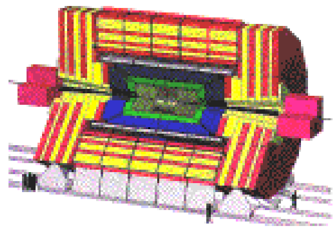
US  CMS

The Compact Muon Solenoid

US CMS FY 1996
Supplemental Funding Request

November 17, 1995

Abstract

This document provides details of the US CMS Collaboration FY 1996 supplemental funding requests to DOE and NSF. The requests are presented in the context of the completed FY 1995 activities, the CMS schedule and milestones, and the management and construction responsibilities of the US CMS groups. Both R&D and travel funds are requested to sustain US CMS activities during the period prior to the anticipated FY 1997 project funding. The FY 1996 supplemental R&D funding request is $2700K from DOE and $500K from NSF. In addition, $300K in supplemental university travel funding is requested of DOE.

Contents

List of Figures

List of Tables

1 Introduction

The US CMS long term project has been given a detailed exposition in the US CMS Letter of Intent (LOI) [1]. That construction project represents at present the aspirations of 324 physicists from 40 US institutions.

This document is the global US CMS FY 1996 proposal. A separate document gives more detail for the NSF requests [2]. Much more information in regard to the FY95 accomplishments is provided in the US CMS LOI [1]. In this document we concentrate on the requests for FY96 to both DOE and NSF in the light of the completed FY95 activities and the long range schedule.

A summary of the major milestones appears in Annex 9 of the CMS Interim Memorandum of Understanding (IMOU) [3]. The full set of CMS milestones for each subsystem appears in the relevant subsection of Section 3 of this document. The schedule for CMS from now until the initial run of CMS in 2004 appears in Fig. 1. Within CMS, the US CMS responsibilities are spelled out in broad terms in the IMOU. A short version of the participation of US CMS groups in the subsystems of the detector appears in Table 1. It is within the context of the schedules, milestones and responsibilities of the US groups that this R&D request is made. The participation of US CMS groups in the R&D, prototyping, and construction efforts of the CMS detector subsystems appears in summary in Annex 6 of the IMOU [3].

Given where the US CMS Collaboration is in FY95, and where it is going, the request for FY96 occurs within a well defined framework. The US CMS groups are wholly responsible for building the endcap muon detectors, for designing the endcap steel return yoke, for building the barrel and half the very forward hadron calorimeter, and for constructing the related muon and calorimeter level 1 trigger systems. In addition, US CMS groups are responsible for major and coherent efforts within the other subsystems. Within the electromagnetic calorimeter, we are responsible for APD evaluation, front-end electronics R&D, and crystal characterization. Within the tracking system, US groups are leading the R&D in forward pixels and forward microstrip gas chambers (MSGCs). In the area of software and computing we naturally lead in detector performance modeling for the EMU and HCAL systems.

A summary of the level of support required to sustain these R&D activities in FY96 is given in Table 2. The M&S and labor cost estimates shown include institutional overhead charges. A detailed breakdown of the activities, the deliverables, the associated costs and the participating groups is given in Section 3 of this document on a subsystem by subsystem basis. Also shown in Table 2 is a summary of the supplemental travel support requested of DOE. The context of the requested travel support is included in Section 3, and details are provided in Section 4. We note that the requested level of funding is the minimum necessary to sustain the US groups in their ongoing activities.

US CMS physicists also have project management responsibility in CMS for the EMU, HCAL, and Trigger systems. These responsibilities require some supplemental funding in order to fulfill our obligations. In particular, travel to frequent meetings with LHCC referees and to subsystem group meetings is needed. The need for this support is explained in more detail in Section 4 of this document.

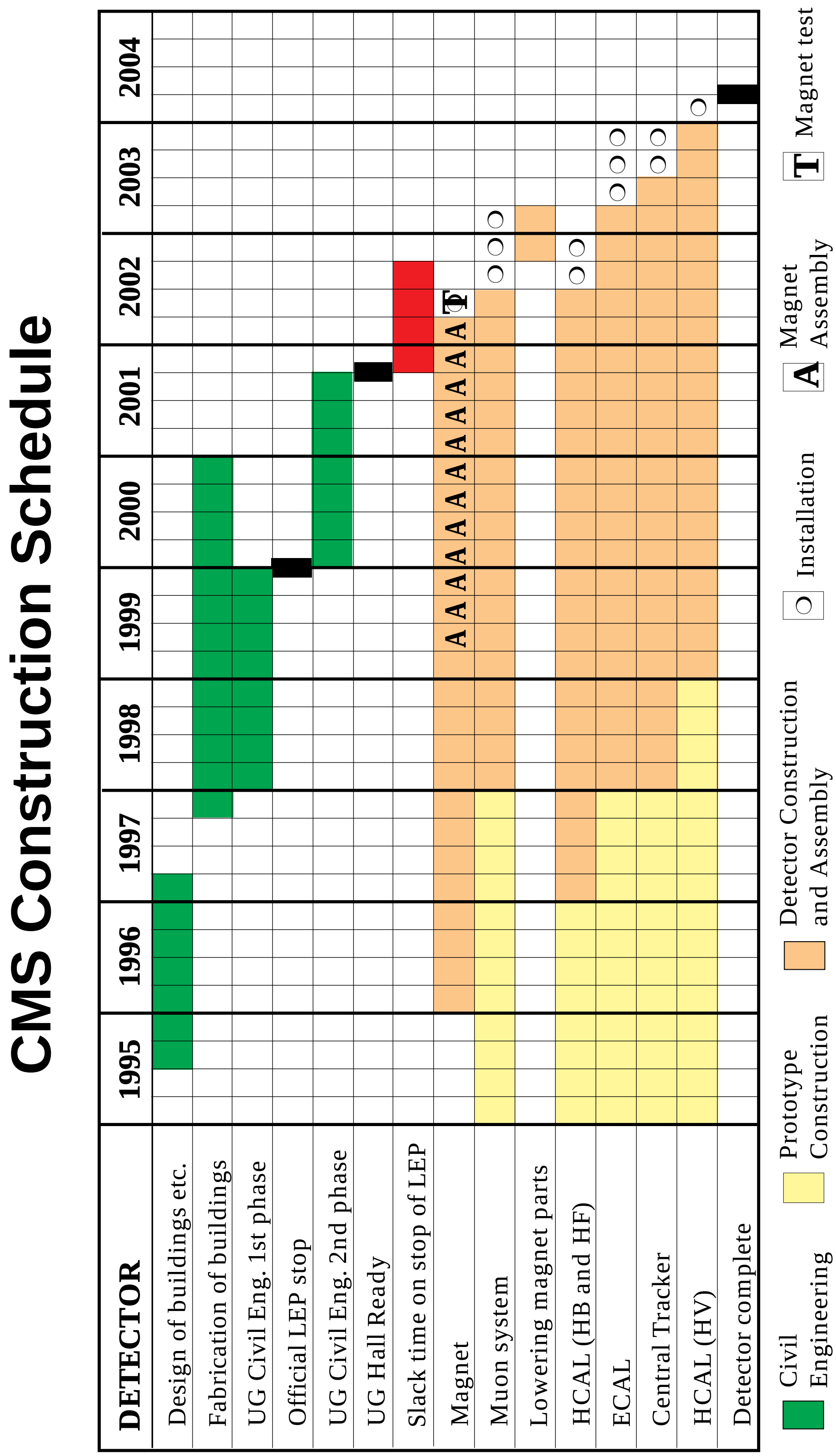


Figure 1: CMS construction schedule: 1995 to 2004.

Table 1: US CMS Subsystem Participation.

Endcap Muon	HCAL	Trigger/DAQ
Alabama	Boston	UC Davis
UC Davis	UCLA	UCLA
UCLA	Fairfield	UC San Diego
UC Riverside	Fermilab	Fermilab
Carnegie Mellon	Florida State	(Iowa)
Fermilab	Illinois Chicago	Iowa State
Florida	Iowa	MIT
Livermore	Iowa State	Mississippi
MIT	Maryland	Nebraska
SUNY Stony Brook	Minnesota	Ohio State
Ohio State	Mississippi	Wisconsin
Purdue	Notre Dame	
UT Dallas	Purdue	
Wisconsin	Rochester	
	Rockefeller	
	Texas Tech	
	Virginia Tech	

ECAL	Tracking	Software
Brookhaven	UC Davis	UC Davis
Caltech	Fermilab	UCLA
Fermilab	Florida State (SCRI)	UC Riverside
Jet Propulsion Lab †	Johns Hopkins	UC San Diego
Livermore	Livermore	Caltech
Minnesota	Los Alamos	Carnegie Mellon
Northeastern	Mississippi	Fermilab
Princeton	Northeastern	Florida State (SCRI)
	Northwestern	Johns Hopkins
	Rice	Livermore
	Rockefeller	Maryland
	Texas Tech	SUNY Stony Brook
		Northeastern
		Rice
		Wisconsin

† Applying for CMS membership.

Table 2: US CMS FY 1996 Supplemental Funding Request (K$).

Subsystem/Activity Description	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
US CMS FY 1996 Supplemental Funding Request	**1726**	**1474**	**2700**	**500**	**300**
Endcap Muon Detector	**440**	**450**	**890**	**0**	**80**
CSC Chambers	260	143	403		42
Electronics	155	115	270		12
Steel Design		137	137		
Trigger	15	15	30		8
Alignment	10		10		
RPC Chambers		40	40		
Endcap Management					18
Hadron Calorimeter	**465**	**525**	**830**	**160**	**80**
HB Optical System Design	92	90	110	72	14
HB Calibration System	30	19	49		8
HB, HF Photodetector R&D	44	18	34	28	
HB, HF Electronics R&D	22	8	30		1
HB Test Beam	149	72	161	60	22
HB Electron Beam Welding	36	10	46		4
HB Engineering	13	232	245		12
HV Calorimeter	79	76	155		19
Trigger and Data Acquisition	**225**	**245**	**410**	**60**	**40**
Level 1 Calorimeter Trigger	79	109	188		10.5
Level 1 Muon Trigger	20	50	70		10.5
Data Acquisition	111	51	152	10	19.0
Luminosity Monitor	15	35		50	
Electromagnetic Calorimeter	**260**	**140**	**340**	**60**	**40**
Photodetectors	120	50	110	60	20
Electronics	60	50	110		10
Crystals	80	40	120		10
Tracking System	**239**	**81**	**160**	**160**	**30**
Pixel Tracker	131	29	80	80	17
Forward MSGCs	108	52	80	80	13
Software and Computing	**80**	**0**	**20**	**60**	**30**
Common Software & Workstations	45		15	30	7.5
Subsystem Software Development	20		5	15	16.7
Physics Tools					0.8
Computing Model	15			15	5.0
Project Management	**17**	**33**	**50**	**0**	**0**
Information Systems	8	2	10		
Document Preparation	2	13	15		
Cost and Schedule Integration	3	12	15		
Liaison to CMS at CERN	4	6	10		

2 CMS Milestones

The CMS project was defined by the submission of the technical proposal on December 15, 1994 [4]. Since that submission, the CMS collaboration has had a continuing dialogue with the CERN LHC experiments Committee (LHCC) on the technical feasibility of the experiment. This dialogue has culminated in approval of the CMS experiment in regard to the science at the November 16, 1995 meeting of the LHCC.

This dialogue has also resulted in the establishment of milestones by joint consultation with the LHCC referees and the project managers of the CMS subsystems. These milestones define the steps which need to be accomplished if the CMS experiment is to maintain the schedule given in Section 1 of this document.

The implications for the US CMS groups follow from the responsibilities which they have taken in CMS. In particular, since the endcap steel yoke and the HCAL are critical path items, the engineering effort necessary to specify the design of the yoke and the barrel wedges must be done in FY96. This is true because the technical design report for the magnet subsystem must be completed in 1996 in order to maintain the CMS schedule. For the HCAL, the bids for the wedge preproduction prototypes must be fully prepared in 1996 in order to stay to the schedule.

The time before FY97 is an R&D phase for the US CMS groups. Beyond that time, the fact that the US CMS groups are responsible for detector critical path items requires that project funds be spent. The cost for these components has been estimated in European accounting [5] and in full US work breakdown structure (WBS) accounting in the LOI [1]. The US CMS Project should begin in FY97 if we are to keep to the schedule shown in Fig. 1.

3 Supplemental R&D Request

A summary of the funds needed for each US CMS subsystem has been shown in Section 1. We now indicate the FY95 program which is in train, the FY96 program which logically follows, and the schedule and milestones which require the pace which we have adopted. These elements dictate the funding requirements which are given in detail in the subsequent subsections of this Section.

3.1 Endcap Muon Detector

The US CMS groups have taken responsibility for the Endcap Muon System, comprising the cathode strip chambers, the front-end readout system, and the local CSC-based muon trigger, the design and integration of the endcap flux return, and the alignment of chambers relative to the global CMS alignment system. US CMS groups will also participate in R&D work on RPCs.

The management structure for the muon system is shown in Fig. 2. Among the US members of that structure are the Institution Board Chair (Layter), the Endcap Project

Manager (Mitselmakher), and the Endcap Technical Coordinator (Loveless). Travel funds needed to support these management and oversight responsibilities are mentioned in Section 4 of this document.

Groups active in the area of chamber development and testing are UCLA, UC Riverside, Fermilab, Florida, LLNL, MIT, SUNY Stony Brook, and Purdue. Electronics development activity is led by Ohio State, with contributions in particular areas from UC Davis, Carnegie Mellon, and UT Dallas. The US trigger effort for muons is centered at UCLA, while LLNL is the principal focus of US R&D on dedicated trigger detectors. Steel design and system integration work is led by Wisconsin, and endcap alignment is handled by Fermilab with participation from Alabama. Simulation and software for the muon detector has been organized by UC Davis and is described in a separate section.

Chamber R&D work during FY95 focussed on studies of materials and construction techniques which could lead to simpler and cheaper designs. An engineering prototype T0 incorporated many of these ideas in a working chamber. A performance prototype P0 was constructed and tested in the H2 beam at CERN over the summer, with and without magnetic field, with different operating voltages and thresholds, and with varying angles of incidence and particle rates. This chamber was outfitted with electronics constructed entirely in the US but based on an existing CERN-designed chip. Development work was done on switched capacitor arrays for the eventual readout system. A conceptual design was elaborated for a CSC-based trigger, and a US group began tests of components of a parallel dedicated trigger detector.

Progress was made on a simplified alignment scheme to link the endcap muon detectors to the global alignment system. The design of the endcap iron flux return is a major US responsibility. Tests done on a possible method of fabrication of this critical path item have indicated shortcomings and shown the need to develop alternatives. A high priority has been placed on R&D work in this area. The R&D plans outlined in the following sections are critical to meet the long range milestones set down by the LHC Committee and listed in Table 3. The R&D plans and costs are summarized in Table 4.

3.1.1 Endcap Muon Chambers

R&D efforts to be pursued in FY96 involve several different chambers: P0, T1, P1, and a number of smaller chambers built for particular studies.

The P0 Chamber

The P0 prototype is a 6-gap chamber with an active area 0.5×0.5 m^2. It has wider strips than previously built CSCs and has no floating strips. P0 was tested at CERN during the past summer. FY96 R&D objectives for P0 are:

- Analysis of the large data set obtained during the CERN beam test.
    1. Continued development of analysis suite on the CMS UNIX cluster.
    2. Analysis of timing and spatial resolution and chamber efficiency as functions of high voltage, threshold, B-field, and angle.

