manager part of the Event Flow Control and the SFI part of the Filter Units (i.e. the entire FUs but excluding the Filter Nodes, i.e. the processors). The total number of modules to be delivered are: one Event Manager (EVM) and 432 SFIs (including spares).

Filter Units

The requirements for the Filter Units are shown in Fig. 1.3.2.3. There are two high-speed (event-data) ports and two (slower) control and monitor ports. The Input data port must be capable of reading data from the switch ports. The Output data port must be capable of feeding a number of CPUs (Filter Nodes) that run the HLT algorithms. With an event size of 1MB and 400 FUs, each FU will contain roughly 1 MB of event data at a rate of 150 Hz. However, the FUs are designed to function at rates of up to 100 kHz, which translates to 200 Hz. The maximum sustained average data per FU is thus 200 MB/s

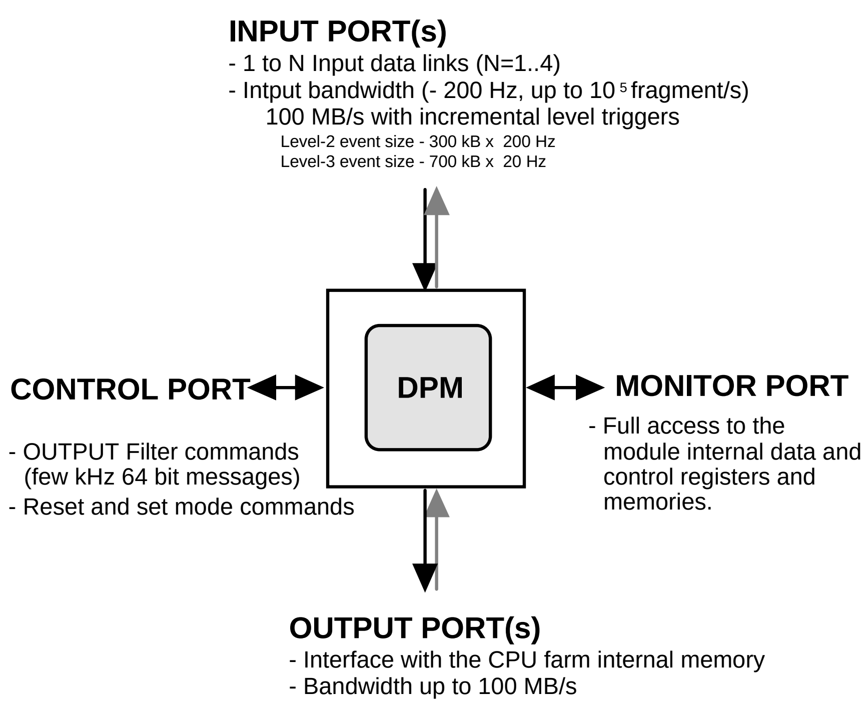


Figure 1.3.2.3: I/O Requirements for the Filter Unit (FU)

FU: Functional Decomposition

The functions of the Filter Unit are summarized in Fig 1.3.2.4. The Filter Unit is split into two logical parts: the SFI and the CPUs. The SFI is functionally split into three stages:

- Input, performed by the Filter Unit Input (FUI),
- Event Storage, performed by the Filter Unit Memory (FUM) and
- Event Output, performed by the Filter Unit Output (FUO).

The Control and Monitoring tasks are performed by the Filter Unit Supervisor (FUS) intelligence.

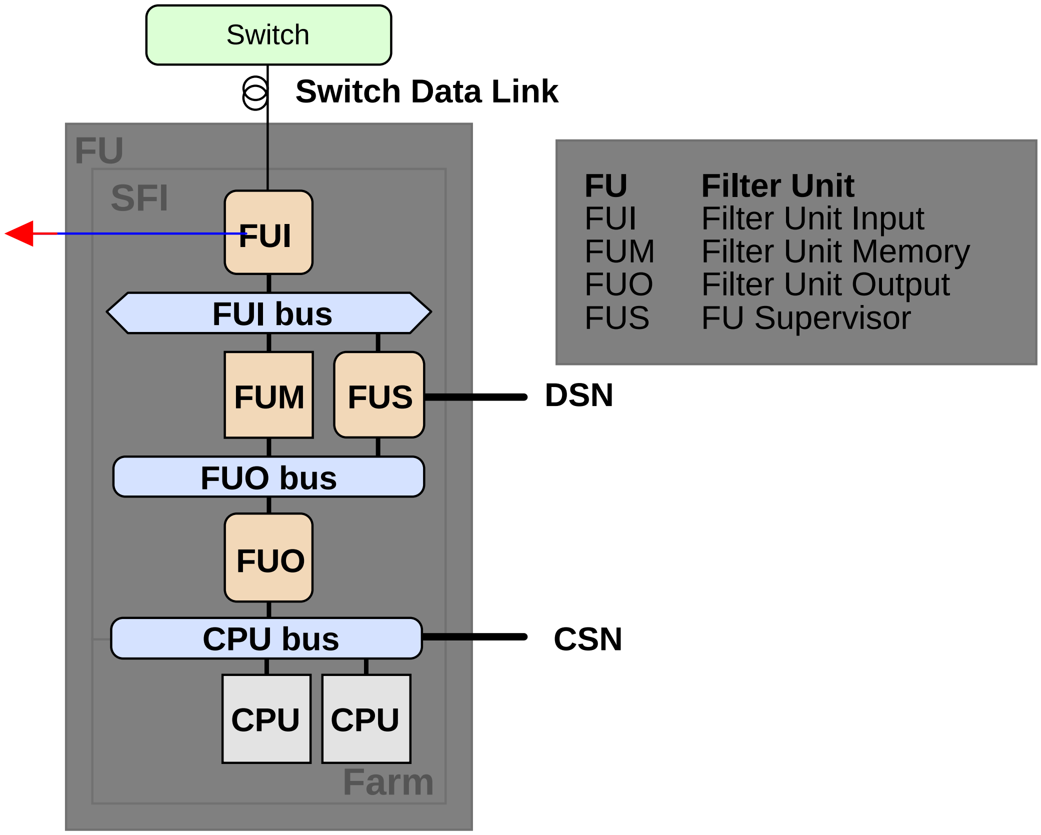


Figure 1.3.2.4: Functional Decomposition of the Filter Unit

The interconnections required for data traffic by the FU are:

1. FUI bus: a good candidate is the PCI bus (66 MHz, 64 bits)
2. FUO bus: same as the FUI bus
3. CPU bus: this could be either a workstation bus (connecting the SFI to multiple CPUs) or a network connection (e.g. Ethernet in sub-farm architecture)

The interconnections required for the control traffic of the FU are:

1. Level-2/3 request data message. This message will be sent to the Event Manager, via the Filter Control Network (FCN) and indicate to the EVM which Readout Units should send their data for the next step in the Event Building process. There are no strict latency requirements on this message. A good candidate is a commercial network like Ethernet.
2. Control and Status Network. This is a standard commercial network.

FU: Current Prototypes

In the current R&D program, the FU functionality and performance is being investigated using two complementary approaches:

1. A CMS-designed module (VORTEX) which provides, via the Texas Instruments C80 microprocessor, the full functionality of the FUI, FUM and FUO.
2. A sandwich of modules, consisting of a special-purpose FPGA memory module for the FUM, and two I/O modules: currently based on the Intel I/O Processor (IOP) family — i960RP.. In this option, the FUI, FUO and FUM modules are identical to the equivalent modules in the CMS Readout Units.

