Proposal to the National Science Foundation

CMS Detector R&D

Draft of August 30, 1996

Project Summary

In this proposal, an outline is given of the R&D activities of the eight NSF supported university groups who are members of the Compact Muon Solenoid (CMS) collaboration and a request is made for financial support of these activities. These groups all have the exciting opportunity to contribute to the construction of the CMS detector at the CERN Large Hadron Collider (LHC) and their R&D work will help answer crucial questions related to design details. CMS will undertake an experimental investigation of the interactions of protons on protons at a center of mass energy of 14 TeV. In order to explore the TeV mass scale, the LHC is designed to operate at very high luminosity ($\geq 10^{34}\text{cm}^{-2}\text{s}^{-1}$); this produces a challenging experimental environment. The physics program includes studying electroweak symmetry breaking and the origin of mass, investigating the properties of the t-quark, searching for new heavy gauge bosons, probing quark and lepton substructure, looking for supersymmetry and generally seeking any new phenomena beyond the Standard Model. The LHC project was approved by CERN Council on December 15, 1994 for construction at CERN in the LEP tunnel. CMS was approved on January 31, 1996. Without doubt, the LHC will be the major instrument for high energy research beyond the Standard Model in the first quarter of the next century. It is surely important for US groups to take part in this exciting research enterprise. Each of the eight NSF groups has important and well-defined responsibilities within the CMS collaboration based on their expertise and previous work. After a brief description of the CMS experiment and the role of these NSF groups, the NSF portion of the CMS detector R&D funding request is presented.

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1 Introduction

1.1 Physics Motivation

Our current understanding of the basic building blocks of matter and their interactions is encapsulated in the theoretical framework of the Standard Model. The Standard Model has provided a remarkably good description of both electroweak data from LEP and SLC experiments, and hadronic data from CDF and DØ at the Tevatron. However, there are crucial limitations to the Standard Model that make it important to investigate physics at the TeV scale. Bearing this in mind, the CMS physics program includes:

- Studying electroweak symmetry breaking and seeking the Higgs particle in the crucial mass range between ~60 GeV and ~1 TeV.
- Investigating properties of the t-quark.
- Searching for new, heavy gauge bosons.
- Probing quark and lepton sub-structure.
- Testing supersymmetry predictions.
- Seeking the "expected" new phenomena in the ~TeV mass scale.

The *only* presently approved accelerator capable of investigating all such phenomena is the LHC, which will be built in the LEP tunnel at CERN. In order to enable studies of rare phenomena at the TeV scale, the LHC is a 14 TeV proton-proton collider designed to operate at a luminosity up to $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is clear that the most significant questions in our current understanding of elementary-particle physics will be addressed at the LHC accelerator. It is also clear that if the US is to maintain its leading position in science, then US participation in the LHC program is absolutely essential. In no other way can this country continue to participate in frontier research and technology and train future scientists in this important field.

Two general-purpose detectors to investigate these and other phenomena have been approved for the LHC accelerator. These are the CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC ApparatuS) detectors.

1.2 Overview of CMS

The CMS detector is designed to function at the highest luminosities available at the LHC. The detector has a high-field (4T) superconducting solenoid with a compact muon spectrometer outside and hadronic and electromagnetic calorimeters (HCAL and ECAL) inside. At the core of the detector system is the central tracker consisting of pixel detectors, silicon microstrip devices and gas microstrip chambers. In order to detect new physics signatures efficiently, identification of muons, electrons and photons has been emphasized. CMS is described extensively, including R&D and construction details, in the CMS Technical Proposal [1]. The CMS collaboration consists of some 1500 members from 140 institutions in 30 countries. The US component of CMS comprises more than 20% of the total. The CMS collaboration has assigned leadership responsibility to US groups for the HCAL and forward muon (EMU) systems, as well as associated aspects of the Trigger and DAQ system and the Luminosity Monitor. In addition, US groups have been assigned important and well-defined responsibilities in the ECAL, Tracking and Computing/Software systems.

1.3 US Participation in CMS

A US team has been formed and has joined the CMS collaboration. This team consists of some 320 physicists and engineers from 38 US institutions (34 universities and 4 national laboratories). Of these groups, 32 have DOE base program support and 8 have NSF base program support. The US part of the CMS experiment was described in the September 1995, Letter of Intent [2]. In that document, the project was discussed in some detail and an attempt was made to identify the amount of financial support requested from both DOE and NSF. It also contains the coherent sum of the entire US CMS project while underlining the NSF and DOE group activities. Governance aspects of US CMS are covered in the US CMS Project Management Plan [3]. In separate proposals last year, the DOE groups and the NSF groups sought monies in support of the FY96 R&D phase. With this proposal we seek NSF support for the remainder of the CMS R&D program. It is written with a one-to-one correspondence to the companion proposal "CMS Construction Project" [4] which describes the entire proposed budget for the NSF construction responsibilities.

1.4 NSF-Supported Group Involvement in CMS

In the following table we show the US CMS institutes with specific responsibilities in the individual subsystems: Endcap Muon (EMU), Hadron Calorimeter (HCAL), Trigger/DAQ, Electromagnetic Calorimeter (ECAL), Tracking and Computing/Software. The NSF groups are at the following universities:

The University of California, Los Angeles (P. Schlein (PI), S. Erhan, and J. Zweizig); The University of California, San Diego (H. Paar (PI), G. Masek and M. Sivertz); The University of Illinois, Chicago (M. Adams (PI), M. Chung and J. Solomon); The Johns Hopkins University (C-Y. Chien (PI), B. Barnett, D. Gerdes, A. Gougas, G. Hu and A. Pevsner); The University of Nebraska, Lincoln (G. Snow (PI), S. Atkins, W. Campbell, D. Claes, M. Hu and C. Lundstedt); Northeastern University (S. Reucroft (PI), G. Alverson, H. Fenker, P. Hanlet, J. Moromisato, Y. Musienko, T. Paul, D. Ruuska, J. Swain, L. Taylor, E. von Goeler, D. Wood and T. Yasuda); University of Notre Dame (R. Ruchti (PI), B. Baumbaugh, J. Bishop, N. Biswas, J. Warchol and M. Wayne); Virginia Polytechnic Institute and State University (L. Mo (PI), K. Blankenship, B. Lu and T. A. Nunamaker).