- Tests at UCR cosmic ray test facility.

  1. Continued studies of timing and spatial resolution and chamber efficiency as functions of position in the chamber.
  2. Establish chamber acceptance by determining the extent of dead zones around the edges.
  3. Change discriminators from leading edge to zero crossing mode and redo the timing resolution study.
  4. Incorporate comparator electronics to implement the 1/2-strip trigger scheme.
  5. Determine level of noise pickup with an RPC attached to the chamber.

Studies of the effects of wider wire spacing on timing resolution and of narrower strips on spatial resolution will require partial rebuilding of the chamber.

The T1 Chambers

Two 2-gap 1.5×0.5 m^2 chambers have been built to continue study of engineering design aspects and their effects on chamber performance:

- Full length wires of different diameter will allow to study mechanical stresses, HV operation, electrostatic instabilities, signal induction and reflection, and, also, noise parameters.

- Engineering solutions to guard edge wires, to group wires in HV-independent segments, to provide intermediate wire support, to compensate for bulging due to overpressure and temperature gradients and, also, for possible panel nonflatness.

- Using a liquid RTV as a gas seal O-ring.

These T1 prototypes essentially test materials and most of the design solutions to be used in the P1 prototype. Both prototypes will be tested in the cosmic ray test setup at Fermilab. When used together, four planes of the T1 chambers and two planes of the T0 prototype, built last year, will allow us to study many chamber performance features.

The P1 Chamber

This cathode strip chamber will measure $3.3 \times 1.2/0.8$ m^2 and will have 6 gaps. It will be a full scale CMS CSC and will be the largest chamber of this type ever constructed.

- Development of a cosmic ray facility adequate to test the full scale chamber.

- Tests in cosmic rays to determine: operation reliability, gas gain variations, spatial and timing resolution, and efficiency measured over large chamber area.

Along with designing and construction of the P1 prototype, we will continue an extensive technological R&D program aimed at finding cheap and adequate materials and simple engineering solutions to ensure high operational reliability. Based on accumulated experience in chamber design and construction, we will come to an improved and detailed labor cost estimate.

Chambers for Particular Studies

A number of smaller chambers are being built or will be built to examine particular questions. Some of these are:

- Aging studies: capabilities of chambers to withstand high background radiation loads will be studied on small chambers made according to the design of the P1 prototype and using the same materials.
- Gas mixture studies with small chambers. Search for gases with:
    1. high drift velocity and small Lorentz angle,
    2. improved quenching properties,
    3. lower HV operating point,
    4. small dependence of gas gain on HV,
    5. low gas gain dependence and time slewing versus hit rate.
- Alternative CSC Designs: Explore modular designs which could limit vulnerability to wire breakage.

3.1.2 Endcap Electronics and Trigger

Electronics built thus far are adaptations of existing designs. The next generation electronics will be tailored to the baseline CMS chamber design and will involve R&D steps spelled out below. Muon trigger R&D during FY96 will concentrate on delivery of an engineering version of the comparator/LCT chip.

Cathode Front-End Board

- Preamplifier/Shaper
    - 4-channel engineering ASIC Versions I-III (10/95 – 2/96)
    - 16-channel ASIC with slow output only (5/96 – 9/96)
    - 16-channel ASIC with all design requirements (8/96 – 12/96)
- Switched Capacitor Array
    - 3-channel engineering ASIC (12/95 – 4/96)
    - 16-channel engineering ASIC Version I (11/96)
- Strip Comparator/Local Charge Track Chip
    - Review of prototype tests (8/96)

- Delivery of Engineering ASIC (12/96)

- Readout Control
  - Review and finalize conceptual design (12/95 – 5/96)
  - Submit Engineering ASIC (9/96)
  - Delivery of first Engineering ASIC (12/96)

- 96-channel DAQ Board
  - Prototype version IA (DAQ only) (5/96 – 9/96)
  - Prototype version IB (DAQ + SCA) (11/96)

Remarks on cathode electronics:

1. The cathode front-end board is presently planned to be a 6-layer board. The top 4 layers make up the "DAQ board" (with Preamp, SCA, Control ASICs plus MUX, ADC and RAM). The bottom two layers make the "Trigger board" (with COMP/LCT ASIC(s)).
2. The development of the DAQ board is planned to take two stages: a) 96 ch pilot PCB-1A with new preamp ASICs read into CAMAC ADC board; b) 96 ch pilot PCB-1B with full SCA readout.
3. An engineering ASIC is one which is for engineering study to achieve the desired performance for a small number of channels. A presample ASIC is a prototype ASIC with the required number of channels and identified input and output pin assignments. A preproduction ASIC is the end product of the ASIC prototype work. Typically 2-3 presample submissions are assumed to get to the preproduction stage.

Anode Front-End Board

- Preamplifier/Shaper
  - Fix requirements for anode front-end (12/95)
  - Delivery of presample ASIC (4/96)

- Discriminator
  - Delivery of version I presample ASIC (6/96)
  - Delivery of version II presample ASIC (12/96)

- 4-channel DAQ Board
  - Finish prototype

- Local Charge Track/Beam Crossing
  - Review of prototype test (7/96)
  - Delivery of engineering ASIC (12/96)

Deliverables by 12/96

Cathode PA/SH ASIC R/D	16 ch ASIC presample (2nd round)
Cathode SCA ASIC R/D	16 ch ASIC presample (1st round)
Cathode Control ASIC R/D	96 ch ASIC presample (1st round)
Cathode 96ch PC-Board PTTP	96-ch PCB-1A (Readout only, no trigger)
Anode PA/SH/DS & PCB-1 R/D	4-ch ASIC presample + PCB
Frontend Trigger R/D	Engineering ASIC for Comp/LCT
Pilot System-1a Production	384 ch Cathode readout for P1
	192 ch Anode readout for P1

3.1.3 Endcap Iron Design

By October 1996 the CMS collaboration must produce a technical design report (TDR) for the magnet (both coil and yoke). The US responsibility for this task is the design of the endcap yoke iron. From the schedule it is clear that this task must be accomplished with FY96 R&D funding. Each endcap consists of 3 iron disks (2 are 600mm thick, 1 is 300mm thick) and a nose section (1m thick); the total weight per endcap is 1900 metric tons. The total magnetic force per endcap is 84 MN ($\sim$ 9000 metric tons). A description of the endcap conceptual design is given in the CMS Technical Proposal [4].

The FY96 R&D tasks necessary to produce the October 1996 magnet TDR include:

1. develop disk fabrication design:
   - continue development of welded plate design
   - perform additional electroslag welding test (1st test failed)
   - develop alternate design for bolted plates
   - select preferred option: welded or bolted
2. endcap calculations:
   - magnetic field
   - magnetic forces on iron endcap disks
   - structural effects of magnetic forces: deflections and stresses

- develop bolt-load or weld requirements
- finite element analysis of support carts

3. develop specifications for the endcap disks:

    - physics requirements: absorption and flux return
    - mechanical requirements: allowable stresses and deflections
    - manufacturing requirements:
        - block quantity, size and shape
        - block tolerances
        - chemical composition
        - magnetic permeability
        - strength and ductility
        - weldability and/or machineability
        - quality assurance: testing, responsibility, acceptance
    - support requirements:
        - floor loading
        - roller/rail tolerance
    - requirements for surface and underground halls due to assembly plans

4. develop assembly plans:

    - storage
    - shipping
    - schedule
    - installation of blocks: rigging and registration
    - connection: welding or bolting

5. develop disk support and connection design:

    - z support of endcap on inner barrel ring RY1
    - endcap connections: RF3 to RF2, RF2 to RF1
    - nose connection
    - design support carts
    - design support scheme: mechanical rollers on rails or air pads
    - design rail system for hall and assembly area
    - design/specify movement system

3.1.4 Endcap Alignment

The endcap muon position monitoring subgroup will design, develop, test, prove, and build the local hardware system plus calibration tooling. The subgroup will calibrate and install the subsystem devices to monitor fiducial references in the endcap cathode strip chambers with respect to the spatial points provided by the link system, and will install and cross reference sensors on the CSCs and maintain a chamber alignment database. The R&D effort for FY96 will undertake the following tasks to address questions regarding the silicon link monitor (SLM) concept:

- Optimize a protected diode-optics module source for beam intensity/wavelength-shape-stability for a 15m SLM.
- Using a number of transparent amorphous Si sensors, evaluate unit output response, linearity vs displacement, dynamic range, noise levels, threshold stability, long term stability, plus air turbulence, magnetic field/gradient, and thermal effects.
- Measure the refraction variation pattern and beam distortion effects for each of the units and develop a correction algorithm.
- Demonstrate the adequate radiation hardness of the diode sources and Si sensors and electronics and test CMS slow control system readout.

3.1.5 Dedicated Trigger Detectors

Resistive Plate Chambers (RPCs) are currently being studied for use as the dedicated trigger system for the CMS Detector both in the barrel and in the endcap. These two environments, however, are expected to be quite different in terms of background rates of particles emanating from the high luminosity collisions of the Large Hadron Collider. In particular the endcap muon system is expected to receive a rather large counting rate of about 1 KHz/cm^2 in the high eta regions due to the large flux of neutrons and photons emanating from the interaction region. Muons derived from collisions associated with physics events in CMS must be resolved in this background. This places stringent requirements on the efficiency of RPCs for triggering on muons in the presence of background particles. Additionally the 25 ns beam crossing time requires that RPCs have a time resolution for tracks that is much better than 25 ns, typically < 5 ns.

The proposed RPC R&D program for FY96 has the following goals:

- Confirm power requirements and operating characteristics for standard Bakelite and wide-gap chambers in high rate environments using beams, gamma and neutron sources.
- Study RPC materials properties including resistivity dependence on humidity, radiation dose, temperature, etc.
- Study RPC operation in avalanche mode for different gas mixtures.
- Study RPC operation using a range of wider gas gaps (4, 6 and 8 mm).

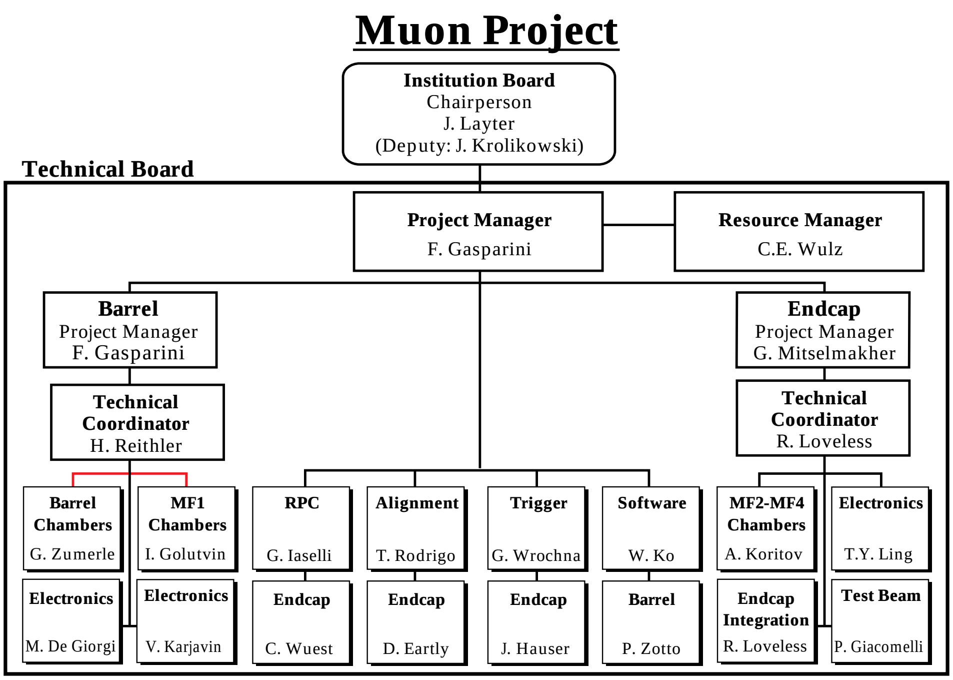


Figure 2: CMS Muon Project organization.

Table 3: Endcap Muon Milestones.

Muon Measurement System

- Dec. '97 – Technical Design Report

Endcap Iron

- Oct. '96 – Technical Design Report for coil and yoke

Cathode Strip Chambers Stations MF1/2, MF1/3, MF2, MF3, MF4:

- Dec. '96 – full-size large chamber (6 layers)
- Dec. '97 – final chamber suitable for mass production
- Dec. '98 – preseries sample

CSC Electronics

- Dec. '97 – front-end cards for anode and cathode readout
- Dec. '98 – readout system tested

Resistive Plate Chambers

- Dec. '96 – definition of final RPC parameters
- June '97 – front-end final chips
- Dec. '97 – final prototypes suitable for mass production
- Dec. '98 – preseries sample

Alignment

- Dec. '96 – full-scale link system bench test
- June '97 – integrated design for barrel/forward/link
- Dec. '97 – full scale system test

Table 4: Endcap Muon FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Endcap Muon Detector		**440**	**450**	**890**	**0**	**80**
CSC Chambers		**260**	**143**	**403**	**0**	**42**
P0 prototype		**33**	**22**	**55**	**0**	**14**
Modifications	UCR, (LLNL), UCLA	6	17	23		6
Cosmic ray tests	UCR, (LLNL), UCLA, MIT	12	5	17		8
CERN tests	UCR, (LLNL), MIT, UCLA	15		15		
P1 prototype		**156**	**95**	**251**	**0**	**13**
Design	FNAL, MIT, Wisc, SUNY SB	38	45	83		8
Winding machine	Fermilab	55		55		
P1 fabrication	Fermilab	43	35	78		
DAQ and tests	Fermilab, Purdue	20	15	35		5
Design studies		**71**	**26**	**97**	**0**	**15**
Aging studies	Carnegie Mellon	12		12		
Performance studies	MIT, Florida, CMU	33	16	49		
Alternate designs	UCLA, Wisconsin	14	10	24		
Tension meter	Purdue	12		12		
Simulations	UC Davis					15
Electronics		**155**	**115**	**270**	**0**	**12**
Cathode readout		**120**	**70**	**190**	**0**	**8**
PA/SH ASIC	Ohio State	35	15	50		7
SCA ASIC	UC Davis	40	25	65		1
Control ASIC	Ohio State	35	15	50		
96ch PC-board PTTP	Ohio State	10	15	25		
Anode readout		**35**	**15**	**50**	**0**	**4**
PA/SH/DS	Carnegie Mellon	35	15	50		4
Integration		**0**	**30**	**30**	**0**	**0**
Pilot system-1a production	Ohio State, CMU, UT Dallas		30	30		
Steel Design		**0**	**137**	**137**	**0**	**0**
Engineering		**0**	**137**	**137**	**0**	**0**
Engineering design	Wisconsin		137	137		
Trigger		**15**	**15**	**30**	**0**	**8**
Frontend design	UCLA	**15**	**15**	**30**	**0**	**8**
Alignment		**10**	**0**	**10**	**0**	**0**
Laser test system		**10**	**0**	**10**	**0**	**0**
Si sensors, laser module	Fermilab, Alabama	10		10		
RPC Chambers		**0**	**40**	**40**	**0**	**0**
R & D engineering	UCR (LLNL), Purdue	**0**	**40**	**40**	**0**	**0**
Endcap Management	Florida, Wisconsin	**0**	**0**	**0**	**0**	**18**

3.2 Hadron Calorimeter

US CMS physicists are responsible for the project management of the HCAL subsystem as a whole. The organization of the HCAL Technical Board is shown in Fig. 3. US physicists are the Institution Board Chair, the Project Manager, the Resource Manager, the barrel Technical Coordinator and the very forward Co-coordinator. In order to call, chair, and attend the many meetings needed to launch the HCAL Project, significant travel funds are needed, as indicated in Section 4 of this document. In addition to their managerial responsibilities, US groups have very major construction responsibilities in HCAL.