Both approaches use the PCI bus for the mechanical mounting and electric power supply. The PCI bus is used for both the FUI and FUO buses. The FUS functionality is implemented via an external CPU. In solution 2, the workstation CPU is used to implement the FUS.

Event Flow Control

The requirements for the Event Flow Control subsystem are shown in Fig. 1.3.2.5. The EFC should be capable of sending commands to up to 500 RUs, at a rate of up to 100 kHz, receiving commands (at the same maximum rate) from up to 500 FUs, and also assign FUs to each event that passes the Level-1 trigger (at a rate of up to 100 kHz). Again, in the CMS baseline, the nominal rate is 75 kHz, but the EFC is also designed to operate at up to 100 kHz. The networks implementing this communication are relatively low-bandwidth but also low-latency networks.

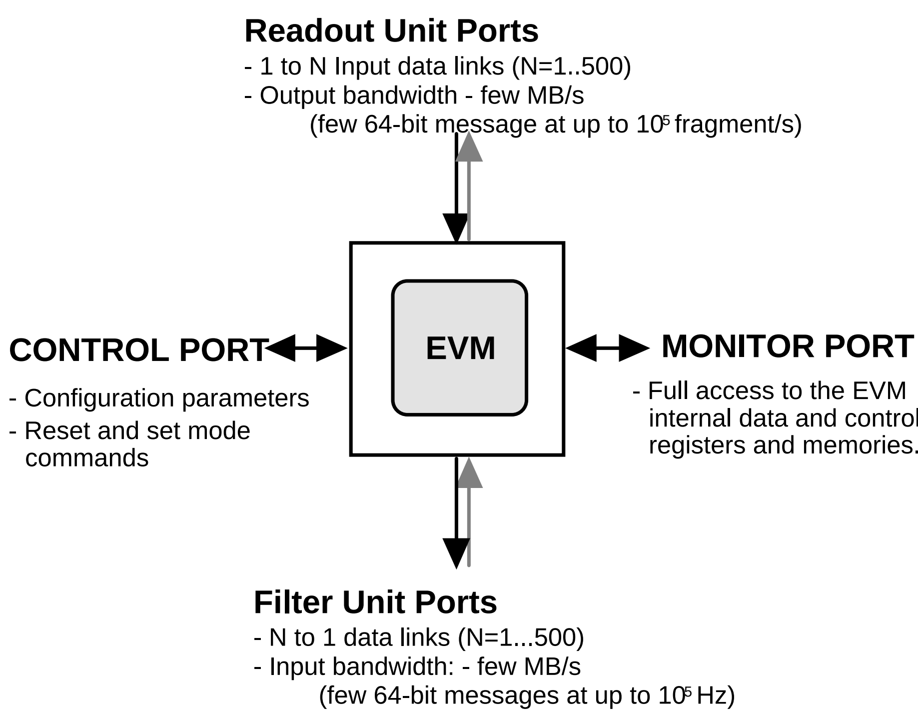
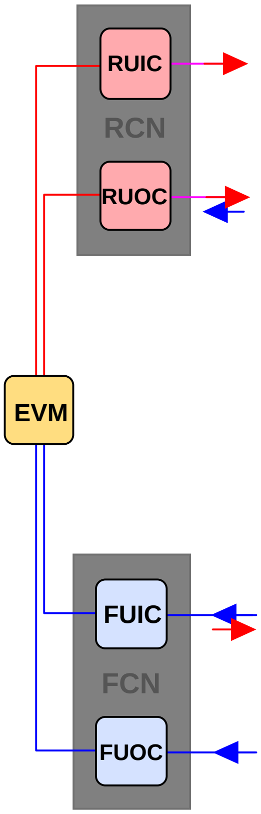


Figure 1.3.2.5: I/O Requirements for the Event Flow Control subsystem

EFC: Functional Decomposition

The functions of Event Flow Control (EFC) are summarized in Fig 1.3.2.6. The EFC is split into three logical parts: the Event Manager and the two communication networks, the Readout Control Network (RCN) and the Filter Control Network (FCN).



RCN. Readout Control Network

RUIC. Readout Unit Input Controller
Broadcast read event message (1 to N-512):
- Level-1 trigger and Event ID (100 kHz 32 bit messages)
- Reset signal(s) (up to 100 kHz)

RUOC. Readout Unit Output Controller
Distribute 1 to x(selectable set) -300 kHz 32 bit EVM commands:
- Associate Event (#ID) to Filter Unit resource (#CPU)
- Send event data to output port
- Flush event pointer
- Set mode/Test/Reset etc.

Collect (merge N-512 to 1) RU resource status
- Buffer occupancy (100 kHz strobe)
- Fault messages (few kHz 64 bit)

FCN. Filter Control Network

FUIC. Filter Unit Input Controller
Collect Filter Unit resource status (N-512 to 1)
- FU(SFI) free event buffers (-300 kHz 32 bit commands)
- Event assembly fault messages (few kHz 64 bit)

Distribute FU control messages
- Cross check information (e.g. #ID next event)
- Set mode/Test/Reset

FUOC. Filter Unit Output Controller
Collect Filter Unit messages:
- High level messages (fault & trigger back pressure ..)
- Event Builder Reset commands

Figure 1.3.2.6: Functional Decomposition of the Event Flow Control subsystem

The interconnections required for the EFC control traffic are:

1. Readout Control Network. This consists of two sub-networks, the RUI Control and the RUO Control. They (may) be different due to the different latency requirements on the RUI and RUO.
2. Filter Control Network. This consists of two sub-networks, the FUI Control and the FUO control. This second network is optional.

In the current R&D program, the EFC functionality and performance is being investigated using an Event Manager which is a software process running on a CPU, coupled with either a VME interface or a fast Ethernet interface.

1.4 Electromagnetic Calorimeter (ECAL)

Technical Description.

The deliverables for the electromagnetic calorimeter fall into three categories three categories: Avalanche Photodiodes, Front-end electronics and the Calibration Monitor Light Source.

1.4.1. Avalanche Photodiodes. (36,000)

Avalanche photodiodes (APD) are semiconductor diodes with internal electronic gain. There are two APD's per crystal in the barrel electromagnetic detector each with an active area of 25 mm^2. The APD operating gain will be 50, the ambient temperature of 18^oC. The anticipated neutron flux for 10 years is 2 x 10^{13} neutrons/cm^2. The APD parameters are given in Table 1.4.1

Table 1.4.1

Active Area	5 x 5 mm^2
Operating Voltage	< 500 V
Capacitance	<120 pF
Serial resistance	< 5•
Dark Current at M = 50	<10 nA
1/M * dM/dV (voltage sensitivity)	< 5%/^oC
1/M * dM/dT (temperature sensitivity)	< 2.5%/^oC
Spread of operating voltage	< 5V
Excess Noise Factor	< 2.3 at M = 50.
Passivation Layer	Si_3N_4
Quantum Efficiency at 420 nm	> 70%
Dark Current after 2x10^{13} neutrons/cm^2	< 5 • A
Survival rate	99.8%

The total number of components required for the ECAL are 120,400, with 2,000 spares. The US is responsible for the delivery of 36,000 of these.The design and development of the APD was shared with PSI. The final engineering run is a US responsibility as is a pre-production run of 2000 APD's. Responsibility for QA/QC for the APD's is shared with PSI.

1.4.2 Electronics.

The principle items for which the US are responsible are:

1) The design, test, production and verification of a custom radiation hard integrated circuit to be used in the front-end readout signal acquisition and digitization. (FPU)
2) The design, test, production and verification of a custom radiation hard integrated circuit to be used in the conversion of the output signal from the ADC to a serial data stream for fiber-optic data transmission.(Bit Serializer)
3) The design, production and verification of the front-end readout card, which houses the front-end readout circuitry.