NSF Groups	Muon	HCAL	Lumi	Trigger/DAQ	ECAL	Track	Computing
UCLA			✔	✔			
UC San Diego				✔			
U. of Illinois, Chicago		✔					
Johns Hopkins						✔	✔
Nebraska			✔				
Northeastern	✔			✔	✔		✔
Notre Dame		✔					
Virginia Tech		✔					

DOE Groups	Muon	HCAL	Lumi	Trigger/DAQ	ECAL	Track	Computing
Alabama	✔						
Boston		✔					
Brookhaven					✔		
UC Davis	✔			✔		✔	✔
UCLA	✔	✔		✔			✔
UC Riverside	✔						✔
UC San Diego				✔			✔
Caltech					✔		✔
Carnegie Mellon	✔						✔
Fairfield		✔					
Fermilab	✔	✔		✔	✔	✔	✔
Florida	✔						✔
Florida State		✔					
Florida State/SCRI						✔	✔
Iowa		✔		✔			
Iowa State		✔		✔			
Livermore	✔				✔	✔	✔
Los Alamos						✔	
Maryland		✔					✔
Minnesota		✔			✔		
MIT	✔			✔			
Mississippi		✔		✔		✔	
SUNY Stony Brook	✔						✔
Northwestern						✔	
Ohio State	✔			✔			
Princeton					✔		
Purdue	✔	✔				✔	
Rice	✔					✔	✔
Rochester		✔					
UT Dallas	✔						
Texas Tech		✔				✔	
Wisconsin	✔			✔			✔

US CMS Group Responsibility Matrix

2 Project Description

The NSF-supported groups in CMS are responsible for several major subsystem projects. Some of these involve close collaboration with other non-NSF groups. Some are the sole responsibility of NSF groups. In this section we review the R&D activities of each of these subsystem projects and indicate their relevance to the projects themselves described in the accompanying proposal entitled "CMS Construction Project" [4].

2.1 Endcap Muon Alignment System

NSF groups involved: **Northeastern University**

One of the main goals of CMS is to determine muon momenta with high precision. The muon detector cannot perform this task unless the locations of its elements are known accurately and monitored continuously. Moreover, in order to obtain the best possible precision, information from the muon detector has to be combined with information from the central tracker. An elaborate alignment/position monitoring system has been designed to accomplish this and the conceptual design and the present status of the work on the muon alignment and monitoring system is reviewed in a recent progress report[5]. The system consists of three subsystems: Link, Barrel and Forward Muon Alignment.

The Northeastern University group participating in the Endcap Muon (EMU) group (J. Moromisato, P. Hanlet, E. von Goeler, D. Wood and T. Yasuda) has extensive experience with muon systems, most recently at SMC and DØ. The group has recently accepted the responsibility, and will use their expertise to provide EMU with a complete Forward Alignment System which consists of a combination of optical and mechanical elements which connect to the Link system elements and transfer lines. The system determines the location of the endcap muon stations (MF1 through MF4) and, relates them to the tracker coordinates, i.e. the linking points.

Since the endcap chambers are mounted on the magnet return yoke, a significant amount of motion is expected. The z motion may be of order 5 mm; the ϕ and r motion should be less. It is not enough to establish the locations of the muon chambers during mounting; they have to be monitored continuously.

The forward system's task is to ensure proper alignment and monitoring of the approximately 600 muon chamber modules in stations MF1 to MF4, mounted on the endcaps. Optical straight lines will run parallel to the z axis, in six planes (separated by approximately 60 degrees in ϕ) along the outer perimeter of the detector. They allow transfer of the link point coordinates to local reference points (connecting points) distributed on the endcaps. This transfer requires combinations of 'straightness' systems and 'distance' systems. A straightness system is an alignment tool able to measure the distance of points from a straight line. The r and ϕ coordinates are transferred this way. A distance system measures the distance between two points. The z coordinates will be transferred by distance systems to the connecting points and ultimately to the chambers.

Position sensing across each station, and tie-in with the outer connecting points is provided by multipoint straightness monitors (radial laser beam devices in conjunction with transparent photosensors). Fiducials on the chamber modules are tied to the local coordinates by a combination of proximity sensors and optical position sensors. Additionally, tracks will be used for both local and global r, ϕ measurement in the ϕ overlap region.

Most of the R&D work so far has been done at Fermilab and has consisted of studies of a number of proximity sensors and their readouts. Urgent R&D tasks planned by the Northeastern group and that need to be supported by the NSF and started right away are: proof of principle of straight line monitors (SLM) and secondary monitors; robustness and radiation hardness of sensors; the prototyping of sensor mounts for the cathode strip prototypes; a study of the mechanical layout and integration with the Link system; design of the endcap SLM hardware and calibration fixtures; test of the integration of the Forward system with the Link system.