During FY95, the US HCAL groups built and tested two complete full-scale hadronic calorimeter prototype systems. One system was used in 2 beamlines at CERN during 4 distinct running periods. Data taken informed on the issues of HCAL barrel and endcap design, the effect of magnetic fields, the e/h response in conjunction with a $PbWO_4$ crystal EM segment, the effect of dead material in the system, and the use of different transducers. The US groups are fully responsible for building the complete barrel HCAL, the endcap transducers and front-end electronics, and half the very forward system.

The schedule for the barrel HCAL is shown as a bar chart in Fig. 4. Similar schedules exist for the endcap and the very forward systems. The full milestones list for the period up through 1997 is given in Table 5 for the HCAL Project. In FY95 work concentrated on the test beam runs, the optics and photon transducers, and the engineering. Based on the achieved results, there will be new test beam work in FY96. Due to a low level of support, the electronics effort was deferred until FY96. That effort must ramp up if the preproduction prototype is to be designed in FY96 and bid in FY97, as dictated by the overall CMS construction schedule.

In addition, the engineering effort must ramp up sharply if the bid is to be ready at the end of 1996. The HCAL is on the critical path, so that this ramp-up is clearly required. In addition, the FY95 test beam data are playing a crucial role in achieving the decision milestones shown in this document. The data are also allowing an informed optimization procedure for the HCAL subsystem. As shown in Fig. 4 and Table 5, the complete FY96 effort leads to the construction and assembly of the HCAL preproduction prototypes in 1997.

The second full-scale hadron calorimeter prototype which was constructed in 1995 was a novel copper - quartz fiber detector module which is a candidate for the very forward region. That region is quite challenging experimentally, and the US groups have pioneered the use of this novel radiation hard technology. The data taken in 1995 were crucial. That data form the basis for a choice of technology by CMS during the December 1995 collaboration meeting. Fuller details of the R&D achievements in FY95 are contained in the US CMS LOI [1].

The HCAL FY96 R&D activities are summarized in Table 6. The barrel and very forward systems are broken down by task. For each task, the participating institutions are indicated. Also shown by task are the requested DOE and NSF R&D funds, together with the travel funds requested of DOE.

3.2.1 HCAL R&D Tasks for FY 1996

The FY96 R&D activities for the barrel calorimeter system are:

1. Optical System Design:
   Continue design of optical system. Build full size prototypes of scintillator tile-trays. Develop optical connectors of appropriate width and fiber count. Build quality control station. Improve fiber splicing mechanism. Continue evaluation of optical materials (scintillator, fiber).

   (a) Optical materials evaluation. Obtain large sheets of Kharkov scintillator (baseline). Measure mechanical, optical, and radiation hardness properties.

   (b) Build full size prototypes of tile trays.

   (c) Develop proper geometry optical connector made by injection molding technology.

   (d) Improve on fiber splicing machine (originally built by Michigan State University). Target is to improve machine speed, and reduce maintenance requirements.

   (e) Build moving radioactive source scanning table of size appropriate for CMS tile trays. Build moving UV lamp "pig-tail" scanner for fiber lengths appropriate for CMS barrel.

2. Calibration System:
   Analyze 1995 test beam data for performance of prototype systems. Explore option of injecting blue light into each scintillator plate. Improve design of moving wire source mover.

   (a) Laser system development.

   (b) Source mover design.

3. Photodetector R&D:
   Continue study of photodetectors. Make choice of photodetector "baseline". Purchase quantity for uniformity, aging studies, and use in test beams.

   (a) Purchase quantities of remaining 2 phototdetector options. Continue evaluation.

4. Electronics R&D:
   Acquire partial FERMI electronics system, evaluate performance. Evaluate SDC/KTeV charge integrator and encoder (QIE). Evaluate candidate preamplifiers.

   (a) Purchase, evaluate front-end electronics system.

   (b) Purchase, evaluate preamplifiers.

5. Test Beam Work:
   Two test beam efforts are planned for 1996: the H2 test beam at CERN; and an 800 GeV beam at Fermilab. The H2 test beam will be in a "barrel" magnetic field environment. We will test the "baseline" system of absorbers, scintillators, photodetectors, and calibration systems. In the Fermilab 800 GeV beam line, we will investigate hadron shower leakage at the highest available energy.

   (a) Prepare optical system (scintillators, cables, decoder box).
   (b) Purchase photodetectors and high voltage supply.
   (c) Calibration system (laser, moving wire radioactive source).
   (d) Infrastructure for H2 (electronics, shipping, ...).
   (e) Infrastructure for Fermilab test beam.

6. Electron Beam Welding:
   Continue R&D on structural welds between copper and stainless steel using electron beam welding technique. Purchase copper plates and perform "long welds" to verify technology. Study weld quality on lower grade (cheaper) copper alloys.

7. Engineering:
   Move toward finalization of mechanical design of calorimeter wedges and installation fixtures. Build full size mock-up of end of wedge to study fiber and cable routing issues. Build mock-up of "decoder" box to verify mechanical design.

   (a) Engineering design.
   (b) Wedge mock-up.
   (c) Decoder box design and mock-up.

3.2.2 The Very Forward Hadron Calorimeter (HV)

During 1995 a hadronic (HAD) prototype was constructed at CERN by the Boston, Fairfield, Iowa, Texas Tech, and ITEP groups and its performance evaluated. In all regards its characteristics were as anticipated. This prototype fully conforms to the baseline design of the CMS Technical Proposal for the forward region.

The prototype is 1.35 m ($8.8\lambda_{int}$) long and contains 1.5% by volume of quartz optical fibers with 300 μm diameter. The fibers are clad with fluorine-doped quartz, and are therefore radiation tolerant to gigarad levels, enough to live for a decade at the LHC design luminosity of 10^{34} cm^{-2} s^{-1}.

The design of the '95 prototype follows an extrapolation from the results obtained in '94 from CERN beam tests of the '94 Tail Catcher (TC). The TC prototype was built as an SSC close-out project for a GEM forward calorimeter for similar design. In the '95 CERN tests, the TC module was placed in the beam immediately after the '95 module. Additionally an electromagnetic module from SSC closeout funds was briefly tested in 1995 at CERN as an e-m front end for the prototype, and more extensively at SLAC.

At least two independent groups in our subdetector team have addressed many of the above goals using data from test beams at SLAC in February 1995 (for the '95 electromagnetic module) and at CERN (for the '95 combined EM/hadronic module). Since the 1995 module had mirrored quartz fibers, with beam coming in the front we could evaluate the performance of a hadronic module; with the detector rotated by 180 degrees relative to the beam, we evaluated its performance as an electromagnetic module, with readout of the fibers from the front. In the tests at CERN the 1994 module was used as a tail catcher to tag the leakage out the back of the HAD module.

3.2.3 HV R&D Tasks for FY96

The April 1995 run had four serious constraints: a) only 5 days of running; b) a limitation to positive particles only, and therefore a maximum of 150 GeV in pion energy, and up to 100% contamination by protons at 300 GeV; c) partial operation in the 1 to 3 Tesla fringe field of the neighboring test beam; and d) an inability to veto events with double tracks traversing the detector in the same bunch. Although some of these constraints were alleviated in our July 1995 run (currently under analysis) all of these constraints will be ameliorated in FY96. Two test beam efforts are planned for 1996: the H4 test beam at CERN and a 800 GeV beam at Fermilab. The goals for FY96 are the following:

1. Optimize the longitudinal sampling using a detector with three compartments and event by event correlations:
   (a) the GEM close-out electromagnetic module as the electromagnetic compartment
   (b) the CMS '95 hadronic module (sideways) as the first hadronic compartment
   (c) the GEM close-out tail catcher as the second hadronic compartment, with the optical readout modified for low background.
2. Activate additional towers by filling the grooves with fibers coming from two new suppliers, Belarus and Russia, as well as with plastic fibers (the baseline for the tail catcher of the TP).
3. Fill in missing data to 375 GeV to relieve the positive pion/proton ambiguity from the April data and to determine the functional form of the hadronic energy resolution at high energies. The resolution may indeed drop logarithmically (faster than $1/\sqrt{E}$, as expected from dominance of the fragmentation function over Poissonian shower fluctuations.
4. Energy linearity and resolution measurements and longitudinal shower size evaluations with 800 GeV proton beam at Fermilab.
5. Develop a calibration/monitoring system using LED and lasers to develop a prototype light distribution system.

6. QF radiation damage studies for neutrons and gammas together with the ORNL group. Studies will include quartz fibers with plastic cladding (plastic/silica) and quartz fiber cladding (silica/silica).

7. Measure response of prototype to neutrons and gammas and radiation hardness.

8. Modifications to present EM module to be used at CERN H4 96 and FNAL 96 test runs.

9. Detailed data analysis of April and July 1995 test runs and new test data runs for CERN H4 96 and FNAL 96.

10. Initial evaluation of fiber vendors and test of fiber samples from vendors and final selection process.

11. Design of heavy lift table and (robotic) transporter.

12. Studies for the shielding design.

13. Studies for the choice of absorber Cu/Fe.

14. Mechanical assembly drawings.

15. Photodetector tests:
    We propose to test rad insensitive PM prototypes similar to the R5600 miniature (8 mm dia) PMT tested in FY95.

16. Optical readout package development:

    (a) Readout mock-up.

    (b) Air light guides and collectors:
        In FY96 we would equip the calorimeter prototype in test beams with a complete set of 1 m long air light guides appropriate to $\eta = 5$, and concentrators for $\eta = 3$, qualified by bench tests.

    (c) Beam-induced background in the readout:
        This task is to fully quantify beam induced background in the above optical readout systems, as a function of energy.

17. Prove the feasibility of < 25 ns gates to do interbunch timing with a first run FERMI board:
    In the very forward region, the occupancy in each readout channel reaches 100%, posing unique challenges not only to the calorimeter technology but also to the readout electronics. Using the fast digital waveforms recorded from the Cherenkov test run at CERN, we are simulating the response of the proposed circuitry.

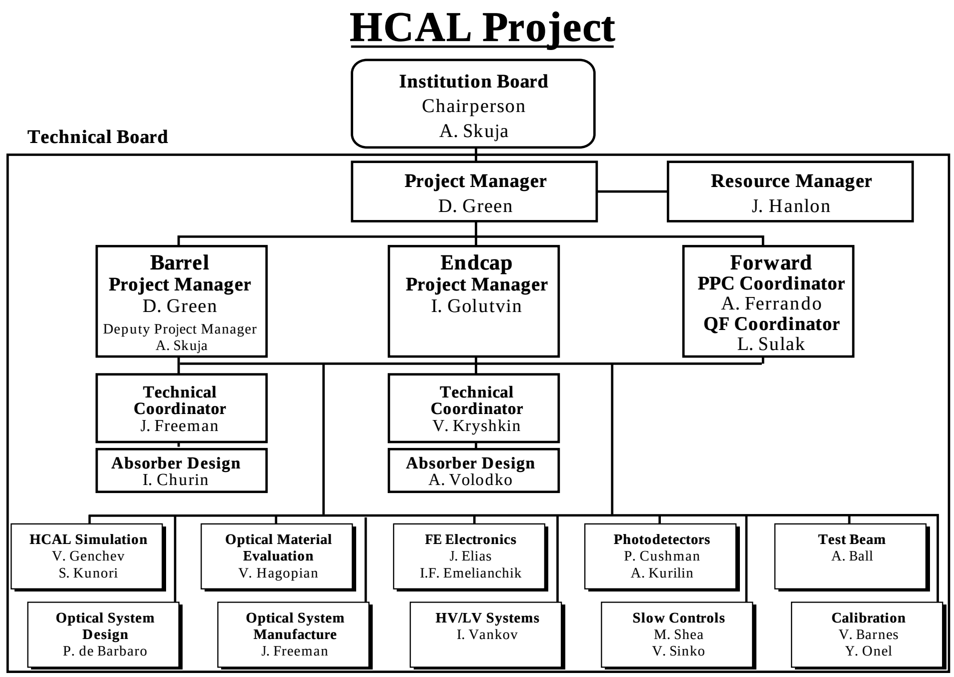


Figure 3: CMS HCAL Project organization.

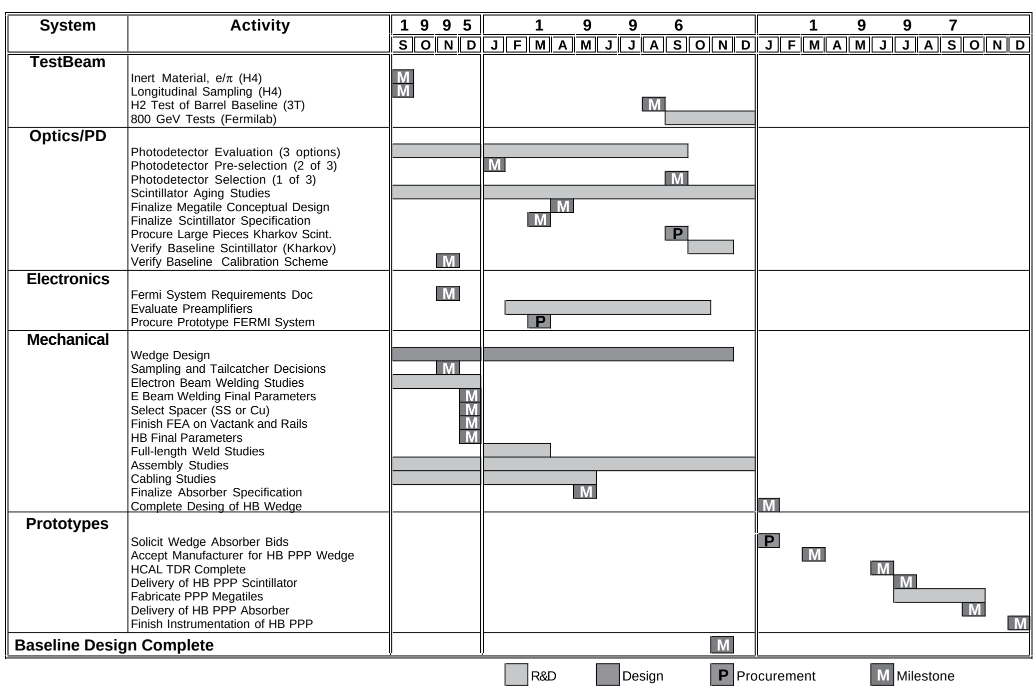


Figure 4: 1995-97 barrel HCAL schedule and milestones.

Table 5: HCAL Milestones: 1995-1997.

