THE COMPACT MUON SOLENOID (CMS) DETECTOR

PROPOSAL 892

UNITED KINGDOM

Bristol University; Brunel University; Imperial College, London;
Rutherford Appleton Laboratory, (University of the West of England*)

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INTRODUCTION

CMS, the Compact Muon Solenoid experiment, is a general purpose detector for the Large Hadron Collider currently under construction at CERN. CMS will identify muons, photons and electrons, and measure their momenta and energies with high precision. The detector will be capable of studying the full range of LHC physics, and is optimised to search for the Higgs boson over the mass range from 90 GeV/c^2 to 1 TeV/c^2.

Substantial progress has been made during the past year, both by CMS as a whole, and by the UK groups. Globally, construction of the superconducting magnet is proceeding well, and remains within budget with 75% of the expenditure committed. The Hadron Calorimeter group has begun to take delivery of several major components, while fabrication of components for the muon systems has started. The ECAL barrel project has passed a major milestone with the delivery of 1000 pre-production lead tungstate crystals to CERN; acceptance tests on these crystals are under way using automated quality control instrumentation and the CRISTAL database.

A significant change in the design of the central tracker system, with MSGCs replaced by silicon microstrip detectors, was approved by the Tracker Institution Board in December 1999. This change, which is discussed in more detail below, will be put before the CMS Collaboration Board for endorsement in January.

The estimated cost of the CMS detector is 466 MCHF, comfortably within the ceiling of 475 MCHF set by CERN when it approved the project. The funding agencies have now signed all of the Memoranda of Understanding approved by the Resources Review Board in April 1997. The Collaboration has recently been enlarged by two groups from China-Taiwan.

The progress of the UK groups is described in detail in the remainder of this report.

TRACKER AND DATA ACQUISITION

Overall Tracker progress

The CMS Tracker Technical Design Report (TDR) was approved in July 1998. The tracker system has an active volume extending to a radius of 115 cm over a length of approximately 270 cm on each side of the interaction point, covering a range of $|\eta|$ to 2.5. The sub-detector described in the TDR was based on three technologies: pixels, and silicon and gas microstrips, arranged in concentric cylindrical volumes of radii about 20 cm, 60 cm and 115 cm.

The major area where questions had not been fully resolved concerned long term operation of the MSGC detectors. Despite much progress with MSGCs, attention has continued to be focused on potential weaknesses, particularly spark rates and strip damage. The CMS detectors are operated with low gas gain, below 2000, but rare discharges could damage strips and even a low rate of strip loss could prove significant over a 10 year period. In November 1999, 50 chambers were exposed to a high intensity 300 MeV pion beam at PSI and were demonstrated to meet the requirement of a very low rate of strip loss in operation under LHC conditions.

However, questions still remained about the ability to translate this successfully into large scale fabrication of the CMS tracker. The number of commercial sources of MSGCs is limited and further investment would be necessary to ensure production at the rate and quality required to meet the CMS and LHC schedule. Meanwhile, developments of silicon microstrip technology have demonstrated detector production on increased wafer sizes at a much lower cost than previously. At least two manufacturers have production facilities large enough to meet CMS quantities for a full silicon tracker, and automated module assembly has been proven in CERN, which would ensure that the schedule and quality uniformity can be met. Simulation studies have shown there is little change in performance of a silicon tracker with one layer fewer than a silicon-MSGC system, because of the improved timing and the greater spatial precision of silicon compared to MSGCs.

A second factor which played an important part in the consideration of the tracking system was the spectacularly successful development over the last year of a front-end readout chip in a new, deep sub-micron technology by a UK team from Imperial College and Rutherford Appleton Laboratory. This will reduce the cost of the CMS tracker electronics by several MCHF, which would allow the tracker proposed in the Technical Design Report to be constructed in a single phase, instead of two stages as would have been necessary to stay within the available budget.

In view of these developments, the Tracker Steering Committee recommended the adoption of an all-silicon tracker to the Tracker Institution Board, following a week-long internal system review. This was accepted and has been recommended for endorsement by the CMS Collaboration Board in early 2000. An addendum to the TDR will be prepared as soon as possible for submission to the LHCC by the end of February. Production of the first series of components of the tracker should then start in late 2000, following engineering reviews.

Progress in the UK

The UK involvement in the detector hardware is principally in the electronic readout of the microstrips. The system has advanced considerably in the last year.

Analogue readout is to be used, based on the APV chips developed by RAL and Imperial College. Each microstrip is read out by a charge sensitive amplifier whose output voltage is sampled at the 40 MHz beam crossing rate. Samples are stored in an analogue pipeline and, following a trigger, are processed by an analogue circuit to further filter the signals, then multiplexed from pairs of front-end chips over a short distance of twisted pair cable to a laser driver. A laser converts electrical signals to infra-red light levels which are transmitted approximately 100 m over a fibre optic cable to the counting room where digitisation and data reduction are carried out by the Front End Driver (FED) module. The APV chips and the FED are the two items which the UK has taken a significant responsibility to deliver.

APV developments

Radiation hardness

In mid-1997, the APV appeared to be in the final stage of development. The APV6 (for silicon microstrips) had been delivered in January, from a new process line owned by Harris. The chip worked well and results on noise, uniformity, linearity, calibration and other parameters were very good, indicating that only final tuning of chip parameters would be needed prior to production. Modifications to the APVM

for MSGC detector readout were almost complete, including larger protection diodes, current monitoring and modifications to the deconvolution circuit based on extensive simulation studies.

However, in July 1997 it was discovered that the APV6 performance deteriorated under irradiation in the Brunel ^{60}Co source, while irradiation tests on all four previous Harris runs had established that the process was hard to more than 1 MGy. The results were confirmed on other APV6 chips and test structures and discussed with Harris.

A decision was made to submit the APVM, despite the radiation hardness uncertainty, as it would verify important design changes, be required for validation with MSGCs where radiation levels were lower and add more data on radiation effects. The APVM was delivered in May 1998 and worked well, including in tests with MSGCs.

Meanwhile UK groups collaborated closely with French teams from Strasbourg, Lyon and Saclay in translating the APV6 into the TEMIC DMILL technology with an identical chip footprint and parameters; the first APVD version was delivered in January 1998. This provided extra assurance that the CMS developments would converge in time for CMS construction. The APVD worked well on the first submission, except for a low level amplifier instability whose origin took some time to identify. This has successfully been corrected in the latest chip, delivered in November 1999.

0.25µm technology

The radiation hardness problems and the high cost of the front end ASICs encouraged a close look at a new option, following successful translation of the APV into DMILL. In September 1997, first indications of unexpected hardness of sub-micron feature size technologies were presented; until then limited results had been extremely variable. While the thin gate oxide, which reduces with minimum feature size, had been long believed to be a key parameter, leakage paths between devices were a possible cause of erratic data. The work of RD49, originally aimed at applications at about 300 kGy, demonstrated that designs could overcome this. Further work has verified the results in 0.25 µm and 0.35 µm processes. Use of 0.25 µm processes potentially offers significant gains in noise, power, circuit size, yield and, ultimately, very large cost savings. Possible risks are time to complete the work, lower voltage operation and increased sensitivity to Single Event Effects (SEE).

In May 1998, having evaluated the data and practical problems, the UK team proposed the 0.25 µm technology to the CMS Tracker and was asked to continue as fast as possible. The APV25 was submitted, in a run shared with smaller chips and test structures, in July 1999; it arrived back in October. The design was rapidly shown to be spectacularly successful on the first iteration, as it works perfectly, with only a very few minor changes necessary before being considered final. This was a remarkable achievement by the IC-RAL team, with important support from the CERN microelectronics group.

The performance of the chip is considerably improved compared to previous versions, in noise, power, memory depth and several other details, as illustrated in Figures 1-5. These are all due to the advanced electronic technology and fine feature size. Yield also appears to be very high; from the first twenty chips measured, only one was found to be defective, which is very unusual for such a large, complex

circuit. Within a month of testing, a chip was irradiated to 200 kGy, with no change in performance.