2.2 Hadron Calorimeter Readout

NSF groups involved: **University of Illinois, Chicago**
University of Notre Dame
Virginia Polytechnic Institute and State University

The NSF groups participating in HCAL have extensive experience with optical fiber technology and optical connectors, and with photodetectors and associated readout.

The CMS HCAL is a copper/scintillator sampling calorimeter. It consists of a copper absorber structure, interleaved with "tile trays" of scintillator, with imbedded wavelength shifting fiber readout. The tile tray terminates at an optical connector. Optical cables carry the light to "decoder boxes" where the light is reorganized from the layer oriented cables into towers for readout by the photodetectors. The magnetic field insensitive HPDs (hybrid photodetectors) reside in the decoder boxes, along with their associated preamplifiers. The amplified electrical signals are sent to remote front-end electronics for digitization. There are three separate geographic regions of calorimeter: the barrel (HB) and endcap (HF) detectors which reside inside the solenoidal magnet, and the late-shower sample that resides outside.

The calorimeter logically separates into 2 major subsystems: the absorber/scintillator structure, and the optical/electronic readout system. US (DOE and NSF) groups have construction responsibility for the barrel absorber/scintillator structure and for the entire (HB, HF, late-shower) readout system.

NSF groups will be responsible for developing and supplying all required optical connectors for the hadron calorimeter, as well as for supplying the optical cables for the barrel.

In the barrel, endcap, and late shower regions, the NSF groups will have responsibility for providing decoder boxes with associated temperature stabilization, HPDs and HV supplies, preamplifiers, cables, and front-end electronics.

In addition to the above production responsibilities, the US groups are planning to produce two pre-production prototype barrel wedges. NSF groups will make a contribution to the development and implementation of the optical/electronic readout system for the pre-production prototypes.

University of Illinois, Chicago

The University of Illinois, Chicago High Energy Physics group (M. Adams, M. Chung and J. Solomon) has the following planned R&D tasks, several of which will be undertaken in close collaboration with the Notre Dame group:

- Design and fabricate prototype optical connectors and lightguide. Connectors link the wave shifting fibers imbedded in scintillation tiles to lightguides. The lightguides transport the signals to decoder boxes which optically map tile outputs from HCAL layers into towers. Decoder outputs will also use lightguides to transport signals to HPD photodetectors. The tile connectors need to be a factor 2 thinner than those recently molded at UIC for the DØ preshower. Both molded and machined connectors will be investigated. Machined connectors were adopted for the DØ central fiber tracker but both solutions have greater than 90% transmission. This task includes studies of materials, surface finishing and couplants.

- Modify our 4m long fiber transmission facility at UIC to allow quality control tests with blue LED excitation over the length of the readout fiber and connector assembly.

- After connector design is fixed, fabricate optical readout components for the HCAL wedge test.

- Participate in design and production of HCAL decoder boxes. This task is similar to our DØ fiber tracker light guide effort which optically maps fibers in cylindrical shells into ϕ sectors for triggering.

- Participate in beam test of prototypes.

University of Notre Dame

The University of Notre Dame Collider Physics Group (R. Ruchti, B. Baumbaugh, J. Bishop, N. Biswas, J. Warchol and M. Wayne) intends to perform the following R&D tasks:

- Design and fabricate a "pigtail" quality control scanning station. This system will be based on a gallium nitride (blue) LED excitation system and a photodiode/picoammeter detection system. Pigtails consisting of twenty multiclad waveshifter fibers and fiber waveguides, in lengths of up to 6 m, will be testable with this system.

- Undertake studies of scintillation materials, waveshifters, and waveguides. The objective is to obtain a faster, yet high-efficiency, blue/green waveshifter which is sufficiently radiation resistant to replace the baseline Y11/K27 for which the fluorescence decay time is > 12 ns. An additional objective is to develop a fast, red waveshifter to read out green scintillating tiles, a detector combination which could be utilized in areas of HCAL that are exposed to elevated levels of radiation.

- Participate in the design and fabrication of prototype optical connectors/interconnects which will form the optical interface between layer elements (tiles) of HCAL and the decoder boxes which organize the optical signals into tower geometry. This will include materials studies for the choice of machining or molding of connectors, studies of finishing of optical surfaces, and selection of optical couplants (in close collaboration with UIC).

- Finalize the connector materials and designs. Molding and fabrication technology will be selected. An initial fabrication run will be undertaken to produce elements for the HCAL test wedges (in close collaboration with UIC).
- Fabricate scintillator tile and waveshifter fiber for testing. This includes new, fast, blue/green shifter fiber and red shifter fiber.
- Participate in the design and a fabrication of prototype decoder boxes for HCAL readout. These will provide appropriate optical mixing of calorimetry signals from "pizza pan" geometry to "tower" geometry, and will provide ancillary environmental and electrical support for the hybrid photodetector (HPD) optical transducers.
- Participate in beam tests of prototypes.
- Participate in the writing of the technical design report for CMS/HCAL.

Virginia Polytechnic and State University

The Virginia Polytechnic Institute and State University group (L. Mo, K. Blankenship, B. Lu and T. A. Nunamaker) is involved with the on-going ZEUS experiment at the HERA electron-proton collider as well as the CMS experiment at the LHC proton-proton collider.

Virginia Tech is a member of the HCAL (hadron calorimeter) project of the CMS collaboration. Since the SDC days, we have been working on R&D for hybrid photodetectors (HPD). Now the HPD has been selected by the CMS collaboration as the baseline photon detector for the HCAL, it is natural for us to continue to work in this area.

