Projects Peer Review Panel
September 2002

CMS UK
Collaboration

Status Report of UK Activities on CMS

1. OVERVIEW OF THE STATUS OF CMS

The UK groups in CMS have lead responsibilities for two major subsystems in CMS: the readout electronics for the Tracker and the endcaps of the crystal Electromagnetic Calorimeter (ECAL). The Tracker Readout work overlaps strongly with the development of the overall CMS Data Acquisition System and the Calorimeter responsibilities include the design and implementation of the Global Calorimeter Trigger system. The UK is also centrally involved in the development of software for reconstruction and physics analysis and in the development of GRID based computing facilities.

The status of these projects, with emphasis on the UK contribution to them, is given in Sections 2, 3 and 4. Section 1 summarises the situation for the other parts of the CMS project and reports on a new UK responsibility.

1.1 Overall Status of CMS

At the time of the previous report in September 1999, CMS was just moving from the development phase to construction. Enormous progress been made since then and a number of major hardware items have already been completed and delivered to the CERN site. Space allows here only a very brief summary of the overall status of the experiment; more detailed information can be found in the reports made regularly to the LHC Committee and the CMS Resources Review Board (see Appendix D).

1.1.1 Schedule

The schedule of the LHC machine has slipped substantially since the last report, initially because of civil engineering problems and more recently because of delays in the production of superconducting cable for the accelerator magnets. In the current plan, first beam is due to circulate in April 2007, with first collisions occurring in June 2007, almost two years later than originally foreseen. The excavation of the underground caverns for CMS has also been delayed by geological problems, by about 12 months, and delivery is now foreseen for July 2004.

A new 'master assembly sequence' (v33) has been drawn up for CMS which takes account of these delays and which plans for the installation of a complete low luminosity detector in time for physics in 2007. (Only the outer pixel layers and sections of the fourth endcap muon stations, which are 'staged' items required later for high luminosity running, will be missing at the start.) The new CMS schedule is due for approval at the end of September.

1.1.2 Civil Engineering and Assembly

After the initial delays, the excavation of the two underground caverns for CMS at Point 5, USC55 (services) and UXC55 (experiment), has proceeded well and is nearing completion. The current date of May 2005 for beneficial occupancy might even be brought forward and the v33 planning has contingency to allow for this. An important feature of the CMS design is that it plans for assembly of major detector components on the surface. The assembled items will then be lowered to the experimental area using a crane with a 2000 tonne capacity.

1.1.3 Magnet

The CMS magnet consists of a 4 Tesla superconducting solenoid, 13 m long and 6 m in internal diameter, and a segmented steel return yoke with a total mass of 11.6 kilotonne. The magnet yoke provides the mechanical support for all the detector elements. All five rings of the barrel yoke and all six endcap discs have been delivered to CERN and have been assembled at Point 5.

The superconductor consists of Rutherford cable, co-extruded with pure aluminium and reinforced with aluminium alloy. It is manufactured in 2.65 km lengths; 20 of these are required for the final coil with an additional one for the prototype. So far, 18 lengths of cable have been produced and 10 lengths of reinforced conductor have been completed. (The machine for producing cable from superconducting strands, at Brugg Kabelwerk, failed this summer. However, if it restarts as foreseen in October, this will not delay the CMS coil construction.)

The production of the coil is delayed by 6 months compared to the original planning because of problems (now overcome) with the supply of special elements in high strength alloy. This delay is accommodated in the v33 schedule, which foresees a full test of the magnet on the surface in the first quarter of 2005.

1.1.4 Hadron Calorimeter

The CMS hadron calorimeter comprises three subsystems: the Barrel, Endcap and Forward detectors. The Barrel and Endcap detectors consist of plastic scintillator tiles with fibre light collection, interleaved with brass absorber. The Forward calorimeter uses quartz fibres as the active element, embedded in steel 'wedges'.

All the absorber for the Barrel has been delivered to CERN. The scintillator and fibres have been installed in the absorber modules and tested. The first half-barrel has been assembled at Point 5 (Figure 1) and assembly of the second half-barrel will be completed by the end of this year. All the components for the first endcap have been delivered to CERN, and assembly will start in October. Of the 36 absorber wedges required for the Forward calorimeter, 20 have already been produced and delivered to CERN. 'Stuffing' with quartz fibres has started and two wedges will be tested in a beam this autumn.

A 100-channel beam test of the full electronics chain for the Barrel and Endcaps has just been completed. An Electronic System Review will be held in October, prior to the start of production.

Figure 1. The first half-barrel of the CMS HCAL, assembled at Point 5. The assembled Barrel section of the magnet yoke can be seen in the background

1.1.5 Muon System

The Barrel Muon System uses Drift Tube Chambers (DTC), together with Resistive Plate Chambers (RPC). Cathode Strip Chambers (CSC) and RPCs are used in the endcaps. The build-up of DTC production has been slower than originally planned. The latest CMS schedule allows for the delay, and sets a milestone for the completion of 70 chambers by the end of this year, with the full set of 250 to be completed by mid-2005.

The construction of CSCs started in May 1999. Assembly at FNAL is running ahead of schedule with 60% already completed. Assembly in St Petersburg and Beijing is also underway, at close to the planned rate. Mounting on the endcap yokes is scheduled to start at the end of this year.

Questions have been raised by the LHCC, in the light of experience from BaBar and elsewhere, concerning the noise performance of RPCs and the manufacture of bakelite electrodes of the required quality. Further tests are underway to establish definitively that RPCs can operate reliably over ten years at LHC. For the barrel chambers, the electrodes will be oiled. For the endcaps, where the noise from particle backgrounds is higher, a decision will be made later this year on the application of oil.

1.1.6 Trigger and Data Acquisition System

The Trigger design is proceeding well. Testing of second-generation prototype calorimeter trigger cards is underway, and final prototypes of many other elements are being constructed and tested. An optical link system for the RPC trigger has been successfully tested and the control logic for the Global Trigger has been designed.

The design of the Event Builder for the DAQ has evolved into a more modular architecture with eight independent slices, each able to handle trigger rates up to 12.5 kHz. This simplifies commissioning and staging for initial low luminosity running, and provides an easier upgrade path to benefit from future advances in technology. The DAQ TDR is in preparation and will be submitted at the end of this year.

1.1.7 Overall Financial Situation

At the time of the Memorandum of Understanding (MoU) in 1998, the estimated cost of CMS was 465.7 MCHF and the indicated funding was 457.7 MCHF. Despite the unprecedented technical challenges of the project and inflationary pressures which have been exacerbated by delays to the schedule, CMS has been extremely successful in containing costs. In October 2001, the estimated price of the initial low luminosity detector stood at 500.8 MCHF, with a further 12.5 MCHF required for commissioning and integration. However, following financial problems in Russia and elsewhere, the anticipated funding had fallen to 445.4 MCHF, leading to a shortfall of 67.9 MCHF at that time.

In April 2002, CMS presented to the Resources Review Board (RRB) a Financial Plan for covering the cost to completion of the detector. This showed a deficit of 62.7 MCHF, approximately 5 MCHF smaller than that previously reported. (The reduction had been achieved by further descoping and staging, without damaging the initial physics reach.) CMS proposed to cover the shortfall with pro-rata additional contributions from the Funding Agencies. The response of the RRB was very positive and at that meeting it was already apparent that a substantial fraction of the required resources could be made available. It was therefore agreed that CMS should seek to confirm the amounts expected and to finalise a financial plan based on that information.

The sum requested from the UK is 1.53 MCHF. In June, Janet Seed wrote to the Spokesperson of CMS stating that the Collaboration could assume for planning purposes an additional contribution from PPARC of 918 kCHF. The letter also states that the UK CMS collaboration may bid to PPARC for additional funds to cover the remaining portion of the calculated pro-rata UK share (612 kCHF).

Overall, CMS has established that 49.7 MCHF of additional funds can be relied on for planning, with the possibility of further resources later. Although the confirmed amount is 13 MCHF less than the sum requested, CMS has identified further economies and descoping that will allow a fully functional initial detector to be completed in time for the start of LHC operation.

It must be stressed that in reducing costs to this level, CMS has reached the limit of what is possible without severely compromising the physics. The risks associated with making every possible saving at this early stage are self-evident since there is no contingency left to deal with unexpected problems during installation and commissioning. Even if all goes perfectly to plan, once the experiment starts running it will quickly become necessary to rescope certain items, particularly the DAQ system, to deal with the planned growth in luminosity. Strenuous efforts will therefore continue in order to attract further funds. Several existing funding agencies have already indicated that additional money should become available in the future. Extra resources will also come from new groups that are in the process of joining CMS, including universities in Brazil and New Zealand, University College Dublin, and members of the US heavy ion community. The UK Collaboration will certainly exercise the option to bid for the balance of the 'UK share', mentioned in Janet Seed's letter.

1.2 Changes to the ECAL Electronics

Of the 62.7 MCHF total shortfall reported in the CMS Financial Plan, 24.2 MCHF is attributable to the ECAL, arising mainly from an initial underestimate of the dollar cost of the crystals and from an unfavourable dollar/Swiss franc exchange rate. (The crystal procurement is in dollars, whereas the funding, from CERN and ETH Zurich, is in Swiss francs.) The ECAL overrun would have been even greater had not drastic action been taken recently to contain the cost of the readout electronics.

In the ECAL Technical Design Report, the proposed electronics chain consisted, for each of the 76,000 crystals, of a photo-transducer (an avalanche photodiode (APD) or a vacuum phototriode (VPT)), a preamplifier with four gain ranges, a 12-bit 40 MHz sampling ADC, a bit serialiser and an optical link to transmit the digitised data to the Upper Level Readout in the Services Cavern. Unfortunately, the affordability of this system was based on a projected fall in optical link costs with time that has not been realised.

Initially, a plan was made to achieve substantial savings by re-engineering the optical data links to operate at higher speed, thus reducing the number required. A proposal for the UK to take a leading role in this work was included in the CMS submission to the GPD Mid-term Review. However, at the end of last year, an in-depth reappraisal of all ECAL costs revealed that further measures would be required to keep the electronics costs at or below the level assumed in the CMS Financial Plan. As a consequence, a radically different approach to the ECAL readout architecture has been adopted.

In the new scheme, the generation of 'Trigger Primitives' has been moved from the Upper Level Readout to the Front-End electronics on the Detector. This allows the transfer of full digitised crystal data to be restricted to events satisfying a Level-1 trigger, thus reducing the number of data links and the amount of off-detector electronics by almost an order of magnitude. Central to the new scheme is the implementation of a new Front-End ASIC in radiation-hard 0.25 µm CMOS technology (the 'FENIX' chip) to perform the Trigger Primitive generation and data storage on the detector.

The change to the ECAL electronic system comes at a late stage. However, because the optical links will now be based on the technology developed for the Tracker and have already been thoroughly evaluated at the speed required for the ECAL, there is little doubt that the components will conform to ECAL specifications, and contractual issues are also well in hand. The new system will make extensive use of other components developed for the Tracker, especially for control, and the substantial expertise acquired in 0.25 µm CMOS by the Tracker team provides a solid basis for the FENIX development.

The new ECAL electronics architecture was endorsed by CMS in March. The proposal was well received by the LHCC in May and the Committee has requested an addendum to the ECAL TDR to allow final approval. The 'Feasibility Study' phase of the project has been completed, confirming that the proposal is technically sound and that the cost and schedule targets are achievable.

1.2.1 Implications for the UK

Implementation of the new electronics scheme will have consequences for the UK. Geoff Hall has agreed to be Project Manager for the Front-End sub-system of which the FENIX chip is part. Bristol has been undertaking simulations to verify that the new scheme does not compromise the ECAL trigger performance in the endcap region. The engineering team at RAL must make major changes to the 'mechatronics' and cooling aspects of the ECAL endcap design. It is planned that this additional work be contained within the current (post SCP4) approved resources.

The CMS Collaboration requested that the design of the crucial FENIX chip and associated circuit board be undertaken by the Microelectronics Group in Instrumentation Department at RAL, thus benefiting from their development of the very successful APV25 ASIC for the CMS Tracker. The UK CMS Management Committee has agreed to this request. The effort required is estimated to be 4 SY, and PPARC and CMS have accepted that part of the 918 kCHF 'cost-to-completion' funds will be used to pay for this effort, thus avoiding an impact on existing agreed UK deliverables.

1.3 Impact of SCP4

In responding to SCP4, CMS-UK formulated a plan to implement the requested cuts, without defaulting on any of its agreed deliverables. Given the critical financial status of CMS overall, it should be clear that this approach was essential.

Crucial to achieving this aim was the avoidance of any reduction in TD effort. Delays in the schedule, and other factors outside the UK control, such as the impact on mechanical design caused by changes to the ECAL electronics, have put strong pressure on this resource. As a consequence it was necessary to cut even more deeply elsewhere. The measures taken (swingeing cuts in Travel, loss of a post in PPD, delays in hardware procurement (at the cost of even deeper cuts in exploitation later)) substantially increase the risk that the UK will fail to install and commission its hardware on schedule.

Even more worrying is the damage that will be caused by carrying the cuts through into the exploitation phase. After the Herculean efforts made over more than a decade to develop and build the detector, it is incomprehensible that the UK might be prevented from reaping the full scientific benefit from this investment. A document detailing these concerns has been submitted to PPARC through the Chair of the Particle Physics Advisory Panel.

1.4 Summary

Overall, CMS is making impressive progress. Not surprisingly for a project of this size and complexity, a number of technical problems have been encountered. However, these are being successfully dealt with and the delays that have accrued have been accommodated in the latest CMS master assembly sequence. This plans for a complete low luminosity detector installed and ready for LHC physics in June 2007. A Financial Plan, demonstrating that sufficient resources are available to achieve this goal, is close to being finalised.

The UK has a crucial role in the redesign of the ECAL electronic system, a project that is key to containing the overall cost of the ECAL within the provision made in the CMS Financial Plan.

2. CMS TRACKER

Very briefly, the CMS Tracker is a system of 9.3 million silicon microstrip sensors, containing two layers of pixel detectors at small radius.

A unique feature of the CMS microstrip Tracker system is the analogue readout. Each microstrip is read out by a charge sensitive amplifier whose output voltage is sampled and stored in an analogue pipeline for 3 – 4 µs. The 128-channel APV readout chip is designed to operate with minimal deadtime up to trigger rates of 100 kHz. Each APV channel contains a preamplifier and shaper, with a 50 ns peaking time, followed by a 192-location memory into which samples are written at 40 MHz. Following a trigger, three samples are processed with a deconvolution circuit which re-filters the data with a shorter time constant. The APV also contains system features including programmable bias networks, remotely controllable internal test pulse generation system and a control interface.

Analogue pulse height data, without zero suppression, are transmitted from the front-end via a linear semiconductor laser over a fibre optic cable to the counting room in the Services Cavern. The optical signals are converted to electrical signals and digitised on the Front End Driver (FED), which performs some signal processing and stores data locally until required by the CMS data acquisition system.

The UK hardware deliverables are in the electronic readout system, shown schematically in Figure 2, which has changed little conceptually since original UK approval. Our cash contribution to the CMS Tracker CORE budget was fixed at 2.7 MCHF, to purchase a share of components for which we were technically responsible: APV readout chips, the associated APVMUX chips and the VMEbus FEDs. This is distributed as 1.95 MCHF on on-detector electronics, and 0.75 MCHF on FEDs. There is an additional contribution of 0.45 MCHF to the CMS Data Acquisition system, to be closely linked to the UK Tracker project.

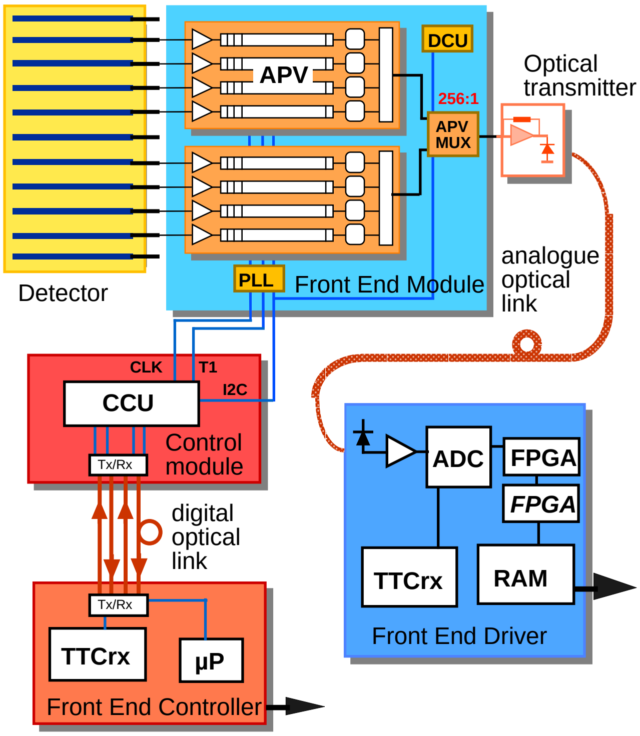


Figure 2. CMS Tracker readout and control system

2.1 Overall Tracker status

Since 1999 progress towards production of the Tracker has been substantial. CMS reported excellent results to the latest LHCC Comprehensive Review in October 2001 in beam tests using final silicon modules read out by final electronics. It was recognised that there is no further scope for staging the silicon microstrip Tracker to cover funding shortfalls. In the feedback from the LHCC, the Tracker progress since the 2000 Comprehensive Review was said to have been impressive and all concerns expressed at that time had been addressed. In particular the organisation was said to be a major success and the project management commended.