The formal decision to choose 0.25μm technology for the APV was made in December 1999. This will result in cost savings of 6-7 MCHF for the tracker and will permit the construction of the system described in the TDR, which would otherwise have been built in two stages, provided sufficient funds became available.

Other issues

One issue which has begun to receive more attention recently, as progress was made with radiation hardness of the electronics, is Single Event Errors. These are changes of logic state of individual logic elements in chips due to a very heavily ionising particle transit into a silicon chip. Most of them will be due to rare, but inevitable, energetic silicon ions dislodged from their lattice position in the chip by a charged particle or neutron in the experiment. They will occur at different rates everywhere in the experiment and their most important effect will be on control circuits. Simulations of the CMS environment have been made and comparisons made with the limited published data. These allow upper limits on the error rates to be set but the detailed consequences are much harder to establish. For this reason, it is becoming necessary to measure experimentally SEE effects in real circuits, exposed to severe conditions, such as encountered in a heavy ion beam.

First measurements of Single Event Upsets in the APV6 were made by IC in collaboration with INFN Padova in July 1999 using oxygen and silicon heavy ions at the Legnaro tandem accelerator. This allowed the SEU threshold to be measured but problems with the accelerator prevented a complete scan of the interesting linear energy transfer (LET or dE/dx) range. This will be completed in a future run in February 2000 when the APV25, and possibly APV6, chip will be exposed to heavy ions in Legnaro.

FED and DAQ developments

Following development of a prototype 9U VMEbus FED module in 1996/97, to demonstrate density, cost and functionality targets, the second phase switched to a PCI Mezzanine (PMC) format in order to allow users in many CMS institutes to make use of a single module in various system configurations. A block diagram of this module is shown in Figure 6. The work was completed in October 1998, and used in successful beam tests in May and October 1999. About 30 such modules have now been distributed, at cost, to several tracker teams within the community. The PMC FED provides a flexible module for system developments over the next few years and matches with advances in commercial off-the-shelf processors. The final FED will now be developed using the same components but configured in a lower cost (and larger) form factor, but probably with less modularity. The detailed planning for this is now beginning, in parallel with the writing of the Technical Design Report for the DAQ project.

The prototype version of the FED based upon the popular commercial PCI bus Mezzanine Card (PMC) form factor is now in use at a dozen CMS laboratories around Europe. The FED-PMC consists of an 8-channel, 9-bit ADC, card, providing a data buffer 64k samples deep behind each ADC, and operating at the LHC frequency of 40 MHz. The core of the card is a re-programmable FPGA which allows the functionality of the card to be modified without difficulty. The card is supported

by a comprehensive library of C routines. Figure 7 shows a photograph of the FED-PMC card.

The PMC implementation provides a cost effective solution for instrumenting detectors in test beam and laboratory set-ups during the prototyping phase of the experiment. The PMC form factor allows the card to be plugged onto a wide variety of processor carrier boards and also, using a simple adapter card, into desktop PCs. The flexibility of the FPGA based design permits the card to be used in a variety of ADC based applications. It has already been employed successfully during beam tests of prototype detectors for the LHCb experiment.

The first FED-PMCs were produced during summer 1998 and commissioned during tracker test beam running at CERN in October 1998. A second version of the card was used extensively during further beam tests at CERN throughout 1999. It is noteworthy that FED-PMCs were integrated into the test beam system in a matter of hours and operated successfully, without further expert intervention, throughout the data taking periods.

Radiation hardening of silicon detectors

The UK groups in CMS have contributed significantly to the work of the RD48 collaboration which has worked on radiation hardening of silicon detectors. RD48 is a joint R&D project with participants from all the major LHC experiments and elsewhere, with a UK CMS co-spokesman.

Recent work has shown that the addition of oxygen into the silicon at levels of greater than 10^{17} cm^{-3} improves the radiation tolerance of the material by a factor of three for charged hadron irradiation. This effect was predicted by Brunel and Imperial College, based on the simulations of migration of mobile vacancies and interstitial silicon atoms following removal of atoms from their lattice sites by high energy particles. Figures 8 and 9 show the measured data and model predictions for irradiation by 1 MeV neutrons and 24 GeV protons.

A simple process has been found to obtain the required oxygen levels in the material by diffusion of oxygen from an oxide layer on both sides of the wafer at a temperature of 1150 °C for several hours. Recent work has concentrated on finding the optimal process and transferring the technology to the silicon detector manufacturers. The process can be performed on any silicon wafer at the detector manufacturer. Full-scale detector prototypes have been made for silicon strip and pixel detectors for both CMS and ATLAS and are currently being tested before and after irradiation. Results are due shortly. The technique has been implemented at SINTEF, Micron Semiconductor, SGS-Thomson, CSEM, and CiS. The key effect is that the depletion voltage after inversion grows at a rate which is a factor three less in this material. There is also a beneficial change to the time constant for reverse annealing, which is increased by a factor of two. This result is preliminary and is being investigated further.

ELECTROMAGNETIC CALORIMETRY

Overview

The UK has the lead responsibility for the design and construction of the CMS crystal Endcap Electromagnetic calorimeters (EE). This work is being carried out in close collaboration with institutes from Russia together with groups providing common items which will be used throughout the barrel and endcap regions of the detector. The endcap calorimeters comprise a total of 16,000 narrowly tapered lead tungstate crystals, each approximately 3x3x22 cm^3 in size, read out with one inch diameter Vacuum Phototriodes (VPTs).

The past year has seen the production of 20 full sized EE crystals with the final double doping of Nb/Yb from Bogoroditsk in Russia, and the start of EE crystal R&D in the Beijing Glass Research Institute and Shanghai Institute of Ceramics, China. The Russian crystals show very good radiation tolerance and light yield, on a par with crystals being produced for the Barrel section of the calorimeter.

The EE crystals are contained within 5x5 units, known as supercrystals, by thin walled (400 μm) carbon fibre alveolar structures. The first 3 batches of alveolars, a total of 14 samples, have been received from Myasichev (Moscow) and have been extensively measured. They are found to have impressively small spreads in wall thickness (fwhm 40 μm) and cell size. A further 50 alveolar units have been made in Russia. These will be cut to suitable dimensions once the design studies at RAL have been completed. Construction and tests of supercrystal engineering models are underway.

The engineering design and integration of services on the EE is making progress. In particular, the supercrystal design is converging. This has permitted initial planning, and jig and tooling design, to be started for the UK Regional Centre at RAL, to produce all the supercrystals for the EE. The Regional Centre will be set up and equipped in 2000.

At Imperial College, the transmission properties of crystals have been successfully measured in the Crystal Laboratory and compared to data from CERN. The results are entirely compatible, opening the way for detailed independent irradiation studies of EE crystals to start in the UK.

At Brunel, mechanical and electrical equipment is being prepared and assembled for the mass production testing of VPTs at 4 T.

At Bristol, work is well advanced for receiving the CRISTAL database from CERN which will be used to control and record all the operations of the UK Regional Centre. Jigs and tooling for the Regional Centre are in preparation.

Test beam studies

A full size endcap supercrystal was constructed in May 1999 with crystals of the size specified for use in CMS. The array was instrumented with prototype 1" VPTs from three different manufacturers. The structure of the supercrystal, which is close to the final design, is shown in Figure 10. The supercrystal was tested in a high energy electron beam at CERN at zero magnetic field. The expected performance at 4 T was deduced using measurements made with the same array in a high magnetic field. Beam tests were also carried out with a prototype preshower radiator and detector in front of the supercrystal. Figure 11 shows the energy distribution for 180 GeV electrons measured in the combined preshower and supercrystal detector.

The tests provided three important results :

The constant term, measured to be ~ 0.3-0.4%, satisfied the design goal. Very importantly, this was achieved with crystals which were simply polished, within an alveolar unit without a reflective liner. This greatly simplifies the construction.

The combined crystal and VPT performance at 4 T, in CMS, (noise target of less than 150 MeV per channel) is met by VPTs from at least two manufacturers.