Additional items contained within this element include R&D on radiation-hard power regulation systems, needed to provide power for the front-end readout electronics, and on the specification and radiation hardness assurance of a commercial analog-to-digital converter circuit which will be used in the front-end readout to digitize the signals.

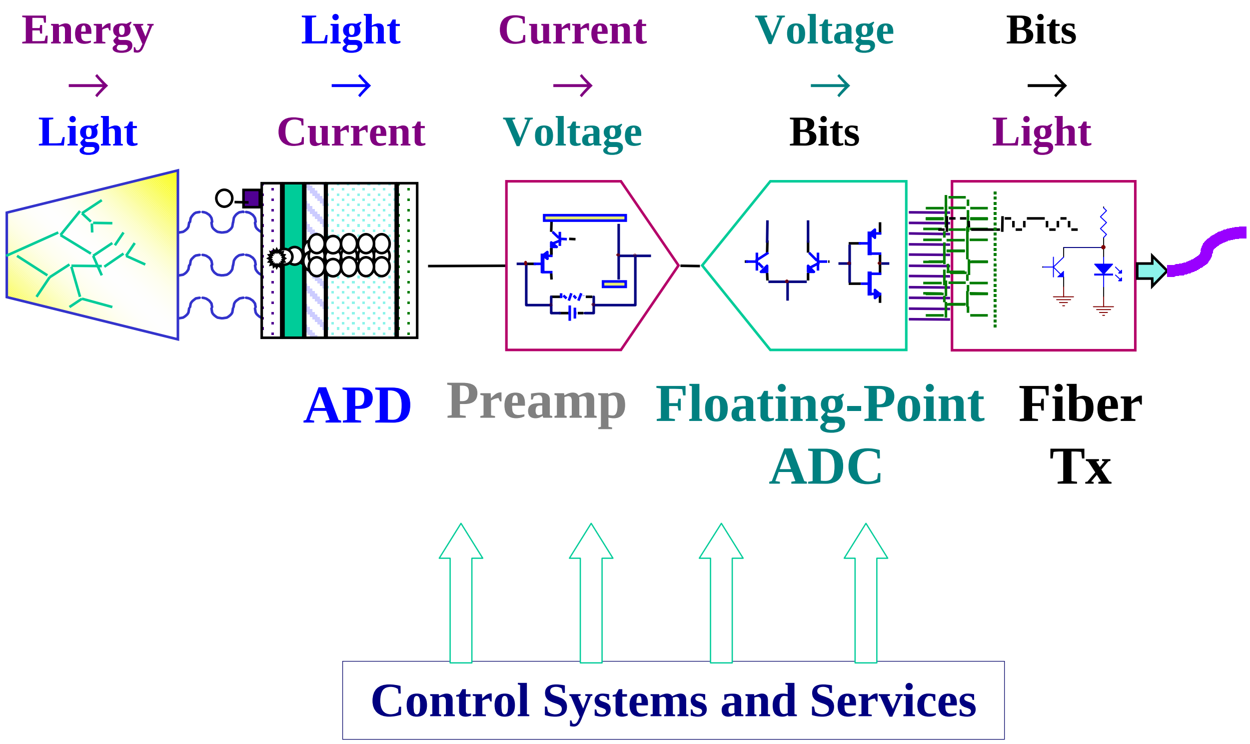


Figure 1.4.1 Schematic of the Very Front End Electronics Readout.

The FPU readout chip for the barrel front-end readout.

Deliverables: 61,200 pieces.

Functionality: The output of the two preamplifier outputs will be spilt between four amplifier channels 1, 8 and 32. The highest output which is not in saturation is selected by internal logic and routed to the output. Operationally the device works like a multi-ranging sample-and-hold operating at 40 mHz. The operation is shown schmatically in Figure 1.4.2.

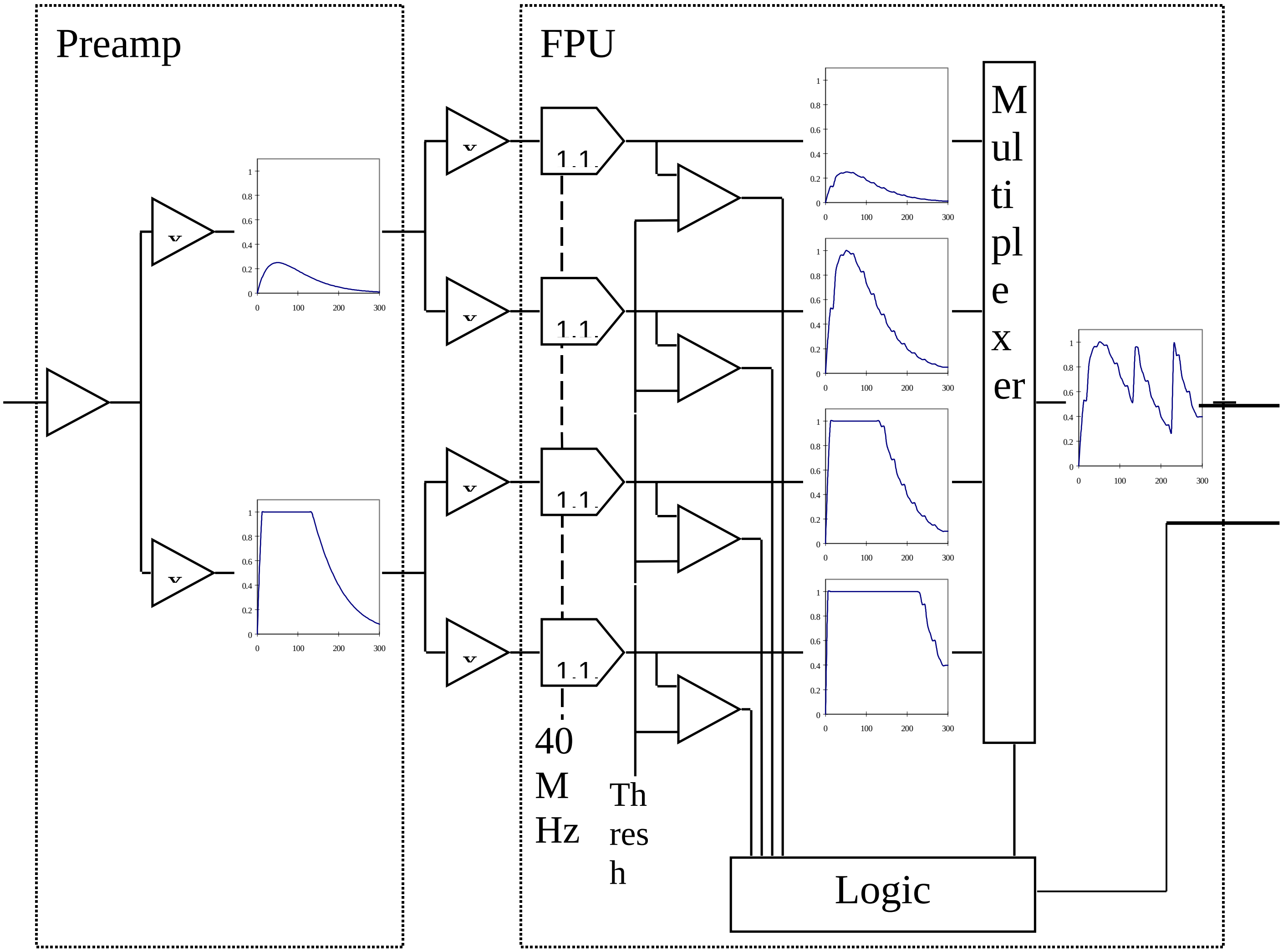


Figure 1.4.2 Block diagram for the Preamp and FPU

Bit Serializer:

Quantity: 62,100

Functionality: Receives the 12-bit output of the ADC and two gain bits from the FPU in parallel with a frequency of 40 MHz. This parallel stream is then converted to serial stream with four code bits. The 18 bits are sent as a serial steam to the diode driver circuit and thence to a VCSEL laser diode from where the signal is transmitted via a fiber optic link out of the detector. The US is responsible for the bit serializer and its packaging.