Our plan is to launch large scale production of modules for the Tracker in 2002. All assembly centres and tooling are ready to go. Pre-production deliveries of several hundred silicon sensors have been received and the quality has been excellent. Electronics are available, now in the final packaged format (except for the APV which is unpackaged). The main remaining obstacle is the completion of development of the final hybrid and its commercial assembly and testing, which has taken longer than hoped. A ceramic design was adopted as the baseline, but has proven difficult to implement industrially with the required quality. Several companies are now producing very promising hybrids based on FR4 with an integrated kapton interconnection cable: these have now only to meet final acceptance criteria. It is hoped that this will allow production of several hundred modules by the end of the year.

The total cost of the Tracker is estimated at 77.6 MCHF, including 8.2 MCHF for the pixel detector, in which the UK plays no role. There is a shortfall in the foreseen CMS budget but following recent negotiations and staging of the DAQ, the Tracker missing funds now appear to be less than ~1.5 MCHF, based on firm commitments from agencies, with hope of modest increments later. It will be an important task in the coming months for the Tracker management to find a way of delivering a working system in 2007 which is as complete as possible.

2.2 System changes since the last report

In December 1999, there was a major change in the Tracker project, which decided to construct the entire Tracker from silicon microstrip detectors and to abandon the use of MSGCs. The decision was taken despite considerable success in a very demanding series of milestone tests to demonstrate that high voltage operation of the chambers under LHC-like conditions did not damage more than a very small fraction of readout elements by electrical discharges. However, the need to work on two different detector technologies had caused a neglect of systems issues, such as hybrid, power supply and cooling system development; some problems had to be solved twice and progress was not fast enough to match the CMS schedule.

The principal reasons for preferring silicon were proven **reliability and robustness**, **improvement in performance** – silicon detectors have a faster time response and smaller signal amplitude fluctuations – the CMS demonstration of **automated assembly of silicon modules**, to speed up production, and finally, **cost savings** obtained from companies by large scale manufacture and the demonstration, in November 1999, of the **APV25 chip** so that savings from 0.25 µm technology could be relied on. This was a UK achievement, in collaboration with CERN engineers working on technology development. An important consequence affecting UK plans was the removal of the need for an MSGC-specific APV25, thereby reducing future demands on engineering and test effort.

Although the overall cost of the Tracker was not reduced, equal or better physics performance could be obtained with an all-silicon system by layout optimisation, which has been completed, and as a result of its large volume requirements, CMS has secured from the tender process considerably lower unit prices for silicon sensors than previously obtained. An uncertainty associated with the production costs of MSGCs was thus removed. MSGCs had never been manufactured commercially in significant numbers, so contingency was not easy to evaluate, and long term performance of companies who would produce them could not be easily verified.

Two major silicon sensor suppliers have been selected through competitive tendering and deliveries of pre-production sensors received. Automated assembly gantry systems are in operation and the first modules have been produced. Individual modules equipped with final components have been assembled without human intervention in about ten minutes. The CERN Frame Contract for procurement of 0.25 µm electronics was signed in 1999.

2.3 UK Deliverables

2.3.1 Front End electronics

By 1997 the RAL/Imperial College APV development was already well advanced using a Harris (US) CMOS rad-hard technology, with the same design in the DMILL (France) process to minimise risk. In late 1998, we began to investigate a standard commercial 0.25 µm process, for several reasons: very significant cost savings, superior performance of 0.25 µm circuits, and serious doubts about radiation tolerance of both Harris and DMILL processes, and uncertainties surrounding their long term commercial survival.

The APV25 implementation was extremely successful. By the end of 1999 a fully working chip had been produced which met all the specifications for the CMS Tracker; an impressive achievement for a large complex chip. The chip required modest fine-tuning, completed by mid-2000, and the design has been frozen since. All further, and many more detailed, tests which have been carried out have confirmed excellent performance and long term reliability of the circuits and technology.

The cost saving was estimated to be 6 – 7 MCHF, which reduced the electronic system component cost from 2.65 to 2.0 CHF/channel, including development, spares and contingency (but not cables, power supplies, etc).

The UK will now test the entire production of APV wafers, while the French team following DMILL have agreed to manage assembly of front-end hybrids; i.e. this is no longer a UK responsibility. We have equipped RAL and Imperial College with automatic 8-inch wafer probers on which we have a well established test system which requires about 1 minute for comprehensive testing of a working

APV25 site, so two APV25 wafers can be tested a day. We will test all APV25 wafers at Imperial to reduce RAL staff effort costs.

The 0.25 µm radiation tolerance originates from the very thin transistor gate oxides and a single design feature: enclosed geometry NMOS transistors. The process is much more tolerant of high doses than so-called ‘radiation hardened’ technologies (CMOS processes are immune to neutron, or other bulk, damage). Nevertheless monitoring the quality of delivered wafers, to ensure no changes arise, will take place regularly.

The APVMUX chip is a much simpler design than the APV25. It has been completed to specification and procurement has begun, in conjunction with Tracker ancillary chips, to match the production schedule for silicon Tracker modules. Since the 2001 mid-term review we have also agreed that the APVMUX packaged die will be tested, along with ancillary chips, by a commercial test house.

The only other change to 1997 deliverables is the production of a few APV state machine emulators which inhibits the CMS trigger to avoid effects of rare, but inevitable, trigger rate fluctuations which would cause APV pipeline buffers to overflow. The resulting deadtime is negligible (~0.2%). We plan to produce a small number of boards, on which the APV logic is implemented in an FPGA, to communicate with the Global Trigger. It is naturally a UK responsibility because it is so tightly linked to the functioning of the APV. The production cost will be absorbed into the UK CORE contribution. Imperial College will be responsible; the prototype has been designed and has just returned from manufacture.

2.3.2 Measurements

A large number of measurements have been made on, and using, the APV25. The performance of the chip has been found to be excellent and the radiation tolerance and robustness well established. Some specific tests in heavy ion beams were carried out to establish Single Event Upset rates, which are in excellent agreement with circuit simulations combined with nuclear interaction simulations. The results were verified in a high intensity, low energy pion beam which provides the closest approximation to LHC conditions in the CMS Tracker.

One unexpected result was obtained in the most recent LHC-like beam test. A series of modules was inserted in a 25 ns test beam in CERN in November 2001. An effect was seen which was quickly correlated with nuclear interactions in the silicon whereby, following a nuclear recoil which can deposit ~1000x minimum ionising particle (MIP) signal, the analogue baseline in the whole APV25 is lowered to its minimum level. It is mainly due to a shared power line to the inverter stage following each preamplifier. The chip experiences some deadtime due to the high current drawn by a transistor which has been switched hard on following an enormous signal, which occurs very infrequently (~few $\times 10^{-4}$ per incident pion). However, as the effect is then felt by all channels on the chip, it is multiplied by a factor of about 50 – 100, compared to inevitable single, and nearby, channel saturation.

The effect was studied in the laboratory, in data taken during the test, and by simulations of nuclear events in the Tracker. Rates, deadtimes and effects on Tracker efficiency were calculated. It was concluded that the maximal data loss will be at the 1% level and it may be reduced further with careful choice of resistors mounted on the front-end hybrid. A beam test was carried out in May 2002 at PSI in a 300 MeV, 50 MHz pion beam, to verify the rates. Measured rates are in good agreement with predictions. The detailed behaviour of the chip can be further scrutinised using the data taken, and results support the previous conclusions.

2.3.3 Technical issues

The only problem we have encountered with APV25 production is that recent deliveries have shown unexpectedly variable yield. From the engineering runs (mid-2000) we obtained 10 wafers with an average yield of ~75%, which appeared to be consistent with many results from multi-project runs for APVs and other chips. However, the first 48 wafer order (January 2002) delivered two 24 wafer lots (one incomplete) with quite low yield and the company exchanged the wafers, although they were within specification, acknowledging a probable processing fault. The replacement lot had a very high yield (~79%) but two subsequent lots have shown low values (~40%). There are clear circular patterns of high and low yield on the wafers. An example of such a wafer is shown in Figure 3.

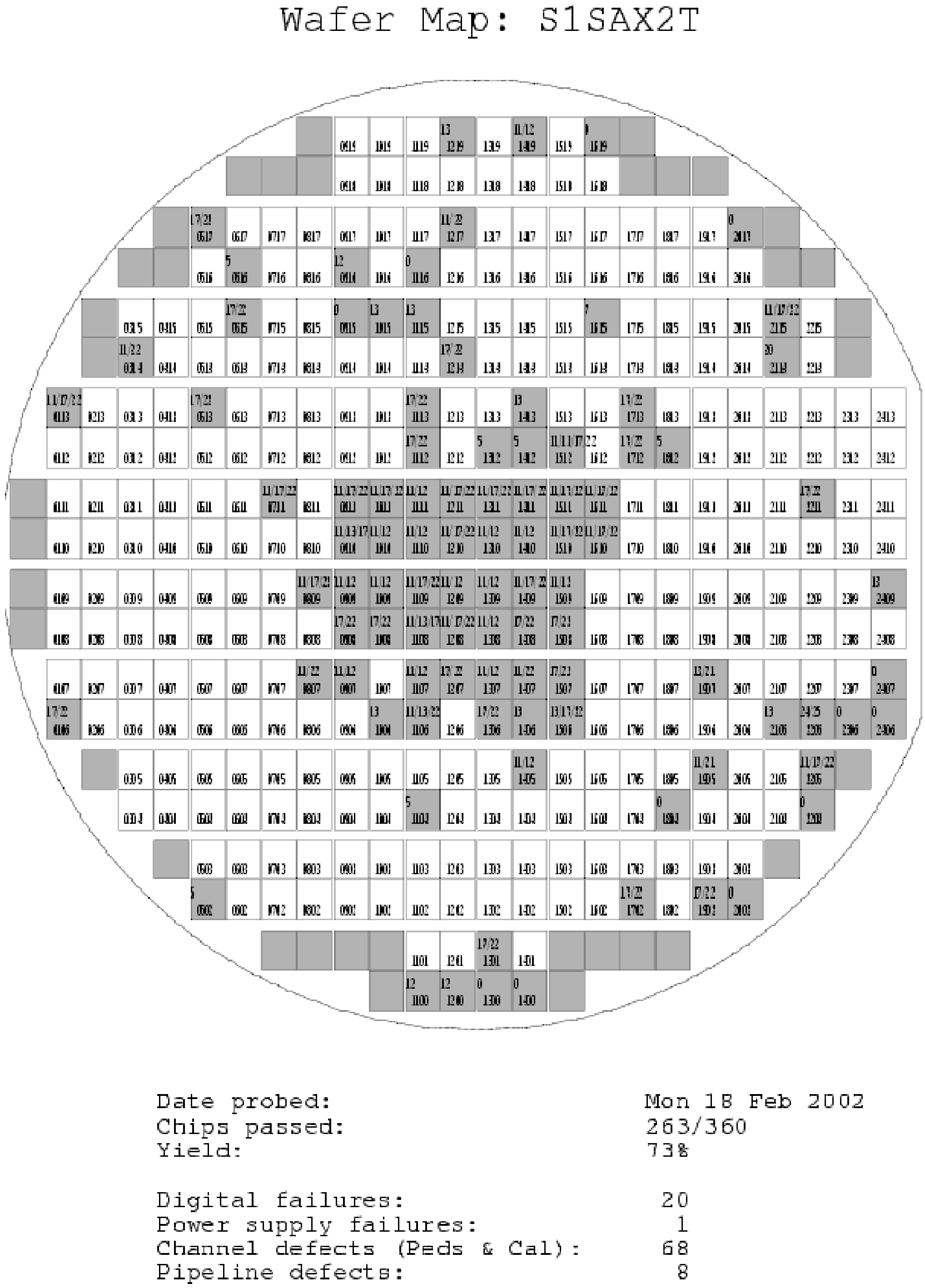


Figure 3. An example of a wafer with a high yield but showing evidence of a systematic variation across the wafer

A similar effect has also been seen by other projects but the statistics from APV wafers are far greater and there is a massive amount of information from tests. However, despite considerable efforts by the manufacturers and ourselves (and others), the origin of the reduced yield has not been linked to any aspect of the processing, nor to any feature of the design or chip layout. Radiation tolerance is not affected by the production quality, i.e. yield; there is no evidence for any degradation of radiation quality in any wafers. Samples from 23 wafers were irradiated at Imperial College to 10 Mrad, of which 13 are from 2002 wafer deliveries, with die selected to be near regions of low yield to look for any possible correlation. Further irradiations are under way in Padova and results are consistent so far.

The dilemma is whether yet to launch the large orders we planned at this stage. Dies which pass acceptance tests appear in no way inferior, so reduced yield simply means increased cost. Given the low chip cost and contingency which remains in the budget, this may be tolerable, but we prefer to proceed cautiously, and a resolution of the issue is in any case important to other projects. We are planning further meetings with the manufacturers, including more with process specialists and design experts. Our own measurements will be repeated or extended to look at various details.

2.3.4 Front End Driver

The FED has progressed considerably since 1999 and, again, technological developments have had an impact. Performance will certainly meet CMS requirements and there is growing confidence that the cost target can be achieved. As with front-end electronics, a silicon-only Tracker simplifies FED requirements, so has a positive effect on our activities.

During 1997 – 98, an 8-channel PCIbus Mezzanine Card (PMC) FED was produced by Instrumentation Department engineers at RAL as a final system prototype, but it was shown that it would be difficult to meet budgetary and power dissipation targets. However, the prototype generated a large demand for PMC FEDs to satisfy beam test and prototyping needs, since it is closely compatible with the final system. Almost 70 PMCs were delivered to CMS users (and a few other UK projects) between 1998 and 2000 at cost price and they have been central to all CMS Tracker DAQ in beam tests.

Technology changes have had important repercussions. In 1999 it still seemed likely that parts of the digital processing would be implemented in an ASIC. However, Field Programmable Gate Array (FPGA) developments have been so rapid that large, fast FPGAs can now be afforded. The benefits are that the risk of including design errors is reduced to a very low level and the FED can even respond to (reasonable!) late changes in requirements. Given the complexity of the digital logic, this is a great advantage. This has repercussions for skills required, e.g. firmware programming, both in RAL and in the universities. Imperial College has increased effort in this area, to ensure sufficient strength.

Conversely, some technical developments have slowed the FED progress. The novel optical receivers which must be placed on the FED must perform to link specifications and experience is limited to prototypes. The optical link development has been lengthy and challenging and, although successfully carried out with great skill by a CERN team, there have been unavoidable repercussions in time and manpower in the UK.

The FED must also be compatible with the CMS Data Acquisition System (DAQ). Digital data are transferred via a high-speed switch network to the CMS computer farm whose input from the FED conforms to the S-link protocol. There are important data monitoring, control and synchronisation requirements also imposed at the system level, with which the FED must be fully compatible. The time required to converge on requirements within CMS has been a source of concern and has used engineering effort. The DAQ TDR in December 2002 should be the final word.

The specification of the FED functionality by RAL and Imperial College physicists was finished in 2001. The design of the 96 ADC channel FED by Instrumentation Department engineers at RAL is now complete. Board layout and routing is being finalised and the first pair of prototype cards is about to be manufactured; delivery is expected in late November. Following exhaustive testing of the design, a further dozen cards will be produced for CMS users for large-scale module (endcap petals, outer barrel rods, inner barrel units) testing in 2003. Full production should commence in 2005 following a small pre-production series. Figure 4 shows the board layout.

The FED has been implemented to minimise PCB manufacturing and assembly costs. All components (apart from the DAQ interface card) are located on the 9U mother-board. Commercial components and solutions have been used where ever possible. The card is double-sided to accommodate the high density of components. The number of signal termination resistors is reduced by the use of the Digitally Controlled Impedance feature of Virtex-II. Digital links are kept separated from analogue signals to avoid interference.

The FED has been designed with testing and monitoring in mind. Interconnections between all digital devices can be tested using JTAG Boundary Scan test chains. The JTAG chain may also be used for

FPGA configuration directly from a PC via a standard cable. A dedicated opto-test card is under design at Imperial, which will be able to drive all 96 FED optical channels simultaneously. The electrical part of the chain can also be tested independently by injecting signals on to connectors at the opto-receiver outputs.