Basically, the HPD is an image tube. The photo-electrons are accelerated to approximately 15 keV and focused onto a silicon diode detector. If the tube axis is parallel to the magnetic field, the whole configuration of the electron trajectories will simply rotate around the magnetic field but remain focused at the same location. Therefore, the gain of the HPD should remain constant in the magnetic field. This concept was shown to be correct in an experimental test at CERN once the magnetic field was above 1.5 Tesla. The HCAL of CMS will be located inside a 4 Tesla superconducting solenoid. The conventional photomultiplier tube cannot be used because there is no way to shield the magnetic field. The HPD is the only option. The avalanche diode (APD) was considered but found inadequate because its gain is only about 50, while the gain of the HPD is about 8,000.

For the photodetector R&D, Virginia Tech plans to make the following effort in the CMS experiment:

- For the SDC experiment at SSC, we built a data acquisition system on the platform of a Sparc-10 workstation. It was used for the cosmic ray testing of a prototype SDC calorimeter module at Fermilab. This system will be moved back to Virginia Tech for the testing and evaluation of HPDs. We will set up the necessary equipment for this task. It includes light source, light-tight box, preamplifiers, electronics, etc. Since the data acquisition system is a very powerful one, it is more than adequate to handle this job. The setup can be used later for large scale testing during the production stage of the hadron calorimeter.

- The DEP Corporation of the Netherlands used to provide single pixel HPDs. Now they deliver multi-pixel devices in a package of 5×5 channels. The unit cost is about \$5K. We plan to procure 100 channels per year at a cost of \$20K per year for the next two years. These devices will have their performance evaluated to enable us to suggest possible improvements to the vendor. Previous experience indicated that the radiation hardening of the silicon diode was a problem area. The constant bombardment of the diode by electrons can eventually destroy the diode. We would like to evaluate the useful lifetime of these newly available multi-pixel devices. The good HPDs from this procurement will be made available to the HCAL prototype calorimeter module.

- Each HPD needs a local high voltage base of the Cockcroft-Walton type to supply ~15 kV. It is preferable to have individual controls via a network. We are experienced in making this kind of base and controller for the conventional photomultiplier tubes used in the ZEUS calorimeter. In that case, the rf power was supplied to the Cockcroft-Walton capacitor chain through a stepping up ferrite transformer. For the CMS case this would not work because the device has to be placed inside the superconducting solenoid. In addition the voltage is much higher than with the conventional PMT and the safety issue has to be addressed. We intend to conduct an R&D project to determine the best way to build the base and network controllers adequate for the HPDs. It has to be economic, compact, individually controlled and safe.

2.3 Luminosity Monitoring System

NSF groups involved: **University of Nebraska**
University of California, Los Angeles

The new experimental high energy physics group at the University of Nebraska, Lincoln (G. Snow, S. Atkins, W. Campbell, D. Claes, M. Hu and C. Lundstedt) and the UCLA group (P. Schlein, S. Erhan and J. Zweizig) are requesting support for the development of the luminosity subsystem in the CMS experiment. The UNL Department of Physics and Astronomy plans to hire two additional faculty members to join the high energy group in the next few years. The group has complementary activities in the Fermilab DØ experiment and Fermilab E868, a search for antiproton decay at the FNAL antiproton accumulator. The UCLA group is involved with HERA-B.

The CMS luminosity subgroup, led by G. Snow, was formed in 1994 with representatives from several associated areas within CMS. Snow is also an observer-member of the CMS Technical Board. The aim of the luminosity project is to produce a detector subsystem which is capable of providing precise ($\sigma_{Lum} \leq 5\%$) luminosity measurements for determining cross sections [11]. It will also provide the LHC machine with real-time feedback of the luminosity and beam conditions in the CMS area.

An introduction to the luminosity measurement is given in Section 13.3 of the CMS Technical Proposal [1]. The luminosity measurement and beam-condition monitoring will be based on three types of detector elements: the dedicated luminosity counters, the Roman pot spectrometers, and the beam-scraping monitors. The baseline designs for these elements and their particular uses are described in the NSF proposal "CMS Construction Project" [4]. The details will not be repeated here. Rather, this section of the R&D proposal will focus on the development issues to be addressed in the upcoming two years.

R&D activities at the University of Nebraska will involve detailed Monte Carlo simulations and prototype fabrication and testing. The group will draw heavily on undergraduate and graduate student research contributions, as well as the in-house electronics and machine shops. Engineering support and substantial equipment and materials purchases are needed in the development stage. Support for travel to CERN is also requested, due to the need for close coordination with LHC machine physicists in the development of the luminosity detectors.

The dedicated luminosity counters will be two arrays of fine-grained, thin scintillator tiles, one one each side of the interaction region, covering the pseudorapidity range of approximately $4 < |\eta| < 5$. The longitudinal placement of the arrays is coupled to the granularity, but arrays of fewer than 100 elements each are foreseen. Both hexagonal tiles and concentric half-rings are being considered for the counter layout. The light read-out scheme, presently based on embedded wavelength-shifting fibers carrying light to remote phototubes, is under study and will influence the final counter geometry.

The luminosity counters are required to have the following characteristics: good and well-determined acceptance for detecting hard-core scattering, very tight (i.e. sub-ns) timing resolution in the high-rate environment, high efficiency for single minimum ionizing particles, a large dynamic range and radiation hardness. The option to read out the counters with a stand-alone DAQ system independent of the central CMS DAQ system is being considered. This can be accomplished with an inexpensive PC-based system and will enable the counters to provide high-statistics feedback to the accelerator during separated beam scans and beam tuning while the CMS DAQ may not be operating. The independent read-out system and information links to the LHC machine will be developed in coordination with the CMS Slow Controls Group. The utility of a laser-based or source-based calibration/pulser system is also under study.