The energy resolution met the design goal; 0.45% with the supercrystal alone and 0.6% with the preshower, for electrons at 180 GeV.

The success of these tests has been a crucial step in preparing for the start of the VPT tendering process.

VPT testing

An extensive programme of R&D on 1" diameter VPTs has been conducted. The UK groups have evaluated triodes from Electron Tubes (UK), Hamamatsu (Japan) and Photonis (France), while Russian collaborators have worked with the Research Institute Electron (St Petersburg) and MELZ (Moscow). Over the last year more than 60 1" prototype VPTs have been produced with designs optimised for 4 T operation in CMS. The VPTs have been appraised in magnetic fields up to 1.8 T at RAL, and in a 4.7 T high-field magnet at Brunel.

Figure 12 shows the relative response of prototype VPTs from one manufacturer as a function of magnetic field. The response falls by less than 20% and is flat beyond 1 T. Measurements have also been made at 4.7 T to verify that this behaviour continues at higher fields. The tolerance of VPTs to radiation, and their ability to deliver a large total integrated charge in the presence of a magnetic field, are currently being verified by measurements made at Brunel and RAL.

The VPT technical specification received the endorsement of the CMS ECAL Technical Board on 22 October 1999, and the VPT tender and procurement exercise is now under way. A pre-production batch of 500 devices is required to be delivered in 2000.

Glue studies

A critical element in the ECAL detector assembly is the bond between the lead tungstate crystal and the VPT. The RAL group has carried out a series of studies to identify a suitable adhesive which satisfies the CMS requirements concerning refractive index, optical transmission, resistance to radiation darkening, and curing time. Following a survey of commercially available adhesives, a single component, air-drying, silicon resin (Dow-Corning RTV 3145) has been selected.

In order to confirm the radiation resistance of this resin, thin films of adhesive, sandwiched between quartz plates, have been exposed to a ^{60}Co source. Several thicknesses of adhesive were tested at doses up to 205 kGy. In all cases, the deterioration in optical transmission was found to be negligible. An example is shown in Figure 13.

Similar studies have also been carried out with neutrons using the irradiation facility at ISIS. No optical degradation has been observed with fluences of 10^{14} n cm^{-2}.

The curing rate of thin films of adhesive sandwiched between glass plates has been studied using a staining technique, and by applying mechanical stress to the bond.

It has been found that, under conditions of normal humidity and temperature, a VPT bonded to a crystal can be handled after 2 hours and the glue joint is completely cured after 10 days.

Bubble formation during curing, a potentially serious problem encountered in tests of other adhesives at CERN, is eliminated with the RTV resin, using a centrifuge technique developed at RAL.

Damage to VPTs by helium diffusion

It is known that the normal atmospheric levels of helium (0.7Pa) can limit the life of quartz envelope vacuum tubes. The envelopes of the VPT tubes being developed for the ECAL endcaps are made from borosilicate glass which has a much lower helium diffusivity than quartz. Nonetheless, exposure to a high level of helium, even transiently (for example, following a magnet quench) could result is gas absorption over the surface of the glass leading to later failure. Theoretical and experimental studies are under way at RAL to determine the precise level of risk from helium, and the gas-purged environment of the tubes will be designed to take account of this information.

Global Calorimeter trigger

The main calorimeter processing provides two types of trigger information: electron/photon and jet candidates, collectively known as trigger "objects"; and sums of transverse energy and its components over the whole region up to $|\eta|=5$. Energy sums are also produced for the forward calorimeters. The job of the GCT is to sort the different types of object, passing on the best four of each type for use in the Level 1 decision, and to calculate total and missing energy for the whole detector. The test and prototype work to date has focused mainly on the "sort processing" required to find the four objects having the highest E_T, and overcoming the difficulties associated with getting nearly 3000 input signals into the system.

An ASIC to perform a low latency pipelined sort, finding the largest four values from up to 32 inputs, has been designed. This ASIC used BiCMOS technology, in order to be compatible with ECL input and output signal levels, and was fabricated by Austria Mikro Systeme. In order to test the ASICs at clock rates up to the design value of 160 MHz, four times the LHC crossing frequency, a test platform has been built, together with a system of memory modules to send and receive wide data sequences. The construction of this test platform has provided experience with working with very high speed ECL signals.

The sort ASIC was designed to be compatible with the requirements for the preliminary stages of object sorting in the Regional crates, as well as those in the GCT. In late 1998 however, the designers of the Regional crate system decided to implement their own sort ASIC with additional functionality. This prompted the UK to investigate alternative technologies for the GCT sort, and it has been found that the same low-latency algorithm can be performed using the Virtex family of Field Programmable Gate Arrays (FPGA) from Xilinx. Simulations using Xilinx software have shown that the speed of these devices is adequate, and so a second test platform is being constructed, incorporating a Virtex FPGA, to be used with the memory module test system. Tests using this platform began in October 1999.

The choices of data link technology are also being reviewed, both for transporting the input data from the Regional crates to the GCT and between boards within the GCT system. In particular, the possibility of using optical links, rather than copper,

is being investigated, to carry the data from the Regional crates over distances of up to 25 m. Tests of both ECL and optical data transmission are being prepared, with the aim of reaching a decision in the first half of 2000.

The CMS trigger TDR is now being prepared, with the publication date set for November 2000. This will include a full design of the GCT. A further prototype will be constructed during 2000, incorporating elements of the final design such as pipelining and readout of the input data. With the move from ASIC to FPGA processing, it is hoped that the sort and adder portions of the final system can be made very similar, if not identical. Production of the final boards should begin in 2002.

Simulation

During 1999, many details of the ECAL endcap design have been reviewed and debated within CMS. The RAL group has continued to carry out detector simulations to investigate the physics effect of each design option, and to study the combined performance of the electromagnetic and hadronic calorimeters. The principal area of interest has been the outer edge of the endcap and the endcap-to-barrel transition region. Single photons, single charged pions and hadronic jets have been generated, and the calorimeter response has been studied as a function of rapidity. Figure 14 shows a sample of the results; each set of points shows the mean energy reconstructed in the combined ECAL and HCAL, normalised to the incident energy, for jets of hadrons originating from the fragmentation of d and b quarks with 200 GeV energy; the different symbols refer to various ECAL endcap design options, as described in the caption. These results show that the hadronic response of the calorimeter is not strongly affected by the detailed design of the ECAL endcaps, though a high-statistics study is continuing to investigate subtle effects which could affect the resolution of a small fraction of events. The difference in the measured energy for the two quark flavours arises because of the greater rate of neutrino production in the fragmentation of heavy quarks.

PHYSICS STUDIES

A Physics Reconstruction and Selection initiative, started in April 1999, has led the CMS collaboration to restructure its physics and software development effort by creating four working groups, each having responsibility for a single physics "object": electron/photon, muon, jet/missing E_T, and b/τ vertex. A UK physicist was appointed convenor of the electron/photon group. The basic task of these groups is the reconstruction and selection of physics objects starting from the Level-1 trigger.

The idea is that the reconstruction of physics objects will proceed by successive refinement of the selection algorithms employed at successively higher levels of the trigger. The first step in this process has been to implement a full simulation of the higher level trigger system, and to understand its implications for data rates in the data acquisition system.

This initiative follows closely on the decision to discontinue development of FORTRAN based software and concentrate all effort on object oriented (OO) methodology using the C++ language.

The immediate milestone set for the working groups was to show, by November 1999, that the data rate received from the Level-1 trigger could be reduced by a factor of 10 using about ¼ of the total event information: i.e. for the electron/photon group, to get the rate of electromagnetic triggers down by a factor 10 using calorimeter information alone. This milestone was very challenging because of the enormous effort involved in the changeover to OO, and the large data samples involved (350k jet background events fully simulated with GEANT, for the electron/photon group). Nevertheless it was partially met. Excellent results were obtained for single electron rates in the barrel. Work continues with the aim of reaching the milestone with a complete study by June 2000. It is also intended that first attempts at matching ECAL Level-2 candidates to tracks and tracker hits will be in progress by that time.

