8 May 2014

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Upgrades of the Tracker and Trigger of the CMS experiment at the CERN LHC

1 Executive Summary

The new project started in April 2013; it continues work on the tracker and trigger begun in the previous R&D project. For the Phase I upgrades of the L1 calorimeter trigger, this is a construction project.

In the last six months there has been further excellent progress with the UK activities:

- A beam test of the first prototypes of a small 2S-module read out by the CBC2 chip took place at DESY in November 2013 and demonstrated identification of track-stubs consistent with momentum selection as expected.
- The FC7 general purpose data acquisition board has been successfully developed and the first production versions are in manufacture, for the upgraded CMS TTC (TCDS) system.
- The first production versions of the MP7 have just been delivered; the full complement needed for CMS should be available within the next couple of months.
- An Engineering Design Review of the L1 Trigger project took place in November 2013, which expressed some concerns about progress. However, the UK parts of the project are fully on schedule and requests have been made for the UK to take on extra work
- A new co-project manager of the CMS L1 Trigger has been appointed by the new (since January 2014) CMS Spokesperson. This is Costas Foudas, who is well known to the UK. His principal task is to ensure timely delivery of the TDR trigger and a working interim trigger in 2015, if required by increases in LHC luminosity.
- A Time Multiplexed Trigger architecture is a very promising concept for the implementation of the Track-trigger needed for the Phase II upgraded CMS. The basic ideas can be demonstrated soon using MP7s and other hardware already developed for the trigger project, which allows the UK to maintain its leadership in the trigger, and offers a flexible route for future construction contributions.

The UK project is on the envisaged schedule but the long term plan remains under review because overall CMS objectives have been evolving gradually in the last 1-2 years. As the long term LHC schedule has changed, the CMS plans for Phase II have altered, which has had a knock-on effect on WP2.

2. Project history and recent developments

The LHC upgrade is proposed to take place in two main stages, with an increase in luminosity reaching ~2.5 10^{34} $cm^{-2}s^{-1}$ a couple of years after 2015 in LHC Run 2, then after a two to three year shutdown from 2023 in the most recent CERN ten-year plan announced in December 2013, to ~5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity, denoted as Phase II at the High Luminosity (HL)-LHC. A total of 3000 fb^{-1} in integrated luminosity over about a decade is the goal. The latest version of the machine schedule is shown in Fig 2.1.

The current phase of the project began on 1 April 2013. There are two technical work packages: WP2 for the Phase II outer tracker readout R&D for HL-LHC; WP3 for the calorimeter trigger construction for Phase I, starting in 2015, and further R&D aimed at Phase II.

CMS and the LHC are currently in a Long Shutdown (LS1) with the LHC planning to restart with first collisions at ~13 TeV expected around March 2015; this remains on schedule and first CERN beams are expected in October 2014. The exact LHC operating conditions are still under discussion; the machine will not aim initially for the full 14 TeV and the collision frequency should be 40 MHz. The bunch crossing interval is likely to be kept under review during early operation and the machine may revert to 50 ns bunch spacing if difficulties emerge. However, both ATLAS and CMS have pressed strongly for 25 ns operation in view of implications for pileup.

CMS shutdown activities are also proceeding broadly according to schedule. The tracker has been sealed and operated at low temperature, which was one challenge met. The problems with the new beam pipe manufacture were overcome and it is due to be installed between late May and mid-July, followed by a month of bake-out. Recommissioning is beginning and global and cosmic ray data taking runs will take place regularly in the coming months. First beam should circulate through CMS in February 2015.

Fig 2.1. The latest version of the LHC machine schedule (December 2013).

2.1 LHC upgrade schedule and planning

The main questions at present concern the luminosity during Run 2, and when it will it reach the level which exceed pileup conditions experienced in 2012 which might then motivate an improvement in the trigger; this is estimated to be ~3.5 10^{33} $cm^{-2}s^{-1}$ at 13 TeV and 25 ns. Should this happen during 2015 then the case for operating a new trigger instead of the present, "legacy" trigger will become stronger, because of the potential for discovery in a high pileup environment. At the end of 2015, an upgraded trigger meeting the selection requirements for heavy ion running is also considered essential.