Development questions will focus on finalizing the counter location, layout, light read-out scheme, mounting and integration, estimating performance degradation with accumulated radiation exposure, simulating the effect of particle splash to other detector systems, etc. A cosmic ray testing stand will be constructed to study the light collection and uniformity characteristics of prototype counters.

The luminosity group proposes to design and install the only "extreme forward" detectors in CMS, located in Roman pots and placed symmetrically at large distances (> 100 m) from the interaction region. The Nebraska group will work together with the UCLA group in the development of these detectors. The Roman Pot spectrometers are designed to measure the tracks of particles which emerge from a pp interaction at extremely small angles with respect to the beam. The detection of recoil protons at low-t will be essential for measurements and monitoring of elastic and diffractive cross sections at $\sqrt{s} = 14$ TeV, which will play an important role in the luminosity measurement. A system of at least 6 pots are proposed, 3 on each side of the interaction region.

Roman pot detectors and their associated mechanics (pot movement, position monitoring, vacuum interface, interlocks, ...) have already been used widely at CERN, DESY and Fermilab. Thus, we anticipate using standard technologies. Detectors based on scintillating fibers and silicon pixel devices are being studied. The final design of this system will no doubt be influenced by the experiences of the CDF and DØ experiments which will be using the latest state-of-the-art Roman pot detectors during Run 2 of the Tevatron. In addition to detector issues, R&D activities will be organized with LHC beam experts to study optimal placement of the detectors, space constraints, and possible modifications to the beam optics to enhance the measurements.

The luminosity subgroup has responsibility for implementing a system of detectors surrounding the beam pipe in the vicinity of the CMS detector for monitoring the beam condition. Discussions are underway to enlist the support of the LHC accelerator division in the development and construction of the beam monitors.

R&D activities will focus on the choice of appropriate, radiation-hard technology, placement of the detectors, and timing requirements. Cerenkov detectors based on plexiglass or fused quartz will be considered in which the optical geometry allows one to distinguish particle direction. The read-out of the beam monitors will tie into the independent system foreseen for the dedicated luminosity counters described above.

2.4 High Level Trigger and Data Acquisition System

NSF groups involved: **University of California, Los Angeles**
University of California, San Diego
Northeastern University

At the LHC design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, an average of 20 inelastic interactions will occur every 25 ns, the bunch crossing time. The goal of the CMS Trigger/DAQ system is to record the most interesting collisions out of the $\mathcal{O}(10^9)$ interactions per second at the LHC. This will be achieved by a three-level trigger system.

The Level-1 Trigger System aims to reduce the input interaction rate to a rate of 100 kHz. Data are transmitted to the DAQ system for every crossing satisfying the Level-1 trigger. Each triggered event is estimated to contain 1 megabyte of data distributed over about 1000 front-end deep memory buffers called Readout Dual Port Memories (RDPM). The DAQ system thus handles about 100 gigabytes of data per second. Data from the RDPMs must be transported to a single location for further physics analysis (the "event building" process). This is achieved using a switching network to connect these buffers to a farm of processors. At the output of the switch, events are assembled by about 1000 Switch Farm Interface (SFI) modules, then passed on to the processor farm when complete. All of this is controlled by an Event Flow Control system which must communicate with the various modules of the Event Builder and with the processors.

The processors run dedicated physics algorithms to further select the most interesting events (the "event filtering" process). Given the limitations of offline mass storage and processing, the final output of the experiment should not exceed 100 Hz.

CMS plans to perform the event-building and filtering processes in two steps: the "virtual Level-2 Trigger" and the "Level-3 Trigger". For each event accepted by the Level-1 Trigger, only a small fraction of the detector output is transported upstream into a single processor which is capable of making a refined analysis of the event based on this limited information. This is the "Level-2" decision on the event. If the event is accepted by Level-2, the rest of the event is transported to the same processor for full analysis and final decision ("Level-3") on whether to output the event to mass storage.

Level-2 is referred to as "virtual" because it is a software task running on the same farm of processors which analyzes the full event at Level-3; *i.e.* it does not use special-purpose hardware processors. The choice of a "virtual Level-2 Trigger" is driven by its obvious flexibility and by the realization that the additional event building needed to provide input to a hardware level-2 trigger is more expensive than memory needed to cope with the latencies associated with a processor-based Level-2 system. Preliminary estimates indicate that a set of 1000 processors, of $10^3 - 10^4$ Mips each, is required for the Level-2 and Level-3 farm.

US role in CMS DAQ

Several US institutions on CMS are currently participating in the design and development of the entire DAQ system. In particular, US institutions are working on:

- the Readout Dual Port Memories (RDPM), including the links to the switch;
- the Control and Status System for the readout crates;
- the Switch Farm Interface (SFI);
- the Event Flow Control system;
- the High Level Trigger system.

The US institutions will construct one-half of the full DAQ system, including RDPMs, SFIs and Control and Status Systems, together with the full Event Flow Control System. They will also participate in the installation and integration of the system into CMS. Current plans in CMS call for the completion of testing a prototype system 18 months prior to installation. While prototypes will be constructed with both industrial and lab participation, it is expected that the final construction will be mainly industrial. The labs will have to assure quality control, provide software, and participate in the installation at CERN. We expect that our European colleagues will bear the majority of the installation and maintenance task. Nevertheless, a significant US effort will be required to assure that the US components are integrated smoothly into the experiment.