The UK groups plan to play an increasingly significant role in this work, which will eventually lead to a CMS Physics Technical Design Report, and beyond that will enable a smooth and rapid transition to physics analysis of the data from the CMS detector.

A UK physicist acted as a convenor, representing CMS, of the electroweak working group of the CERN LHC Standard Model Workshop during 1999.

SUMMARY

The CMS Collaboration has made substantial progress in 1999 towards the goal of constructing the detector by 2005. The construction of the superconducting magnet, the principal structural element of the detector, is proceeding steadily, while fabrication has started on some of the other major subsystems. The funding of the experiment is securely based, and the collaboration continues to grow.

In the areas of particular UK interest, the tracker and the electromagnetic calorimeter endcap, the year has seen significant developments. The tracker community has decided, subject to endorsement by the collaboration as a whole, to move to an all-silicon design instead of the previous combined silicon-MSGC solution. In the UK, the development of radiation-hard readout electronics using 0.25μm technology has achieved excellent results.

The development of the electromagnetic endcap took an important step forward with successful beam tests of a prototype 5×5 supercrystal module. The prototype was constructed from 25 full-size crystals and instrumented with VPTs from three manufacturers, and achieved the required energy resolution in conjunction with a prototype endcap preshower module tested at the same time. The tendering process for the eventual order of 16000 VPTs has begun, and preparations are in hand for the large-scale testing of VPTs at RAL.

The successes of the past year provide a sound basis for the collaboration to move into the construction phase of the experiment in the years to come.

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M. French, G. Hall, B. MacEvoy, M. Raymond, S. Watts et al
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Proceedings of 4th Workshop on Electronics for LHC Experiments, Rome, Italy, September 1998
CERN/LHCC/98-36 (1998) 96-99.

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T. S. Virdee
Invited talk at IEEE Nuclear Science Symposium, Toronto, Canada, November 1998.

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G. P. Heath
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P. R. Hobson
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The CMS Electromagnetic Calorimeter
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IEEE Nuclear Science Symposium, Seattle, Washington, October 1999

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J. Batten, J. Troska et al
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Neutral Pion Rejection at L2 using the CMS Endcap Preshower
C. Seez et al
CMS Note 1999/076

Design Patterns for Description-Driven Systems
R. McClatchey, Z. Kovacs et al
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The Operation of Vacuum Phototriodes in a Non-Axial Magnetic Field, a Monte-Carlo Study.
J.E. Bateman
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APV Logic Simulations
N. Marinelli
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Performance of the Front-end Analogue Filter for MSGCs signals in CMS at Different Track Incidence Angles
F. G. Sciaccia
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Energy leakage in the barrel/endcap transition region of the ECAL
B. W. Kennedy
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A Device Model Simulation of Neutron Radiation Effects in Avalanche Photodiodes
M. Osborne
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C. Seez
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Monte Carlo studies of the CMS electromagnetic endcap calorimeter
B. W. Kennedy
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Energy Leakage in the Barrel/Endcap Transition Region of the ECAL II: simplified endcap designs and hadronic energy containment
B. W. Kennedy
CMS Note 2000/xxx

CMS ECAL Endcap Geometry Specification
B. W. Kennedy
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Studies of the Electromagnetic Calorimeter and Direct Photon Production at the CMS Detector
E. C. Reid
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J. Troska
ICSTM Ph.D. Thesis, 1999.

Analogue Readout and Signal Processing for Microstrip Gas Chambers of the Compact Muon Solenoid at LHC
F. G. Sciacca
ICSTM Ph.D. Thesis, 1999.

FIGURES

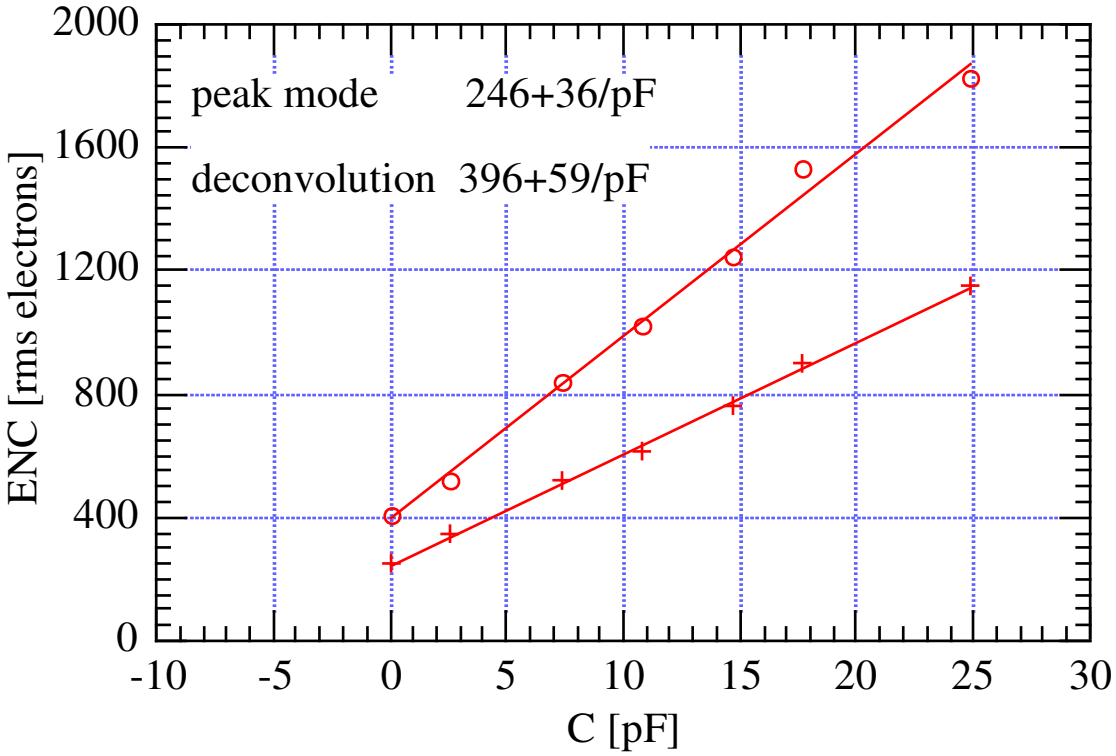

Figure 1. APV25 Equivalent Noise Charge vs load capacitance.

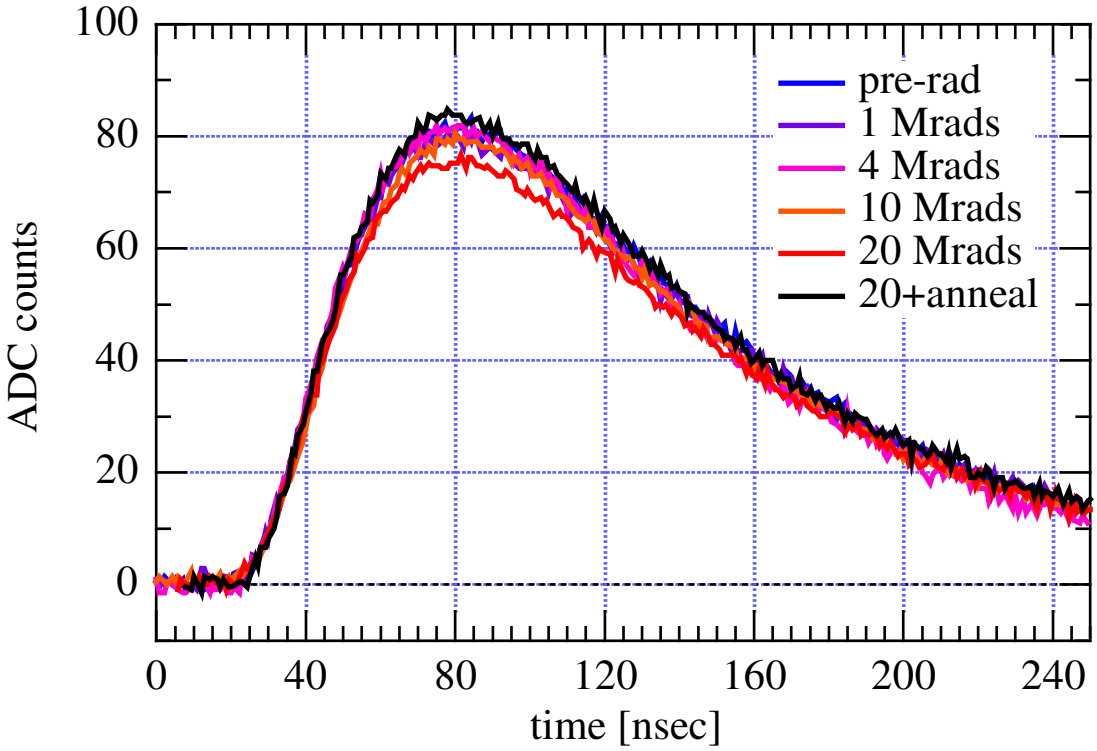

Figure 2. APV25 pulse shapes in peak mode after irradiation up to 200 kGy.