Readout Card:

This element includes the costs of a circuit card for the VFE elements, as well as EDIA on possible packaging alternatives. Various assembly techniques have been considered:
individually packaged components on standard PCB. This method requires the largest amount of space, and is fairly high cost due to the individual component packaging.
single PCBs with chip-on-board. This is the most economical technique, although issues of mechanical robustness must be studied.

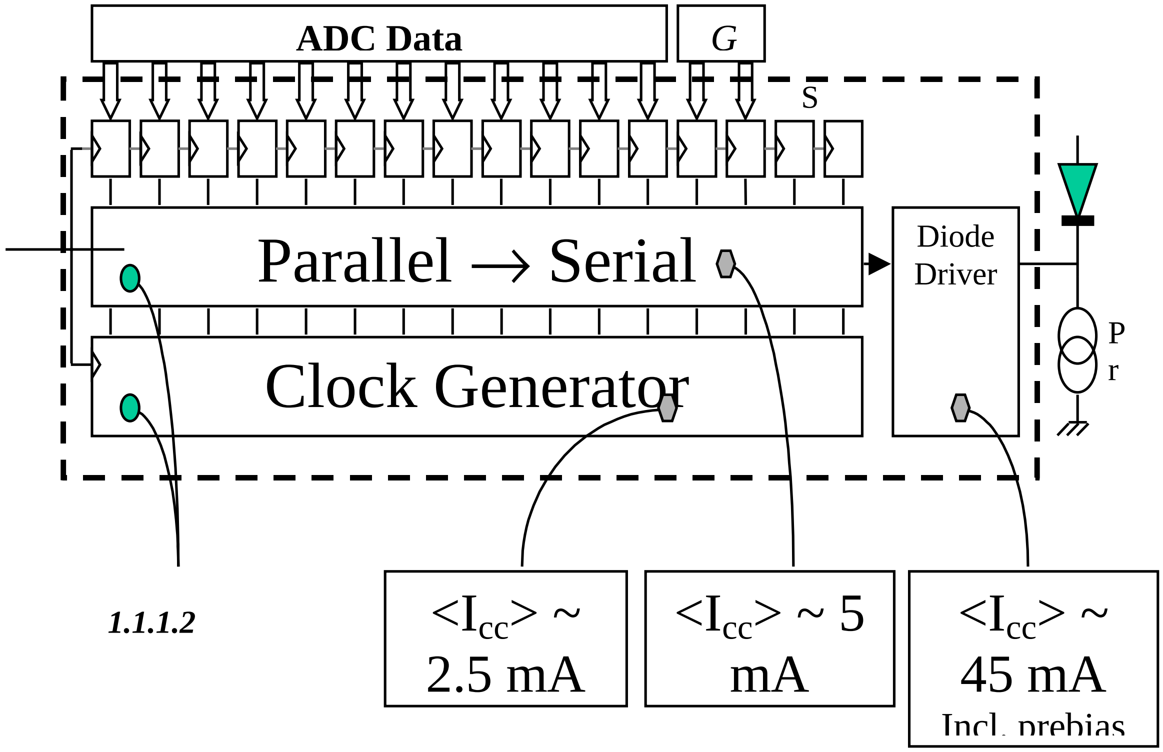


Figure 1.4.3 Schematic representation of the Bit Serializer.

1.4.3 Monitor Light Source

The light source will be a ND:YLF laser from Photonics. Model GM-30. The light from this high-power laser will be shifted to the suitable frequency for the lead tungstate crystals (420 nm) and distributed using a computer controlled optical splitter.

The light monitoring system is designed to inject light pulses into each individual PWO crystal to measure the optical transmission of crystals. The pulses are distributed via an optical fiber system organized into three levels: a light source and high level distribution system (LSDS) which sends pulses to a selected calorimeter element (1/2 barrel supermodule or group of endcap supercrystals), and a two lower level distribution system mounted on each calorimeter element which delivers the pulses to PWO crystals. The relative calibration of the injected light for each group of crystals is achieved by simultaneous injection on reference PN silicon photodiodes included in the distribution system. Calorimeter elements are pulsed serially to limit the power requirement to the light source, the size of data transfers, as well as low voltage current demands. The system is designed to continuously monitor the calorimeter in one of two operational modes:

1. Continuous In-fill monitoring during 3 us gaps in every 88.924 us in the LHC beam structure.

2. Stand-alone monitoring runs outside LHC fills to follow the recovery of the PWO crystals.

The principal goal of the system is the monitoring of any short-term evolution of the crystals' light transmission for intercalibration. The system will also be used to checkout the entire crystal-readout chain during assembly, and will permit a rapid survey of the full CMS ECAL during installation or after long shutdowns. Furthermore, the light monitoring system can be used to measure response linearity of the PWO crystal's photodetector and its readout chain from an equivalent energy of 500

MeV up to 100 GeV, representing 5 X 10^4 to 10^7 photons injected at the crystal, respectively. This should complement measurements with electronic charge injection at the preamplifier level which do not test the photodetector, but would have a larger dynamic range.

The construction responsibility of the entire monitoring system is shared by Caltech and Saclay groups. While Caltech is responsible for the construction of the light source and high level distribution system (LSDS), Saclay group is responsible for the lower level distribution chain and the reference PN diode readout.

The LSDS provides light pulses at two wavelengths, one at the emission peak of the doped PWO crystal (~420 nm) and the other at peak of pure PWO crystal (~510 nm). (Note, this is our present knowledge. We have to test new Nb/Y doped samples from BTCP and Sb doped samples from SIC to reach conclusion.) The pulse length is 20-40 ns of full width to match the electronics readout. It also provides up to 10^7 photons per pulse per crystal, which corresponds to 100 GeV equivalent in dynamic range. Since the overall optical transmission efficiency from the light source to individual crystal is better than 5 x 10^{-8}, the maximum pulse intensity sent to level-2 fanout is required to be 0.2 mJ/pulse. The light source is also triggerable at a rate of 1 to 11 kHz, synchronized to the 3 • s beam gap in LHC beam structure. The exact operation rate will depend upon the fraction of the 3 us gaps really used for monitoring. The LSDS switches the light pulses to one designated ECAL barrel supermodule half or endcap Dee half. This reduces the total power requirement to the light source. The LSDS has also an ability to send the light pulses of defined intensity to each individual crystal by monitoring the pulse intensity sent to level-2 fanouts and adjusting the light source intensity correspondingly.