NSF groups on Trigger/DAQ

There are currently three NSF-funded institutions active on the CMS Trigger/DAQ system:

- **The UCLA NSF group** (P. Schlein, S. Erhan and J. Zweizig) intends to work on the CMS trigger and DAQ project. Presently, members of the group play leading roles in these areas in the HERA-B experiment. The event rates and bunch structure at HERA are similar to those at the LHC, so many problems which will be encountered by CMS will first be faced by HERA-B. The expertise and experience gained by this group on HERA-B should greatly benefit the US CMS Trigger/DAQ effort.

- **The UCSD NSF group** (H. Paar, G. Masek and M. Sivertz) has been working in close collaboration with the DOE group from the same institution. They have contributed the development of prototype RDPM and SFI modules. Their level of contribution to this activity will increase in the future, particularly as the RCS and RDL (described below) are integrated into the system. They will also contribute to Level-2 algorithm development.

- **The Northeastern group** (L. Taylor, G. Alverson, T. Paul and J. Swain) is expected to make major contributions to the High Level Triggers. The group has extensive experience in the installation and management of large clusters of processors (workstations) for the L3 experiment and are already involved in numerous CMS offline computing activities, as described below. They will capitalize on this experience to take a leading role in the design and implementation of the Level-2 and Level-3 Trigger systems.

In this document we propose that the NSF-funded institutions on the CMS DAQ project acquire full responsibility for the development of (a) the Control and Status system (RCS) for the readout crates and (b) the Readout Data Links (RDL) from the RDPMs to the switch. All of these groups are also expected to participate in the development of the physics algorithms for the High Level Triggers.

Both subsystems (the RCS and RDL) are integral parts of the basic readout unit (RDPM) in the CMS DAQ. The development of the RDPM (i.e. the input to the switch) and the SFI (i.e. the equivalent module for data output from the switch), represent a key contribution of the US to the CMS DAQ system. With this suggested sharing of responsibilities, we expect to establish a close collaboration between the DOE and NSF-funded institutions. We expect to share development platforms across institutions. In addition, this breakdown is quite modular, in that it allows the development of the RCS-RDL subsystems in parallel with the RDPM-SFI system. We expect that this plan will maximize our ability to independently address design details while maintaining our ability to address the CMS DAQ Readout Crate as a full system, developed in the US.

It is also expected that all three institutions will participate in the design and implementation of the software algorithms running on the Level 2/Level 3 processor farm. The software algorithms running on the processor farm will be based on those used by the offline reconstruction programs. At one extreme, the two programs will be identical. At another extreme, the high rates expected will result in the creation of dedicated fast algorithms with little resemblance to the offline program. A crucial feature of this software system is that, unlike the equivalent systems of previous experiments, it must be robust and reliable essentially from the beginning of the first data-taking period.

2.5 Electromagnetic Calorimeter Readout

NSF groups involved: **Northeastern University**

The CMS electromagnetic calorimeter must be able to measure electrons and photons with sufficient precision so as not to compromise physics performance. Powerful isolation cuts and two-shower separation capability are required to eliminate the background from jets and single π^0's. A high resolution, good lateral granularity crystal calorimeter surrounding the inner tracking volume inside the coil is the chosen design. The US group responsibilities in ECAL are directed primarily towards the overall front-end electronics and the photodetectors, with some efforts aimed at crystal surface treatment and other processing techniques.

The Northeastern University group (S. Reucroft, Y. Musienko, D. Ruuska and J. Swain) has extensive experience with optical transducers and it plans to concentrate its ECAL efforts on the readout devices for the lead tungstate crystals.

The development of a stable and reliable photodetector which can operate in the CMS environment requires a systematic approach in which the collaborating institutions will work closely with the manufacturers. The avalanche photodiode (APD) is a particularly suitable device [14].

R&D activities will focus on the following tasks: device development in direct collaboration with manufacturers; development of a temperature/bias/gain measurement system; development of low-cost APD packaging; APD characterization studies; radiation damage studies, especially using low-energy, high-fluence neutron sources; high magnetic field tolerance studies; designing, building and testing a large-scale prototype system.

Our research is targeted towards three main goals; accurate characterization of APD parameters before and after neutron irradiation damage, device development in collaboration with the appropriate manufacturers and preparation for the eventual calibration and installation of these APDs in the CMS ECAL barrel. In particular, we have taken the responsibility for the following R&D tasks:

- Detailed device characterization studies in close collaboration with the PSI group. Our plan is to combine and develop our techniques for the characterization of many APD parameters and to perform these investigations on all of the APD prototypes to ensure consistent results across the different APD types. One of our students will be spending time at PSI this summer to begin the exchange of techniques and ideas.

- A study of radiation damage of APDs by neutrons using an Oak Ridge National Laboratory (ORNL) ^{252}Cf source. We have used the facilities at ORNL to perform preliminary exposures of APD's from EG&G and RMD to neutrons from ^{252}Cf sources while under bias [15][16][17]. The environment there is much better than the reactor environment (for example, both temperature and humidity can be controlled). The neutron yield for ^{252}Cf is 2.3×10^{12} neutrons/s/gm of ^{252}Cf. The mean neutron energy is close to 1 MeV. We plan to expose up to $\sim 5 \times 10^{13}$ neutrons/cm^2. Following our initial studies, we will be irradiating new devices from three manufacturers to quantify changes in bulk current and, where applicable, surface current. In addition, we will be looking for temperature dependent changes in these two currents and any neutron dependencies in the responsivity of these devices to ^{55}Fe and blue light input signals. Designs for APD's can vary widely, with different doping profiles and device structures making it possible to control important parameters such as noise, gain, radiation hardness, quantum efficiency, and sensitivity to the direct passage of charged particles (the "nuclear counter effect"). These studies are expected to play a critical role in the choice of APD for the CMS ECAL.