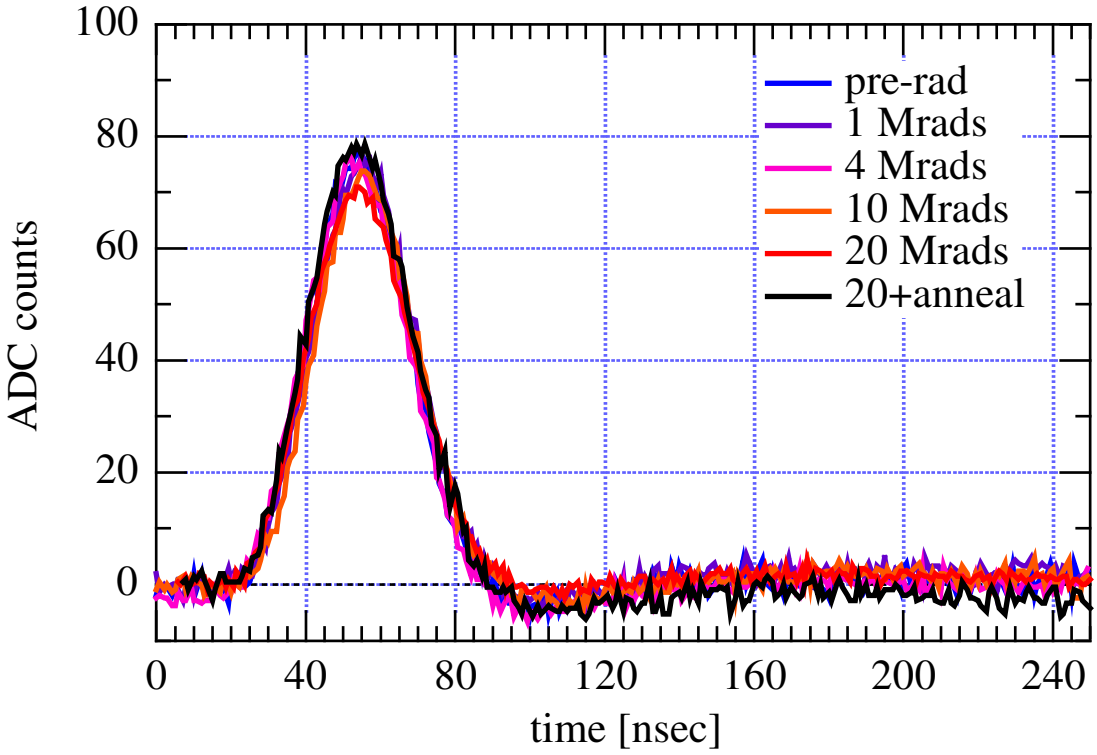

Figure 3. APV25 pulse shapes in deconvolution mode after irradiation up to 200 kGy.

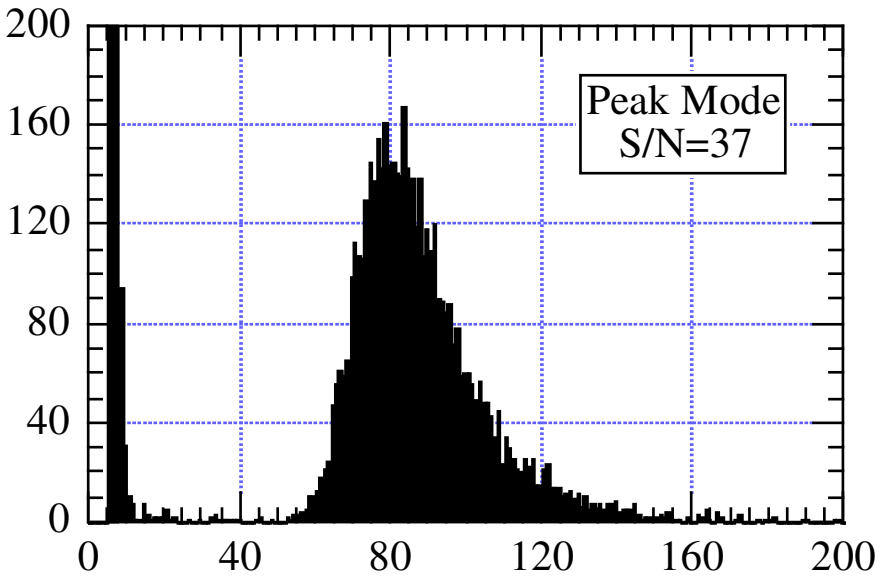

Figure 4. APV25 signal to noise measured in peak mode with a 5 cm, 50 µm microstrip detector using a ^{90}Sr β-source.

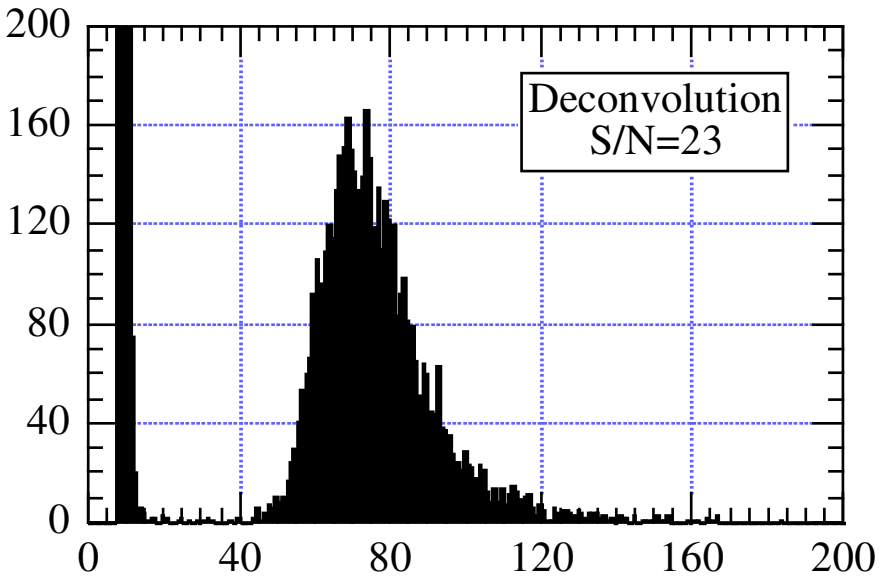

Figure 5. APV25 signal to noise measured in deconvolution mode with a 5 cm, 50 μm microstrip detector using a ^{90}Sr β-source.