The LSDS consists of four components: a laser system, a mechanical fiberoptical switch, a pulse intensity monitor and a PC-based control system. We plan to use a laser based light source consisting of two Q-switched GM-30 Nd:YLF lasers and one TU-UV tunable titanium doped sapphire laser. The GM-30 green laser is a commercial available pump laser, designed for scientific applications. It is based on intracavity frequency doubling technology via LBO nonlinear crystal. Intracavity high peak power of fundamental beam makes efficient frequency conversion to 527 nm green laser beam. Folded resonator combines both green laser beams generated in two directions into one single laser output. The Nd:YLF crystal medium is continuously pumped by a Krypton arc lamp. With the Q-switch on, the Q of the cavity is kept low to prevent lasing action. When the Q-switch is off, the Q of the cavity is immediately changed to a high level, and stored energy is released in a short time to produce short, intensive laser pulse. In our system, one GM-30 is used as a pump for the TU-UV and the other GM-30 is used for a linear amplifier to achieve the designed intensity. The TU-UV Ti:Sapphire is a pumped, intra-cavity, frequency doubled laser, and is also commercially available. The use of TU-UV Ti:Sapphire laser enables tunable wavelength.

This laser system will provide light pulses of up to 0.4 mJ/pulse with a pulse width of 20-40 ns and a repetition rate of up to 11 kHz. The pulse to pulse intensity stability is about 3%. The laser system may be triggered by an external TTL signal with a delay about 4 us. The trigger delay jitter is less than 10ns, and can be improved to about 3 ns if required. The output of the laser system is optically coupled to the fiberoptical switch, and the operation of the laser system is controlled by the PC in the control system through a commercial interface from National Instruments.

The mechanical fiberoptical switch distributes light pulses from the laser system to 80 level-2 fanouts, where 72 are barrel supermodule halves and 8 are endcap Dee halves. The principle component of the fiberoptical switch is a precision step motor which moves the input fiber to couple to one of multi output fibers with an air gap. The insertion loss of this fiberoptical switch when using 365 um fibers is about 2 dB, and the isolation between any two channels is less than -80 dB. The average switch time between any two level-2 fanouts is about 1 s. The output fibers of the fiberoptical switch are optically coupled to the 150 m long phi 265 um quarts fibers connected to the level-2 fanouts. The switch is also controlled by the PC in the control system through a GPIB interface.

The light source monitor consists of 80 PIN photodiodes, which monitor the intensity of light pulse in level-2 fanouts, and four Biplanar PMTs, which monitor the sum of the light pulse intensities in two half barrels and two endcaps.

The entire operation of the LSDS is controlled by the PC-based control system, which controls and displays the working conditions of the laser system and the fiberoptic switch. It also controls the designation and the intensity of the light pulse sent to level-2 fanouts.

1.5 Forward Pixels (FPIX)

Component. (required units): Pixels. (12 x 10^6) / Sensors. (672)

The majority of the pixels (95.64%) are squares of 150 μm sides, as indicated in Table 1. The rest of the pixels have rectangular shape and are located on the sensors in the region between two neighboring Readout Chips. Figure 1 indicates how the pixels are layout on the sensors including the region between two Readout chips. Also shown are the locations of the bumps. Figure 2 gives the dimensions of the channel stops. Table 2 gives the dimensions of the sensors, as well as the numbers of readout chips required for each sensor. The sensors are 250 μm thick.

The US CMS will design and procure the sensors.

Readout Chip (ROC). (4,320)

The Readout Chip is 1.0150 cm in *r*, and 0.8010 cm in $r\varphi$. It is 180 μm thick. The sensors of one blade are readout with 45 ROCs. The analog logic of the chip needs ± 2.5 V and the digital logic ± 5 V. Each pixel dissipates 60 μW pixel. The electronics associated with each disk consumes 250 W. The ROC communicates to the rest of the world through 20 wire-bonds.

The US CMS will procure the ROCs developed by PSI.

Blades. (96)

Each of the 4 disks is made of 24 blades configured in a ‘turbine blade’ geometry. The dimensions of the blades and the position of the sensors on the blade are given in figure 3. Also shown are the location of the readout chips on each sensor.

The US CMS will design and build the blades including its cooling.

Disks, ½ units. (8)

There are 2 disks located on each side of the interaction region (IR). The disks are split in 2 halves for installation reasons. These two sets of disks are not identical but have the blades rotated such to have point symmetry relative to the IR. Table 3 gives the position of the disks along the z-axis, as well as the number of components on each disk.

The US CMS will design and build the mechanical support of the disks including the cooling.

Space Cylinders, ½ units. (8)

Two 1/2 disks are mounted on ½ unit of space cylinder. Here too, these cylinders are split in two laves along their axis for installation reasons.

The US CMS will design and build 8 units of ½ space cylinders.

Service Cylinders, ½ units. (8)

From z = 3 m to z = 0.5 m all the lines serving the forward pixels will be carried by units of ½ service cylinders. These lines include power, cooling, optical fibres for the data transmission and monitoring, and bias voltage.

The US CMS will design and build 8 units of ½ service cylinders.

Installation.

The US CMS will supply the hardware needed to install and align the Forward pixels in their final position.

Components along the signal path after the readout chip.(required units)

High Density Interconnect (HDI). (672)

The signals from the readout chip are collected by a multi layered Kapton printed circuit and then carried to an interface (Port Card) through a flex cable. There are 7 HDIs on one blade, one for each of the 7 sensors.

The US CMS will design and procure the HDIs.

Port Card. (192)

Each blade has 2 Port Cards. A Port Card is a low mass printed circuit board with 4 ASICs and 4 laser drivers to transmit the data from the pixels. Bias voltage to the sensors will also be distributed on the Port Card. One of the ASIC, the Token Bit Manager (TBM), is detector dependent and will be designed by the US CMS group. The other 3 ASICs, the CCU (Communications Control Unit), the CDU (Detector Control Unit), and the PLL (Phase Locked Loop), are common to the CMS trackers.

The US will design and build the Port Cards and the TBM. It will purchase the three ASICs: CCU, CDU and PLL.

Optical Links. (768)

Each Port Card sends the data to ADCs through 100 m long optical fibres. This system including laser drivers, optical fibres and receivers are common to all the CMS trackers. The encapsulation of the optical driver must be redesigned because is too massive for the pixels given their proximity to the IR and the concern to keep the material budget to a minimum. The data rates of the Forward pixels is given in Table 4.

The US will redesign the encapsulation of the optical link and procure the optical links as well as purchase the other components of this system.

Front End Controller (FEC). (768 ch.)

Are located in the counting room, receive the signals from the optical fibers and deliver them to the ADCs. They are common to the CMS tracking system and built in 64 channel modules.

The US CMS will procure 14 FECs modules, each one with 64 channels.

ADCs. (768 ch.)

Eight bits VME ADCs will decode the signals. These ADCs are produced in modules of 64 channels. The group from Vienna, members of the Barrel effort, will design these ADCs.

The US CMS will procure 14 ADCs each one with 64 channels.

Services.

The US CMS will procure the necessary power supplies, the cables, and the chiller for cooling the electronics on the blades and the Port Cards.