About 500 FEDs, including spares, must be provided. The UK budget is sufficient to provide about 20% of the total cost, estimated at 4.0 MCHF. Our intention was always to deliver the full complement of completely tested FEDs to the experiment, even if we did not pay for the full procurement.

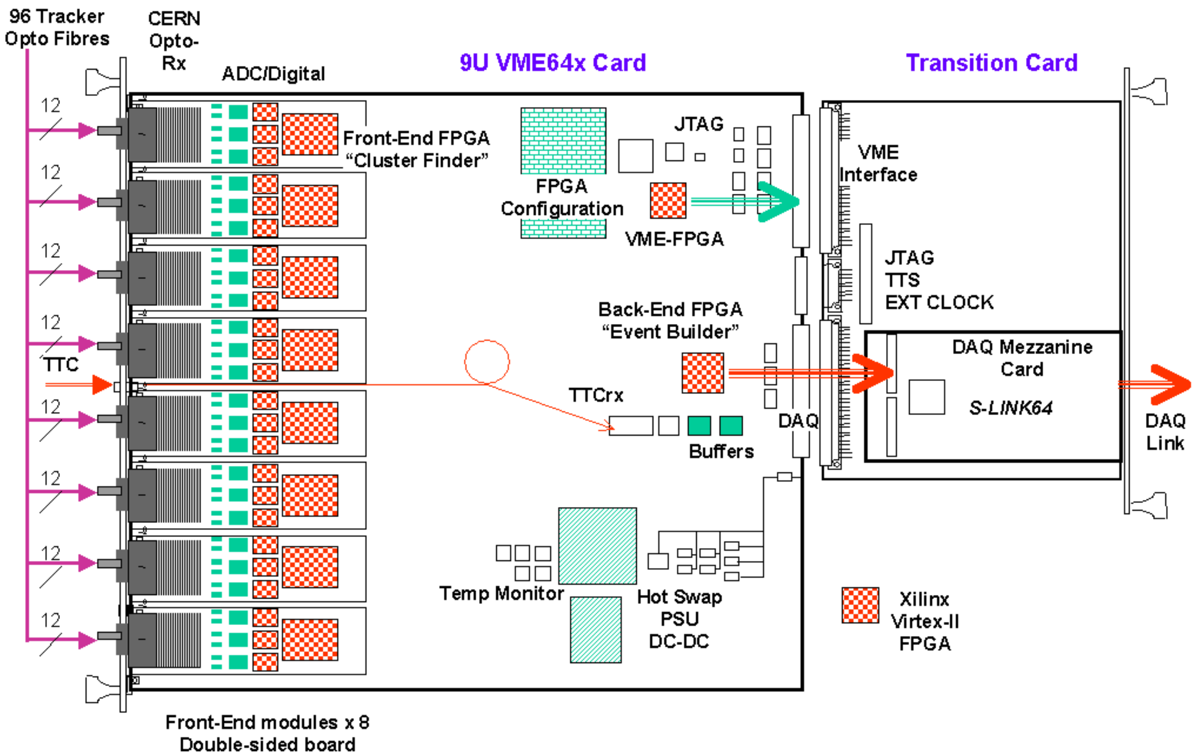


Figure 4. 9U VMEbus FED board layout with transition card

2.3.5 DAQ activity

In 1999, it was also envisaged that the UK would contribute both technically and financially to the CMS DAQ system, to items directly relevant to the Tracker system. Many DAQ components were seen as general purpose items which could be deployed in any sub-system, using a common CMS Front End Driver with limited customisation, conforming to the Tracker model.

As time has passed, this model has changed and the DAQ Technical Design Report will be submitted in late 2002. Only at that time will the system design be considered frozen. Staff available to contribute to the DAQ no longer work in RAL PPD, having transferred to Instrumentation Department. One member of the team (J. Coughlan) is now working full-time on the FED and participates in CMS DAQ as Tracker representative. The other principal contributor (W. Haynes) has been forced to reduce his commitment to the CMS DAQ, since insufficient budget exists to support the activity.

We envisage that the UK financial contribution to the CMS DAQ will be to purchase components which can be deployed in the Tracker, such as the S-link modules which connect the outgoing data from the FEDs to the DAQ switch input. However, only once the TDR is ready can the specific items be categorically identified. For example, recently the RAL engineers proposed to exploit the channel link capability of the Xilinx Virtex-II which would allow us to avoid the transition card, thus both saving money and improving reliability.

2.3.6 Software development

Part of the UK commitment to the Tracker system is in supporting and operating the items we have designed and produced. UK expertise is necessary to define the requirements and we, and our CMS colleagues, have expected that we assume the responsibilities associated with the hardware. There is also an eventual natural link to the physics activity since the data will be formatted by the FED before transmission to the farm.

During 2001, two internal CMS MoUs highlighted the need for substantial manpower to produce the on-line and off-line software for the Tracker. The UK will participate in both these areas.

In the on-line software Imperial College and RAL propose writing the software used to control, calibrate, read out and monitor the final Tracker FEDs. This choice follows naturally from our FED responsibility and builds on the software experience we have gained from regular participation in test-beams.

Concerning off-line software, RAL has taken charge of the CMS Tracker Data-Handling group. This is responsible for providing the basic tools used for off-line analysis of test-beam data, and will ultimately also ensure that data from the final Tracker can be accessed by the off-line reconstruction software. The group will also play a role in preparing the DAQ TDR. Staff from RAL, Imperial and Brunel are now actively involved.

2.4 Milestones and future planning

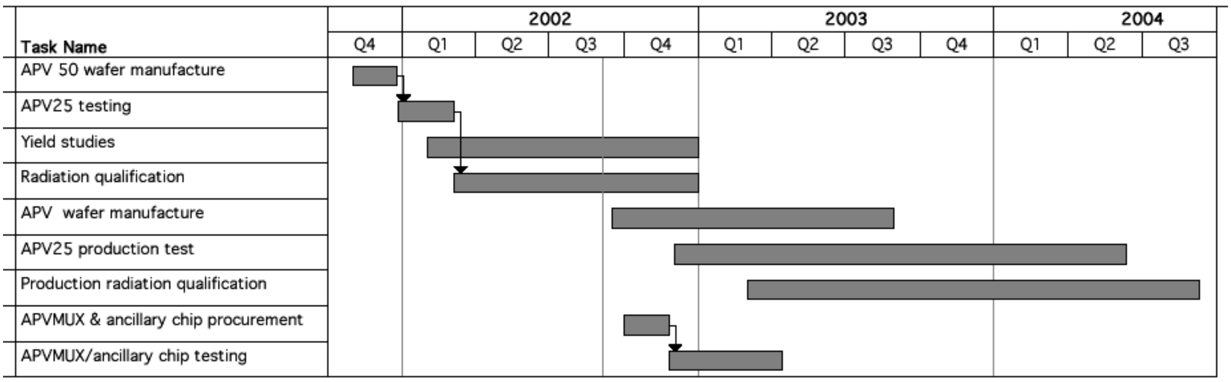
2.4.1 Front End electronics

Production of modules should ramp up during 2002, to meet the schedule foreseeing CMS operation in 2007. Pre-production modules have been produced, although fewer than anticipated because of problems with the hybrid. However, final electronics are now available in adequate quantities and several hundred modules will be manufactured during the autumn. No major difficulties are anticipated in moving to the production phase; all assembly and test systems are in place. However, we expect this pre-production period will be needed to reach full efficiency in using the tools.

The remaining tasks for the UK team are:

- Automated wafer probing of all dies,
- Sample radiation qualification of 10% of production wafers (+10% to be studied in Padova),
- Maintenance of a data base of results,
- Delivery of die to CERN for transmission to production centres,
- Maintenance of designs and documentation, which should be a minor overhead.

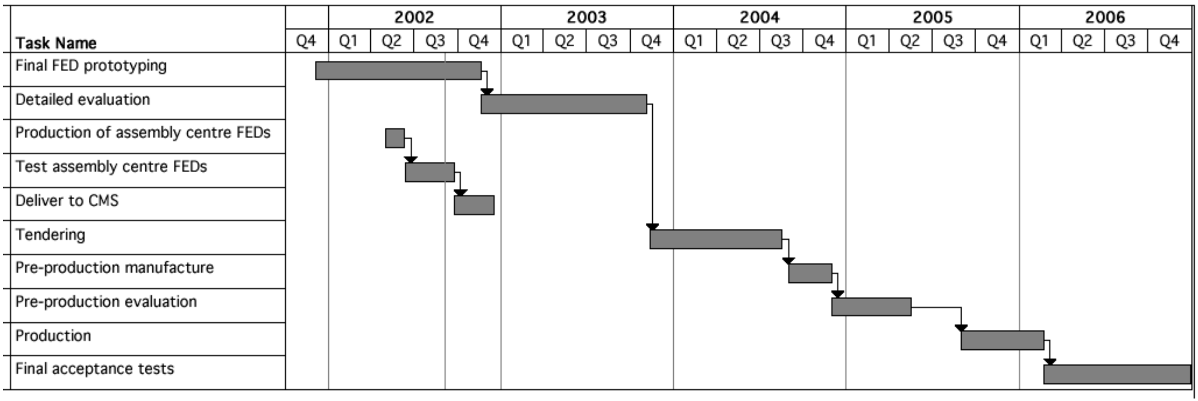
The bulk of the testing and radiation studies will be carried out at Imperial College, as has been the case so far. Our schedule is summarised below:



2.4.2 Front End Driver

The development schedule of the Final FED is shown below. It has three main phases:

- Construction of a final prototype and evaluation as described above,
- Tendering, and pre-production to finalise manufacturing and test procedures,
- Final production, which must still be matched to the schedule and budgetary profile.



2.4.3 Comparison with milestones

Tracker milestones were dominated for a long period by the MSGC-silicon debate and subsequently by the difficulties we have encountered in reaching the start of production because of progress with the hybrid. However, since 1999 there were a number of formal milestones for UK-related commitments, tabulated below, which were met as planned. Since then we have undertaken several reviews, both internal and external, within the system. One notable Tracker milestone was the Production Readiness Review (PRR) in June 2000 which gave the green light for the silicon procurement and there was a PRR for Tracker optical links in May 2001 which allowed us to finalise the planning of the link procurement and place the complex series of related orders for the link components.

The future milestones concern the delivery of the APVs and FEDs to match the construction schedule, as already described.

Milestone	**Date**	**Comment**
Deliver front end chips for prototype construction	February 1999	Achieved successfully with large numbers of Harris APV6 and APVM chips.
Intermediate system review	July 1999	Carried out as planned.
Irradiation studies of each technology	July 1999	Studies of Harris, DMILL and 0.25 µm CMOS complete. Final 0.25 µm results after delivery of APV25 (Nov 1999).
Tendering for front end electronics	November 1999	Contract signed in autumn 1999 with tenders approved in March 1999 CERN Finance Committee.
Final pre-production review	January 2000	Concluded in December 1999 with decision to use 0.25 µm electronics.
Tracker system test in 25 ns beam	October 1999, subject to beam	Successfully completed in May 2000.

2.5 Summary

The CMS Tracker is very close to starting large scale production. The Tracker deliverables from the UK have changed modestly since 1999 and only in a cost neutral way.

There are no major technical problems foreseen in providing the UK deliverables and the UK cash contributions are limited by the MoU commitments, not by numbers of deliverable items. The UK technical contributions to the Tracker have been outstandingly successful, resulting in substantial cost savings to the Tracker detector as it was originally foreseen.

Our major concern is over the consequences of the budgetary cuts imposed in early 2002 as a result of PPARC finances. To contribute our share of the cuts, part of our capital spending was deferred for three years and we strongly hope that this money will be recovered. Our other large saving was achieved by severely cutting the travel budget. This limits considerably our possibility to participate in CERN activities at a crucial stage of the development of the Tracker, since more and more of our components are being employed on a large scale and our support is needed to commission and operate them. The next few years will also be crucial for developing the physics tools needed to be ready to analyse data from LHC start-up and this also requires intimate contact between CERN and the UK. Commissioning CMS will be a major effort in all areas and we are now very concerned that our efforts to date will not be rewarded by optimal participation at this phase of the experiment.

3. ENDCAP ECAL AND GLOBAL CALORIMETER TRIGGER

3.1 Overview

A high precision electromagnetic calorimeter is at the heart of the CMS concept and will be used to address fundamental physics issues such as electroweak symmetry breaking, through the exploration of the Higgs sector, supersymmetry, and the leptonic decay of new heavy vector bosons (W′, Z′) in the multi-TeV mass range.

A scintillating crystal calorimeter offers the best energy resolution, since most of the energy from electrons or photons is deposited within the homogeneous crystal volume. High density crystals with a small Molière radius allow a very compact electromagnetic calorimeter system, and $PbWO_4$ has been chosen by CMS for both the endcap calorimeter (EE) and the barrel calorimeter (EB). In prototype tests, a resolution of 0.6% at 100 GeV has been achieved. Following several years of intensive development and design, the CMS Electromagnetic Calorimeter TDR was approved in April 1998.

The UK groups from Bristol, Brunel, ICSTM and RAL collaborate in the electromagnetic calorimeter project. The calorimeter comprises a barrel and two endcap/preshower regions, as shown in Figure 5. The EE is led by the UK, with strong support from Russia and with important contributions from Saclay (for the monitoring system), ETH Zurich (for crystals and electronics) and CERN (crystals). The endcap Project Coordinator and Project Engineer are both from UK groups.

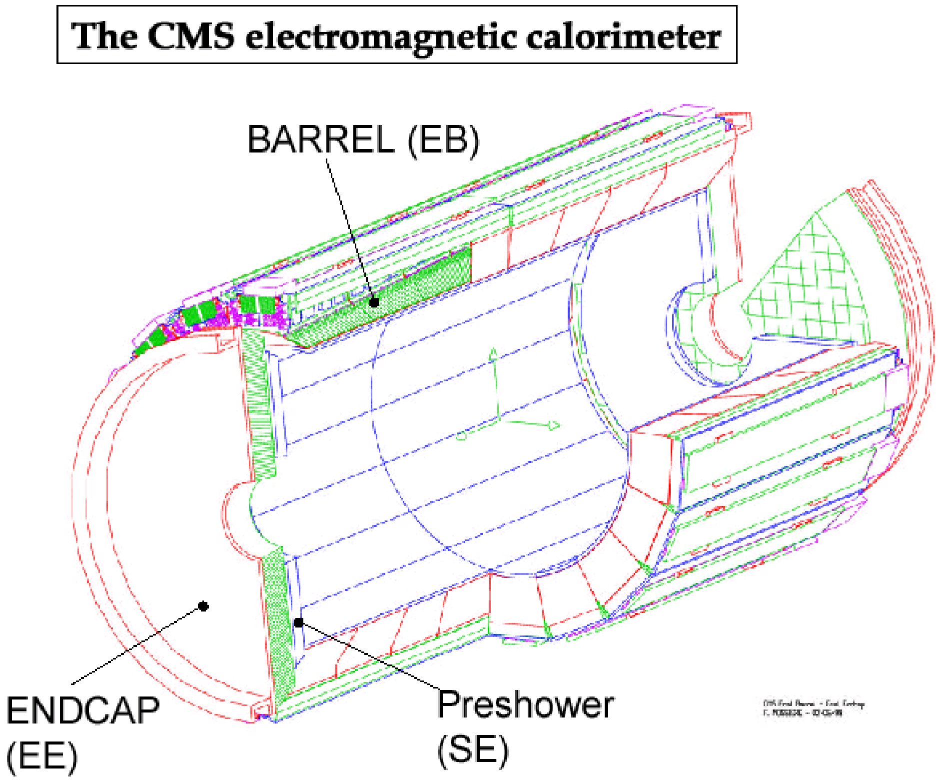


Figure 5. The arrangement of the Endcap (EE), Barrel (EB), and preshower (SE) detectors of the CMS ECAL

The goal has been to keep the designs of the EE and EB as similar as possible, although some important differences have been unavoidable, particularly concerning the structural support and the choice of photo-detectors. Both the EB and EE designs are based on an off-pointing pseudo-projective geometry.

The EE design is remarkable in that all crystals are of identical tapered shape (30x30x220 mm^3 at back face, 2 mm smaller front face in each dimension). Each endcap contains 7324 crystals, and has a total crystal volume of 1.35 m^3 and a mass of 11 tonnes. The crystals are supported by two separate half discs called Dees. There are a total of four Dees for the two endcaps. Silicon avalanche photodiodes are used in the EB, but the high radiation levels in the forward direction excludes solid-state and hybrid devices. Vacuum phototriodes (VPTs) are therefore employed in the EE. (The orientation of the magnetic field does not allow the use of VPTs in the barrel).