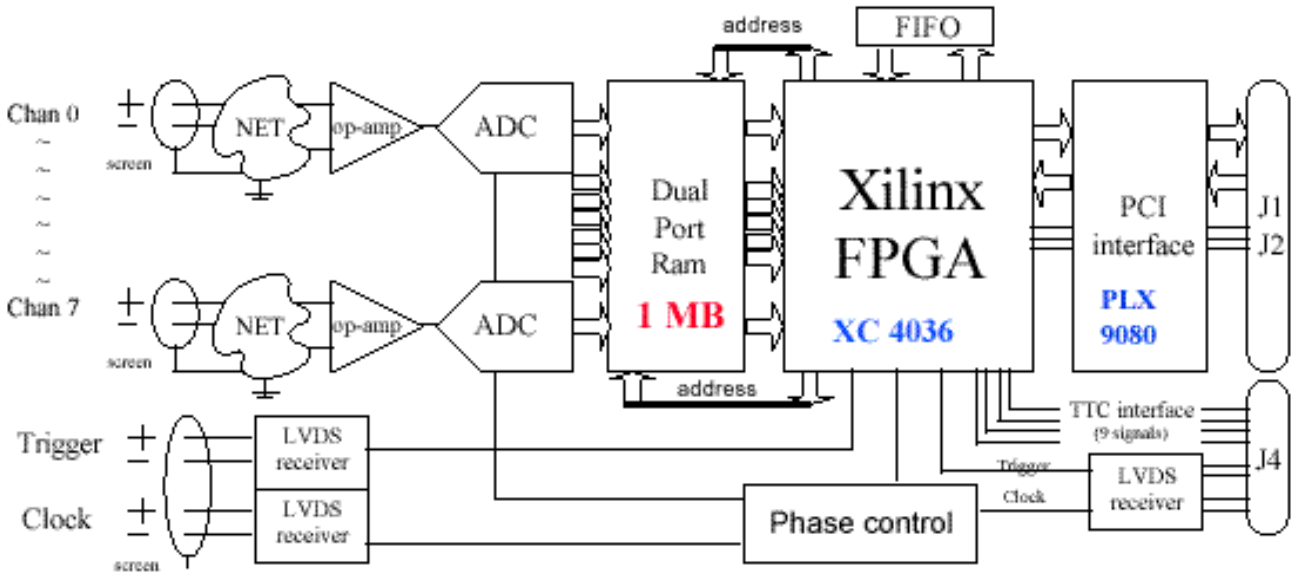

Figure 6. Block diagram of the CMS PCI format Front End Driver module.

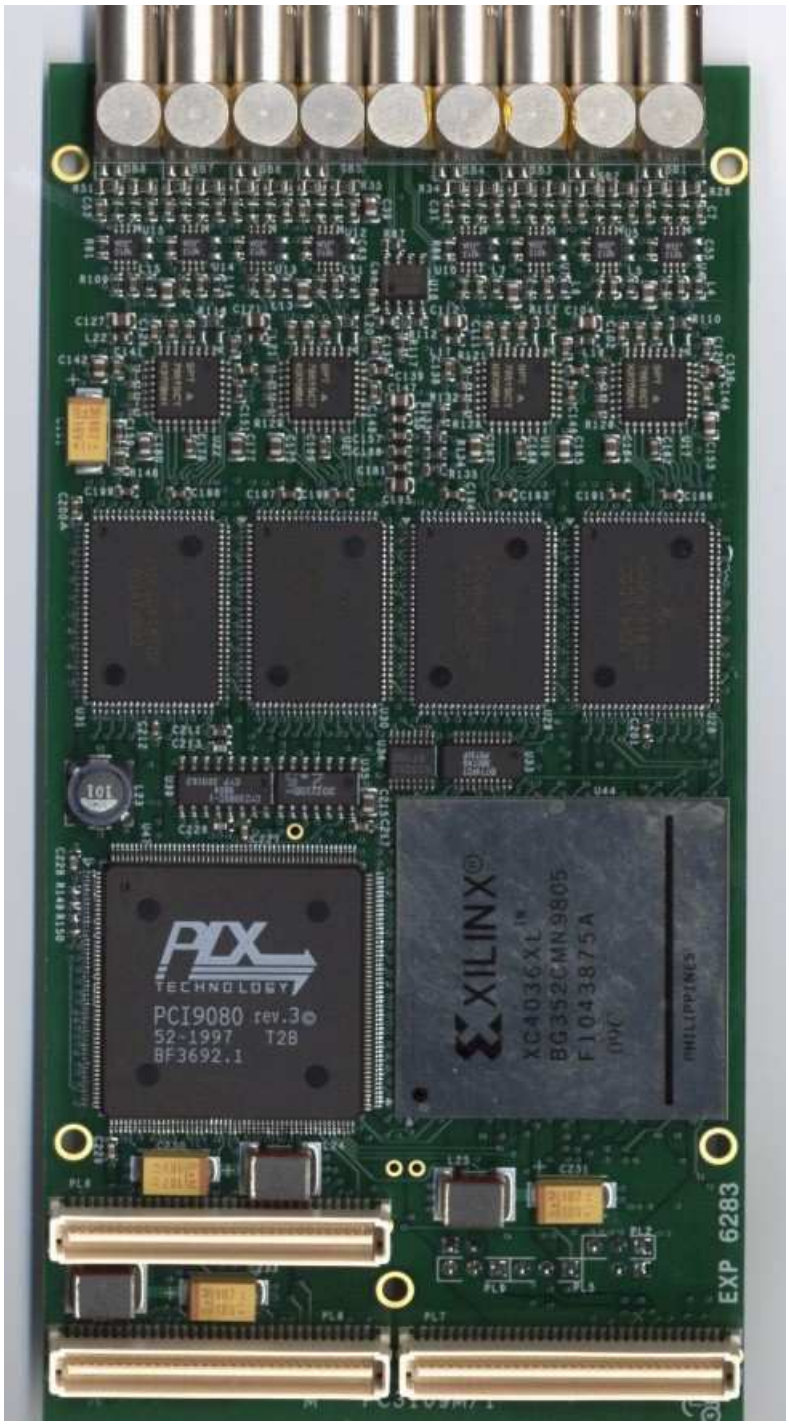

Figure 7. Photograph of the FED-PMC card.

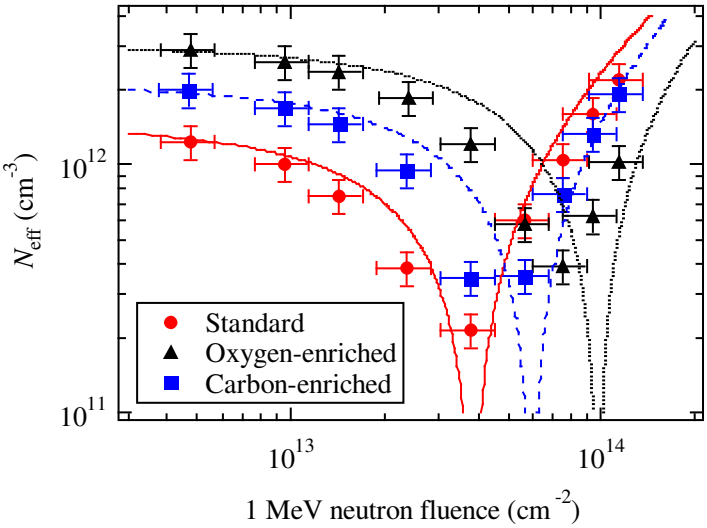

Figure 8. Model predictions (lines) and experimental data (markers) for 1 MeV neutron irradiation. Circles: oxygen 3×10^{15} cm^{-3}, carbon 5×10^{15} cm^{-3}; triangles: oxygen 1.7×10^{16} cm^{-3}, carbon < 2×10^{16} cm^{-3}; squares: oxygen < 5×10^{16} cm^{-3}, carbon 1.8×10^{16} cm^{-3}.