For the longer term, the major uncertainty concerned the timing of LS3, when the tracker can be replaced and other major work undertaken. This is now foreseen (Fig. 2.1) from the end of 2022 to mid-2025, i.e. about 30 months, which is one year later than previously. The concerns about the long term planning include the scale and cost, especially from the agencies, and the scale of upgrades which will permit the best physics, from the experiments who are concerned about possible cost caps until the scope of the upgrade programme is considered well understood.

In the interim LS2 in 2018 the injector chain will be improved to deliver high intensity and low emittance bunches. This has been delayed by six months to mid-2018 compared to previous plans and with a longer duration of 18 months instead of 12, leading to an overall delay of one year for Run 3 which will now commence in 2020. The UK upgrade project is scheduled to end in March 2019, although this does not need to coincide with the start of Run 3, but is relevant for further funding for a future construction project.

There will also probably be an Extended Year End Technical Stop in late 2016-early 2017 when the new CMS pixel detector should be installed.

2.2 CMS planning

As for the machine, the two issues are short term and long term planning, where short term refers to the conditions at the start of Run 2, while long term refers to LS3 and beyond.

The TDR (upgraded) trigger was expected to be operational during 2015 so it could be commissioned in parallel with the legacy trigger. It can only be fully operational once the optical splitters (oSLBs and oRMs) are in place so trigger primitives can be transmitted optically to the new trigger; it also requires the HCAL μHTR cards to be available, which is presently being expedited as much as possible but is constrained by US funding. This was the argument for an interim trigger (Stage 1) in 2015, so that potential for SUSY discovery would not be jeopardised by pileup at the trigger level. This was explained in the last OSC report.

Stage 1 requires only 18 new oRSC cards in the RCT crates, which transmit clustered data to the MP7 which performs the function of the current GCT, except with enhanced performance as a result of the extra bandwidth available. The MP7 required is available and has been ready for testing with the oRSC since early summer 2013, when a milestone of oRSC-MP7 data transmission and synchronisation was scheduled. This was not met because of lack of readiness of the oRSC and its firmware. This prevented achievement of a second internal milestone at the end of 2013, which was installation of all Stage 1 hardware at Point 5. The oRSC-MP7 tests are due to be carried out in a three week slot from 28 April; at the time of writing the oRSC firmware is not complete but expected to be ready shortly.

Following the TMT integration test at the end of September 2013, the MP7 was demonstrated to be ready and could be deployed in both Layer 1 and Layer 2 of the TDR calorimeter trigger. Production orders for up to 32 MP7s were launched in February, following a European-wide CERN market survey. There have been minor delays in component procurements but deliveries are on an acceptable schedule given the sizeable contingency available. The main concern for the TDR trigger remains the availability of US-provided components and their validation. The μHTRs were already mentioned but are not required until mid- to late-2015. The AMC13 is a μTCA service module which is essential for the DAQ interface; it has been shown to perform well in our trigger integration tests but more firmware and software are required for full functionality in the slice test planned for July, which should transmit data from detectors to the Global Trigger, and send trigger information to the DAQ.

Most crucial of all is the availability of US Layer 1 hardware, the CTP7. This board was manufactured at the end of 2013, and has not yet been tested in a real system. Bit error rate tests have been performed successfully in receiving data from the HCAL but the board must transmit data to the Layer 2 MP7s and the required firmware must be written. This looks possible but it will be much later than expected. Once the CTP7 has been proven, it then must be manufactured in production quantities. 36 boards are required for Layer 1 and this cannot start before October 2014 due to availability of US funds, even assuming no modifications are required. Deliveries look likely between December 2014 and March 2015.

The trigger has therefore been subject to some significant reviews, including an Engineering Design Review in November 2013, which normally take place before hardware is manufactured to verify that system requirements and performance targets are met.