- Studies of APD readout in the test-beam environment. We already have participated in and we plan to continue to participate in studies of CMS ECAL crystal alternatives and photo-detector readouts in test beams at CERN and PSI in order to evaluate the resolution and radiation damage characteristics of an ECAL module. The 1996 test will involve 100 lead tungstate scintillator crystals, APD readout, pre-amp/amp chain, DAQ and associated electronics. We will be working on chracterizing, monitoring and analyzing the APDs.

- Device development and evaluation. Currently an attractive option which should improve signal-to-noise characteristics involves a pixellated APD. We intend to participate in the development of this device with EG&G.

2.6 Forward Pixel Tracking System

NSF groups involved: **Johns Hopkins University**

The Johns Hopkins group (C-Y. Chien, B. Barnett, D. Gerdes, G. Hu and A. Pevsner) is responsible for 40% of the forward pixel system. More precisely, responsibilities include the pixel detector diode arrays, local communication chips (LCC), and connection to the VME via the kapton cable, optical fiber and optical transmitter/receiver. It involves the R&D, design, fabrication, and testing of these components. These tasks were selected based on the experience and expertise we acquired from our work on L3 [22] and CDF [23], and the R&D work for SDC [19] [20] [21] and at CERN [24] where we dealt with the development of silicon detectors, radiation damage, kapton cables, and signal handling extensively.

There are two inner pixel disks at z = ± 34 cm, covering from r = 4.5 cm to 15.0 cm. These disks are covered with detector array modules. Each module has a 2.5 cm^2 sensitive area of 16K pixels with four readout chips bump-bonded above it, and with a kapton cable connected on top. The detector diode array module provides signal and power bussing from the bump-bonded readout chips and LCC to wire bond pads at one edge of the detector for the kapton cable.

The overall system operates as follows. When a charged particle passes through the pixel (covering an area of 1/64 mm^2), an electric signal is generated and passed through the bump-bond to the corresponding element of the readout chip attached above where each signal is amplified and processed. Signals above threshold are buffered and time stamped. When the readout chip receives the level 1 trigger, it accepts signals and sends out information corresponding to the associated beam crossing, and clears the remainder. The Local

Communication Chip (LCC) on the detector module is the interface between the readout chips and an Optical Transmitter/Receiver (OTR). The OTR is connected on the one end by a kapton cable to the detectors modules; and on the other end to a remote VME card in the DAQ system via optical fibers .

The requirement for the pixels is to provide 15 μm and 90 μm resolution in the $r\phi$ and r directions respectively. Our current design shows that we can exceed this resolution in r to provide better resolution in z. However, it is also required that pixels can function in partially depleted mode after being exposed to a fluence of 10^{15} p/cm^2, which is equivalent of several years of operation at LHC at full luminosity for the inner pixels. This imposes a severe constraint on the design of the pixel array, requiring much R&D work on a large number of issues. The current results on detectors are very encouraging.

The strategy for the tracking R&D work has been to complete an optimal design on the geometry so that the mechanical and cooling design work can proceed with other parts of CMS; at the same time we can proceed on the detailed R&D work so that an initial design can be completed at the end of 1997 for the Technical Design Report. The work required for Hopkins is:

We must develop a pixel design satisfying all requirements. We need to answer detailed questions such as: effects due to radiation damage, pixel thickness vs depletion voltage, bulk type, readout isolation, cross talk, guard structures, charge sharing, readout pad bumpbonding reliability, yields, and production cost, etc. To coordinate with the development of the readout chips, it will be developed in four stages:

- A 16×16 pixel array with fan-out readout to test geometry and radiation hardening (1996-97).
  The 16×16 arrays have been fabricated and received. We have also obtained readout electronics using VA2 chips. A beam test will be carried out at CERN in summer, 1996 using the beam telescope system and DAQ we developed at CERN.

  Pixel Radiation test. Tests will begin at the Booster of FNAL in Fall, 1996. They will be radiated to 10^{15}protons/cm^2, then retested in a beam. This process will go through several iterations to reach the full fluence required. This is to be completed on the 16×16 arrays in Spring 1997.

- A 24×32-pixel array to test read-out design (1997).
  This design will be based on the radiation test results from the 16×16 arrays, and the optimization from Monte Carlo simulation. It will be completed in 1997 and tested with pixel readout chips from UC Davis and PSI.

- A multi-chip array to test module assembly and communication (1998).

- A full size prototype module in 1999.

- *Local Communication Chips (LCC)*
  The LCC handles communication between the pixel readout chips and the OTR. Both of them are still evolving. So there will be several iterations.

1996	Fall	initial specifications will be determined.
1997	Spring	design of first prototype complete, submission to MOSIS for fabrication.
	Summer	first prototype testing, followed by more iterations.
	Fall	prototype complete for Technical Design Report (TDR).
1998	December	multi-chip prototype module fabricated.

- *Kapton Cable Connection*

1996	Fall	initial specification complete.
1997	Summer	prototype fabricated.
1998	Spring	interconnect for pixel module fabricated.

- *Optical Transmitter/Receiver (OTR) and Optical Fiber*
  The design and fabrication of the front-end electronics of all CMS subdetectors take on a common, except the pixels – because of its special nature and enormous number of channels involved. We will work with CERN and Imperial College to test the common design of the OTR and Optical Fiber to develop necessary modifications for the pixels.

2.7 Computing and Software

Computing software and hardware are of paramount importance to CMS; without appropriate software investment, the detector design will not be optimal and physics competitiveness will be compromised. A full description of the CMS Computing project may be found in the CMS "Computing Technical Proposal" (editor: L. Taylor of Northeastern) which will be submitted to the LHC Computing Board in December of 1996.