Milestones for HB:

- 8/95 – H4 tests of dead material (finished); H4 tests of transducer candidates (finished)
- 9/95 – Measure HB leakage with and without tailcatcher (finished); Measure HB e/pi using crystal EB (finished)
- 11/95 – HB tailcatcher decision (made)
- 11/95 – HCAL FERMI System requirements document
- 12/95 – Finish conceptual study of EB welding; Establish EB Welding (EBW) parameters
- 12/95 – Finish conceptual design of HB/HF; Finish first pass of FEA for vacuum tank and rail system; HB/HF final parameters finalize
- 1/96 – Initial decision on HB/HF transducer (Reduce the number of viable transducers)
- 2/96 – HB/HF Calibration system conceptual design
- 3/96 – Finalize scintillator specification; Begin testing scintillator baseline (presently Kharkov scintillator)
- 3/96 – Procure prototype FERMI System
- 4/96 – Complete full length EBW studies
- 4/96 – Finalize conceptual design of megatiles; Mock-up of full-size megatiles with fiber routing
- 5/96 – Finalize specifications of absorber manufacture
- 6/96 – Establish possible baseline Cu vendors for preproduction prototype wedges
- 8/96 – H2 Test Beam using 3T Magnet in Barrel field configuration; EB+HB combined test; HB uses baseline absorber, scintillator, transducer and calibration system
- 9/96 – Test of HCAL components in 800 GeV beam at FNAL
- 9/96 – Finalize selection of HB/HF transducer and calibration system
- 10/96 – Finish preamplifier evaluation
- 11/96 – Complete scintillator tests (light yield, aging, radiation damage studies)
- 12/96 – Finish assembly and installation study of HB/HF

- 1/97 – Engineering drawings available to bid for the construction of the HB and HF preproduction prototype wedges
- 1/97 – Call for bids for manufacture of HB/HF preproduction absorber wedges
- 1/97 – Call for bids for manufacture of HB/HF preproduction prototype megatiles
- 3/97 – Accept manufacturer of HB/HF absorber preproduction prototypes
- 6/97 – TDR for HCAL is finalized
- 7/97 – Delivery of HB scintillator for megatiles
- 10/97 – Delivery of HB/HF absorber preproduction prototypes
- 10/97 – Finish construction of megatiles
- 10/97 – Finish construction of optical readout and electronics
- 12/97 – Finish instrumentation of HB preproduction prototypes

List of deliverables for HB:

- Engineering drawings for HB
- HCAL TDR
- Two HB wedges (preproduction version)

Milestones for QF Option for HV:

- 12/95 – HV decision (December CMS plenary week)
- 1/96 – Organize expanded QF team
- 2/96 – Preliminary design of heavy lift table and (robotic) transporter
- 3/96 – Procure and evaluate first run FERMI board
- 4/96 – Preliminary shielding design
- 5/96 – Procure additional QF fibers and instrument additional towers in prototype
- 5/96 – Initial selection of fiber vendor(s)
- 6/96 – Design and fabricate fast gating
- 6/96 – Electronics proof of principle test for intrabunch gating (to suppress quadrupole halo)

- 7/96 – CERN beam test: longitudinal sampling, EM module high rate beams
- 8/96 – Detailed optical assembly drawings
- 10/96 – Fabricate EM prototype to TP specifications
- 10/96 – 800 GeV beam at FNAL beam test
- 11/96 – Revised shielding design
- 11/96 – Draft mechanical assembly drawings (except table)
- 12/96 – Choice of absorber Cu/Fe (driven by cost and radiation)
- 1/97 – Full optical readout assembly design
- 2/97 – Evaluate plastic fibers for radiation hardness
- 2/97 – Finish design of heavy lift table and (robotic) transporter
- 3/97 – Final fiber acceptance tests
- 3/97 – Measure response to neutrons and gammas and verify radiation hardness (possibly at Oak Ridge)
- 4/97 – Draft TDR
- 5/97 – Choice of PMTs
- 6/97 – Finalize TDR
- 12/97 – Finish three compartment (Electron/Hadron/Tail catcher) full size prototype.

List of deliverables for QF option:

- Engineering drawings for HV
- HCAL TDR
- Three compartment full size prototype

Table 6: HCAL FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request				Travel
		M&S	Labor	DOE	NSF	DOE
Hadron Calorimeter		**465**	**525**	**830**	**160**	**80**
Barrel HCAL		**386**	**449**	**675**	**160**	**61**
Optical System Design		**92**	**90**	**110**	**72**	**14**
Optical materials evaluation	FSU, Notre Dame	15	10	20	5	6
Full size tile tray prototypes	Fermilab, Rochester	10	20	30		3
Optical connector development	UIC, Notre Dame	27	10		37	
Fiber splicing machine improvements	Mississippi	10	10	20		3
Moving source scanning table	Fermilab, Rochester	10	30	40		2
UV fiber assembly scanner	UIC, Notre Dame	20	10		30	
Calibration System		**30**	**19**	**49**	**0**	**8**
Laser system development	Iowa, Iowa State	15	9	24		3
Source mover design	Purdue	15	10	25		5
Photodetector R&D (HB and HF)		**44**	**18**	**34**	**28**	**0**
Evaluate photodetector options	UCLA, Minnesota,	24	10	34		
	Virginia Tech	20	8		28	
Electronics R&D (HB and HF)		**22**	**8**	**30**	**0**	**1**
Front-end electronics evaluation	UCLA, Fermilab	15	5	20		1
Preamplifier evaluation	UCLA, Fermilab, Minnesota	7	3	10		
Test Beam		**149**	**72**	**161**	**60**	**22**
Optical system preparation	FNAL,FSU,UMD,Miss,Roch,	19	30	49		14
	UIC, Notre Dame	25	10		35	
Photodetectors, preamps, HV supply	UCLA, FNAL, Minnesota,	10	5	15		
	Virginia Tech	18	7		25	
Calibration system	Iowa, Purdue	27	10	37		8
H2 electronics	Fermilab	40		40		
Fermilab test beam electronics	Fermilab	10	10	20		
Electron Beam Welding		**36**	**10**	**46**	**0**	**4**
Study techniques, quality	Fermilab, Maryland	36	10	46		4
Engineering		**13**	**232**	**245**	**0**	**12**
Engineering design	Fermilab, Maryland		205	205		4
Wedge mock-up	FNAL, UMD, Roch, Purdue	10	20	30		4
Decoder box mock-up	Fermilab, Maryland, Roch	3	7	10		4
HV Calorimeter		**79**	**76**	**155**	**0**	**19**
QF Engineering		**2**	**48**	**50**	**0**	**5**
Conceptual	BU, Fair, Iowa, TexasTech		13	13		
Drawings	Boston		5	5		
Integration	Boston		11	11		5
Support at CERN	Fairfield, Iowa, TexasTech		12	12		
Readout mock-up	Iowa		7	7		
Videoconferencing	Boston	2		2		
QF Electronics R&D		**7**	**3**	**10**	**0**	**0**
Electronics	Boston	3	2	5		
Photomultipliers	Fairfield	4	1	5		
QF Test Beam		**63**	**17**	**80**	**0**	**11**
Outfit EM module	Iowa	5		5		
Prototype optics	Boston, Fairfield	4	3	7		
Calibration	Iowa	3	2	5		
Operations	BU, Fair, Iowa, TexasTech	11	12	23		
Travel	BU, Fair, Iowa, TexasTech	40		40		11
High pressure gas wrap-up	Rockefeller	**7**	**8**	**15**	**0**	**3**

3.3 Trigger and Data Acquisition

The FY 1996 CMS trigger R&D program includes three major activities. The first is the study of the performance requirements for the trigger with the goal of completing final requirements for a review in November, 1996. The second is the preliminary design of the trigger system with the goal of completing the preliminary design for a review in November, 1996. The third is the engineering evaluation of hardware proposed for use in the design for the purpose of evaluating the design capability, feasibility, and cost. The specific goal of the hardware studies is to provide the information required for the calorimeter trigger system design and specifications of interfaces to the front-end, trigger and DAQ systems.

The FY 1996 CMS data acquisition R&D program is a natural continuation of our current R&D in FY 1995 and consists of four major activities. The two hardware-oriented tasks are the creation of a prototype test-bench for an ATM-based event-builder, and the development, in collaboration with CERN-CMS, of prototypes of two different architectures for the readout dual port memories (RDPM), the basic unit of the CMS DAQ system. The other two tasks are software oriented and they are related to simulation studies of switching architectures and protocols, and the development and study of processor-based level 2 trigger algorithms.

The FY 1996 CMS luminosity monitor R&D program will involve tests of prototype counters and simulation studies of monitoring in the forward region.

The US CMS group has a number of leadership roles in the CMS Trigger and Data Acquisition Project (TRIDAS), as shown in Fig. 5. P. Sphicas (*MIT*) is the Chair of the TRIDAS Institutional Board. W. Smith (*Wisconsin*) is the CMS Trigger Project Manager. P. Sphicas also is responsible for higher level triggers. I. Gaines (*Fermilab*) is responsible for the event builder. J. Branson (*UCSD*) is responsible for trigger simulation. Finally, as shown in Fig. 6, G. Snow (*Nebraska*) is responsible for luminosity and beam background measurements.

CMS milestones for the Trigger and Data Acquisition System are shown in Table 7.

3.3.1 Level 1 Calorimeter Trigger

Program for R&D in FY 1996

The task in 1996 is to complete the preliminary design of the level 1 calorimeter trigger and to continue the hardware evaluation required to support this design work. Simulation studies are also to be used to evaluate the design performance and to complete the requirements for the trigger. The hardware and engineering parts of this R&D program include:

1. Extract design requirements to set up data flow diagrams, state machines and a VHDL description of the calorimeter trigger system.

2. Trigger system design: refine the specification of the numbers of ASICs, boards, cards and crates, and what is on each. Define the interfaces for each board and the I/O.

3. Electron isolation ASIC preliminary design: produce schematics based on Vitesse libraries.

4. Sort ASIC preliminary design: produce schematics based on Vitesse libraries.

5. Backplane prototype construction/studies: test high volume signal transmission, connectors, clock distribution, power distribution, and cooling.

6. Electron isolation prototype board for testing of data transmission path from backplane.

7. Dataflow test from prototype receiver card to prototype backplane to prototype electron isolation card.

8. Jet/summary card preliminary design.

9. Study of intercrate data transfer techniques.

10. Preliminary design and test of board level JTAG/boundary scan diagnostics.

11. Refine the calorimeter trigger latency calculation.

12. Produce a more detailed cost and schedule.

The cost for the FY 1996 US CMS calorimeter trigger R&D program is shown in Table 8.

3.3.2 Level 1 Muon Trigger

Program for R&D in FY 1996

The task in FY 1996 is to complete the design of the sector electronics for the level 1 endcap muon trigger and to continue the hardware evaluation required to support this design work. The R&D program outlined here does not encompass the parallel R&D that also must take place on the endcap muon front-end electronics. The time scale for the FY 1996 effort is set by the summer 1997 test beam at CERN, which will have bunch spacing of 25ns and will thus be ideal for trigger/DAQ system tests. There will be a full design review of the endcap muon trigger during the fall of 1997. It is our goal to have first prototypes of each element of the endcap muon trigger electronics in place for the summer 1997 test beam. Simulation studies are also to be used to evaluate the design performance and to complete the requirements for the trigger. The hardware and engineering parts of this R&D program include:

1. Our recent analysis described earlier seems to show that the 1/2-strip trigger scheme works when applied to offline data from ADCs. However, the real trigger scheme, working from comparators attached to the shaped cathode strip signals, has never been tested. During the latter portion of 1995, we will test the comparator scheme using real electronics on the P0 prototype.

2. Strip comparator circuitry needs to be designed and tested. This circuitry includes test inputs, provision for non-working strips, masking of dead channels, ganging for low-P_T muon triggering, and perhaps suppression of wide hits from delta rays or bremsstrahlung. Several channels need to be combined into a single chip, and the comparators must not inject noise into the precision front-end analog circuitry. During 1996 this will be developed in collaboration with the CERN analog engineer who developed the currently used CSC readout track-and-hold and multiplexor circuitry (GASPLEX chip).

3. First production of a digital pattern finding chip for the cathode strip front-end. This chip not only contains muon stub track patterns but also a priority encoder to select the best pattern among the (possibly many) ones satisfied. Simulation studies are necessary to produce acceptable lists of patterns and priorities among them, in order to properly configure the pattern chips.

4. Monte Carlo track simulation, programming, and testing of pattern-finding circuitry using the P0 chamber prototype. Efficiency and position resolution are the most important parameters to be determined from prototype tests of strip trigger circuitry.

5. Development of an analogous chip for patterns among wires which can also find the 25 ns time bucket that a muon came from – this may require two time windows: a longer one to find track patterns in six layers, and a shorter time window with only a two- or three-fold coincidence.

6. Programming and testing of the wire pattern chip on the P0 chamber prototype. Track finding efficiency and bunch identification efficiency (i.e. time resolution) are the most important parameters to be determined from these prototype tests.

7. Locally, the detection of a muon stub by the cathode strip trigger is used by the SCA chips as a pointer to the bunch crossings and strips which contain information to be digitized. Therefore, we hope to test "self-triggering" of prototypes of the precision data acquisition electronics by the strip trigger electronics.

8. Provide a more detailed conceptual design of the motherboard, a single card per chamber, which correlates the precise position and rough timing information from the strip cards with the rough position and precise timing information from the wire cards. The motherboard also handles clock distribution and pipelining of trigger data, as well as correction of muon stub positions and angles due to muon chamber misalignment.

9. Design the interfaces between the front-end chamber cards and motherboards, and between motherboards and the sector muon trigger electronics located in the trigger room.

10. Using Monte Carlo tools, study track linking momentum resolution versus latency, robustness.

11. Develop a more detailed design of the sector muon trigger electronics. Because of the complex magnetic field in the forward direction, track finding in the forward region

must either use large lookup tables or else employ sophisticated tracking methods which may not be possible to implement in a fast pipelined trigger. This will therefore require much detailed simulation work.

12. Design compatibility in the sector muon trigger with barrel muon trigger data for the region of overlap, $0.9 < \eta < 1.3$.

13. Provide firm estimate of total muon trigger latency.

14. Design electronics layout: fiber optic interface, internal bussing of signals, clock distribution.

15. There are lingering concerns that the present design may not provide sufficient rejection of all types of background. Alternative chamber designs requiring different trigger strategies have been proposed (see, *e.g.*, CMS TN/94-213). Continued study of backgrounds and alternate chamber/trigger schemes is necessary.

The cost for the FY 1996 US CMS muon trigger R&D program is shown in Table 8.

3.3.3 Data Acquisition (DAQ)

The FY 1996 CMS Data Acquisition R&D program is a natural continuation of our current R&D in FY 1995 and consists of four major activities:

- The creation of a prototype test-bench for event-building schemes. We propose to install this system at Fermilab.
- The development, in collaboration with CERN-CMS, of prototypes of two different architectures for the Readout Dual Port Memories (RDPM), the basic unit of the CMS DAQ system.
- Simulation studies of switching architectures and protocols, and comparison with results from the event builder testbench.
- The development and study of processor based level 2 trigger algorithms to further validate the latencies and rejection factors assumed in the design of the DAQ.

Program for R&D in FY 1996

The event builder testbench program of work consists of three stages:

1. Point-to-point data link tests (for general protocol and driver development). These tests were initiated in FY 1995.
2. Low speed ATM (155 Mbit/sec) switch tests.
3. High speed ATM (620 Mbit/sec) switch tests.

4. Comparison of synchronous vs. asynchronous switch operation.

5. Implementation of two options of control transmission information (via the reverse switch datapath and via an independent, external, control path), along with measurement of the timing overheads associated with each option.