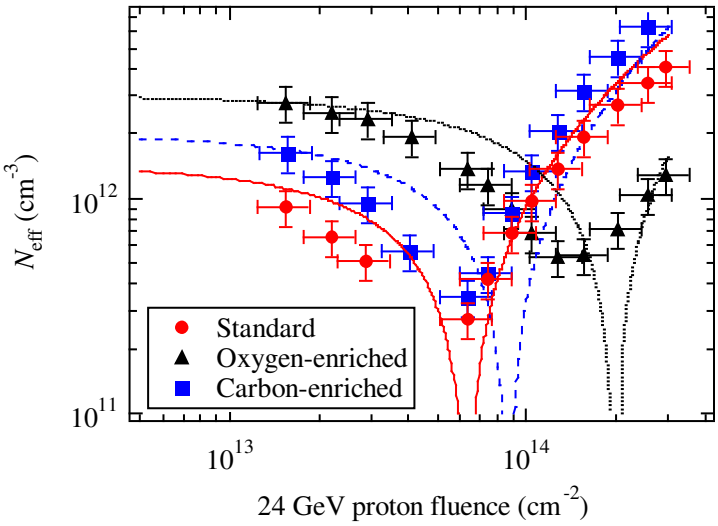

Figure 9. Model predictions (lines) and experimental data (markers) for 24 GeV proton irradiation. Circles: oxygen 3×10^{15} cm^{-3}, carbon 5×10^{15} cm^{-3}; triangles: oxygen 1.7×10^{16} cm^{-3}, carbon < 2×10^{16} cm^{-3}; squares: oxygen < 5×10^{16} cm^{-3}, carbon 1.8×10^{16} cm^{-3}.

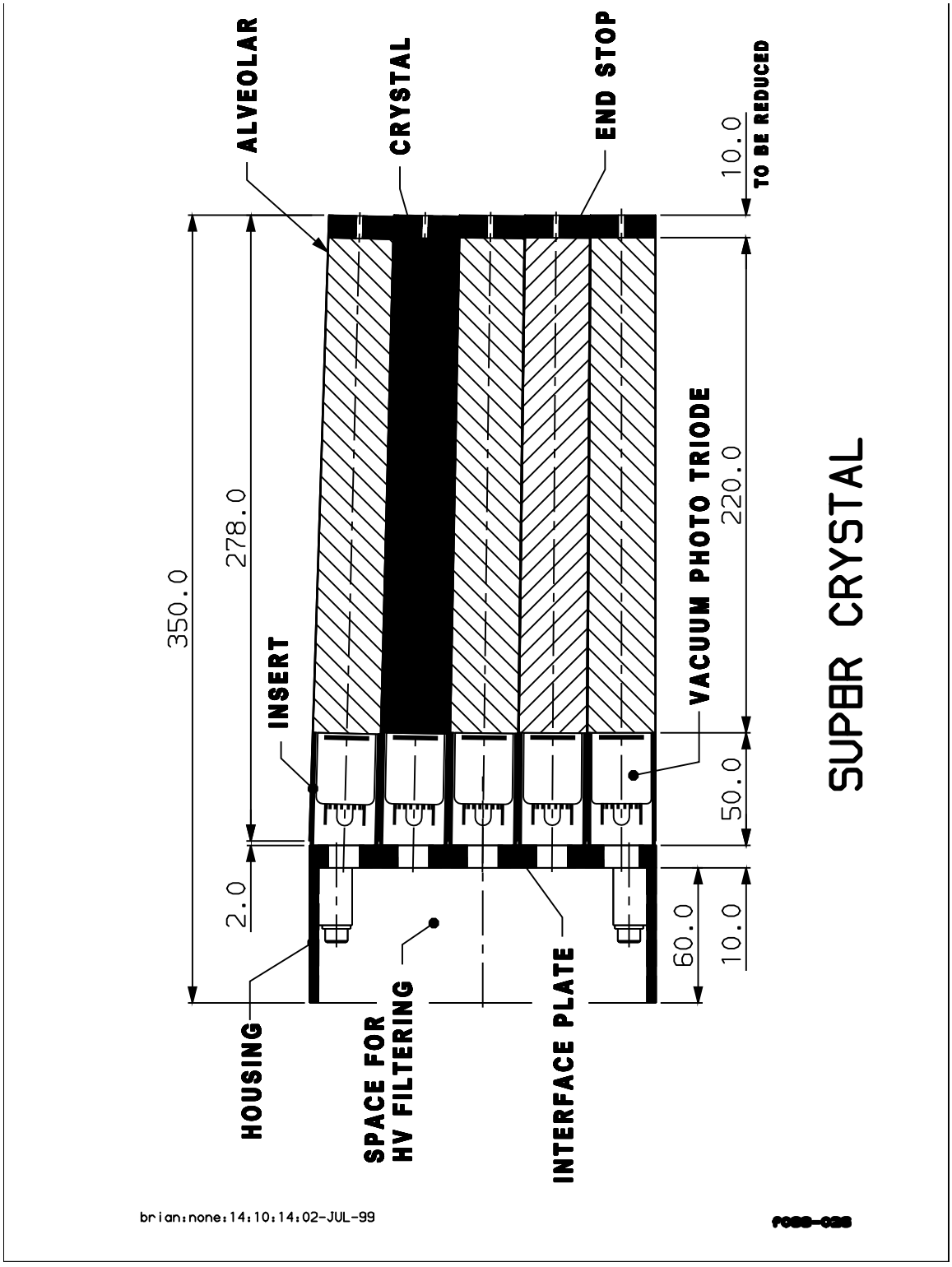

Figure 10: The arrangement of components within a supercrystal

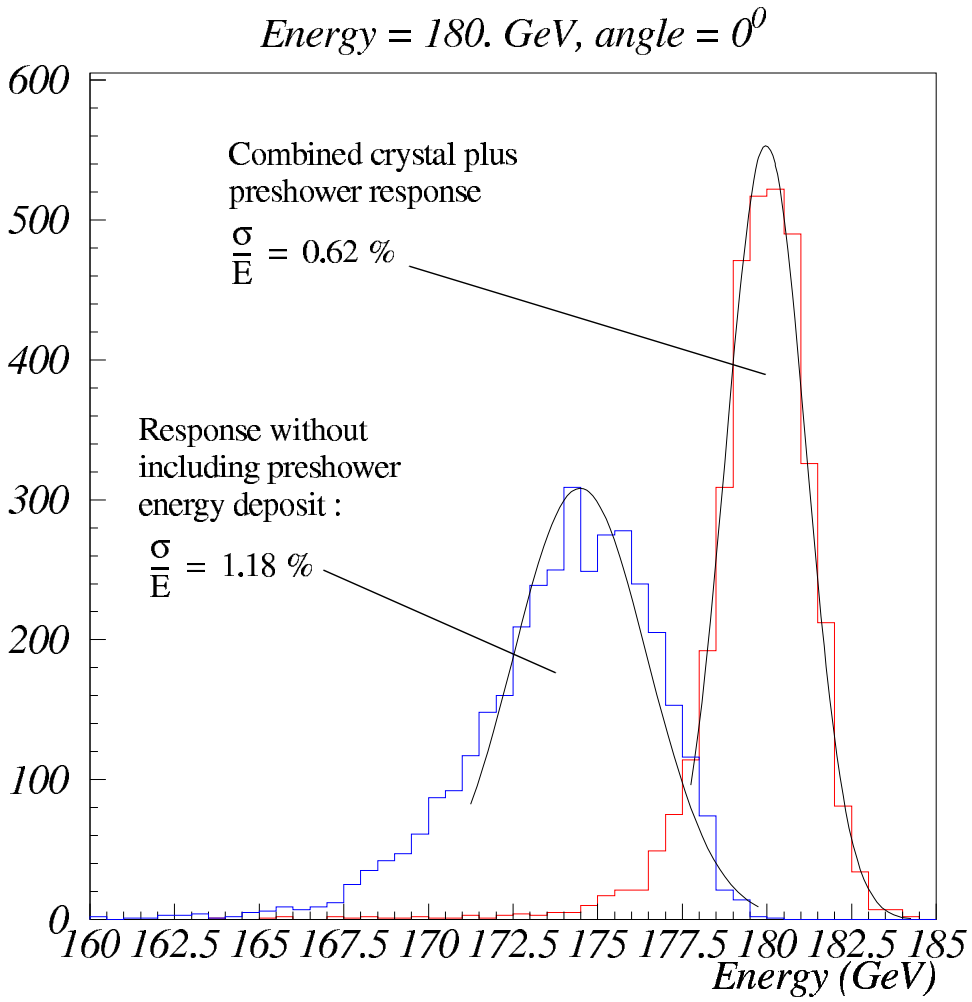

Figure 11. Energy distribution for electrons of momentum 180 GeV/c measured in the combined preshower and supercrystal prototype module. The energy resolution is 0.62%, meeting the required performance target for the endcap ECAL.