Pixel size [μm]	Chips / Sensor Unit **(Units needed for one blade)**					**Pixels / blade**
	2 chips (1)	5 chips (1)	6 chips (2)	8 chips (2)	10 chips (1)	
150 (r) x 150 ($r\varphi$)	5406	13356	15808	21008	26208	118602
225 (r) x 150 ($r\varphi$)	-	-	304	404	504	1920
150 (r) x 300 ($r\varphi$)	106	424	416	624	832	3442
225 (r) x 300 ($r\varphi$)	-	-	8	12	16	56

Table 1. Number and sizes of Pixel cells on a Blade

Columns x rows	**Sensors / blade**	**($r\varphi$) [cm]**	***r* [cm]**
2 x 1	1	1.730	0.935
3 x 2	2	2.540	1.745
4 x 2	2	3.350	1.745
5 x 2	1	4.160	1.745
5 x 1	1	4.160	0.935

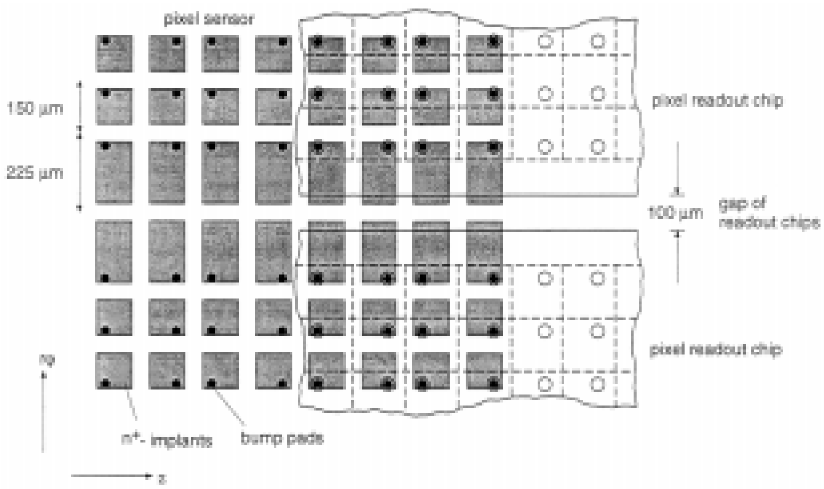
Table 2. Outside Dimensions Sensors

z cm	Radius **mm**	**Blades**	**Sensor Modules**	**Chips**	**Pixels**	**Area m^2**
± 32.5	60 - 150	24	7	1080	3.0×10^6	0.07
± 46.5	60 - 150	24	7	1080	3.0×10^6	0.07

Table 3. Parameters of the CMS pixels End Disks.

	1.5.3.1
Number of readout chips	4320
Luminosity $L = 10^{34}\ cm^{-2}\ s^{-1}$	1.0
Average number of hit pixels per chip	0.52
Number of transmitted signals per hit pixel	10
Average number of signals per chip per event	5.2
Chips per link	3 - 9
Average data rate per link [MHz]	2.1
Number of links	768
Number of FEDs	12

Table 4. Data rates in the Forward Pixel.



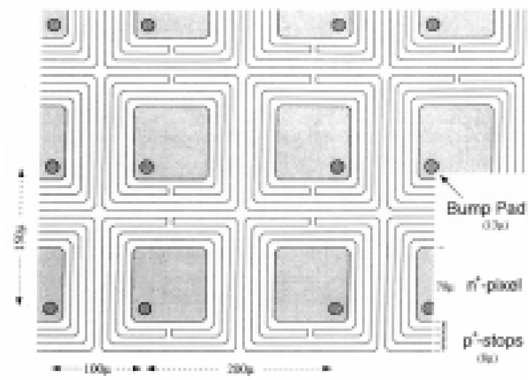


Figure 1. Layout of sensors, in region of two neighboring Readout Chips.

Figure 2. P-stop rings around n+-type pixels.

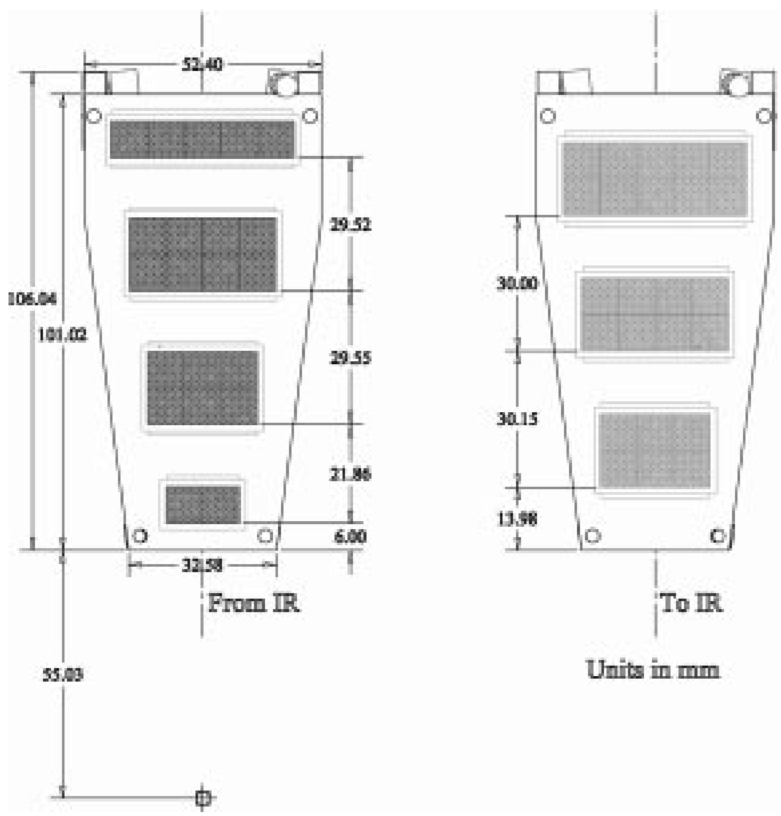
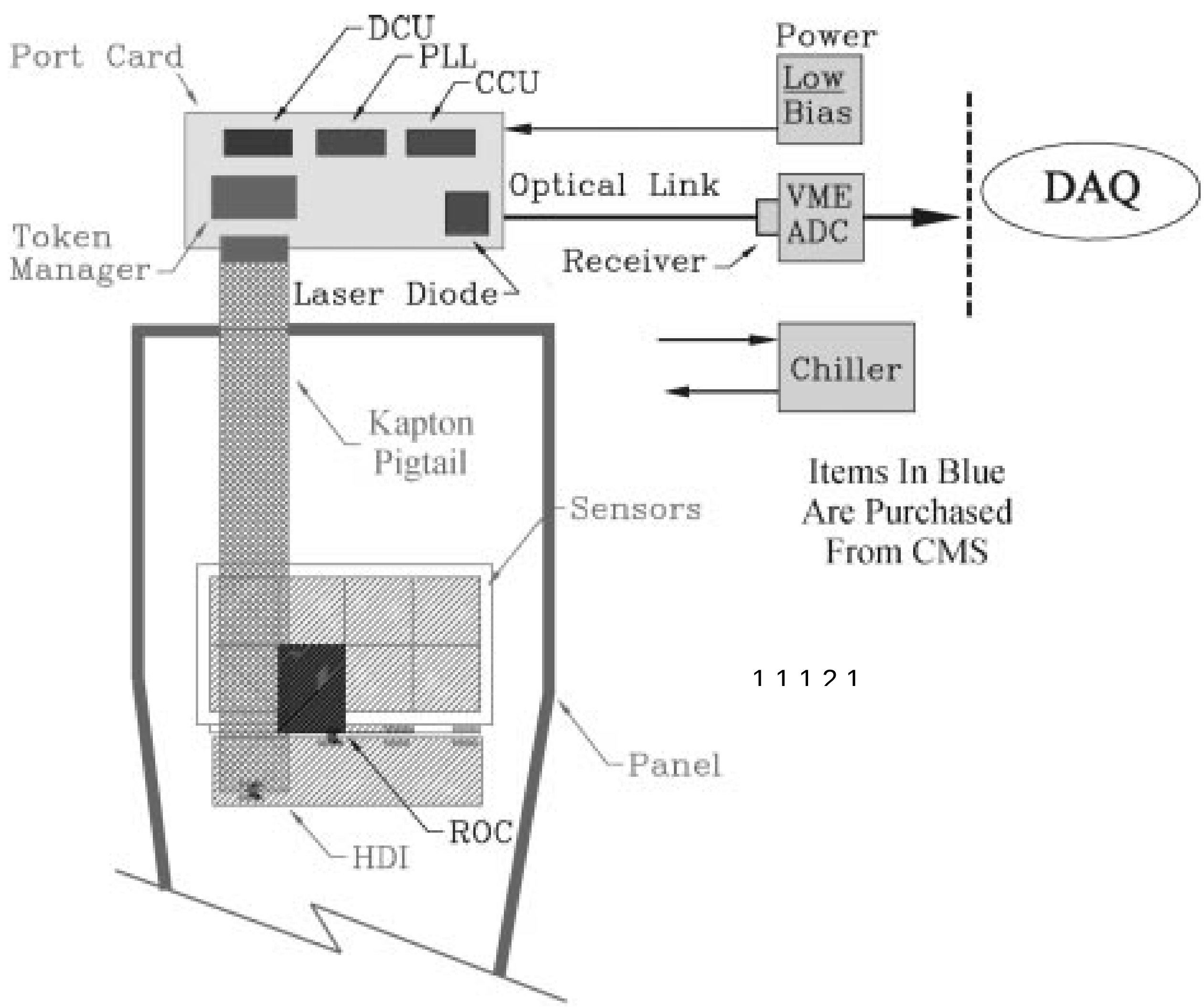
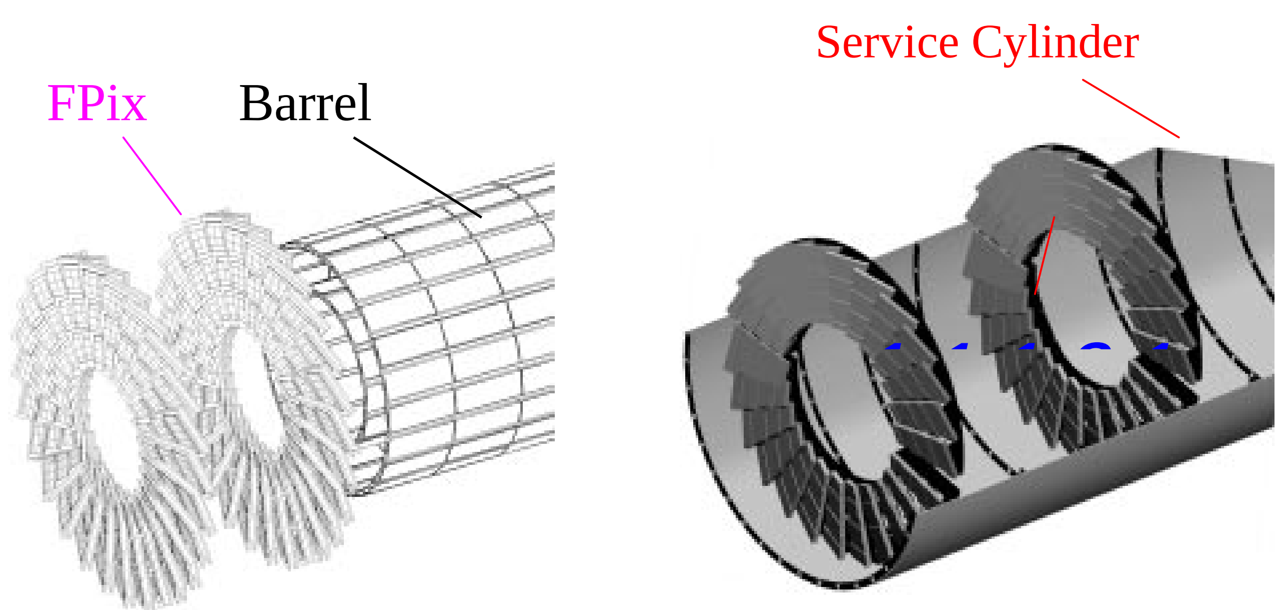