The RDPM program of work consists of the following tasks:

1. Complete debugging of the FPGA-based prototype RDPM.

2. Complete debugging of the embedded-processor prototype RDPM.

3. Redesign RDPM to add the functionality necessary for the event builder output (the switch farm interface, SFI).

4. Introduction of PCI bus on FPGA-based RDPM.

The program of work on the simulation of the event builder consists of:

1. Complete the C++ software package.

2. Include the processor farm and event management protocol in the simulation.

3. Simulate and compare two architectures, with and without a central Event Manager intelligence.

Finally, on the level 2 algorithms we plan to

1. Derive a faster version of the detector simulation from the current full CMS detector simulation.

2. Investigate calorimeter-based high-level triggers to reduce the rate into level 3.

The cost for the FY 1996 US CMS data acquisition R&D program is shown in Table 8.

3.3.4 Luminosity Monitor

Program for R&D in FY 1996

The R&D effort in FY96 will focus on simulation studies for elastic and inelastic rate monitoring in the forward region and prototype studies of scintillator-based and quartz-based detectors for the dedicated luminosity and background monitors. The scope and objectives of the Luminosity Monitoring project are described in the R&D request submitted to the NSF [2].

We will machine, assemble and test prototype counters for the CMS luminosity monitor and construct a cosmic ray stand for testing the prototypes. Prototypes will be made from polystyrene and quartz scintillator stock, wavelength-shifting optical fibers and wrapping materials. We will study the light collection and uniformity characteristics of prototype counters for the CMS luminosity monitor. We will procure four phototube assemblies (photomultiplier tube, base, magnetic shield) and data acquisition electronics, including a CAMAC-based analog-to-digital converter and interface electronics, for these tests. We will perform simulation studies of the particle multiplicity, rates and radiation exposure which will be encountered by the luminosity and beam background monitors. In addition, we will investigate the use of event rates of various inclusive particle production processes to supplement the information from the dedicated luminosity monitor.

The activities above will culminate in an integrated proposal for the luminosity and beam background monitoring techniques which will be presented to the CMS collaboration for review in the latter half of 1997. Milestones for the luminosity monitor are included in Table 7, and the cost for the FY 1996 US CMS luminosity monitor R&D program is included in Table 8.

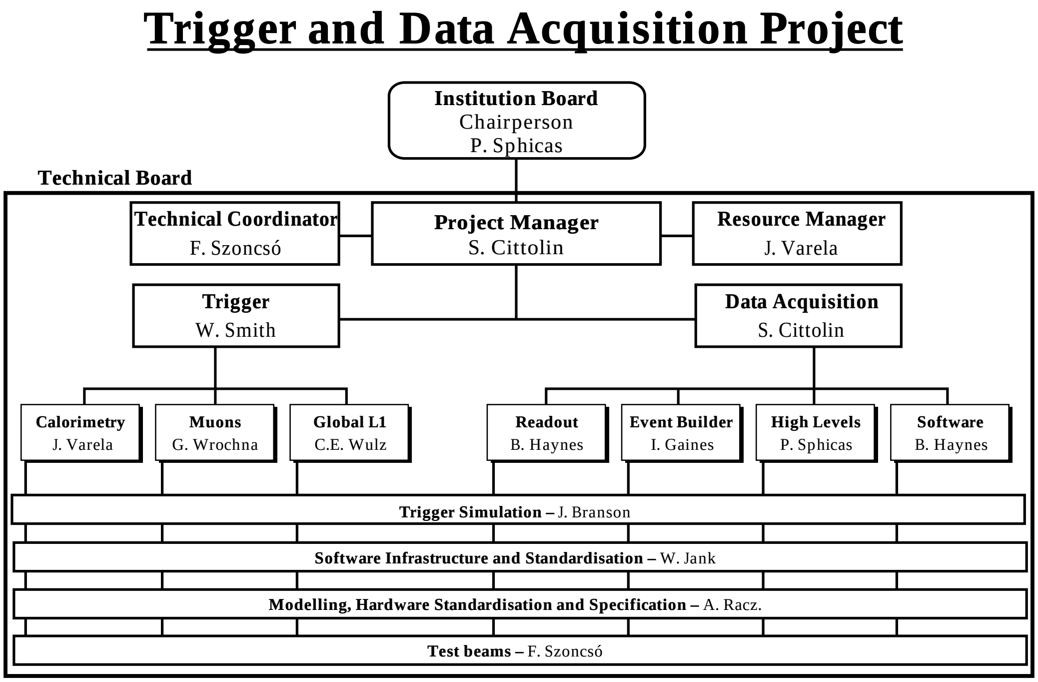


Figure 5: CMS Trigger/DAQ Project organization.

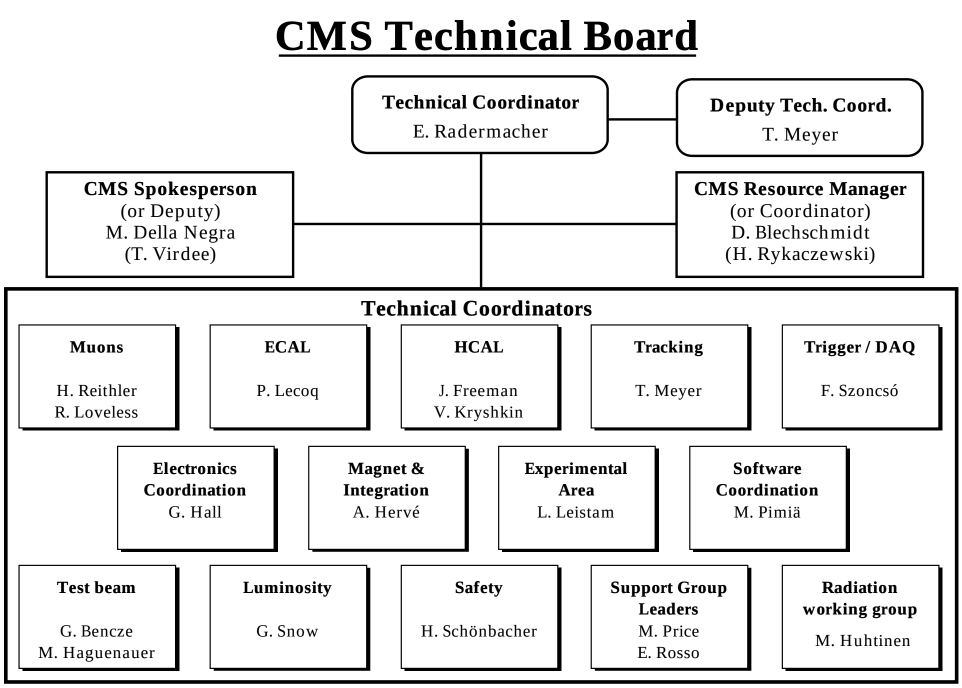


Figure 6: CMS Technical Board organization.

Table 7: Trigger/DAQ Milestones.

General:

- 1996 Nov: Trigger and data acquisition requirements review (final choice of trigger algorithms) and preliminary design review (presentation of preliminary conceptual design of hardware).
- 1997 Nov: Trigger and data acquisition Technical Design Report

Calorimeter trigger:

- 1996 Nov: Review of primitive extraction and optical transmission prototype test with FERMI.
- 1996 Jun: Review of prototype test of backplane, Receiver Card (incl. Adder ASIC), and Electron Isolation Card dataflow.
- 1996 Nov: Review of test of global processor prototype card.
- 1997 Jun: Review of test of control and readout prototype cards.

Muon trigger:

- 1996 Jun: Review of test benches with FPGA prototypes of PAC, synchro/readout and sorter chips.
- 1996 Jun: Review of FPGA prototype tests of the muon sorter ASIC.
- 1996 Jun: Review of FPGA prototype tests of the meantimer ASIC.
- 1996 Nov: Review of FPGA prototype tests of the Track Finder ASICs.
- 1996 Nov: Review of prototype tests of comparator tree and pattern finding chips for cathode strip chamber trigger.
- 1997 Apr: Delivery of first presamples of PAC, synchro/readout and sorter ASICs.
- 1997 Jun: Review of prototype tests of wire pattern-finding and bunch i.d. chips for CSC trigger.
- 1997 Nov: Delivery of first presamples of ASICs for strip and wire LCT generation for CSC trigger.
- 1997 Nov: Delivery of first prototype motherboard circuits for CSC trigger.
- 1997 Dec: Delivery of meantimer and correlator final chips for full trigger test.

Global trigger:

- 1996 Nov: Review of Integration of Timing, Trigger and Control (TTC) chain in readout sub-systems.
- 1997 Nov: Review of tests of prototypes of PSB and GTL cards.

Data acquisition:

- 1995 Dec: RDPM.FPGA memory management prototype and ATM(AT&T)-PCI.
- 1996 Jul: ATM-PCI-PPC 4*4 event builder test.
- 1996 Dec: RDPM/SFI and data link prototypes.
- 1996 Dec: First results of high level trigger algorithm studies.
- 1997 Jul: Readout chain test - FED,RDPM,link,SFI.
- 1997 Nov: Review of test of 256 Mbit/s and 1 Gbit/s trigger/DAQ optical link prototypes.
- 1997 Nov: RDPM-SFI event builder system.
- 1997 Nov: High level trigger studies including tracking.

Luminosity monitor:

- 1996 Sep: Review of simulation results on radiation exposure, rates, and occupancy for dedicated luminosity monitor and beam background monitors.
- 1997 Mar: Review of prototype test results for scintillator- and quartz-based prototypes of counters for dedicated luminosity monitor and background monitors.
- 1997 Sep: Presentation of integrated proposal for luminosity measurement, beam-gas and beam halo background monitoring to CMS collaboration.

Table 8: Trigger/DAQ FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Trigger and Data Acquisition		**225**	**245**	**410**	**60**	**40**
Level 1 Calorimeter Trigger		**79**	**109**	**188**	**0**	**10.5**
Equipment (Backplane Study)		**59**	**0**	**59**	**0**	
Crate	Fermilab, Wisconsin	2		2		
Backplane construction	Fermilab, Wisconsin	20		20		
VME controller	Fermilab, Wisconsin	4		4		
Test cards (3 data, 1 clock)	Fermilab, Wisconsin	15		15		
Power supplies, cooling, distribution	Fermilab, Wisconsin	15		15		
Cabling hardware	Fermilab, Wisconsin	3		3		
Equipment (Jet/Energy Sum & Electron Trigger Studies)		**20**	**0**	**20**	**0**	
Trigger boards (4)	Fermilab, Wisconsin	20		20		
Engineering and Technical		**0**	**109**	**109**	**0**	
1 MY engineering	Wisconsin		109	109		
Level 1 Muon Trigger		**20**	**50**	**70**	**0**	**10.5**
Equipment		**20**	**0**	**20**	**0**	
Track-finding prototype	UCD,UCLA,MIT,Ohio State	20		20		
Engineering and Technical		**0**	**50**	**50**	**0**	
0.5 MY engineering	UCD,UCLA,MIT,Ohio State		50	50		
Data Acquisition		**111**	**51**	**152**	**10**	**19**
Equipment		**109**	**0**	**101**	**8**	
115 Mbps ATM/SONET adapter (16)	FNAL, Iowa St, MIT, Miss	16		16		
16-port ATM switch	FNAL, Iowa St, MIT, Miss	35		35		
2-channel PCI sources (8)	FNAL, Iowa St, MIT, Miss	24		24		
FPGA RDPM prototypes (2)	FNAL, Iowa St, MIT, Miss	8		8		
PCI test equipment	FNAL, Iowa St, MIT, Miss	2		2		
ATM card VME/SUN	UC San Diego	1			1	
JTAG analyzer	UC San Diego	1			1	
VORTEX RDPM prototypes (2)	UC San Diego	16		16		
C80 H/W emulator	UC San Diego	6			6	
Software		**2**	**0**	**0**	**2**	
C80 source debug S/W	UC San Diego	2			2	
Engineering and Technical		**0**	**51**	**51**	**0**	
0.5 MY engineering	UC San Diego		37	37		
0.8 MY technician	UC San Diego, MIT		14	14		
Luminosity Monitor		**15**	**35**	**0**	**50**	**0**
Equipment		**15**	**0**	**0**	**15**	
PMT assemblies	Nebraska	2			2	
DAQ electronics	Nebraska	5			5	
Disc. and coinc. units	Nebraska	3			3	
Prototype materials	Nebraska	5			5	
Engineering and Technical		**0**	**35**	**0**	**35**	
0.3 MY engineering	Nebraska		18		18	
1.0 MY technician	Nebraska		17		17	

3.4 Electromagnetic Calorimeter

The US CMS groups working on the electromagnetic calorimeter are concentrating on a few specific areas where they have unique expertise so that a significant contribution can be made. These areas are front-end electronics, the avalanche photodiode readout, thermal finite element analysis, crystal surface treatment and scintillation properties, and the laser light source for the calibration monitoring system.

In the management of the ECAL project we have responsibility for the electronics, the avalanche photodiodes and the crystal processing; see Fig. 7. In all cases this responsibility is shared with at least one of our European counterparts, illustrating the way in which we have become embedded in the organization of this mostly European project.

In FY95 the US groups worked on the development of a new type of APD with EG&G, making detailed physical measurements of the devices, including measurements of noise, response uniformity, radiation damage by neutrons and of thermal variations of the signal. Electronic components for the front-end readout, such as high-speed ADCs and analog compression circuits were fabricated and tested in beams with $PbWO_4$ crystals. US groups also carried out many precision measurements of the physical properties of the lead tungstate crystals as part of the CMS crystal development program.

In the schedule for construction of the 110,000 $PbWO_4$ crystal calorimeter, the production of crystals is planned to begin with a preproduction phase in 1997, in which mass-production procedures will be developed and checked in preparation for the start of full production in 1998. The production of other elements must follow a similar path, as all the crystals will, after assembly into baskets, be calibrated in a test beam. The electronics readout, including the phototransducer, needs to be completely standardized and production begun, so that crystals coming off the production line can be immediately assembled into modules complete with readout electronics for calibration in a beam.

The ECAL milestones relevant to the US FY96 program are shown in Table 9. The FY95 ECAL R&D activities, participating institutions, and the estimated costs are summarized in Table 10.

3.4.1 Photodetector R&D Program

There are two major manufacturers of APDs: Hamamatsu and EG&G. The US groups are working with EG&G to optimize their detector for the crystal readout, accordingly we are requesting funds for a subcontract with them for this development. This will be the second part of a three-part program with EG&G. The first part, paid for by our collaborators at PSI, was devoted to the reduction of the excess noise factor (ENF) in the avalanche process. In the second part of the program the company will:

- Redesign the non-magnetic APD package, both to circumvent problems in hermeticity and attachment found in 1995 with the current package, and to reduce manufacturing costs.

- Improve the internal structure of APD, that is to tailor the response to the requirements of the CMS. (The many parameters that describe the performance of the APD, which include the response to ionizing radiation, the temperature and voltage dependence of the gain, and the excess noise factor of the amplification process, cannot be simultaneously optimized. The best solution for CMS will be ascertained.)
- Incorporate a temperature sensor in the package, for precise monitoring of the gain.

As part of this subcontact the US groups will receive from EG&G samples for evaluation and measurement. Furthermore, the simulation package which is used to design the APDs, SILVACO, is available at the University of Minnesota, and the group there will work with this package to to accurately predict effects like the response to ionizing radiation, which are not available in standard simulations.

The groups will also continue the neutron radiation damage measurements at ORNL with Cf^{252}, started in 1995, and participate in the test beam program at CERN.

3.4.2 Electronics R&D Program

Princeton is responsible (along with ETH Zurich) for the overall management of the ECAL readout electronics. The group, which is based at CERN, works in close contact with the ECAL management and thus is able to play a leadership role in these efforts. Their responsibilities in this phase is the development, in conjunction with the various interested groups, of the best possible design for the readout chain.