The crystals are grouped into units of 25, referred to as Supercrystals (SCs), as shown in Figure 6. The main structural component of the SC is a 5x5 carbon fibre alveolar structure that supports the crystals. Figure 7 shows a photograph of the principal components which make up a Supercrystal. At the back, a housing contains passive filtering and decoupling circuits for the VPTs together with optical fibres for injecting light to monitor the stability of each channel. The SCs are cantilevered from the Dee backplates, as shown in Figure 8. A pre-shower detector (which is not a UK responsibility) is located in front of the EE to improve π^o identification.

Bristol, supported by Instrumentation Department at RAL, is responsible for the Global Calorimeter Trigger (GCT). The GCT receives trigger information from 18 input crates and passes summary information for each beam crossing to the Level-1 trigger decision logic. The 18 input crates, known as Regional crates, process data from the central electromagnetic and hadronic calorimeters, divided into 18 (η,φ) regions, and the forward calorimeters covering the range $3 < |\eta| < 5$.

3.2 Overall ECAL status

Mass production of lead tungstate crystals has been underway since 1999. Some 9000 of the 62000 crystals required for the barrel have now been delivered to CERN. Recent upgrades have been completed at the production facility (Bogoroditsk, Russia), and 138 ovens are now available or in use.

The photo-detectors for the EE and EB are in production. About 42000 of the 130000 APDs needed for the barrel have been delivered from Hamamatsu. The target production rate of 5000 APDs/month has been achieved. 2600 of the 15500 VPTs for the EE have been delivered to RAL from Research Institute Electron (RIE, Russia).

Barrel crystals and APDs are contained in 36 structures called supermodules, each with 1700 channels. Two ‘bare’ supermodules (all mechanical/crystal/photo-detector components, but without readout electronics) will be completed by March 2003.

As discussed in Section 1.2, there has been a major change to the architecture of the ECAL electronic system. This has necessitated a revision of the planning for the construction of barrel supermodules. Mechanical assembly will proceed as planned, but the front-end electronics will be added later.

3.3 UK Commitments and Deliverables

The UK commitments and deliverables for the CMS ECAL and Global Calorimeter Trigger presented at the last submission to the PPESP (PPESP/99/27 in September 1999) have not been changed. They are:

- Develop, prototype and contribute to the procurement of VPTs,
- Design and prototype Supercrystals,
- Design and procure Supercrystal mechanics and their associated support structures,
- Set up a Regional Centre for Supercrystal production,
- Construct and test Supercrystals, and ship to CERN,
- Design, prototype and construct the Global Calorimeter Trigger, and associated ancillary equipment.

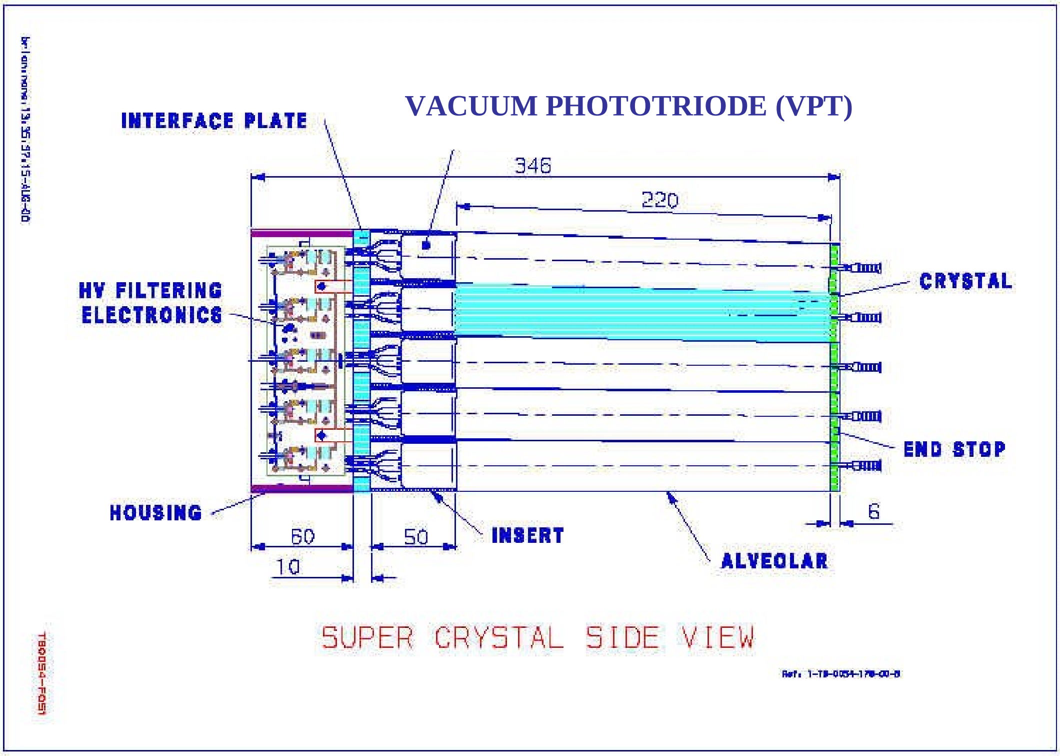


Figure 6. The arrangement of components within a Supercrystal

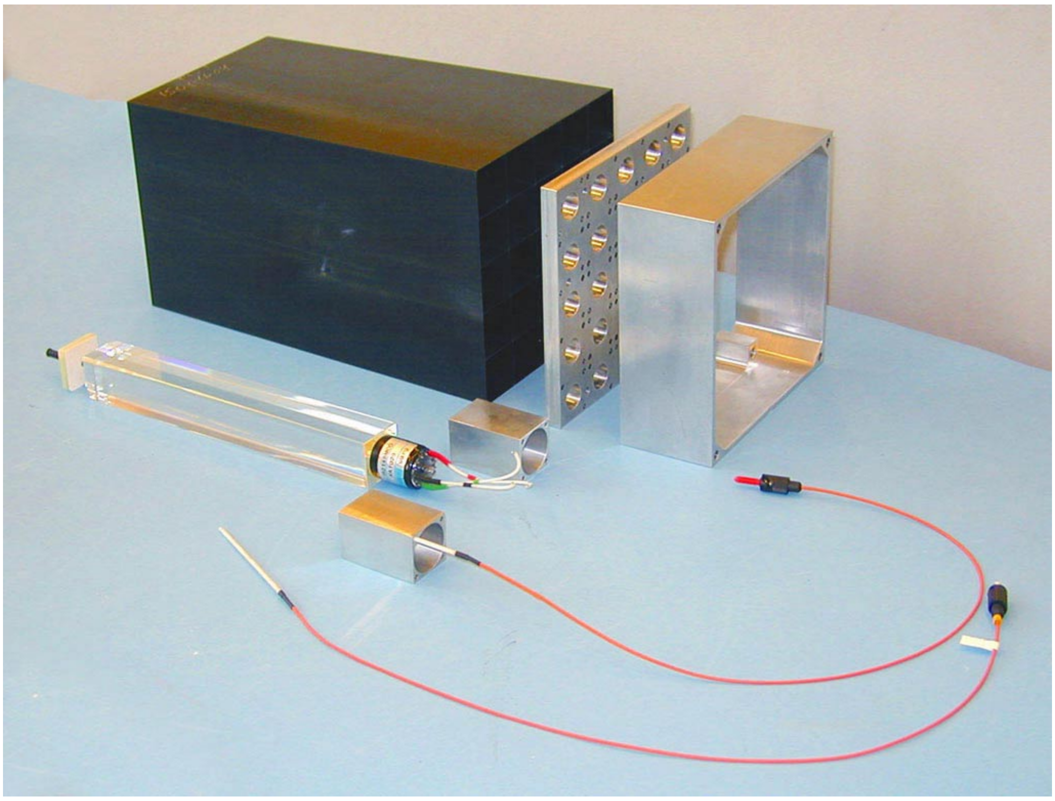


Figure 7. A photograph of the principal components of a Supercrystal, including a $PbWO_4$ crystal with VPT, fibre optic monitoring components, an alveolar unit and mechanical parts

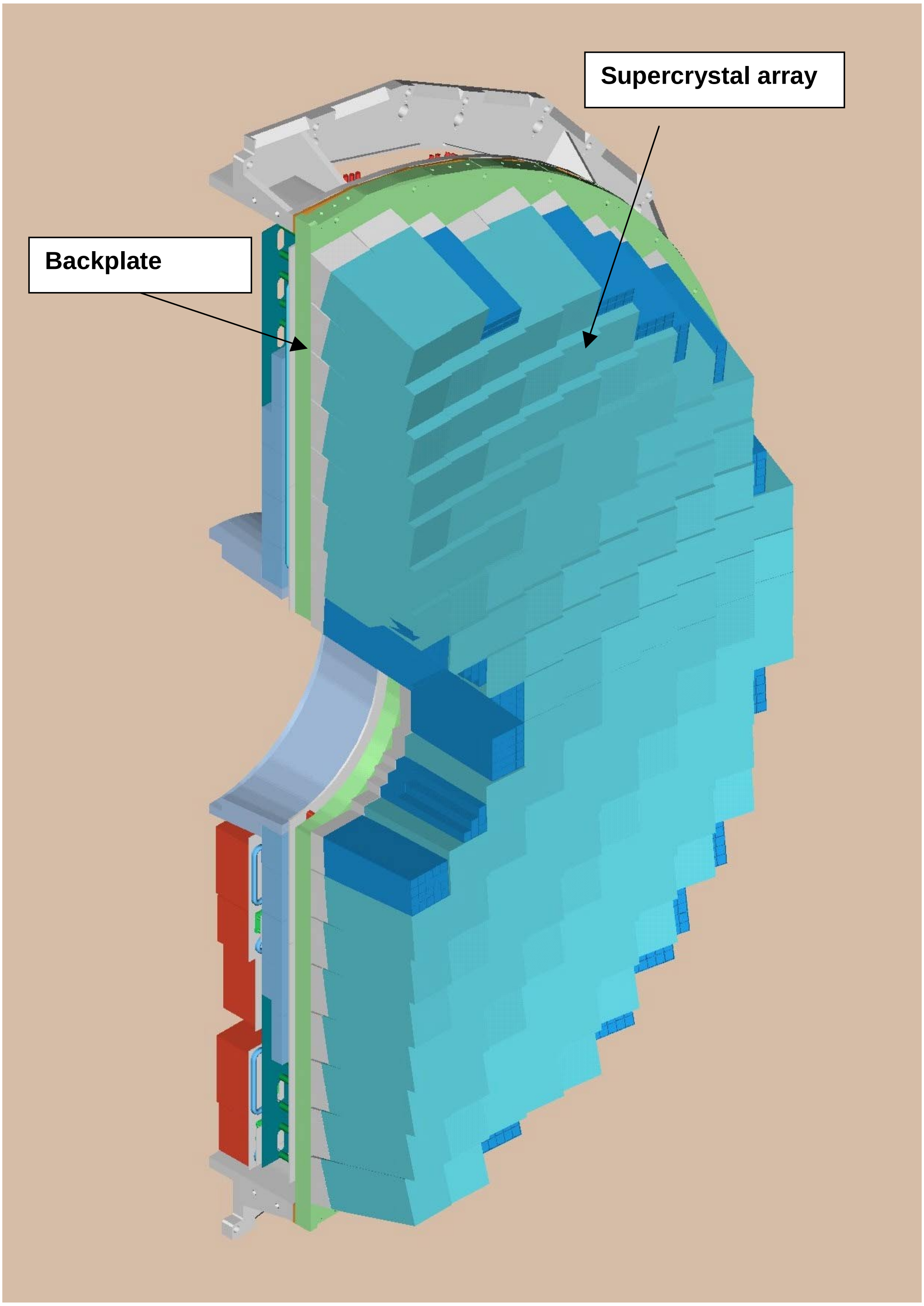


Figure 8. The arrangement of Supercrystals on a Dee

3.4 Current Status of the Project

3.4.1 VPTs

After successful Supercrystal beam tests at CERN in 1999, with prototype VPTs from three manufacturers, an international tender was launched in February 2000 for the supply of 15,500 devices to CMS. In April 2000, Research Institute Electron (RIE, St. Petersburg, Russia) was chosen by a CMS Evaluation Committee to supply the VPTs for CMS. An example of a VPT from RIE is shown in Figure 9.

A successful pre-production contract was completed in November 2000 for 500 devices. A further contract, with optimised specifications for the remaining 15,000 devices, was launched in October 2001. The contracted production rate is 4000 devices per annum. High magnetic-field test rigs have been established at RAL and Brunel University to carry out acceptance tests and yield measurements on the VPTs. All of the devices will be tested at RAL, where fields up to 1.8T are available, while the Brunel system will be used for sample testing at 4T.

To date, 2100 production devices have been delivered to RAL of which 1300 have been visually inspected and 1150 tested to 1.8T at RAL. Over 160 VPTs have been tested to 4T at Brunel. The UK has purchased the 500 pre-production VPTs and has committed to the purchase of 7000 production devices. The remaining 8000 will be purchased by ETH Zurich.

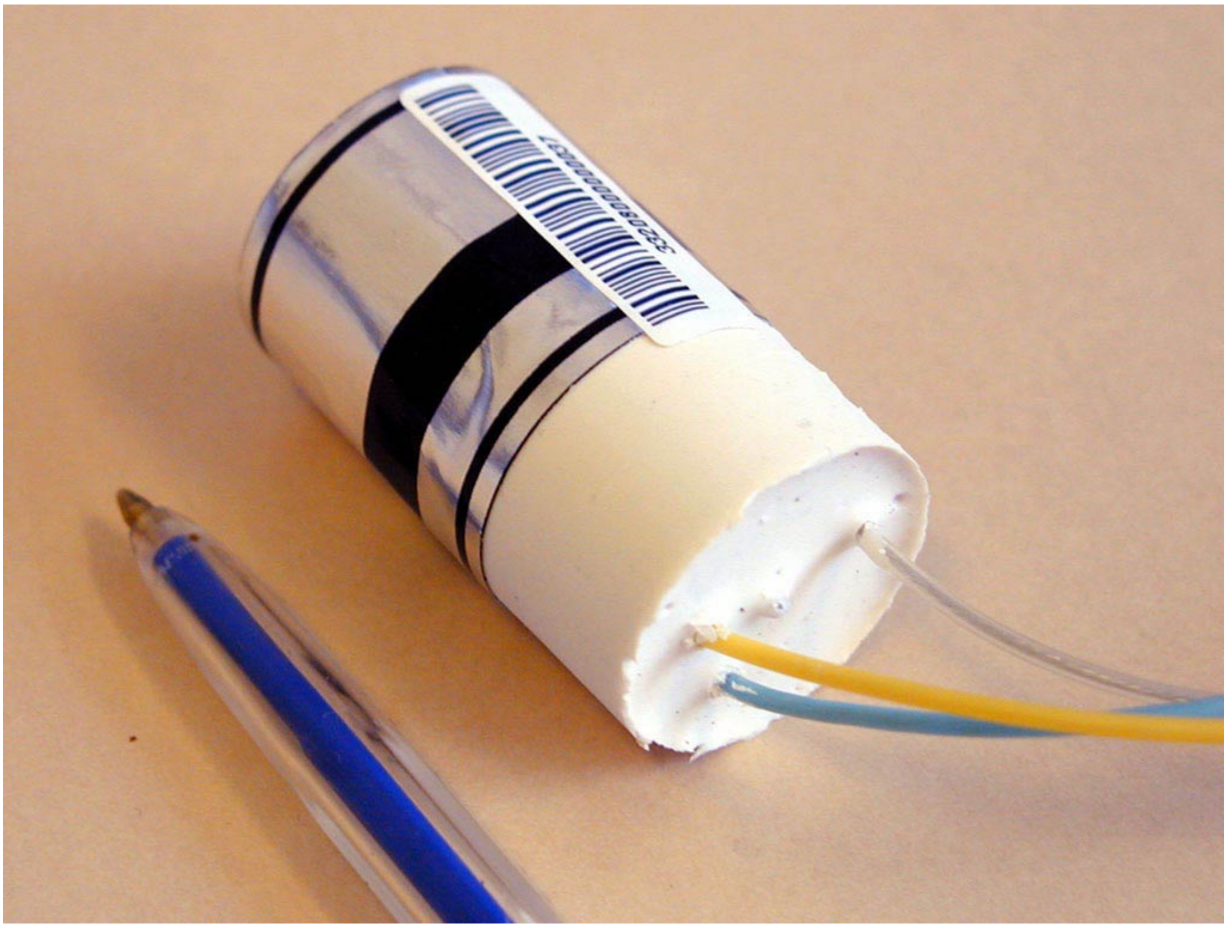


Figure 9. A VPT supplied by Research Institute Electron, St Petersburg

3.4.2 The RAL variable-angle test rig

3.4.2.1 Overview

The test rig at RAL is based on a water-cooled magnet providing fields up to 1.8T over an area of approximately 0.5 m^2. The vertical distance between the pole tips is approximately 10 cm. VPTs are held in rows of 8 aluminium cans. Up to 6 such rows can be mounted in the rig, and the rows are rotated in unison to present the VPTs to the magnetic field at any desired angle up to 90°.