Two NSF groups have already started to work in this area. These are the Northeastern group (L. Taylor, G. Alverson, T. Paul and J. Swain) and the Johns Hopkins group (A. Gougas et al). It is anticipated that eventually all NSF groups will become involved. Even though we are not requesting any funds for computing and software, nevertheless we note that continuing R&D activities of these groups include:

- The Northeastern group is responsible for providing the standard CMS simulated physics event samples and for the code used to generate them. The group has written the CMKIN[28] package which provides a uniform interface to distinct event generation programs, such as Pythia and ISAJET, and a standard output event format which is read by the CMS simulation program, CMSIM.

- The group is actively involved in the development of CMSIM. They are responsible for the general utility routines, and have designed and implemented the I/O, file-handling, and database package, known as CMDB[27].

- The critical need for large amounts of CPU power for the generation of Monte Carlo simulated events has prompted the Northeastern group to investigate two complementary solutions involving a) dedicated farms of low-end, large CPU but modest I/O computers and b) the exploitation of the spare CPU power of under-utilized CMS computers. This evaluation work is being carried out with support from Hewlett-Packard and in the context of the CERN Research and Development project, known as HEP PC[29].

- Northeastern is responsible for the detector and event visualization program, known as CMSCAN[30]. CMSCAN is an invaluable tool for optimizing the design of the detector and its sensitivity to interesting physics processes. Using CMSCAN, a CMS event picture library has been made available on the WWW.

- Ensuring the high quality of the CMS software is of paramount importance, especially since offline reconstruction algorithms will be used in the Level 2/3 trigger farm. The Northeastern group has taken the lead by defining the CMS coding standards[31]. They have implemented an automatic code-quality checker for the standard CMS code, the results of which are available to distributed collaborators via WWW.

- The Johns Hopkins group has started developing algorithms to be used with the GEANT package in order to: a) change the dimensions of arbitrary detector shapes, controlling for their boundaries in a user-friendly (graphic) way. b) calculate the corresponding number of channels, after each geometry change by either readjusting the pitch or by getting input from the user c) calculate the corresponding material in terms of radiation length The code is being developed primarily for the geometry optimization of the pixel and microstrip silicon detectors. It can find application with other subdetectors of CMS.

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4 Biographical Data

The next few pages give brief biographical sketches of the Co-Principal Investigators and project contact persons. These are:

- Steve Reucroft, Northeastern University (ECAL Readout)
- Mark Adams, University of Illinois, Chicago (HCAL Readout)
- Chih-Yung Chien, Johns Hopkins University (Forward Pixel Tracking)
- Luke Mo, Virginia Polytechnic Institute and State University (HCAL Readout)
- Jorge Moromisato, Northeastern University (EMU Alignment)
- Hans Paar, University of California, San Diego (DAQ)
- Randy Ruchti, University of Notre Dame (HCAL Readout)
- Peter Schlein, University of California, Los Angeles (DAQ and Luminosity Monitor)
- Greg Snow, University of Nebraska (Luminosity Monitor)
- Lucas Taylor, Northeastern University (Computing/Software and High-Level Triggers)

5 Budget

The larger context for this proposal and these R&D costs is contained in the CMS Technical Proposal (CERN/LHCC 94-38), in the US CMS Letter of Intent of September 1995 and in the companion NSF proposal "CMS Construction Project". The governance aspects are covered in the US CMS Project Management Plan.

5.1 R&D Budget Summary by Project

In this section, we present the proposed R&D budget divided up by subsystem. The detailed distribution of monies to the eight groups will be decided later based on the specific subsystem needs. The nominal budgetted amounts per R&D activity are shown in the table below. We don't yet know the year-by-year breakdown. The US CMS Management Board has the ultimate responsibility for the detailed allocation of monies to tasks and it is quite likely that the amounts in the table will be subject to fine-tuning before distribution to individual groups. This distribution will be administered via sub-contracts to the appropriate university groups.

The FY96 budget request covers R&D work for the following subsystems: Endcap Muon (EMU), Hadron Calorimeter (HCAL), Trigger/DAQ, Electromagnetic Calorimeter (ECAL), Tracking and Computing/Software (although in actual fact no funds are being requested for the Computing and Software work). Work related to the Luminosity Monitor is included in the Trigger/DAQ subsystem. Monies will be used for equipment and materials, travel and necessary short-term engineering and technical support. No monies will be used to pay the salaries of research personnel.

R&D Budget Summary by Subsystem. (All amounts in FY96 $K).

Subsystem	Request
EMU	100
HCAL	300
Trigger/DAQ	300
ECAL	100
Tracking	100
Computing/Software	0
Total	900

5.2 R&D Budget Summary by Group

The requested amounts according to university group are shown in the following table. As noted above, these amounts may change slightly after consultation with the Management Board, although the total will not.

R&D Budget Summary by Group. (All amounts in FY96 $K).

Group	Subsystem Activity	Contact Person	R&D Request
UCLA	DAQ and Luminosity Monitor	Schlein	100
UC San Diego	DAQ	Paar	100
Johns Hopkins	Forward Pixel Tracking	Chien	100
	Computing/Software	Gougas	0
U Illinois (Chicago)	HCAL Readout	Adams	100
U Nebraska	Luminosity Monitor	Snow	100
Northeastern	ECAL Readout	Reucroft	100
	Endcap Muon Alignment	Moromisato	100
	Computing/Software	Taylor	0
U Notre Dame	HCAL Readout	Ruchti	100
Virginia Tech	HCAL Readout	Mo	100
Total			900