During 1995 the Princeton group has built, and tested in beams, discrete analog compression circuits and high speed ADCs, fabricated in 1.2 micron AMS BiCMOS, an IC version of an analog compression circuit (in collaboration with IPN Lyon) and carried out a test of the complete readout (IC Preamp+IC Compressor+ADC) coupled to a crystal in a test beam at CERN.

The development projects for FY96 in this area are:

- Perform tests with 36-crystal matrix at CERN, which will include dynamic range compression, ADC cards and Trigger Filter logic built by Princeton in collaboration with IPN Lyon.
- Participation in the design and evaluation with beam and laboratory tests of components.
- Assembly of a complete chain, from the crystal through to the main readout and trigger, for component evaluation.
- Design and build front-end readout components in a new radiation-hard process at Honeywell: CHFET (Complementary Heterojunction FET) GaAs.
- Fabricate further Bi-CMOS compressor prototypes.

- Perform tests at PSI with the high-rate proton beam of crystals coupled to readout components.
- Prototype a high-speed readout coupled to digital trigger circuitry.

3.4.3 US Crystal R&D Program

The Caltech and BNL groups will continue to work on the program to develop high quality $PbWO_4$ crystals. In 1995 they made many contributions to this program, most notably in the characterization of the scintillation properties, including measurements of the emission and the decay time constants and their variation during and after irradiation. The development projects planned for 1996 are:

- Characterize full size crystal samples supplied by CERN, including measurements of the transmittance, the emission spectrum, the light yield, the light response uniformity and the decay time.
- Carry out radiation damage studies at Gamma irradiation facilities at JPL and BNL for these full-size samples, and charged hadron irradiation studies at BNL.
- Carry out material analysis at commercial companies of the crystals to identify the correlations, if any, between impurities/defects and the crystal properties.
- Acquire a set of doped crystal samples from the Shanghai Institute of Ceramics to understand the effects of specific impurities.

In addition to these crystal studies at Caltech and BNL, the LLNL group have the responsibility to develop and prototype a crystal end-face cutting machine. They have this responsibility due to their unique expertise in this field. They will define the proper cutting and polishing methods and then design and fabricate a prototype cutting machine. This prototype must be delivered to CERN at the end of 1996 in order to allow the construction of replicas (not a US responsibility) for delivery to the crystal processing centers in time for the beginning of the preproduction phase.

3.4.4 Other R&D Efforts

Besides these main R&D programs, groups from the US will work in two other areas.

The LLNL group will begin a collaborative effort with CERN to model the thermal environment of the crystal matrix and the associated electronics. As both the light yield of the crystal and the gain of the avalanche photodiodes increase with decreasing temperature, to give a combined signal variation of 4%/°C, this is an essential part of our engineering design. As thermal FEA is a unique capability of the LLNL, this effort, which must progress in conjunction with the engineering design of the calorimeter, needs to begin in FY96.

The Caltech group have taken on responsibility for light-source and the high-level distribution network of the Light Monitoring system. This group, in collaboration with JPL, will prepare the light source for the test beam run in 1996 at CERN.

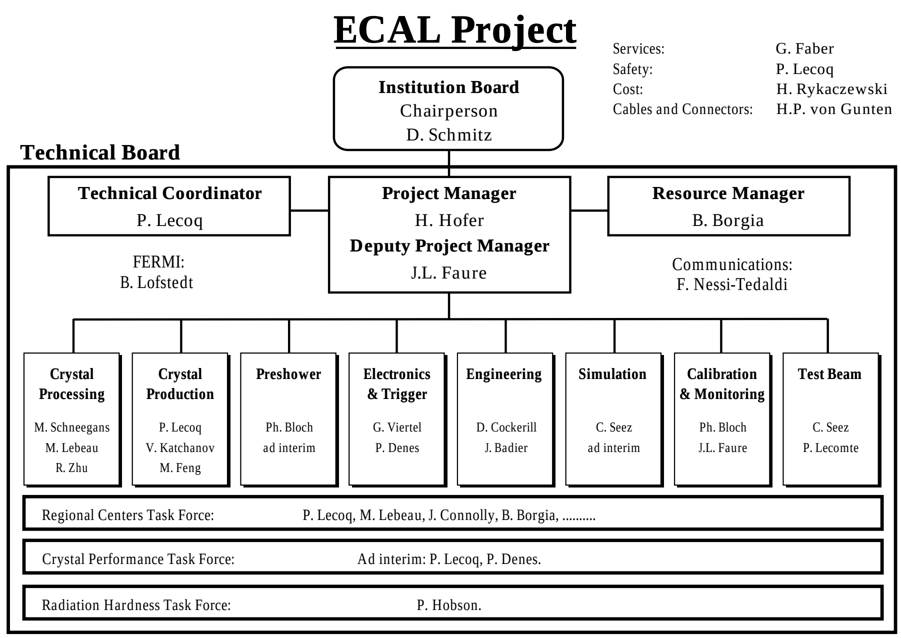


Figure 7: CMS ECAL Project organization.

Table 9: ECAL Milestones.

- For the end of 1995:

  1. Produce 20 radiation-hard crystals with a 30% improvement in the light yield over the level achieved in 1994;
  2. Produce EG&G and Hamamatsu avalanche photodiodes with a reduced response to ionizing radiation;
  3. Improve the Hamamatsu diode such that the dark current is < 100 nA, the capacitance is < 100 pF, and the gain versus voltage performance is improved;
  4. Produce rad-hard crystals with light attenuation length longer than 1 m after 0.5 Mrad irradiation.

- For the end of 1996:

  1. Produce 100 crystals with ≥ 12 photons/MeV and the same radiation hardness achieved in 1995;
  2. Produce and test a 100-crystal matrix with $\Delta E/E$ at 100 GeV $\sim 0.6\%$, with voltage and temperature stabilization;
  3. Design and prototype a crystal end-face cutting machine for the crystal preproduction period;
  4. Produce a radiation hard version of the front-end electronics;
  5. Reduce the excess noise factor of EG&G diode to < 2.5.

- For June 1997:

  1. Select the avalanche photodiode.

- For December 1997:

  1. Perform global ECAL system test, including complete front-end electronics;
  2. Complete Technical Design Report.

Table 10: ECAL FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Electromagnetic Calorimeter		**260**	**140**	**340**	**60**	**40**
Photodetectors		**120**	**50**	**110**	**60**	**20**
Subcontract to EG&G for APD	Minnesota	65		65		
Device Evaluation	Minnesota, Fermilab	10	30	40		
Device Evaluation	Northeastern, Fermilab		10		10	
APD Neutron Irradiation	Northeastern, Minnesota	20	10		30	10
Travel to test beams and vendors	Minnesota					10
Domestic Travel	Northeastern	10			10	
APDs for test beams	Minnesota	5		5	0	
APDs for test beams	Northeastern	10			10	
Electronics		**60**	**50**	**110**	**0**	**10**
Electronics Test Bench	Princeton	30		30		
Bi-CMOS Compressor Prototypes	Princeton	20		20		
Full Chain Development	Princeton	10		10		
Travel to vendors and PSI	Princeton					10
Engineer (B. Wixted 4 months)	Princeton		50	50		
Crystals		**80**	**40**	**120**	**0**	**10**
Crystal Characterization	Caltech, BNL	20		20		
Travel to CERN	Caltech					10
Technician Salary (D. Ma)	Caltech		40	40		
Monitoring light Source	Caltech, (JPL)	5		5		
Crystal Endface Cutter	Fermilab (LLNL)	40		40		
Crystal Surface Treatment	Fermilab (LLNL)	5		5		
Crystal Matrix Thermal FEA	Fermilab (LLNL)	10		10		

3.5 Tracking System

The CMS R&D program for tracking in FY1996 concentrates on the development of the forward pixel detector system and the forward MSGC/MGC wheels. These efforts are taking place in light of the relevant tracking milestones as set out in Annex 9 of the CMS Interim Memorandum of Understanding [3]. Specifically, those relevant to the US CMS groups are:

- Tracking system
  - 12/97 Technical Design Report
- Pixel detectors
  - 12/97 Readout Architecture Decision
  - 12/97 Prototype module with LHC adequate analog block
- MSGC/MGC detectors
  - 12/96 Engineered prototypes of single sided modules
  - 12/96 Choice of microstrip gas technology for stereo measurement
  - 06/97 Prototypes of sectors of a wheel and a disk partially equipped with engineered single sided prototype modules.

The organization of the CMS Tracking Project is shown in Fig. 8. The MSGC schedule and milestones are shown as a bar chart in Fig. 9. Tracking milestones are listed in Table 11, and the FY96 R&D activities, the participating institutions, and estimated costs are summarized in Table 12.

3.5.1 Pixel Detectors

As stated in the CMS Technical Proposal [4], the US CMS pixel group has responsibility for the design and construction of the forward pixel disks for the CMS central tracker. An overview of this system and a discussion of the R&D program for FY 1996 are given in the 1995 US CMS Letter of Intent [1]. The high priority areas for R&D are (1) proof of principle of column architecture pixel readout technology including a beam test of a 12 x 64 pixel array; (2) design of the pixel array layout, mechanical supports and cooling for the forward disks; and (3) development of pixel diode arrays for the forward disks. The specific tasks for these R&D areas are described below. The groups working on pixels are UC Davis, Florida State (SCRI), Johns Hopkins, LLNL, Los Alamos, Rice, and Texas Tech.

Pixel Readout Development, Hybridization

The 12 x 64 readout array establishing proof-of-principle of the column readout architecture is under development at LBL. It will be suitable for bonding to a detector array for use in beam tests later in 1996. UCD has prepared bump-bonding prototypes in collaboration with LBL for use in indium and solder bonding tests, and is currently bonding test structures. Solder bumping would be achieved using the MCNC fluxless process.

Hybridization and testing of the 12 x 64 array will take place 1996. Electronic simulation, hybridization and bench tests of the readout and hybridized detectors will take place at UCD. Beam tests of detectors will be performed in conjunction with LBL/ATLAS.

While the front end design of the 12 x 64 array will satisfy many of the requirements for LHC use, further work is required to achieve lower thresholds, reduced power dissipation and reduced time walk. Although these goals may be achievable within the context of the existing "time-over-threshold" approach, alternate front end designs (still coupling to the same column architecture) may be better suited to the CMS forward pixel disks, particularly if significant charge sharing with neighboring pixels is not needed or available. UCD will investigate the suitability of alternate front end designs in the context of physics simulations of the pixel disk performance.

Pixel readout and hybridization milestones are included in Table 11.

Mechanical and Thermal Design and Evaluation

An engineering study is required to establish the feasibility of the mechanical concept for the forward pixel detector modules (Phase I), and to perform a detailed analysis of the pixel disks and related systems issues (Phase II). The outcome of the full study would include CAD drawings for vendor quotes to establish manufacturing costs.

Cooling: The detector temperature will be of order or less than 0° C, to reduce the effects of radiation damage to the detector. A suitable coolant must be used (consistent with the rest of the CMS silicon tracker) and sufficient flow provided. Analysis must account for heat conduction and thermal gradients in supporting material and deal with CTE of detectors, readout and support, as well as strength of bonding adhesives under thermal stresses.

Mechanical support: The issues here are stiffness, low radiation length, and freedom from distortion under gravitational and thermal stresses; also to be considered are the method of connection to rest of the tracking system and alignment issues.

Electrical connections: The pixel detector arrays will connect to multilayer kapton cables for local electrical interconnections. The combined arrays will connect to the outside world through other cables and fiber optic links. The mechanical structure must provide support for the local interconnection cables and points of attachment for the external connections.

For Phase I, engineers must develop a finite element model for analysis of thermal and mechanical performance of the basic unit (*e.g.,* arc and subring). Assuming a constant heat load (due primarily to the pixel readout electronics), analyze fluid channel sizing and flow rate. Find thermally induced distortions assuming suitable end connections. Analyze the effect of cooling from room temperature to the operating temperature. Evaluate alternate materials to reduce thermal strains and improve the stability of the detector. Review design concept relative to alternatives (e.g., "fan-blade" approach to pixel array construction) in light of this analysis. This will determine the overall dimensions of the pixel detector arrays.

For Phase II, a finite element model must be developed for the entire disk consisting of subunits defined in Phase I. Define and analyze support structure to asses gravitational and thermal strains. Propose design variations to achieve goals of accuracy, stability, minimum temperature gradients and minimum radiation length. Prepare design sketches as required for these improvements. Assess dynamic behavior of structure and modify design parameters as required to achieve goals. Prepare reports and transparencies as required for technical briefings. Develop CAD drawings of resulting system for vendor quotes.

Mechanical and thermal design/evaluation milestones are included in Table 11.

Pixel Detector Diode Array Development

Following determination of the pixel array geometry from Phase I of the mechanical and thermal design studies, layouts must be made of prototype pixel arrays. These must include channel stops between pixels since electrons will be collected. The design must take into consideration the results of radiation tests of pixel arrays at PSI and elsewhere. The goal is to develop diode test arrays for hybridization with readout arrays including prototype multichip modules with interconnection traces for the readout chips.

Pixel detector diode array milestones are included in Table 11.

3.5.2 Micro-Strip Gas Chambers (MSGC)

The US MSGC team is committed to build one fourth of the forward tracking of CMS. The detectors will be MSGCs arranged in "forward wheels" as described in the CMS Technical Proposal [4]. In the present design one "wheel" includes two disks made with 5 concentric rings of detectors. Each MSGC unit is trapezoidal in shape to avoid gaps, has an average area of 10cm $\times$ 12cm, and has a maximum of 512 channels. One "wheel" requires nearly 500 MSGCs. The detectors supplied by the US group are to be assembled and tested in the US before installation at the LHC. The US groups involved in this R&D are Fermilab, Mississippi, Northeastern, Northwestern, and Rockefeller.

During 1995 the US group tested its first MSGC in a test beam at BNL. Detectors were built on different substrates (glass and polyimide). The sensitive area was 34 by 65 mm^2 and was equally subdivided in two regions with anodes of 200μm and 400μm pitch respectively. The signals of groups of anodes as well as of the individual 120 cathodes have been read out using a CAMAC system and also using the very first version of the SVXII-B chip. Efficiency curves for nine different gas mixtures have been measured. The resolution was measured for MSGCs tested at BNL. The sigma, for the 400μm pitch region is 75μm, while for the 200 μm region it is about 60μm. These numbers include the contributions of the multiple scattering and of the geometry of our telescope of MSGCs. A Monte Carlo program built on Geant shows that the attainable resolutions (after removing multiple scattering and geometry) are consistent with values of 60μm (40μm) for 400 and 200μm pitch respectively. These numbers agree with the best measured values today.

R&D Tasks for MSGCs in FY 1996.

The immediate goal of the CMS group for forward tracking is to carry out, by the end of 1997, a system test with one partially instrumented "forward wheel". The results of this test would then allow CMS to select the technology and proceed with the construction phase of these detectors which must be installed in the second half of 2003; see Fig. 1.

The R&D in 1996 will allow some time to choose between the different substrates and geometries of the electrodes. The milestones we have set for the US CMS MSGC group (see Fig. 9) are to design, build and test MSGCs (of 10cm $\times$ 12cm) on substrates of Upilex with overcoating and read out using the CMS electronics. These chambers will be first tested with Fe^{55} sources and possibly with cosmic rays. A beam telescope consisting of 4 MSGC units will then be tested in a test beam at Fermilab. We will test these devices later at CERN together with the one built by our European collaborators. Aging of our MSGCs will be carried out with X-Rays generators and at the test beam facility at the Fermilab Booster. There is great interest, especially in Europe, in using as detectors Micro Gap Chambers (MGC). Fabrication techniques for MSGCs and MGCs using lasers will also be explored.