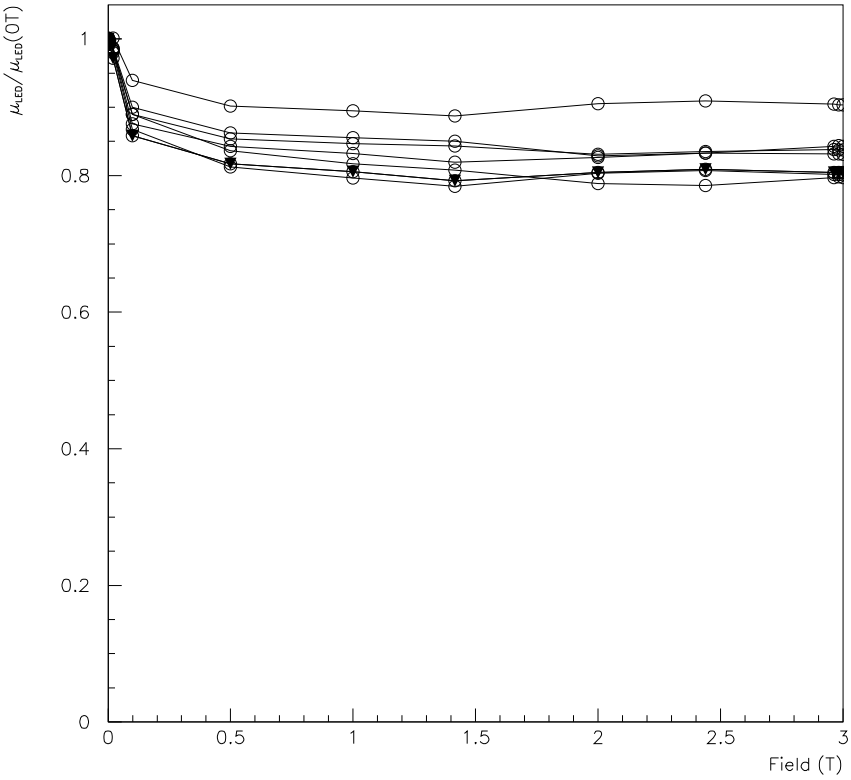

Figure 12: The relative anode response versus magnetic field for a set of vacuum phototriodes from one manufacturer

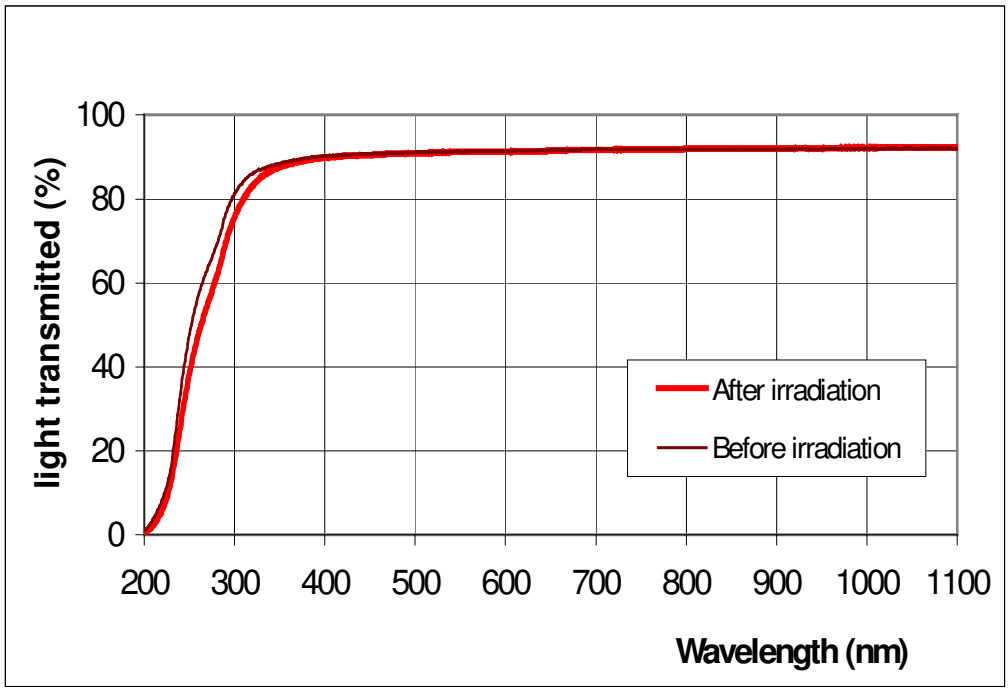

Figure 13. Transmission of a 66 μm thick sample of RTV resin, before and after gamma irradiation to an absorbed dose of 205 kGy.

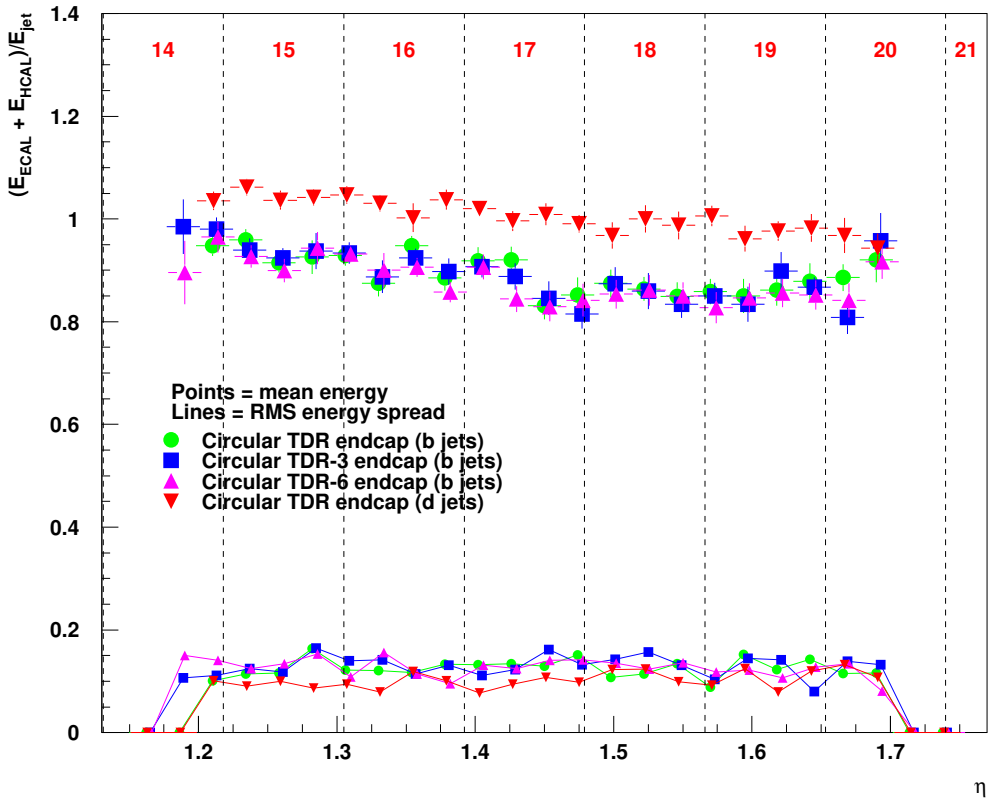

Figure 14. Normalised energy in the combined circular-ECAL and HCAL as a function of η for incident b-quark and d-quark jets of 200GeV energy. The vertical lines represent the pseudorapidity boundaries of the CMS trigger towers. The data sets shown represent modified ECAL endcap designs with the outer radius reduced by 3 cm and 6 cm with respect to the baseline TDR design.