3.4.2.2 Mechanical design

Figure 10 is a photograph of the RAL test rig, with three rows of cans mounted. In operation, the rig slides forward into the region of uniform field between the pole tips. The 1.8T magnet was formerly used as a bending magnet in a beam line.

The VPTs are held in aluminium cans glued together in rows of eight, with each row attached to the rig by a shaft, so that it may be rotated to present the VPTs at any desired angle to the magnetic field. A stepper motor, visible on the left hand side of Figure 10, is used to rotate all of the VPTs simultaneously by means of a system of drive belts.

When the rig is in use, the magnet pole tips are covered with a black cloth to eliminate stray light.

Figure 10. General view of the RAL test rig

3.4.3 Measurements in the RAL 1.8T test rig

3.4.3.1 Angular scans on the VPTs at 1.8T

In the CMS endcap detector, the VPTs will be operated at a range of angles from 7° to 24° to the magnetic field. In the RAL test rig, the devices can be placed at any desired angle with respect to the field. In the standard angle scan, measurements are taken at 35 positions from 30° to –30° with a short settling period after every movement so that any induced instabilities in the VPTs can decay before taking data. Figure 11 shows the variation in output with angle for a typical VPT.

The periodicity shown in this figure is seen in all of the VPTs supplied by RIE, and is dependent on the alignment of the anode grid with the axis of rotation. In the standard measurement procedure the grid lines are aligned with the axis of rotation.

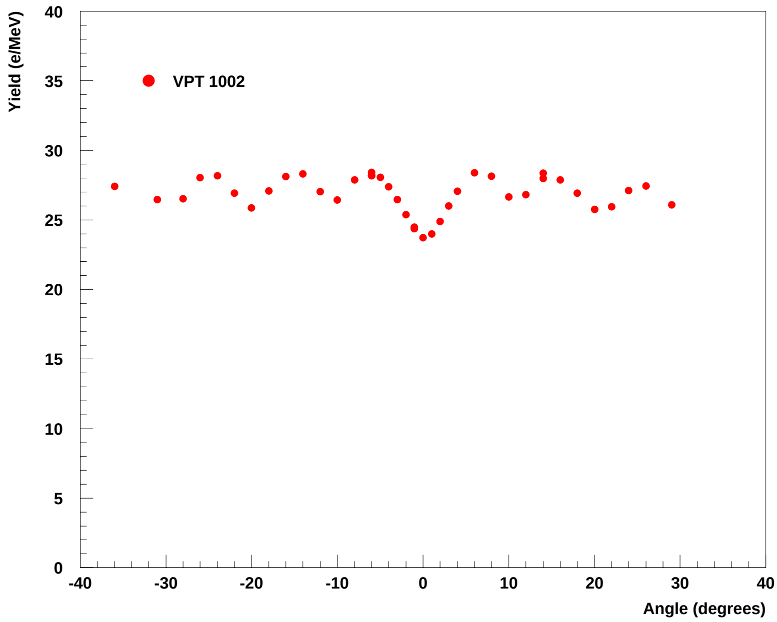


Figure 11. Angular scan at 1.8T for a typical VPT

3.4.3.2 Summary of RAL 1.8T measurements

Approximately 1650 tubes have so far been tested in the 1.8T test rig, comprising a pre-production batch of 500 and 1150 production VPTs. Figure 12 shows the distribution of anode pulse heights measured in the rig at 1.8T for the production VPTs; the quantity plotted is the mean pulse height over the angular range 8° – 25° to the magnetic field. The measured pulse heights have been converted into the expected experimental yield of electrons per MeV of energy deposited in the CMS calorimeter. The performance of the devices is acceptable, being generally superior to a set of prototype tubes from the same manufacturer, which achieved the CMS energy resolution requirements in test beams at CERN.

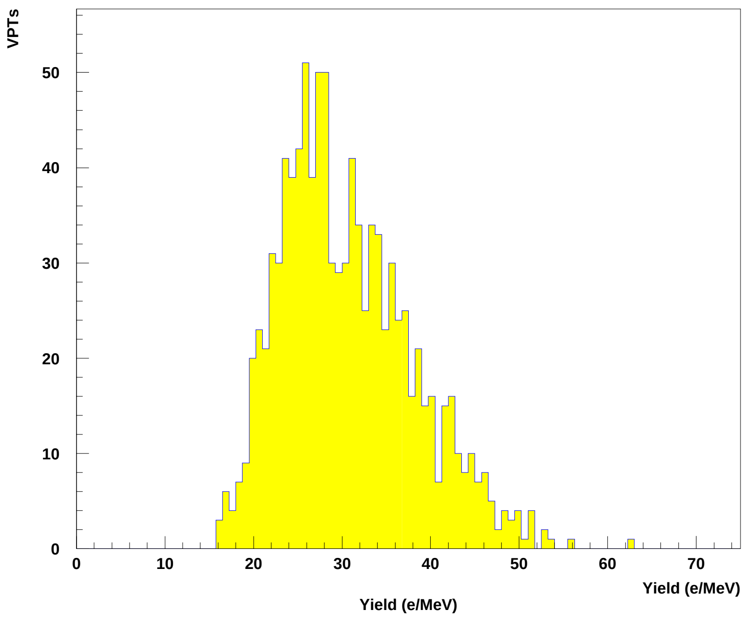


Figure 12. Mean anode pulse height over the angular range 8° – 25° in a 1.8T magnetic field

Figure 13 shows the correlation between the mean pulse height in the 1.8T magnetic field and the quality factor (quantum efficiency $\times$ gain at 0T measured by the manufacturer).

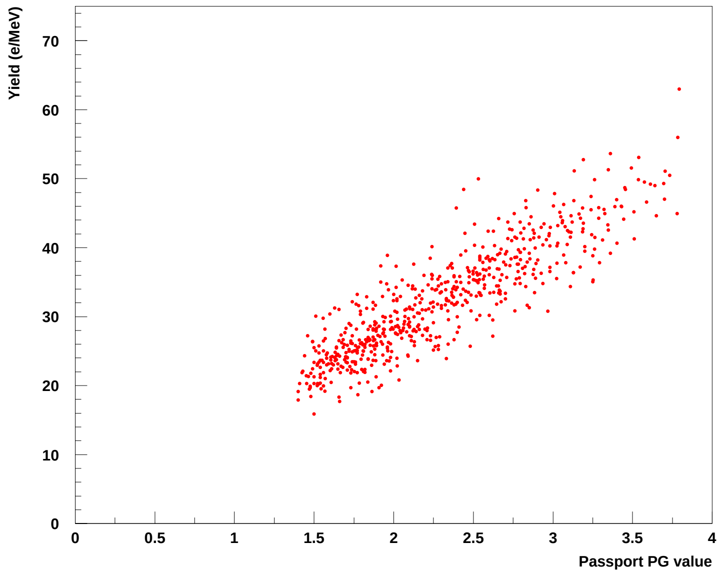


Figure 13. VPT response at 8° – 25° and 1.8T plotted against quality factor PG

3.4.4 Brunel test rig

The Brunel group has designed and built an automated system for evaluating the response of VPT devices at full the CMS field of 4.0T. Tubes are held in a 'torpedo' which is then placed in a superconducting solenoidal magnet (see Figure 14). The tubes are tested at 15° to the field and their gain measured. Other parameters, such as leakage and dark current are also recorded. The system is controlled by a number of IEEE-488.2 instruments controlled using LabView on a PC running Windows-NT. One hundred pre-production tubes, and a similar number of production tubes, have now been evaluated.

Figure 14. A view of the Brunel VPT testing area, showing the 4.0T magnet with the torpedo ready to slide down the bore of the solenoid

The Brunel VPT testing system is designed to evaluate the gain, noise, and leakage current of tubes operating at nominal HT in the full CMS field. The tubes are positioned at the mean angle in the CMS endcap of 15°. Figure 15 shows the distribution of relative gains for random samples from the first batch of production tubes. It can be seen that all but one of the tubes passes our acceptance criterion of > 80% relative gain at 4.0T.

Detailed measurements of radiation induced absorption are carried out on batches of glass faceplates before they are approved for use on production devices. A typical measurement is shown in Figure 16. Our work in this area has enabled affordable VPTs to be produced since we have discovered a glass that is tolerant to 20 kGy and which, unlike quartz, does not require expensive graded seals.

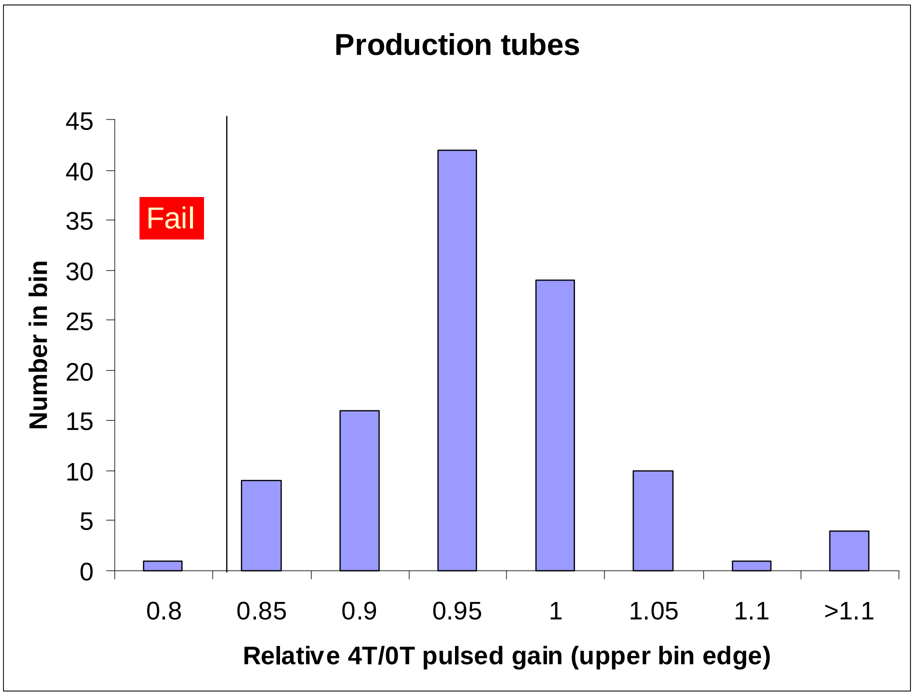


Figure 15. Distribution of relative gains at 15° to the 4T field for typical production VPTs

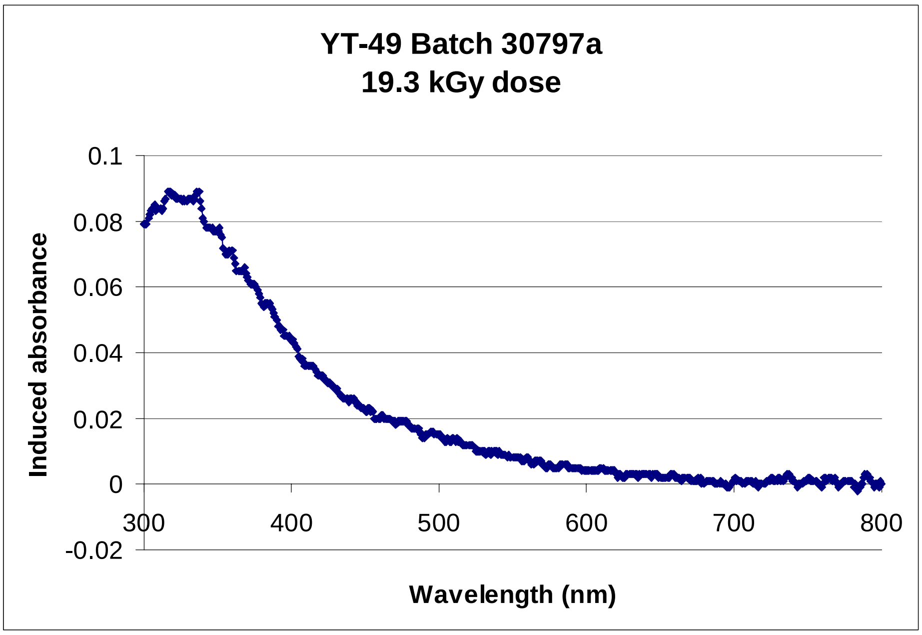


Figure 16. The radiation induced absorbance of a VPT faceplate (1 mm thick) after irradiation of 19.3 kGy with Co^{60} gamma rays. This faceplate cuts the transmitted $PbWO_4$ scintillation light by 8% after irradiation

PWO consolidated production scenario

Years	2001				2002				2003				2004				2005			
Quarters	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q
CERN/ISTC #1718- 30Õ000 barrel																				
Proposed schedule in Sept 2001		1500	1200	2100	2500	2600	1800	2600	2900	2900	2900	2900	2900	1200						
New sched.	1500		500	500	200	200	200	400	2500	4000	4000	4000	4000	4000	3200	800				
Delievered	1500		500	500	200	200														
CERN/ETHZ Contract 26Õ000 barrel																				
Contract SCIONIX							2600	2600	2600	2600	2600	2600	2600	2600	2600	2600				
Delivered																				
Additionnal order for Barrel (37th SM + spares)																				
Potential production																	*2126*			
EndCap crystals production in Russia																				
Potential EE production										*200*	*400*	*400*	*400*	*400*	*1200*	*3600*	*4874*	*3526*		
Barrel Total Grand total	1500		500	500	200	200	2800	3000	5100	6600	6600	6600	6600	6600	5800	3400	*2126*			
End Cap Total Grand Total										*200*	*400*	*400*	*400*	*400*	*1200*	*3600*	*4874*	3526 15000		

Assumes 2 crystals per ingot for barrel and endcap
Add 6000 preproduction crystals for Barrel

Table 1. Planned rate of crystal delivery, 8.6.2002

3.4.5 Mechanical design and procurement

In November 2000, a successful CMS Engineering design review (EDR) was held for the EE mechanical design. The design of the Supercrystal mechanics (see Figure 6 and Figure 7) was approved and permission given to proceed to manufacture. A market survey was completed in August 2002. The call for tenders is underway. The tender action is due to be completed by Nov 1st, 2002 and a contract signed before the end of the year. 332 Supercrystal alveolar units (60% of the total) have been successfully produced by the Russian institutes, as one of their main hardware contributions to the project.

On September 3rd 2002 a successful EDR was held for the major EE mechanical items comprising the Dee backplates and their associated pieces. The EDR committee endorsed the technical details of the design. It is planned to complete the contracts for the manufacture of the Dee backplates and associated pieces by summer 2003.

3.4.6 Crystals

Over the past three years there have been significant advances in the technology for producing lead tungstate crystals using the Czochralsky method (where a single crystal ‘boule’ is pulled from a melt contained in a crucible). It has been possible to increase progressively the boule size and now two barrel or endcap crystals can be cut from the same boule. This has dramatically improved the rate at which crystals can be produced.

In 2001, CMS awarded the contract for barrel crystal production to Bogoroditsk. This included a tender option to provide crystals for the endcap. The proposed crystal delivery profile is shown in Table 1. The planned commencement date for the mass production of EE crystals is Q2, 2003.

In June 2000, 100 R&D endcap crystals were delivered to CERN followed by 100 pre-production endcap crystals in July 2001. Extensive tests have been made on the uniformity of light collection from these crystals and their response to Co^{60} irradiation at the Crystal Laboratory at Imperial College and at Brunel. The work has shown that, if necessary, the uniformity can be further improved by shading the crystal chamfers with graphite. This provides a possible solution for one of the last remaining technical issues concerning EE crystals.

3.4.7 ICSTM Crystal Laboratory

Over the last two years, the CMS Crystal Laboratory at Imperial has been developed into a fully functional state-of-the-art facility capable of making precise measurements of the optical properties of endcap crystals. Quick and precise measurements of longitudinal and transverse transmission are made using a mini-spectrometer containing a CCD array. This equipment has been used extensively over the last two years to investigate the transmission properties of lead tungstate crystals. One result of particular note is that a correlation has been established between a gradient along the crystal in the transverse transmission around 360 nm and the anomalously high light collection non-uniformity seen in some of the pre-production crystals (Figure 17). This provides a quick method of identifying such crystals.

Over the last year, direct measurement of the light collection non-uniformity has been perfected using a hybrid photomultiplier tube (HPMT) to count individual photons (Figure 18). To extract precise measurements, a detailed fit was developed to describe the data (Figure 19). The laboratory now provides the best measurement, by a considerable margin, of the light collection uniformity in lead tungstate crystals and has shown that the technique used to screen crystals at CERN overestimates the non-uniformity of endcap crystals. This is significant because it was previously feared that the crystals would need ‘uniformisation’ by grinding one surface. This in turn would have required the development of wrapping material and had large cost, schedule and performance implications. In addition, a simple technique for further improving the uniformity of the crystals, based on evidence from earlier simulations done at Imperial, has been confirmed in the laboratory.