A bar chart of the MSCG milestones and tasks is shown in Fig. 9. The US CMS groups involved in MSGCs are shown in Table 12, together with the tasks for which they have taken responsibility and the cost estimate.

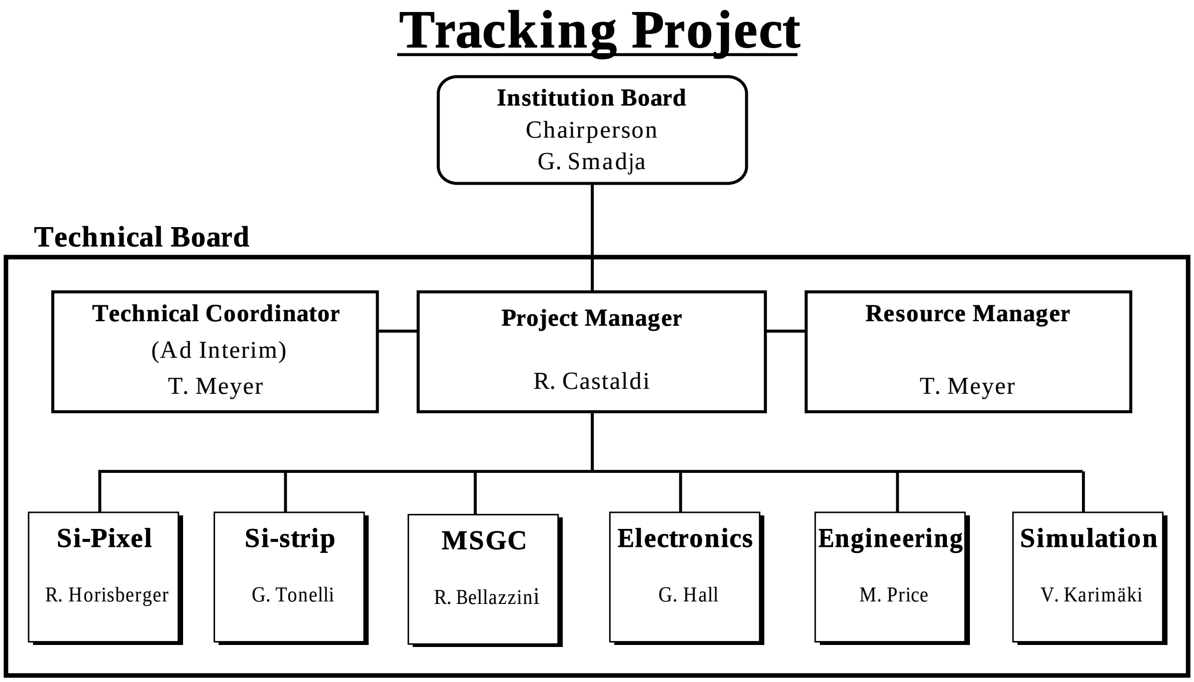


Figure 8: CMS Tracking Project organization.

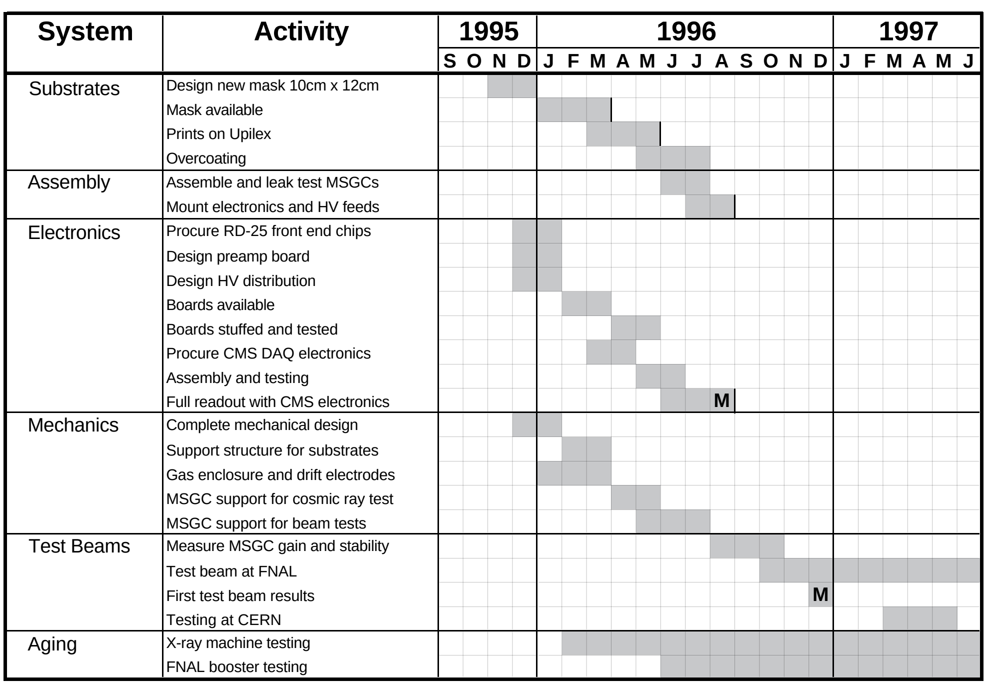


Figure 9: 1995-97 MSGC schedule and milestones.

Table 11: Tracking Milestones.

Pixel Detector Milestones:

- **Pixel Readout Development/Hybridization**
  - 06/96 – 12 x 64 array bench tests
  - 09/96 – 12 x 64 array beam tests
- **Mechanical and Thermal Design/Evaluation**
  - 07/96 – Phase I
  - 12/96 – Phase II
- **Pixel Detector Diode Array**
  - 07/96 – Pixel array geometry specification
  - 09/96 – Layout of diode array prototype
  - 12/96 – Diode array prototype

MSGC Milestones:

- **Substrates**
  - 11/95 – Design new mask for 10cm $\times$ 12cm
  - 01/96 – Mask design completed and submitted to manufacturer
  - 03/96 – Mask available from manufacturer (HTA)
  - 05/96 – Prints on Upilex come back from manufacturer (Max Levy)
  - 05/96 – Survey prints for defects and repair where possible
  - 06/96 – Overcoating of substrates with diamond film
- **MSGC Units**
  - 06/96 – Assemble and leak test MSGCs
  - 07/96 – Mount electronics and HV feeds. Test chambers under voltage
- **Electronics**
  - 12/95 – Procure RD-25 front end chips
  - 12/95 – Design board for front end interconnection (preamp board)
  - 12/95 – Design board for HV distribution
  - 02/96 – Boards available
  - 03/96 – Procure full CERN/CMS DAQ electronics

- 05/96 – Assembly, bench testing
- 08/96 – Full readout with CMS electronics

- **Mechanical**
  - 02/96 – Complete the mechanical design of the support frame for MSGC
  - 04/96 – Frames completed and available
  - 01/96 – Gas enclosures and drift electrodes assembly starts
  - 06/96 – Cosmic ray test support completed
  - 08/96 – Test beam support completed

- **Testing**
  - 08/96 – Measure gas gain and stability of completed MSGCs with Fe^{55} source
  - 09/96 – Start test beam at Fermilab
  - 12/96 – First test beam results become available
  - 03/97 – Testing at CERN begins

- **Aging studies**
  - 02/96 – Long term aging studies with X-ray unit begin
  - 06/96 – Long term aging studies with Fermilab booster begin

Table 12: Tracking System FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Tracking System		**239**	**81**	**160**	**160**	**30**
Pixel Tracker		**131**	**29**	**80**	**80**	**17**
Detector Development		**72**	**8**	**0**	**80**	**0**
Array mechanical design	Johns Hopkins	25			25	
Prototype production	Johns Hopkins	32			32	
DAQ and test electronics	Johns Hopkins	15			15	
Assembly	Johns Hopkins		4		4	
Testing	Johns Hopkins		4		4	
Readout Development		**59**	**21**	**80**	**0**	**12**
Electronic engineering/simulation	UC Davis	24		24		4
Support and cooling studies	UCD, (LLNL), TexasTech	25		25		4
Readout fabrication	UC Davis	10		10		
Hybridization/testing	UC Davis, (LANL)		21	21		4
Software Development		**0**	**0**	**0**	**0**	**5**
Tracking simulations	UC Davis, FSU-SCRI, Rice					5
Forward MSGCs		**108**	**52**	**80**	**80**	**13**
Substrates		**34**	**18**	**26**	**26**	**4**
Masks	NEU, NWU, Fermilab	12	4	8	8	2
Prints	NEU, NWU, Rockefeller	16	10	8	18	2
Overcoating	Fermilab	6		6		
Evaluation and QC	Fermilab, Rockefeller		4	4		
Electronics		**40**	**16**	**17**	**39**	**0**
Procure front-end chips	Mississippi	8		8		
PC boards	NEU, Miss, Fermilab	12	6	6	12	
CMS DAQ electronics	NEU, Rockefeller, Fermilab	20	10	3	27	
Mechanical		**22**	**18**	**28**	**12**	**6**
MSCG frames	Northwestern,Northeastern	10	8	6	12	3
Test beam support	Mississippi, Rockefeller	7	6	13		3
Cosmic ray test support	Mississippi, Rockefeller	5	4	9		
Testing		**8**	**0**	**5**	**3**	**3**
Mixer and flow meters	Northwestern	5		5		
Gas	Northeastern	3			3	
Fermilab test beam	FNAL,Miss,NEU,NWU,Rock					3
Aging Studies		**4**	**0**	**4**	**0**	**0**
Beam monitor	Fermilab, Mississippi	4		4		

3.6 Software and Computing

Software and computing efforts are essential to the success of the CMS experiment. Within CMS, software-related activities are coordinated by the Software Technical Board, whose organization is shown in Fig. 10. Among the US members of the Software Technical Board are the coordinators for Software Engineering, jet/tau/missing E_t, HCAL, Muon, and Trigger Software, and Event Visualization.

A strong software and computing effort is being mounted by the US CMS Collaboration. The US CMS task leaders are listed in Table 13. During FY95, substantial contributions were made by the US software group to the design and optimization of the detector. Important studies were completed on Muon System alignment and track matching, on HCAL resolution and optimization, on Trigger algorithms and design, as well as physics and common software studies. A list of the CMS Technical Notes authored by US software groups in 1995 is given in Table 14.

Software and computing resources are vital to the experiment as a whole, and need to be supported as a coherent effort. To this end, a CMS Technical Proposal for Computing will be submitted to the LHC Computing Review Board (LCRB) at the end of 1996. A separate but parallel software operations funding request will be prepared and submitted to DOE in 1996.

US software and computing milestones for FY96 are listed in Table 15. The proposed software and computing R&D is described below. The FY96 tasks, participating institutions, and costs are summarized in Table 16.

3.6.1 Software and Computing R&D Plan

The US CMS FY96 software and computing R&D plan is described below. US groups have leadership roles in all the R&D tasks described in this section.

1. Development of the common CMS software framework:
   For this task the role of the US groups is pivotal. This development effort will mold the CMS software structure for the coming years. It will require substantial coordination supported by workshops dedicated to intensive development efforts by experts of various subsystems. These workshops are the software-equivalent of beam tests, and have proven to be highly effective.

2. Workstations for US physicists in CERN:
   The new Building 40 at CERN will provide office space for the US CMS collaboration. A small number of workstations is a necessity for the productivity of US physicists working in CERN for beam-test, software development and event visualization. They would also be an important resource for the (highly CPU-intensive) detailed simulation work done by physicists in the US.

3. Study of full pattern recognition, vertex reconstruction, and the effects of background, pile-up and muon radiation on the detector efficiency and physics performance:

These challenging tasks are essential in ensuring that the muon and inner tracker systems perform at their full potentials. The Kalman Filter method is the core algorithm for track reconstruction and pattern recognition. For high event-rate studies, we require a fast simulation that includes realistic parametric detector resolutions and efficiencies, and approximations for beam-related and -unrelated backgrounds.

4. Performance studies of the HCAL design and detailed simulation of the CMS calorimetry system's performance for missing E_t measurements:
   Fully implement HCAL geometry in the framework of CMSIM100; to simulate using GEANT the Spring-Summer '95 CMS HCAL CERN beam test results, and compare these with data; to create a detailed shower library for CMS calorimetry; and to study CMS performance for missing E_t measurements. Issues such as the following will be studied: phi cracks between HCAL modules; cable routing and effect of cable mass; and optimization of massless gap/tail catcher.

5. Physics tools:
   Focus on physics processes involving muons and missing E_t. After we have completed a study of the process $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$, we are embarking on a study of $H \rightarrow WW \rightarrow jj\ell\nu$ and strong WW Scattering (W_L W_L scattering), which explore the ability of the HCAL to reconstruct jet-jet invariant masses. We will investigate the search for charged Higgs in top decays, where the Higgs is reconstructed in the $\tau - \nu$ channel, as a way to benchmark CMS's τ-reconstruction capabilities. We will investigate the ability of CMS to find supersymmetric particles through missing E_t+jet signatures.

6. Pilot computing farm:
   The availability of very inexpensive computers with large CPU power but small I/O capabilities, makes the idea of stacking large numbers of such CPUs into dedicated farms very attractive. The development of efficient algorithms to schedule tasks, allowing the transparent use of such "commodity components" are planned.

7. Evaluation and decision on CMS computing model:
   A taskforce for computing will evaluate the various pros and cons for centralized, regional, and distributed computing, weigh the relative loads on the CPU or the wide-area-network, judge the balance between recalculation and storage, participate actively in the design of the computing model so as to position ourselves to take advantage of the industrial development in this country, and explore commercial software tools developed in US industry.

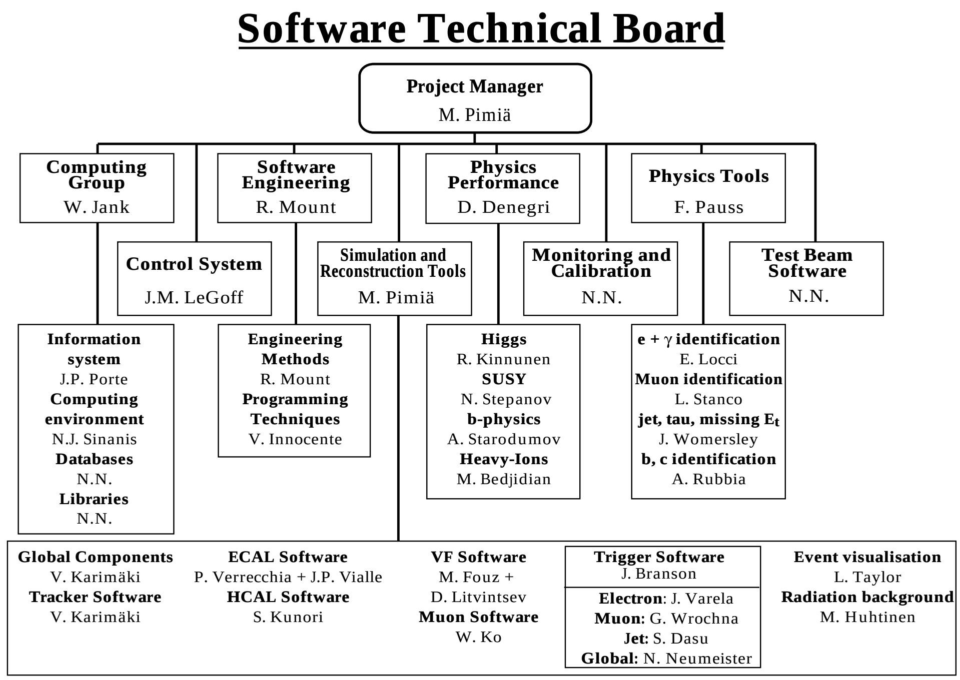


Figure 10: CMS Software organization.