For the longer term, a CMS Phase II Technical Proposal is in preparation for submission to the LHCC in September 2014 with a Tracker Technical Design Report in 2016 or perhaps 2017, given the one year delay in LS3.

The tracker design remains as described in the last report (Fig 2.2), using 2S-modules with CBC readout in the outer tracker, and PS-modules to be developed by CERN in the inner tracker, which are the basis for the track-trigger developments under study, some of which are described later. A major discussion is under way on the future endcap calorimetry with two options now under consideration, since a third option was eliminated following a CMS review in the CMS Upgrade week in April. The two options under consideration are a Shashlik calorimeter based on LYSO crystals, tungsten absorbers and wavelength shifting fibres transmitting data to GaInP photodetectors. A more ambitious alternative design is an integrated High Granularity Calorimeter with silicon sampling layers and brass/copper absorbing layers which would provide essentially particle flow calorimetry, including at the trigger level. A series of R&D issues have been identified for both alternatives and the hope is to have made sufficient progress in the coming year to be able to focus the final phase of R&D on only one of the two options.

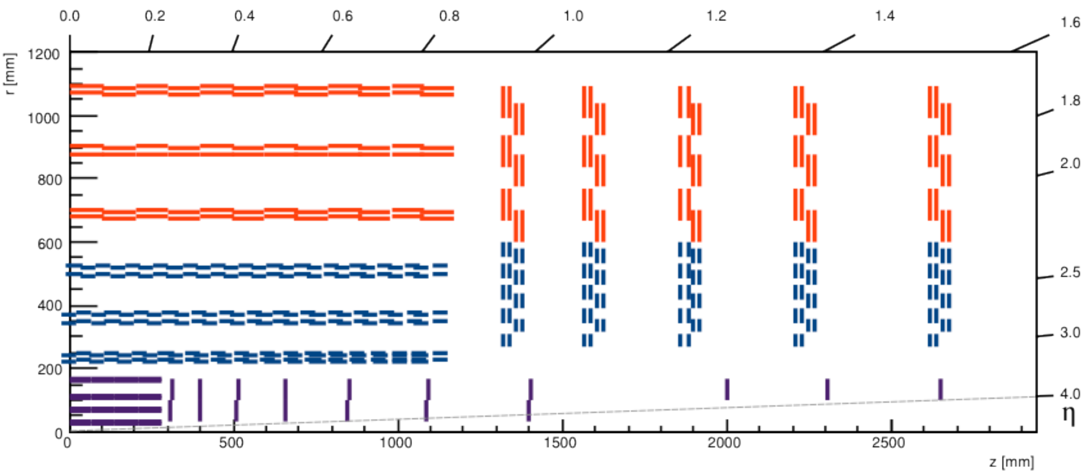

Figure 2.2: A quadrant of the Tracker layout. Outer Tracker: blue lines represent PS-modules, red lines 2S-modules. The Inner Pixel detector, with forward extension, is shown in purple.

The October 2013 RRB received an outline estimate from CMS broadly justifying the physics and technical objectives and providing a cost estimate amounting to 270 MCHF, plus R&D. In the absence of further guidance from CERN or elsewhere, this remains the current target. At the most recent RRB in April, several agencies including STFC again emphasised their concern for clearer global view from CERN of the detector upgrade programme and the strategy for Phase II so that they could discuss what could be accommodated in their planning. This is certainly causing some concern in the experiments, and CERN has not stated its position, as it is thought that a cap on funding is undesirable because of possible "premature" downscoping until more studies have been completed. It is also unclear what the position of other agencies is, both among non-member and other member states, some of whom should contribute substantially more than the UK, or even many of the European agencies combined.