Figure 3. Dimensions of the Blade and position of the sensors.

System Overview





1.6 Common Projects (CP)

1.6.1 Barrel Yoke and Vacuum Tank

The US CMS is responsible for payment to the barrel yoke contract. There is no procurement, or supervision responsibility. Nevertheless, the FEA for the loading of the vacuum tank by the inner detectors, notably HCAL, was performed by Fermilab. Indeed, the vacuum tank was redesigned on the basis of this study and considerably strengthened. In addition, the rails which hold the HCAL are part of the vacuum tank. These rails were designed by the HCAL engineering team, and the through weld technique, again leading to an improved safety margin, was specified by that team. The rail FEA was also performed by the HCAL engineering design team.

1.6.2 Superconductor, Pure Aluminum and Aluminum Stabilizer

The US CMS Project is responsible for the procurement and supervision of the order for the superconductor strand, the ultra pure aluminum and the bulk aluminum for the magnet coil. This effort involves specification of the materials, creating the bid package, evaluating the bids, awarding the contract, and later vendor supervision. Responsibility for this effort resides at Fermilab, with R. P. Smith taking the leading role.

1.6.3 Endcap Yoke

1.6.3.1 Introduction

The CMS endcaps, located at each end of the detector, consist of 3 large diameter iron disks (YE1, YE2, and YE3) and 1 smaller diameter (nose) disk mounted axially along the beam line. The primary function of these endcaps is to return the large magnetic flux from the 4 Tesla field by concentrating it within the iron. These endcap disks provide mechanical support for the CMS endcap muon system. The large quantity of iron in these disks also acts as an absorber to filter out the hadronic backgrounds. Table 1 shows the sizes and weights of each disk.

Iron element	YE1	nose	YE2	YE3
Outer radius (mm)	6955	2630	6955	6955
Inner radius (mm)	975	1000	950	1040
Thickness (mm)	600	920	600	250
Weight (tons)	721	144	721	300

Table 1. Geometry of the endcap disks.

In order to provide access to the CMS detector elements, each endcap must move axially. Each disk is mounted on a cart which moves on four air pads. Hence each disk can move independently of the other disks. When assembled as an endcap the disks are connected at the outer perimeter and have spacer rings providing support at the inner radius. The entire endcap is supported on the barrel yoke by the Z-supports which are located at a radius of roughly 4750mm.

An important design question for the endcap yoke is the large 4 tesla magnetic field. Such a field creates large magnetic forces on the disks which are listed in Table 2. The ratio of magnetic force to weight for the first disk, YE1, shows a static magnetic force equivalent to an acceleration of roughly 8 G's. These large forces act to deflect the disks toward the CMS interaction point. Our calculations indicate a maximum deflection of roughly 14mm when the field is energized. The amount of deflection depends critically on the preload provided by the Superbolts in the disk assembly. The overall design of the endcap disks is greatly influenced by the magnetic loads.

element	Magnetic force (MN)	Magnetic force (tonnes)	Weight (tonnes)
YE1 + nose	61	6200	865
YE2	17	1700	721
YE3	2	150	300

Table 2. Endcap magnetic forces.

The US/CMS Project is responsible for the design of the endcap iron, the supervision of both manufacture and assembly at CERN as part of the US contribution to the CMS Common Projects. The US/CMS is also responsible for much of the procurement of these items. The specific responsibilities are elaborated in each section.

1.6.3.2 YE1 disk

The YE1 disk is composed of 20 roughly equal trapezoidal blocks each weighing about 35 tonnes. The blocks are bolted together using Superbolts (see section 1.6.2.8). Each block has 9 concentric rings of Superbolts, each at a different radius, connecting it at each interfacing surface. When the magnetic field is activated the disk will dish in toward the IP. As a result, on the face away from the IP the surfaces are in compression; the side toward the IP will be in tension. Of course, the Superbolts must provide sufficient preload that all surfaces are in compression. In order to provide additional stability there are inner rings of high strength steel on both the interior (toward the IP) and exterior faces.