Table 13: US CMS Software Task Leaders.

The coordinators indicated by * are also members of the CMS Software Technical Board.

Muon Software	
*Coordinator	Winston Ko (UC Davis)
Track reconstruction	Yuri Fisyak (UC Davis)
Software alignment	Torre Wenaus (LLNL)
HCAL Software	
*Coordinator	Shuichi Kunori (Maryland)
Fast Simulations	John Womersley (Fermilab)
Trigger Software	
*Coordinator	Jim Branson (UC San Diego)
*Jet Trigger	Sridhara Dasu (Wisconsin)
CSC Trigger	Richard Breedon (UC Davis)
Inner Tracker Software	
Forward pixel, MSGC	Martyn Corden (FSU-SCRI)
Event Visualization	
*Coordinator	Lucas Taylor (Northeastern)
CMSIM100 Development	
GEANT Constants	Yuri Fisyak (UC Davis)
Other tasks	All above * coordinators
Software Engineering	
*Coordinator	Richard Mount (Caltech)
Standards	Lucas Taylor (Northeastern)
Physics Tools	
*Jet and missing E_t	John Womersley (Fermilab)
Tau recognition	Marc Mohammadi Baarmand (SUNY Stony Brook)
γ position, π° rej.	Sergey Shevchenko (Caltech)
Computing Systems	
Network & Videoconf.	Harvey Newman (Caltech)
	Irwin Gaines (Fermilab)
Computing Model	Richard Mount (Caltech)
Pilot MC Farm	John Swain (Northeastern)

Table 14: CMS 1995 Technical Notes by US Software Groups.

Common Software:

- TN/95-082, The "CMS-FORTRAN" Standard, J. Swain and L. Taylor
- TN/95-080, GEANT Constants Definition Language for CMS, Y. Fisyak

Muon Software:

- TN/95-141, Muon system and Central Tracker alignment with muons, Y. Fisyak
- TN/95-083, Study of track-matching between the muon system and the inner tracker, Y. Fisyak, W. Ko, J. Rowe
- TN/95-026, Total-momentum dependence of the muon resolution, W. Ko, J. Rowe

HCAL Software:

- TN/95-153, Effect of Dead Material in a Calorimeter, D. Green
- TN/95-147, Quartz Fiber Calorimeter for CMS-VFCAL: April 1995 Test Beam Analysis, S. Doulas and A. Rosowsky
- TN/95-116, GEANT Computer Simulation for the CMS End Cap Test Beam Calorimeter, K. Michaud, P. de Barbaro, A. Bodek
- TN/95-058, CMS Hadronic Calorimetry Simulation Using Hanging File Data, I. Gaines, D. Green, J. Marraffino, J. Womersley, W. Wu, S. Kunori
- TN/95-057, Di-jet Mass Resolution at High Luminosity in the CMS Calorimeter, A. Beretvas, D. Green, J. Marraffino and W. Wu

Trigger Software:

- TN/95-112, New Algorithms for CMS Electron/Photon Trigger - Use of Fine Grain Calorimeter Data, S. Dasu, J. Lackey, W.E. Smith, W. Temple
- TN/95-111, CMS Missing Transverse Energy Trigger Studies, S. Dasu, J. Lackey, W.E. Smith, W. Temple
- TN/95-013, Baseline Design for CSC-based Endcap Muon Trigger, J. Hauser

Inner Tracker Software:

- TN/95-081, CMS tracker radiation length budget calculation with CMS100, Y. Fisyak

Physics Studies:

- TN/95-154, Search for Heavy Higgs in the Channel H $\rightarrow$ WW $\rightarrow$ $\ell\nu$jj, I. Gaines, D. Green, S. Kunori, J. Marraffino, J. Womersley, W. Wu
- TN/95-084, Search for Heavy Higgs in the Channel H $\rightarrow$ ZZ $\rightarrow$ $\ell\ell\nu\nu$, I. Gaines, D. Green, S. Kunori, J. Marraffino, J. Womersley and W. Wu

Table 15: US Software and Computing Milestones for FY 1996.

- Oct '95 - Complete initial CMSIM100 Framework (finished).
- Oct '95 - Complete implementation of CMSIM100 for Muon including geometry, hit and digitization (finished).
- Nov '95 - Complete implementation of CMSIM100 for HCAL including geometry, hit and digitization.
- Dec '95 - Complete jet finding code in HCAL in CMSIM100 framework.
- Jan '96 - Complete implementation of CMSIM100 for Inner Tracker including geometry, hit and digitization.
- Mar '96 - Complete study of missing-E_t signature for supersymmetry.
- Apr '96 - Finalize geometry for HCAL.
- Apr '96 - Complete first implementation of the Muon reconstruction package including the reconstruction bank.
- Jun '96 - Complete fast Muon track finding and reconstruction.
- Jun '96 - Complete fast HCAL shower simulator.
- Sep '96 - Complete tau-finding algorithm.
- Sep '96 - Complete simulation of Muon LCT and timing for trigger.
- Oct '96 - Complete CMS Technical Proposal for Computing for the LCRB.
- Nov '96 - Submit LOI for US CMS Computing to DOE.
- Dec '96 - Complete full Muon track finding and reconstruction.
- Dec '96 - Complete implementation of Inner Tracker track finding and reconstruction package.

Table 16: Software and Computing FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Software and Computing		**80**	**0**	**20**	**60**	**30**
Common Software & Workstations		**45**	**0**	**15**	**30**	**7.5**
Common Software/Computing	UC Davis, Johns Hopkins, Maryland, Northeastern	30		15	15	7.5
Event Visualization	FSU-SCRI, Northeastern	15			15	
Subsystem Software Development		**20**	**0**	**5**	**15**	**16.7**
Muon Software/Comuting	UC Davis, UC Riverside UCLA, CMU, (LLNL)	3		3		9.2
Inner Tracker Software/Computing	UC Davis, FSU-SCRI, Johns Hopkins, Rice	17		2	15	4.2
HCAL Software/Computing	Fermilab, Maryland					3.3
Physics Tools		**0**	**0**	**0**	**0**	**0.8**
Physics Tools	Caltech, UC Davis, Fermilab, Stony Brook					0.8
Computing Model		**15**	**0**	**0**	**15**	**5.0**
Pilot Computing Farm	Northeastern	15			15	
Computing Model Evaluation	Caltech, UC Davis, UCSD, Fermilab, Northeastern, FSU-SCRI, Wisconsin					5.0

3.7 Project Management

The US CMS Collaboration must mount a construction project in FY97 in order to maintain the overall CMS schedule. To that end, a bare bones project office is to be set up at Fermilab which will act as the host laboratory for the US CMS Project. The organization of the US CMS Project Office, which is foreseen to attain full staffing in FY98, is shown in Fig. 11. A first step was taken in FY95 with the establishment of a CMS Department in the Research Division of Fermilab. Partial support is provided by Fermilab as host laboratory.

The steps taken in FY95 were to coordinate the Letter of Intent [1], to assemble the US part of the IMOU [3], to formulate a Project Management Plan [6] and associated US CMS Memoranda of Understanding (MOU), to setup templates for the Project Work Breakdown Structure (WBS), and to coordinate this document, the US CMS FY 1996 Supplemental Funding Request. All these sorts of activities must intensify in FY96 if the US CMS Project is to begin in FY97.

In particular, secretarial assistance has become a pressing issue. It is also necessary in FY96 to take a first cut at integrating the cost and the schedule, given that a set of milestones now exists. The liaison to the parent effort of CMS at CERN also requires the expenditure of resources. For example, the coupling of the US CMS WBS and the CMS Cost Estimate [5] is very tight. For those subsystems where the US groups have complete responsibility it is, indeed, a one-to-one mapping. Maintaining that coupling is a nontrivial exercise. The FY96 R&D request for US CMS Project Management activities is shown in Table 17.

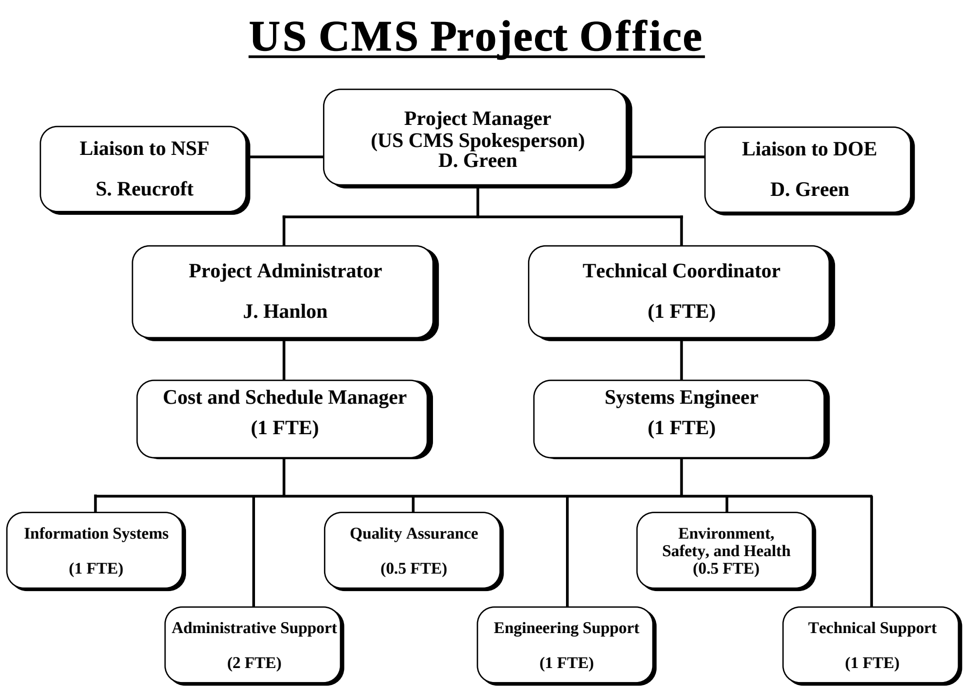


Figure 11: US CMS Project Office organization.

Table 17: Project Management FY 1996 Supplemental Funding Request (K$).

Activity/Task Description	Institution(s)	FY 1996 R&D Request M&S	Labor	DOE	NSF	Travel DOE
Project Management		**17**	**33**	**50**	**0**	**0.0**
Information Systems	Fermilab	8	2	10		
Document Preparation	Fermilab	2	13	15		
Cost and Schedule Integration	Fermilab	3	12	15		
Liaison to CMS at CERN	Fermilab	4	6	10		

4 Supplemental Travel Request

In addition to the costs for M&S and labor needed for R&D in FY96, there are supplemental costs for travel and salary support of physicists. These costs are not part of the subsystem R&D funding already explained in Section 3 of this document.

US physicists play critical roles in the management of the CMS experiment. We hold project management responsibility for the EMU, HCAL and Trigger subsystems. In addition, as indicated in Section 3, US physicists are Institutional Board Chairs for the Muon, HCAL, and Trigger/DAQ subsystems. We are also Technical Coordinators for the EMU and HB systems, and Resource Coordinator for HCAL. In ECAL, US physicists are task leaders for Crystal Processing and for Electronics and Trigger. In the area of Software and Computing, US physicists are Coordinators for Muon, HCAL, and Trigger Software, for Event Visualization, and for Software Engineering.

In order to fulfill these responsibilities within an international collaboration such as CMS, travel support is sorely needed. Although we are pressing the teleconferencing technology, there remains an irreducible travel component to the operation of the CMS Collaboration. In addition to travel support, funding for partial salary support of a physicist is included in the supplemental travel request. The EMU, tracking, and software requests include a total of $30K for the partial support of Y. Fisyak at UC Davis. This support is assumed to be transitional in that it is expected that US CMS project funding in FY97 and beyond will not provide physicist salary support.

A summary table of costs for travel broken down by subsystem and further by task is given in Table 18. Also indicated are the US CMS institutions involved. This table summarizes by university the travel requests already shown in Section 3 where the R&D context of the tasks is available. The R&D request summary is given in Section 1. We request these funds simply in order to allow us to fulfill our positions of authority and responsibility within CMS.

Table 18: US CMS FY 1996 Supplemental University Travel Request to DOE (K$).

Subsystem/Task Description	Institution	Travel Request
US CMS FY 1996 Supplemental University Travel Request		**300**
Endcap Muon Detector		**80**
Simulations, P0 data analysis at CERN	UC Davis	16
P0 tests, P1 tests, trigger work at CERN	UCLA	8
P0 tests at CERN and at UCR	UC Riverside	6
P0 tests, P1 tests (LLNL)	UC Riverside	6
P0 tests, P1 tests	Carnegie Mellon	4
Management, P0 tests	Florida	8
P0 tests, P1 tests at FNAL,trigger tests with P0	MIT	9
P0 tests, P1 tests, trigger work at UCLA	Ohio State	7
P1 tests at FNAL	Purdue D	5
Management, return yoke design work, P1 design	Wisconsin	11
Hadron Calorimeter		**80**
HV test beam	Boston	8
HB electronics	UCLA	1
HV test beam	Fairfield	3
HB test beam	Florida State	6
HB calibration ($6K); HV test beam ($3K)	Iowa	9
HB mechanics ($8K), preproduction prototype engineering ($8K)	Maryland	16
HB optics	Mississippi	6
HB calibration	Purdue G	10
HB optics	Rochester	16
HV test beam	Rockefeller	3
HV test beam	Texas Tech	2
Trigger and Data Acquisition		**40**
Muon trigger	UC Davis	2.0
Muon trigger	UCLA	8.5
DAQ design	UC San Diego	10.5
DAQ design	MIT	7.0
DAQ design	Mississippi	1.5
Calorimeter trigger	Wisconsin	10.5
Electromagnetic Calorimeter		**40**
Travel for crystal characterization	Caltech	10
Travel for transducer evaluation	Minnesota	20
Electronics travel	Princeton	10
Tracking System		**30**
Software development	UC Davis	5
Pixel travel	UC Davis	12
MSGC travel	Mississippi	4
MSGC travel	Northwestern	9
Software and Computing		**30**
Muon software/computing	UC Davis	15.0
Muon software/computing	UC Riverside	1.7
Computing model	Caltech	5.0
Inner tracker software/computing	Florida State (SCRI)	1.7
HCAL software/computing	Maryland	3.3
Physics tools	SUNY Stony Brook	0.8
Inner tracker software/computing	Rice	2.5

References

[1] US Collaboration for the Compact Muon Solenoid Detector, Letter of Intent, D. Green, T. Muller et al., September 8, 1995.

[2] Request for Funding: Detector R&D and Project Costs for CMS, submitted to NSF, September 1995.

[3] Interim Memorandum of Understanding for the Execution of the Initial Phase of the CMS Experiment, final draft, September 28, 1995.

[4] The Compact Muon Solenoid, Technical Proposal, CERN/LHCC 94-38, LHCC/P1, December 15, 1994.

[5] CMS Cost Estimate, version 7, September 15, 1995.

[6] US CMS Project Management Plan, draft, October 13, 1995.