2.3 UK adaptation to CMS planning

The uncertainties in the Phase I trigger project concern adaptation of the schedule to delays in deliverables from the US. The UK has maintained its progress and remains capable of delivering the whole of the calorimeter trigger based on MP7s, which we have regularly offered to CMS. This includes work on optical patch panels, several of which are needed for both the Stage 1 and TDR trigger to transmit data between TPGs and different layers of the trigger. Actually, all the work and most of the planning has been provided by the UK, with little input from others.

The most crucial question, affecting both Stage 1 and the TDR trigger, is what will happen if milestones continue to be missed. Stage 1 has a three week window from 28 April to demonstrate successful integration of the oRSCs with the MP7. This ought to be relatively simple since all the UK-developed firmware has been freely available in open access repositories, and only requires adaption to the oRSC.

The second major milestone is the slice test which should demonstrate full and correct data transmission through a vertical slice of the trigger, from calorimeter sources to the Global Trigger. Again, much of the work for this has already been undertaken and successfully delivered by the UK, and we await the demonstration of working CTP7s, the delivery of various patch panels and optical infrastructure, and the final links to the GT. Once this test is successfully concluded, the green light for CTP7 manufacture can be given and the schedule then again depends on successful deliveries from the US.

Regarding the Phase II upgrades, the specifications for the future tracker have changed relatively recently in an important way. A final objective of L1 readout at rates up to 1MHz and a latency of 10-20 μs is yet to be confirmed, which should take place in June. The highest L1 rate can be accommodated in the CBC with changes to the logic to increase readout rate, but the extension of the latency will enlarge the chip, and add more material and power to the tracker, although affecting the

PS ASIC design more than the 2S and CBC. However, the high L1 trigger rate and latency do have implications for the rest of CMS, especially for the ECAL and end-cap muon electronics, which are not completely understood, hence the requirement to clarify these points. We do not want to commit to a design which requires more resources, including submission costs, then to find the effort and size are wasted, nor to be incompatible with other parts of CMS.

2.4 Simulation studies

An area which overlaps both WP2 and WP3 activities is simulation studies. There is a significant effort in WP3 concerning the performance of the Phase I trigger which mainly involves university and RAL PPD effort. These are not counted under the upgrade project heading for financial reporting purposes but certainly at present are extremely important in maintaining the case for the TDR trigger and demonstrating the importance of the final calorimeter trigger to CMS physics. In addition, these studies should demonstrate the power of new algorithms which must be implemented in firmware.

Conversely, the algorithms should be identical to those which can be implemented in firmware and which are currently still being fully defined by the upgrade project team, and emulators written to match. The Virtex-7 firmware is challenging (and the UK is probably the only team which properly understands the implications of this, because it is the only one which has actually built working trigger firmware for the Virtex-7) as the Xilinx design tools are not yet as mature as for previous FPGA generations and the choice of algorithm architecture and design has an immense influence on the FPGA resources, and build times. It is easily possible to define algorithms which simply exceed the FPGA resources, or fail to synthesise, and one of the important arguments for the Time Multiplexed architecture is the potential for defining algorithms which are much better matched to implementation in an FPGA and profit from the sequential and parallel processing.

For the future, there are a couple of important topical areas which are under study. One is the verification of pT-stub rates in the new tracker to ensure that local data rates are within the capacity of the proposed links to the 2S-modules (and PS-modules), especially in view of the increased latency and L1 trigger rates now foreseen in CMS. The second concerns the architecture to be adopted for L1 track finding in the future trigger, where several alternatives have been proposed.

A proposal from FNAL and Pisa involves the use of custom Associative Memory ASICs, to be loaded with track patterns corresponding to regions of the new tracker, and subsequent improvement of the final parameters in an FPGA. The UK has proposed a Time Multiplexed architecture, based only on track finding in FPGAs, which appears to be very elegant and practical. Both alternatives, and possible variations, require simulation studies to evaluate the potential performance and bottlenecks, especially of the likely latency and subsequent processing of data in combination with the calorimeter and muon triggers. Brunel have been studying track stub data rates for trigger tower tests proposed by Fermilab and have extended these studies to the time-multiplexed trigger proposals made by Imperial.