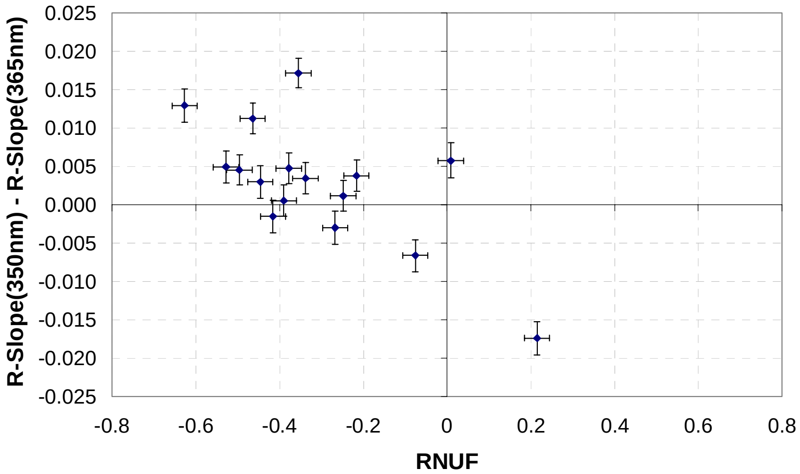


Figure 17. Correlation between the rear light-collection non-uniformity (RNUF) and the change in the slope of transverse transmission between 350 and 365 nm

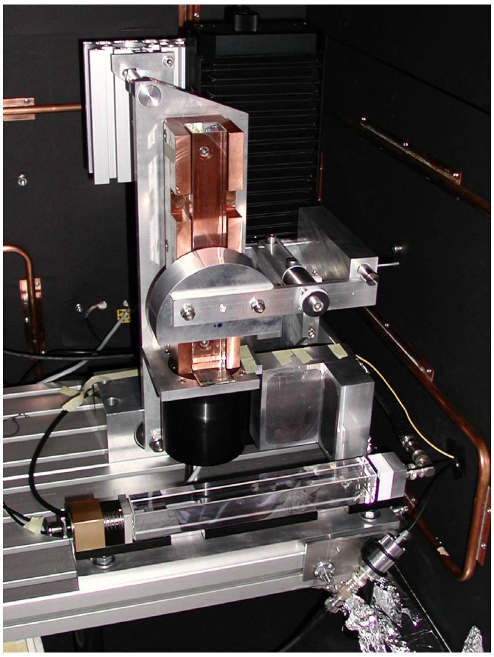


Figure 18. The HPMT rig in the IC Crystal lab used to measure the light collection uniformity along the length of the crystals mounted vertically on top of the HPMT

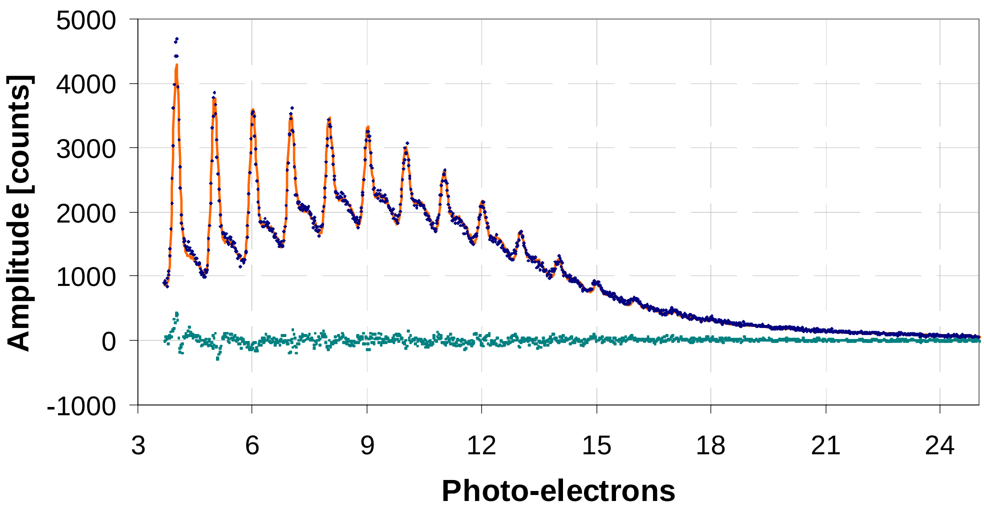


Figure 19. Data from the HPMT (points) and the fit (line)

An annealing oven has been installed to allow controlled investigations of the radiation hardness and recovery of crystals. After annealing to establish the ground state, crystals are irradiated at the Brunel Co^{60} source. Both the transmission and HPMT rigs have been used to investigate the amount of damage, and the recovery kinetics. The results have been fed back directly to the crystal producers in Bogoroditsk, Russia. Recent work has produced results for, and a new understanding of, the R-parameter that characterises the relationship between monitoring data and the physics signal. This work continues.

Exceptional support has been provided to the CMS Crystal laboratory by the HEP mechanical and electronic workshops. The electronics workshop constructed power supplies for the HPMT in the crystal laboratory and provided extensive support in tracking down interference that initially degraded the detector resolution. The mechanical workshop designed, built and refined the HPMT rig as the measurement technique was developed.

3.4.8 EE design completion and prototyping

The integration of the new ECAL readout electronics, into the EE and EB, is one of the last major design issues and is now a top priority. At the request of CMS, a UK engineer has been appointed as the deputy co-ordinator for ECAL electronics integration in order to bring much needed design expertise to this area.

The electronics redesign has caused a significant change to the method of triggering in the endcaps. The analogue signals from each Supercrystal will be re-grouped to form appropriate inputs to the new on-detector trigger by specific re-ordering of the signal cables between each SC and the preamplifiers.

An accurate full sized prototype section of a Dee, known as E0’, has been constructed to study electronics integration, as shown in Figure 20 and Figure 21. It has the capacity to take up to four SCs. At present it consists of two prototype SCs with 50 channels of discrete component readout. This system will be used for noise studies and will be tested in a CERN test beam in September 2003 with initial versions of the ECAL digital electronics. The system will be tested with final electronics and four SCs in 2004.

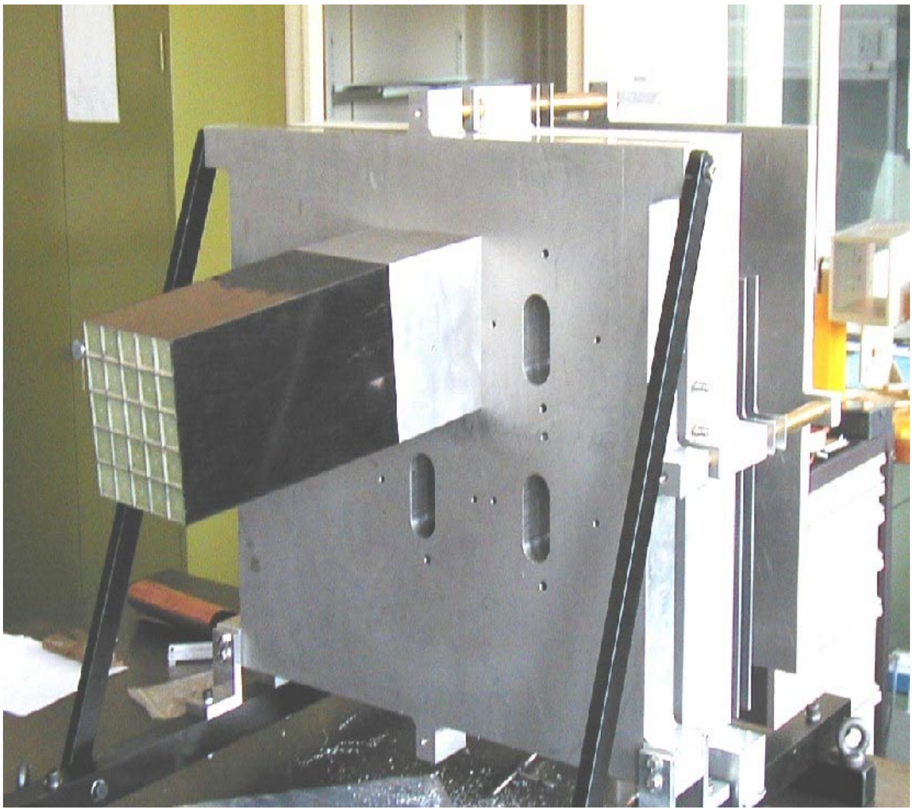


Figure 20. The prototype section of a Dee, E0’, with a capacity for 4 Supercrystals

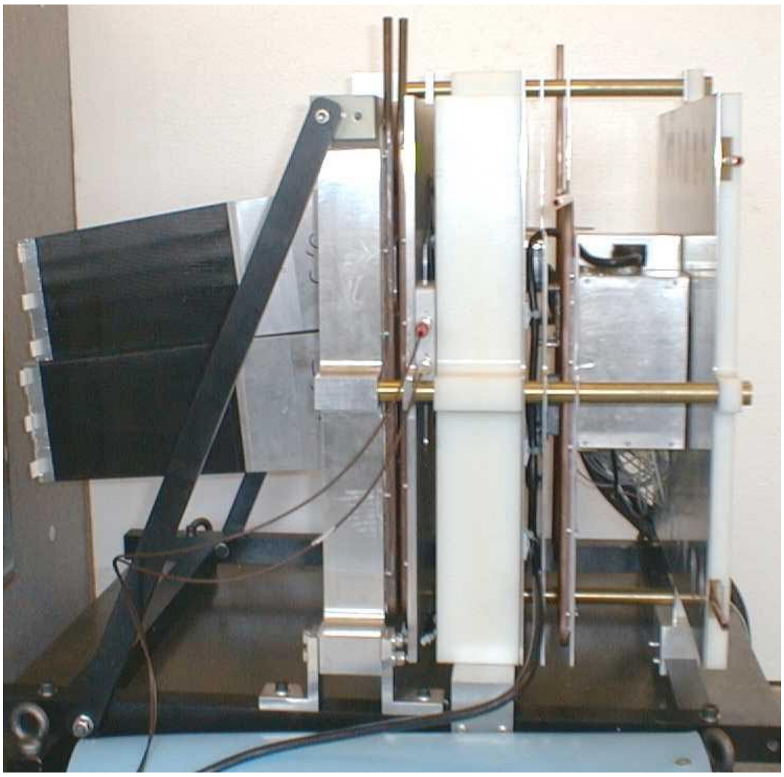


Figure 21. Side view of the Dee prototype, E0', with two Supercrystals, the backplate, neutron moderator and 50-channel discrete component readout unit

3.4.9 Test Beam

In the summer of 1999 the first full-sized endcap Supercrystal was tested in electron beams at CERN. The analysis work on this data has been completed mainly by UK physicists and the main results have been published. An energy resolution (σ_E/E) of (0.48±0.01)% was measured at 180 GeV. In the summer of 2000 the same Supercrystal was returned to CERN and tested in the H2 beamline in magnetic fields of up to 3T, confirming the performance expected from stand-alone VPT tests in magnetic field. The stability of the calibration constants from 1999 to 2000 is encouraging for CMS where the production timescale means that Supercrystals will be produced sometime before installation in CMS.

3.4.10 Regional centre for Supercrystal production

In the current planning for SC production the UK will assemble the SCs for one endcap. Rome will assemble the remainder once ECAL barrel production has ceased. In the UK, the production sequence will be tracked by a computer database and production management system developed by RAL.

The assembly area for SC production at RAL has been equipped with the necessary tooling and jigs. The target is to construct four SCs (which could be placed in CMS) under mass production conditions, by March 2003 and to launch continuous mass production from June 2003 onwards at the rate of two SCs per week. Two prototype SCs have been completed and mounted on the E0' test rig.

3.4.11 Dee Laboratory at CERN

The SCs will be mounted onto the Dees at CERN where they will be equipped with monitoring fibres, to follow changes in crystal transparency and system gain, and electronics readout. The SCs will be tested at each phase of the Dee assembly process.

The work will be carried out by UK and other ECAL institutes. Imperial College is undertaking the design and construction of a prototype jig to mount the SCs onto the Dees. The Dee laboratory will be equipped from Q1, 2003 to be ready for the dry assembly of the large mechanical items for Dee1 and Dee2 in Q3, 2003 and the start of SC mounting on Dee1 in Q4, 2004.

3.5 Global Calorimeter Trigger

The calorimeters provide two types of information to the Level-1 trigger: electron/photon and jet candidates, collectively known as trigger 'objects'; and sums of transverse energy and its components over the whole region up to $|\eta|=5$. The job of the Global Calorimeter Trigger (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. These functions will be performed using a single, generic design of trigger processor module making extensive use of Field-Programmable Gate Array (FPGA) technology.

The UK has conducted an extensive programme of technology evaluation to demonstrate that the generic processor concept can meet the performance requirements of the GCT. We have shown that the required sort and energy sum algorithms can be performed using the Xilinx Virtex family of FPGAs, providing significant cost advantages over fixed-function ASICs for the small quantities required in the GCT. A preliminary design for the GCT based on generic processors was written up for the Level-1 trigger Technical Design Report (TDR), published in December 2000. The publication of this document represented a significant milestone for the trigger project as a whole.

The final processor design for the GCT has demanding requirements on data input/output capabilities as well as logic performance. The input data of 5040 bits per beam crossing will be received by eight processor modules, giving an input rate of more than 25 Gbit/s per module. Recent developments in commercial serialiser/deserialiser (serdes) chipsets allow us to achieve this density using readily available, low cost components. Tests of different serdes chipsets together with FPGA processing have been performed. For these tests we have used a Virtex test module designed at RAL, in collaboration with ATLAS-UK, together with a series of daughter-boards designed and built in Bristol. Design work on a prototype processor module and other components of the GCT is now well under way.

The algorithms implemented in the Level-1 trigger are under continuous review as the simulation tools available to the collaboration are developed. In late 1999, a major revision of the jet finding algorithm was proposed. The new algorithm provides significant improvements in the physics performance and coverage of jet-based triggers. The adoption of configurable logic for the GCT has allowed CMS to incorporate new ideas into the baseline trigger design as they develop, and the UK has played an important part in generating and studying new algorithms.

Prototypes of the components of the GCT will be produced in early 2003. The final specification for the algorithms to be implemented is now being finalised. The system will be produced in 2004 and installed and commissioned during 2005.

3.6 ECAL Milestones and future planning

The list of ECAL milestones presented to the PPESP in September 1999 is shown in Table 2, together with the dates by which the milestones were achieved. The VPT milestone for the launch of mass production was achieved one year later than anticipated. However, due to delays in the LHC programme, the delivery of VPTs is not on the critical path for Supercrystal assembly. We now have 2000 fully tested VPTs at RAL, sufficient to equip 80 Supercrystals. This corresponds to about 40 weeks of regional centre production at RAL at two Supercrystals per week.

The milestones for the delivery of endcap crystals, and the associated milestones for SC production, have not been met. This situation is addressed under Section 3.7, Concerns. However, the capacity of the Bogoroditsk plant has been substantially enhanced since we reported to the PPESP in 1999. The plant will be able to produce endcap crystals at approximately twice the rate that was previously anticipated. This, coupled with parallel SC production at Rome, will enable the current milestones for SC production to be met. These milestones, which are part of the current global CMS ECAL planning, are listed in Table 3 and shown in the Gantt chart in Table 4.

The milestones for the engineering design of the SCs were achieved one year later than anticipated. Nevertheless, the contract for SC mechanics is due to be placed by December 2002, thus providing a substantial stock of components before the launch of SC production at RAL in Q2, 2003.

Milestone	PPESP/99/27	PPRP, September 2002
Delivery of first 30 full sized EE crystals	Dec 1998	Achieved
Delivery of prototype 1-inch VPTs	Mar 1999	Achieved
First full sized SC	Mar 1999	Achieved, May 1999
Beam test of full sized SC	Jun 1999	Achieved
Beam test at 3T		Achieved, July 2000
Launch VPT tender	Sep 1999	Feb 2000
Launch VPT contract	Nov 1999	Nov 2000
Delivery of 120 EE crystals	Dec 1999	Jun 2000, 100 R&D crystals
Conclusion of SC design	Dec 1999	Nov 2000
EE Engineering design review for SCs	Apr 2000	Nov 2000
EE Engineering design review for Dee	Oct 2000	Sep 2002
1576 EE crystals at CERN	Dec 2000	Jul 2001, 100 pre-production crystals
Commence Regional Centre production	Apr 2000	Jun 2003
Commence first Dee at CERN	Dec 2000	Jul 2004
Complete first Dee	Oct 2002	Dec 2005
GCT technical design documentation complete	May 2000	Dec 2000, TDR

Table 2. ECAL Endcap and GCT milestones from last PPESP meeting

The commencement of the first Dee assembly has been delayed from December 2000 to July 2004 and its completion delayed from October 2002 to December 2005. The beam test for the first Dee is now expected in Q2, 2006, as shown in Table 3. In order to accommodate these delays, which mainly arise from the delays in crystal and electronics production, and to ensure that the EE is installed in CMS by Q1, 2007, the assembly of the Dees must proceed in parallel. This will be achieved by switching the CERN centre for ECAL Barrel production entirely to Dee production once Barrel production is completed in 2005.