The steel blocks are made of low carbon steel with a yield strength of at least 250 MPa. The relative permeability must be at least 140 at an induced field of 1.8 tesla, and the uniformity of permeability within one disk must be less than 5% at an induced field of 1.8 tesla. The blocks are 600mm thick (for YE1 and YE2) and 250mm thick for YE3. These blocks may be rolled or forged as long as they meet the specifications stated above.

The interfacing surfaces (where the Superbolts tie the blocks together) are machined. Other surfaces do not need to be machined but they must meet the overall tolerances for the disk. The tolerances for the disks are stated for the assembled disks and not for individual blocks. The manufacturer must insure that the block tolerances are sufficient that when assembled into a complete disk, the tolerances are achieved.

Mounted to the front face of YE1 are two large nose disks (YN1 and YN2) and a very large (300-tonne) forward calorimeter which will be cantilevered from YE1. The anchor points for the supporting struts are placed as high as possible (blocks 12 and 16) on YE1 because of this large cantilevered load.

On the tension and compression faces of YE1 there will be a number of additional holes for interfacing to other elements or subsystems of CMS. On the tension side of YE1 there will be holes for (1) the Z-supports (mechanical support for the endcaps), (2) the mounts for the cathode strip muon chambers, (3) the outer connections (see Section 1.6.2.9) which tie the disks together and to the barrel rings. Drawings exist to locate and specify all these holes. Table 4 gives a list of the hole drawings for YE1.

1.6.3.3 YE2 disk

The YE2 disk is very similar to the YE1 disk; all material specifications are identical. However, since the magnetic forces are much less there are fewer Superbolts required. There are only 6 concentric rings of Superbolts in YE2 (compared to 9 rings in YE1). In addition, since there is no cantilevered load on YE2, the anchor points for the supporting struts are placed at a lower height (blocks 13 and 17) instead of the YE1 location (blocks 12 and 16). There will be two YE2 disks, one for each endcap of the CMS detector.

1.6.3.4 YE3 disk

The YE3 disk is also very similar to the YE1 disk; all material specifications are identical. YE3, however, is only 250mm thick. Once again, since the magnetic forces are much less there are fewer Superbolts required. There are only 3 concentric rings of Superbolts in YE3 (compared to 9 rings in YE1). Furthermore, since YE3 is only 250mm thick these Superbolts cannot fit at the same radius on both the tension and compression side so the locations are offset. The anchor points for the supporting struts are placed at the same height as in YE2 (blocks 13 and 17).

1.6.3.5 Endcap Nose (YN1 and YN2) and HE connection

The endcap nose disks YN1 and YN2 provide mechanical support for the large cantilevered load of the forward calorimeter (HE) as well as shaping the magnetic field for the endcap muon chambers. Both YN1 and YN2 are supported on the nose support tube as shown and attached to the YE1 disk with large tie rods. The YN1 disk has 6 • slots machined for the alignment passages located at z – 6635. The YN1 disk also has machined connections at the outer radius for the five HE connection brackets per endcap.

Because the magnetic forces in this area are very large, the HE connection has been designed with a slip joint. As the YE1 disk deflects it exerts a force couple on the HE; tension at the outer edge (R = 2700) and compression at the inner edge (R = 775). A slip joint at R = 775 decreases the compression force on HE and prevents any bending moment on the back face of HE

As a result of the alignment passages the two endcaps will not be identical. Both YN1 and the nose support tube will be different on each endcap, and separate drawings are specified.

1.6.3.6 Endcap Carts (YE1, YE2, YE3)

Each disk is supported permanently on a large steel cart structure which is also used for moving the disks. These carts are made from a steel weldment, two strut assemblies, and one hinge-keel mechanism. The carts are each supported by four air pads which typically have a 250-tonne capacity. The air pads for the YE1 cart will have a capacity of at least 350-tonne each because of the higher loads on YE1. The expected weight of a fully loaded YE1 cart is 1375 tonnes. Since the experimental floor is inclined at 1.3% slope, the center of gravity for the +z and –z carts will be different so the location points for the air pads will also be different.. Whenever the magnet is energized the carts will rest on grease pads which have a horizontal motion. Hence the +z and –z carts will have a slightly different location for the grease pads.

The hinge mechanism is necessary because as the magnet is energized and the disks bend, the support point must be free to rotate. The struts keep the disk in the vertical position and are used to adjust the attitude of the disks by changing the length. The keel mechanism is a fail-safe device and is intended to keep the disk from falling in case of a total strut failure.

The struts are made from a hollow tube which is attached on both ends to threaded parts with a pair of spherical thrust washers and a pair of nuts. The washers are arranged to make a spherical joint at each end of the strut. Hence the strut length, and thus the disk attitude, can be controlled from either end of the strut.

The hinge for each disk is made in two parts on either side of the keel. The hinge is bolted to the bottom of the disk and to the top of the cart weldment. The keel is a plate attached to the bottom of the disk and is suspended inside a rectangular hole in the cart weldment.

The cart weldments are mostly made from 100mm plate steel. The yield strength of the steel plate must be 240 MPa, which is structural quality steel ASTM A36 or equivalent. Two endcaps are required, items in table are per endcap.

The YE3 cart is quite different from the others . The disk is lighter so the hinges are smaller and located farther from the beam line. The YE3 cart must be designed to carry a large shielding wall behind the ME4 muon station chambers. This wall will not be present at the beginning of CMS so the center of gravity will change by a substantial amount.

CERN has made a preliminary agreement with the Chinese Academy of Sciences that the CAS and CERN will provide funding for the procurement of all the endcap carts. US CMS will have the technical responsibility for supervision of production and acceptance of the carts.

1.6.3.7 Endcap Spacer Rings and Endcap Wall

The spacer rings span the distance between the endcap disks in the closed position. Each ring is permanently attached to one disk by bolting to the center ring on the compression side of the disk. These rings carry the magnetic flux to disks YE2 and YE3. Because of this magnetic flux these disks deflect enough that the spacer rings remain in compression while the field is energized. Thus the spacer rings carry forces between the disks. These spacer rings also provide shielding for the muon chambers mounted on the faces of the disks.

the alignment lines for the muon chambers pass through slots machined in these spacer rings. Due to the asymmetry of the alignment system the +z endcap rings will be different from the –z endcap rings.

1.6.3.8 Superbolts

The Superbolts are large (M72) bolts for the assembly of all the disks. These bolts allow a significant and well-defined preload to hold the blocks together under the large magnetic forces.. Once the disk has been assembled and preloaded, these machined cavities are closed with fill blocks tack welded into place. The right side of Fig. 14 shows the 12 M16?? Bolts used to tighten (preload) the Superbolt.

1.6.3.9 Disk Connection

Each of the disks must be supported at the inner and outer edges against the large magnetic forces. On the inside edge the spacer rings perform this function. On the outside edge the disks are separated by posts. The disk itself is a dodecagon (12-sided) so the post assemblies are located at each of the twelve points of the dodecagon. In order to maximize the space for muon chambers each post assembly contains two small posts rather than one large one. These connections tie together not only YE1, YE2, and YE3 but they also tie YE1 to the barrel iron yoke.

Each post contains a spherical bearing to minimize stresses due to location tolerances for the disks and the bending motion of the disks under magnetic loading. At four post assembly locations per disk there is a hydraulic jack which connects the two disks and is used to pull them together tightly prior to energizing the magnetic field. These jacks can also push them apart for disassembly and maintenance.