3.7 Concerns

3.7.1 Crystal delivery

CMS pioneered the use of lead tungstate, and this very successful development is now finding widespread application. However, the R&D necessary to achieve mass production of CMS crystals of consistently high quality and radiation hardness took substantially longer than anticipated. As a consequence, the crystal delivery schedule is on the critical path for ECAL construction. The problem is particularly acute for the endcaps, since production of these crystals is phased later than the barrel production. Nevertheless, the advances in crystal growth technology at the Bogoroditsk plant allow a delivery schedule which can be accommodated in the CMS v33 planning.

The major remaining concern is the formal confirmation of planned funding at the CMS institute that will be responsible for placing the Endcap crystal contact. It is hoped that this confirmation will be forthcoming in time for the October RRB. Any delay would jeopardise the timely delivery of the ECAL endcaps and would have to be addressed by CMS at a high level.

3.7.2 Electronics

The redesign of the ECAL electronics has provided major cost savings to the project. However this complex system must proceed through a successful prototyping phase before mass production can be launched. The first prototype systems are expected in the first half of 2003. Noise studies, with final electronics, are crucial before the design for electronics integration can be concluded on the Dees. The Dee prototype section E0' will be used to address such critical issues.

3.7.3 Travel budget

Once Supercrystal production at the RAL regional centre has been established there will be a significant shift of emphasis to Dee assembly, and the associated testing and commissioning, at CERN. This work will require visits to CERN by UK physicists, technicians and engineers, particularly for all matters relating to VPTs and EE electronics integration and test. The deep cuts in the provision for Travel, necessitated in order to meet the requirements of SCP4, are therefore a source of some concern.

EE/ECAL Planning	*PPRP, September 2002*
Contract for all EE crystals	Q1 2003
Contract for EE electronics	Q2 2003
EE Front End production electronics	Q1, 2005
Start/Finish SCs, Dee1, RAL	Q2, 2003 – Q3, 2004
Start/Finish SCs, Dee2, RAL	Q3, 2004 – Q3, 2005
Start/Finish SCs, Dee3, CERN/Rome	Q2, 2005 – Q1, 2006
Start/Finish SCs, Dee4, CERN/Rome	Q2, 2005 – Q1, 2006
Start/Finish dry Pre-assembly, Dee1/2	Q3, 2003 – Q3, 2004
Start/Finish assemble/test Dee1	Q3, 2004 – Q2, 2006
Start/Finish assemble/test Dee2	Q4, 2004 – Q3, 2006
Start/Finish assemble/test Dee3	Q4, 2005 – Q3, 2006
Start/Finish assemble/test Dee4	Q1, 2006 – Q4, 2006
Measurement of 4000 production VPTs, in total	Q1, 2003
Measurement of 15000 production VPTs, in total	Q4, 2005
Regional Centre (equipped, phase 1)	Achieved Mar 2002
Regional Centre (equipped, phase 2)	Q4, 2002
4 Pre-production SCs	Q2, 2003
E0', Full sized Dee mock-up, with 2 Supercrystals	Achieved, Sep 2001
E0' beam test, with 2 Supercrystals	Q3, 2003
E0' beam test, 4 Supercrystal, final electronics	Q3, 2004
EE- in CMS	Q1, 2007

Table 3. Present EE milestones

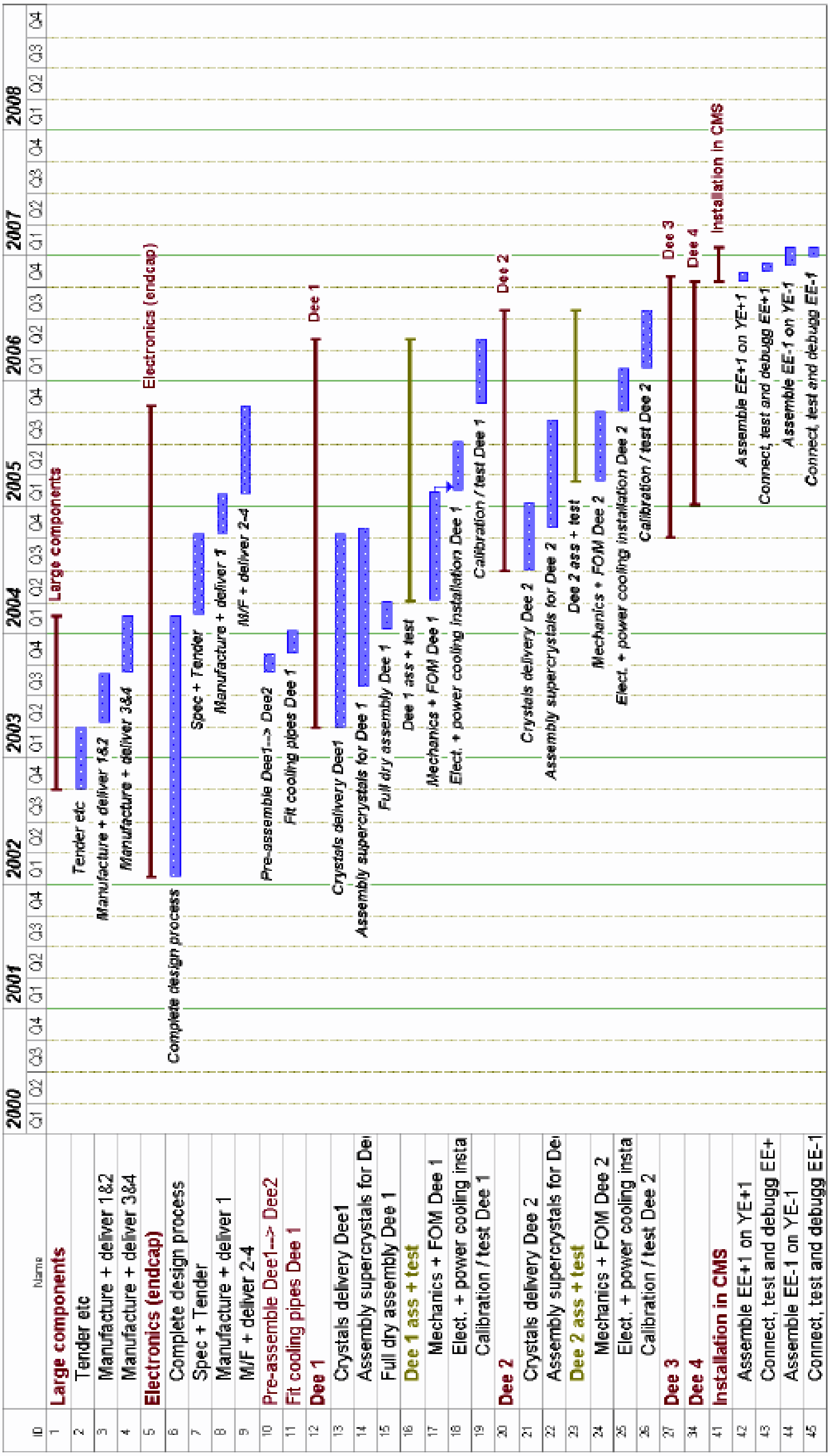


Table 4. Gantt chart showing major EE tasks through to installation in CMS by Q1, 2007

4. PHYSICS STUDIES AND COMPUTING

4.1 Overview

Major progress has been made over the last three years in refining the triggering, reconstruction and physics analysis strategies for CMS. In particular, detailed simulation studies have been made of the performance of the high-level trigger (HLT), which is implemented entirely in software on a large CPU farm. We have successfully demonstrated that this approach will meet the data reduction and physics requirements of the experiment. These results are shortly to be reported in the DAQ TDR, due to be published at the end of 2002. UK physicists have made a significant contribution to this programme of work, in management, execution and support roles. The physics performance of the final CMS detector is under continuing study, with our Physics TDR due in 2005.

In order to support these physics and detector studies, a fully operational prototype computing system has been developed and used on a large scale. Since 1999, CMS has moved from Fortran-based simulation code to a modular object-oriented simulation, reconstruction, analysis and data management framework. Fully simulated data samples of significant size (many millions of events, occupying tens of terabytes) have been produced and reconstructed along with appropriate background, in order to provide sufficient numbers of events for detailed HLT studies. The UK has been a leading contributor in this effort. The worldwide data production programme undertaken by CMS has also been essential in helping to define the requirements for our final software and computing system, to be documented in the forthcoming Computing TDR (2004). The CMS computing system is expected to make extensive use of Grid technologies, and the UK plays a major role in this area of development.

During 1999 and 2000, the CMS physics and computing programme was organised into three component projects: Physics Reconstruction and Selection (PRS), Computing and Core Software (CCS) and Trigger/DAQ. The UK computing and physics contributions lie mainly within the PRS and CCS areas, though we also contribute to the third through our detector responsibilities. The three projects are included under the umbrella organisation CPT, which holds three joint annual meeting weeks, including joint technical meetings. This approach has proved extremely productive.

4.2 Physics Reconstruction and Selection

4.2.1 The PRS project

The four PRS groups – e/gamma, muon, b/tau and jets/missing energy – were set up in May 1999. The basic task of these groups was the reconstruction and selection of physics objects, starting from the output of the Level-1 trigger. It is intended that the HLT will use the same code as will be used for offline reconstruction. The idea was that the reconstruction and selection algorithms would be developed as they were needed for successively higher levels of the trigger. In 2000, the remit of the groups was broadened to include all software tasks related to their corresponding subdetector. The PRS project is unique among the CMS projects in having direct control of no resources. PRS must obtain its resources from the sub-detector projects, and the coordinators of the four PRS groups must work to link the domain of physics and software with those of hardware, electronics, test-beam and so on.

4.2.2 ECAL – e/gamma Group

In 2000, the e/gamma group was renamed ECAL-e/gamma to emphasis its connection with the ECAL project. The group is now responsible for all ECAL software and reconstruction and physics-related tasks, including calibration, test-beam analysis and simulation. A UK physicist has led the e/gamma group since its inception, and the ongoing UK contribution consists of two physicists and two students working full-time, plus a number of additional part-time contributors.

The important milestone up to 2001 was the delivery of a complete selection chain, from the Level-1 trigger to the final sample of events that will be written to permanent storage. The study was performed using a large sample of fully GEANT simulated and digitised jet background events. This 0.6M event sample incorporated pile-up background corresponding to low luminosity, 2.10^{33} $cm^{-2}s^{-1}$, and was used in conjunction with a 1M event sample of signal events and single particles, similarly simulated and digitised. The milestone was delivered in late 2001, and included a detailed breakdown of the signal and background in the 36 Hz event rate to offline storage, together with details of the cuts, thresholds and algorithms needed to achieve this. The efficiency of the chain for signal events, together with plots of efficiency versus background rejection, for most of the selection cuts, was also presented.

In order to achieve this, ECAL-alone reconstruction algorithms were developed for electrons (bremsstrahlung recovery). A Level-2 'pixel matching' algorithm was developed, searching for hits in the pixel detectors corresponding to a reconstructed electron in the ECAL, and track finding for electrons, seeded by pixel hits, was studied. A UK student also studied ECAL isolation cuts.

The group was required to provide rapid feedback to the CMS management concerning the effect of staging or delaying the deployment of the ECAL endcaps. A UK physicist calculated the acceptance for $H \rightarrow ZZ^*$ decaying into four electrons, two electrons or two muons, or into either of these channels, when the ECAL coverage is limited to the resulting smaller pseudorapidity region, relative to that which would be obtained by the full design coverage. Similar studies for Higgs decay to photons were also made, and the results presented to the CMS Steering Committee. On the basis of these results, the Steering Committee concluded that the absence of one or both of the ECAL endcaps would lead to an unacceptable loss in efficiency for Higgs detection.

Further activities of the group involved the improvement and updating of the geometry description for the ECAL. The endcap description is the responsibility of a UK physicist. Final preparations for the full transition to GEANT4 are continuing.

In 2002, UK physicists were responsible for examining the impact of proposed changes to the ECAL readout scheme, with particular reference to the possibility of degraded performance of the Level-1 trigger in the endcap region. A detailed simulation study was carried out, confirming that the proposed changes resulted in only a small change in trigger rate; a new layout of the endcap trigger towers was defined during the course of this study, building on previous work by the UK Level-1 trigger group.

The primary milestone for 2002 was to repeat the HLT study of the complete selection chain with an improved geometrical description of the detector (in particular the Tracker), and to obtain results also for high luminosity running. These results are due to appear in the DAQ TDR. It was also necessary to obtain estimates of the CPU time used by the selection code, demonstrating that the selection could be performed on the DAQ HLT farm.

Other milestones for 2002 included the presentation of a credible scheme for ECAL calibration. Work was carried out on many aspects of this problem, including an important study by a UK student of *in situ* intercalibration using electrons from W decay. A scheme for the intercalibration of ECAL crystals through monitoring the energy flow due to minimum-bias events was developed. This work demonstrated that a 2% intercalibration is achievable in a very short time, which is particularly important at start-up since the installation schedule now makes it impossible for us to pre-calibrate all channels in an electron beam. A detailed simulation was carried out of the selective readout and zero-suppression algorithms, which reduce the raw data volume from the ECAL by a factor of about 15 with little or no impact on the reconstructed physics objects. A UK student developed flexible software to address this need, improving upon the crude 2σ noise cut used hitherto.

4.2.3 HCAL – jet/missing energy Group

Over the last two years, a UK student has studied various aspects of Level-1 jet and missing-E_t trigger performance. This has involved calculating standard trigger performance plots, including E_t resolution, trigger turn-on and rate plots at the initial LHC luminosity of 2.10^{33} $cm^{-2}s^{-1}$. These confirm and add to previous studies by the Level-1 group.

A study of the trigger tower segmentation in the very forward calorimeters was carried out at the request of the HCAL and Level-1 groups to quantify the difference between two proposed schemes. Both schemes were simulated using a full GEANT detector simulation, and a bit level simulation of the trigger electronics. The results show that the segmentation choice affects the Level-1 E_t resolution and trigger rate at the 1% level, but that both schemes provide acceptable performance.

Topological di-jet triggers have been studied in the context of Higgs production via weak boson fusion. This production mechanism includes two jets well separated in rapidity. The proposed triggers included cuts on the spatial separation of the two jets, thereby allowing the E_t threshold to be reduced. However, separate jets from two pile-up events cause sufficient rate such that these triggers are no more effective than the single jet trigger at selecting general weak boson fusion events. The particular case where the Higgs decays invisibly was also studied. It was found that a di-jet trigger including a cut of $\Delta\eta>3.5$ provides better performance than the single jet trigger for this channel. The addition of missing E_t to this trigger gives a trigger efficiency of 87% for invisible Higgs at a trigger rate of 410 Hz.

4.2.4 Tracker – b/tau Group

A UK physicist leads the tracker 'data-handling' group, which is responsible for those aspects of the off-line simulation/reconstruction software, which are related to the tracker readout or electronics. Several UK physicists are involved in the simulation and reconstruction aspects of this activity.

The CMS simulation program (ORCA) was used to identify the best zero-suppression algorithm for use in the tracker FEDs, to verify that the FED dynamic range is large enough not to degrade tracker performance, to estimate the expected data rates from the tracker (for use in the DAQ TDR), and to identify the data format which minimises this data rate. In addition, work is underway to find the best algorithm to calibrate/monitor the tracker pedestals and noise during LHC running. Whilst performing these studies, UK physicists identified many shortcomings in ORCA, such as inappropriate signal to noise ratios and incorrect simulation of Landau fluctuations, and ensured that these problems were fixed.

The group is also responsible for ensuring that real tracker data can be read into the reconstruction program. The group is already providing the software needed to access and analyse test-beam data, and it is foreseen that this software will eventually evolve to allow access to data from the final CMS tracker. UK physicists are not only providing these software tools, but are also playing an important role in the actual analysis of the test-beam data, notably in the study of tracker readout performance in a 25 ns test-beam and in the study of the effect of highly ionising particles on the tracker readout.

4.2.5 Other Physics studies

A UK physicist made a significant contribution to the CERN yellow report on the prospects for Standard Model physics at the LHC. The final editing of the relevant report section (over 100 pages) was carried out in 2000. This report will stand as a major reference work for the next few years. During 2001 – 2002, UK physicists made further contributions to the topic of anomalous vector-boson couplings and background reduction in the form of refereed CMS notes.

Other UK physics studies included the triggering and reconstruction of B decays to low-p_t electrons, and a study of possible techniques for relative luminosity measurement in the Level-1 trigger.

4.3 Core Computing and Software

The roles of the CMS CCS project include:

- Development and support of the software framework which underlies CMS physics and reconstruction tools, and implements data management,
- Review of technologies and approaches, in order to make policy decisions on their use,
- Build up of the world-wide computing infrastructure needed for all CMS activities,
- Management of resources in support of the computing needs of the collaboration,
- Testing of the CMS software and computing approach and infrastructure, demonstrating that it performs at the necessary level to support the planned analysis activities from LHC start-up.

Since 1999, CMS-UK has substantially increased its contribution in each of these areas. The decision was taken in that year that the UK wished to host a major national (Tier-1) computing centre for CMS reconstruction and analysis, in direct support of our physics goals. This will take the form of a fraction of a joint central LHC computing facility at the Rutherford Appleton Laboratory. CMS-UK physicists have been highly active in defining the requirements for such a facility, and in making use of existing UK facilities in support of the CMS prototype computing system. We have established an excellent working relationship with CLRC computing support staff. Our planning has more recently included the exploitation of Tier-2 centres, based in London and in the South of England. These more specialised facilities will form the focal points for CMS-UK analysis computing in the future.

A major activity in the UK has been participation in the CMS production exercises from 2000 – 2002. In 2000 and 2001, the CSF facility at RAL was used to contribute around 1.5 TB of simulated data. In 2002, the scope of the UK production expanded greatly to include local computing facilities at Bristol and Imperial College, the UK contributing over 4 TB of data in total, with six personnel participating. Most of the data produced has directly supported the work of physicists within the e/gamma PRS group. CMS is certain to remain one of the largest users of UK HEP computing and networks in the coming years, as the scale of CMS computing challenges grows. In 2003 – 2004, we will produce and analyse of the order of 100 TB of data over six months, in an extremely demanding 25% scale test of our full computing system. Planning for this major milestone is currently under way.

In addition to the development of large-scale computing facilities, the period since 1999 has seen a considerable improvement in the support available to UK physicists in the use of local computing facilities. The complete CMS prototype software chain is now available and supported within the UK, and may be used on excellent analysis and simulation resources at each institute. We anticipate that full use will be made of these local resources and expertise in the preparation of the Physics TDR. UK physicists are contributing directly to the development of the new CMS GEANT4-based simulation package, OSCAR, and the fast simulation package, FAMOS, both of which will be heavily used from 2002 onwards.

A new and important aspect of our computing programme is the use of Grid technology. CMS collaboration members have long been leading proponents of a DataGrid approach, and the collaboration was the first in HEP to develop, test and deploy Grid-based production tools. CMS-UK has benefited from a strong early involvement in this area. We have received a contribution of 3.5 FTE of manpower via the PPARC GridPP project, in addition to e-science studentships; more than any other UK experiment. This effort will be used directly toward the development of a Grid-based computing system for CMS, with particular emphasis on the construction and testing of the prototype Tier-1 system. Our main contributions will be in the area of workload management (Imperial College), monitoring (Brunel) and data management (Bristol). We will contribute directly to the development and testing of a new event storage layer for CMS, to be deployed in 2003. CMS-UK physicists also occupy a variety of management roles in the GridPP and LCG projects, and have represented CMS within international Grid collaborations.

The development of interest and attainment of new resources within the UK have helped us to achieve a high-profile role within the CCS project, to match our contribution within PRS. We very much hope that an appropriate level of resource will continue to be available, to support this important effort. This is an essential prerequisite for an effective exploitation of the CMS experiment and of UK expertise upon LHC start-up.

4.4 Summary

UK physicists are making important and timely contributions within both the PRS and CCS projects. A clear roadmap towards CMS physics analysis in 2007 is being established, and is supported by a strong UK effort in the development of the necessary computing and software systems. As the exploitation phase of the CMS experiment nears, UK interest is expected to focus on the preparation of the Physics TDR, for which our existing contribution to PRS activities, and our expertise in software and computing, will stand us in excellent stead.

APPENDIX A: UK CMS PUBLICATIONS SINCE SEPTEMBER 1999

Defect kinetics in Novel Detector Materials
B C MacEvoy, G Hall
Presented at the 1st ENDEASD Workshop, Santorini, April 21-22 1999.
Accepted for publication in Materials Science in Semiconductor Processing.

Defect Engineering Rad-Hard Tolerant Silicon Detectors: The role of impurities and inter-defect charge exchange
B. MacEvoy, A. Santocchia, G. Hall
Presented at the 20th International Conference on Defects in Semiconductors, Berkeley, July 26-30 1999.
Physica B 273-274 (1999) 1045-1049.

The CMS silicon strip tracker
Focardi E, et al
Nuclear Instruments and Methods A435 (1999) 102-108.

The R&D program for silicon detectors in CMS
Tonelli G, et al
Nuclear Instruments and Methods A435 (1999) 109-117.

The silicon microstrip tracker for CMS
Pandoulas D, et al
Nuclear Physics B-Proceedings Supplements 78 (1999) 315-321.

R&D for the CMS silicon tracker
Feld L, et al
Nuclear Physics B-Proceedings Supplements 78 (1999) 322-328.

Comparative study of (111) and (100) crystals and capacitance measurements on Si strip detectors in CMS
B. MacEvoy, A. Santocchia, G. Hall, et al
Nuovo Cimento Della Societa Italiana Di Fisica 112 (1999) 1261-1269.

High-voltage breakdown studies on Si microstrip detectors
Albergo S, et al
Nuovo Cimento Della Societa Italiana Di Fisica 112 (1999) 1271-1283.

The silicon microstrip tracker for CMS
Albergo S, et al
Nuovo Cimento Della Societa Italiana Di Fisica 112 (1999) 1307-1316.

Test results on heavily irradiated silicon detectors for the CMS experiment at LHC
B. MacEvoy, G. Hall, et al
IEEE Trans. Nucl. Sci. 47 (2000) 2092-2100.

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Osborne M D, Hobson P R, Watts S J
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The APV25 0.25μm CMOS Readout Chip for the CMS Tracker
M. Raymond, M. French, J. Fulcher, **G. Hall**, L. Jones, K. Kloukinas, L.-K. Lim, G. Marseguerra, P. Moreira, Q. Morrissey, A. Neviani, E. Noah
IEEE 2000 Nuclear Science Symposium, Lyon, France.

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G. Davies, A. Singovski, J.P. Peigneux, C. Seez
J. Phys. G: Nucl. Part. Phys. 26 (2000) 1735-1749.

Performance of CMS silicon microstrip detectors with the APV6 readout chip
Meschini M, et al
Nuclear Instruments and Methods A447 (2000) 133-141.

New results on silicon microstrip detectors of CMS tracker
Demaria N, at al
Nuclear Instruments and Methods A447 (2000) 142-150.

The CMS Silicon tracker
B. MacEvoy, A. Santocchia, G. Hall, et al
Nuclear Instruments and Methods A453 (2000) 121-125.

LHC front end electronics
G. Hall
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Nuclear Instruments and Methods A453 (2000) 353-364.

The CMS Tracker APV25 0.25 μm CMOS Readout Chip
M. Raymond, G. Cervelli, M. French, J. Fulcher, G. Hall, L. Jones, L-K. Lim, G. Marseguerra, P. Moreira, Q. Morrissey, A. Neviani, E. Noah
Paper presented at 6th Workshop on Electronics for LHC Experiments, Krakow, September 2000.
LHC Electronics Board Workshop. CERN Report CERN 2000-010 (2000) 130-134.

The CMS Tracker front-end and control electronics in an LHC-like beam test.
W. Beaumont, M. Bozzo, C. Civinini, J. Coughlan, F. Drouhin, P. Figueiredo, L. Fiore, A. Giassi, K. Gill, J. Gutleber, G. Hall, L. Latronico, C. Ljuslin, M. Loreti, C. Maazouzi, A. Marchioro, **N. Marinelli**, C. Paillard, T. Parthipan, P. Siegrist, L. Silvestris, I. Tomalin, A. Tsirou, P. G. Verdini, P. Walsham, B. Wittmer, A. Zghiche, F. Vasey
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E. Noah, N. Bacchetta, D. Bisello, A. Candelori, I. Dindoyal, P. G. Fuochi, M. J. French, G. Hall, M. Raymond, M. Vassanelli
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S. Albergo, et al.
Nuclear Instruments and Methods A466 (2001) 300-307.

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APPENDIX C: REFEREED CMS NOTES SINCE SEPTEMBER 1999

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Kennedy B W
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Kennedy B W
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The Effect of Tracker Material on The Level-1 Electron Trigger
C. Seez
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B. Camanzi, D. Cockerill, A. Presland
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APPENDIX D: CMS AND RELATED DOCUMENTS TO LHCC SINCE SEPTEMBER 1999

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J. Troska
Imperial College of Science, Technology and Medicine Ph.D. Thesis, 1999.

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F. G. Sciacca
Imperial College of Science, Technology and Medicine Ph.D. Thesis, 1999.

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M. Osborne
Brunel University Ph.D. Thesis, 2000

The development of a dense, radiation hard scintillating glass for electromagnetic calorimetry
P. S. Flower
University of Sheffield Ph.D. Thesis, 2001.

Identification and Measurement of Low-Energy Electrons and the decay $B^0_s \rightarrow J/\psi\,\phi$ *at CMS*
A. D. Presland
University of Bristol Ph.D. Thesis, 2001.

Radiation Effects in electronics for the CMS Tracking detector
J. Fulcher
Imperial College of Science, Technology and Medicine Ph.D. Thesis, 2001.

Level-1 Jet Trigger Studies for the CMS Experiment
J. J. Brooke
University of Bristol Ph.D. Thesis, 2002.

APPENDIX F: UK POSITIONS OF RESPONSIBILITY WITHIN CMS

Primarily Ad Hominem

T. S. Virdee	Deputy Spokesperson Member of CMS Management Board and Steering Committee Member of CMS Finance Board Member of CMS Collaboration Board
R. M. Brown	Chairperson of ECAL Institution Board Chairperson of ECAL Finance Board Member of ECAL Steering Committee Member of CMS Management Board Member of CMS Finance Board Member of CMS Conference Committee, Thesis Award Panel, Paper Review Panel
G. Hall	Member of CMS Steering Committee Member of CMS Management Board Electronics Co-ordinator, Tracker Project Member of Tracker Steering Committee
D. J. A. Cockerill	Co-ordinator, ECAL Endcap Project Member of ECAL Technical Board
R. J. S. Greenhalgh	Project Engineer, ECAL Endcap Project
C. Seez	Co-ordinator, ECAL Simulation and Software Convener, Electron-Photon Group Co-ordinator, ECAL Test Beam
G. P. Heath	Co-ordinator, Global Calorimeter Trigger
D. Britton	Co-ordinator of INTAS-CERN project on alveolars for plug region
P. R. Hobson	Co-ordinator of INTAS-CERN project on VPTs

Ex Officio

G. P. Heath	Bristol Member of CMS Collaboration Board
S. J. Watts	Brunel Member of CMS Collaboration Board
G. Hall	ICSTM Member of CMS Collaboration Board
R. M. Brown	RAL Member of CMS Collaboration Board

APPENDIX G: UK MEMBERS OF CMS AS OF 1 OCTOBER 2002

Also given is current fraction of FTE spent on CMS

Bristol

D. Bailey	70%
T. J. Barrass	50%
J. J. Brooke	100%
D. G. Cussans	90%
R. Frazier	100%
R. D. Head	30%
G. P. Heath	60%
H. F. Heath	60%
D. C. Holmes	100%
D. S. Machin	100%
C. K. Mackay	40%
S. Metson	100%
O. J. E. Maroney	50%
S. J. Nash	80%
D. M. Newbold	70%
M. G. Probert	100%
V. J. Smith	20%
R. J. Tapper	20%

Brunel

B. Camanzi	100%
P. Cooke	30%
C. Da'Via	10%
P. R. Hobson	60%
P. Kyberd	10%
I. Reid	100%
C. Selby	80%
O. Sharif	100%
S. J. Watts	10%

ICSTM

R. Bainbridge	100%
G. Barber	80%
J. Bass	50%
R. Beuselinck	50%
P. Brambilla	30%
D. Britton	60%
W. J. Cameron	70%
I. W. Clark	70%
E. Corrin	100%
G. Dewhirst	100%

C. Foudas	60%
S. Greenwood	30%
G. Hall	60%
R. Hare	60%
G. M. Iles	80%
V. Kasey	30%
M. Khaleeq	40%
B. MacEvoy	20%
N. Marinelli	100%
A. Nikitenko	100%
E. Noah	100%
M. Noy	100%
X. Qu	100%
D. M. Raymond	100%
S. Rutherford	50%
M. Ryan	100%
C. Seez	100%
T. S. Virdee	70%
O. Zorba	60%

RAL

S. A. Baird	5%
D. J. Ballard	75%
K. W. Bell	100%
R. M. Brown	80%
D. J. A. Cockerill	100%
J. A. Coughlan	100%
C. P. Day	75%
E. J. Freeman	75%
P. S. Flower	100%
M. J. French	50%
W. J. F. Gannon	100%
R. J. S. Greenhalgh	65%
R. N. J. Halsall	80%
W. J. Haynes	5%
J. A. Hill	100%
B. W. Kennedy	100%
A. L. Lintern	85%
A. B. Lodge	100%
A. J. Maddox	100%
A. S. Marsh	40%
M. R. Pearson	100%
J. Salisbury	75%
A. A. Shah	100%
B. J. Smith	100%
M. Sproston	100%
R. Stephenson	5%

C. Stephens	10%
S. Taghavirad	100%
I. R. Tomalin	100%
J. H. Williams	100%

Footnote: Five computer scientists from the Centre for Complex Cooperative Systems of the University of the West of England, led by an ex particle physicist, comprise a non-PPARC-supported 'Associated Institute' of CMS, and collaborate in the design, implementation and testing of software for CMS. Similarly, a group of computer scientists from the University of Strathclyde comprise another non-PPARC-supported 'Associated Institute' of CMS. They are developing techniques for the automatic analysis of CMS software. This involves experimenting with a number of software products and measuring attributes of a subset of the CMS software.

APPENDIX H: STAFF YEARS PER CATEGORY AND PER INSTITUTE FOR EACH PROJECT, FOR NEXT FOUR YEARS

	02/03	03/04	04/05	05/06
BRISTOL				
ECAL/Trigger				
HEFCE Academics	2.6	2.9	2.3	1.9
PPARC Advanced Fellow	0.7	0.8	0.8	0.5
RA Physicists	0.8	1.0	1.0	1.0
e-science RA	0.8	1.0	0.8	
Physicist Programmers	0.4	0.5	0.2	
Physicist Engineers	0.9	0.9	0.9	0.8
Technicians	1.2	1.2	1.1	0.8
Research Students	3.5	4.5	4.0	3.5

	02/03	03/04	04/05	05/06
BRUNEL				
Tracker/DAQ				
HEFCE Academics	0.2	0.2	0.2	0.2
RA Physicists	1.0	1.0	1.0	1.0
Technicians				
Research Students				1.0
ECAL/Trigger				
HEFCE Academics	0.7	0.8	0.8	0.9
RA Physicists	1.0	1.0	1.0	1.0
Technicians	1.1	0.9	0.6	0.4
Research Students		1.0	1.0	1.0

	02/03	03/04	04/05	05/06
IMPERIAL COLLEGE✣				
Tracker/DAQ				
Academics	1.4	1.4	1.3	1.5
RA Physicists	3.0	3.2	3.4	3.5
Engineers/Technicians	3.4	3.1	3.3	3.5
Research Students	4.0	4.0	4.0	4.0
ECAL/Trigger				
Academics	1.3	1.3	1.4	1.5
RA Physicists	3.9	4.1	3.3	3.8
Engineers/Technicians	2.2	2.2	2.2	2.2
Research Students	2.5	2.5	2.5	2.5

✣ The division between ECAL and Tracker is somewhat arbitrary, and becomes especially so for staff involved in physics activities.

RAL-PPD*	02/03	03/04	04/05	05/06
Tracker/DAQ				
Academics	1.1	1.1	1.1	1.1
Research Associates	0.5	1.0	1.0	1.0
Support Physicists/Programmers				
Engineers				
Technicians				
ECAL/Trigger				
Academics	2.7	2.7	2.7	2.7
Research Associates	0.25	1.0	1.0	1.0
Support Physicists/Programmers	2.0	2.0	2.0	2.0
Engineers	1.0	1.0	1.0	1.0
Technicians	1.85	1.85	1.85	1.85

RAL-ED and RAL-ID*	02/03	03/04	04/05	05/06
Tracker/DAQ				
Engineers and Technicians	6.9	2.9	4.8	2.3
ECAL/Trigger‡				
Engineers and Technicians	8.1	5.7	3.3	1.8

* The RAL staff years are given in terms of UK financial years, as opposed to academic years.

‡ Excludes the additional 4 SY working on development of the FENIX ASIC and the related PCB.