In the next few months we expect a larger effort on these studies from new students and staff in all the UK institutes, hopefully validating the TMT approach. This could be crucial for the future, and UK leadership, since the TMT is the only architecture which can be evaluated using existing hardware, and the MP7 already has performance sufficient to handle future track-trigger data rates, even though performance gains are expected from further technological progress.

3. Work Package 1: Management

A reminder of the project management is included below. One recent change is that one of the support staff (P. Brambilla) we relied on for placing orders and recording travel and all financial transactions has recently retired. An advertisement for a replacement is open and a temporary replacement may be available for a few months.

Alex Tapper relinquished the post of Trigger Upgrade Project Manager in January, at the end of his term. After discussions, we felt it was more important to concentrate for a period on the delivery of the UK trigger, rather than be loaded with global CMS responsibilities.

WP	Manager	Institute	Role
1	G Hall, PI	Imperial	Overall management, budgetary responsibility and supervising procurements, interface to CMS, as UK CMS PI and CMS Management Board and Tracker Management Board member.
2	M Raymond	Imperial	Overall responsible for CBC specifications, interface to module design team, chip testing and module evaluation and CMS planning
	M Prydderch	RAL TD	Manager of ASIC design team in RAL
3	A Tapper	Imperial	Based in CERN with supervisory responsibilities for G. Iles, Imperial College engineer, also based in CERN.
	D Newbold	Bristol	UK firmware and software coordinator. Trigger Institution Board chair.

4. Work Package 2: Outer Tracker Readout

4.1 Objectives

The objectives of work package 2 as stated in the proposal are:

- To complete development of a readout and triggering chip suitable for the 2S-PT module, bringing the chip to a final state ready for mass production.
- To develop the hardware and software required for the large-scale production testing procedures, and to deliver tested wafers to the CMS experiment.
- To play a major role in construction, definition and evaluation of prototype modules.
- To contribute to development of ancillary chips required for the 2S-PT module, and to participate in the PS-PT module development.
- To contribute to the future large-scale module production programme, and to participate in integration and commissioning activities.

The 2S-PT module concept meets the HL-LHC challenge of providing tracking information to the level 1 trigger decision in CMS by providing coordinates of high pT stubs formed by correlating signals occurring in closely spaced sensor layers. The final deliverable of the previous programme, the CBC2, is a 130 nm prototype CMOS chip containing all the functionality required to allow prototype 2S-PT modules to be constructed.

4.2 Progress to date

CBC and 2S-module developments

The CBC2 main features are:

- 254 readout channels to allow correlation between two sets of 127 sensor channels
- Cluster width discrimination logic: wide clusters cannot be consistent with high p_T tracks
- Correlation logic: A prompt trigger pulse is produced if a cluster in one layer correlates with one found within a window in the other layer
- Coarse pitch bump-bond layout, aimed at inexpensive commercial assembly.

The CBC2 chip works well, as reported last time. Of the eight delivered wafers, two have been probe-tested so far, with a yield in excess of 95%. These have been diced to provide chips for prototype hybrid and module construction.

Our CERN collaborators have primary responsibility for hybrid design and procurement, with the goal of finding manufacturers who can meet the demanding specifications for the front end hybrids which must be produced for both 2S and PS systems. “Flex-rigid” prototypes were produced with Endicott (USA) and have been used successfully to construct 5 mini-pT modules (October 2013 OSC report), although the fragility of these hybrids leads to a loss of channels during the module assembly process. Three modules have been produced using Infineon P-on-N type sensors (strip length 5 cm, pitch 80 μm) and two using CNM N-on-P type (strip length 5 cm, pitch 90 μm). N-on-P type sensors have now been chosen as the preferred variety for use in HL-LHC.

One of the CNM modules with all channels fully working, and one of the Infineon modules (small localized patch of non-working channels) were operated in a DESY test beam in November 2013. Figure 4.1 shows the inside of one of the mini-pT module boxes, which houses the 2CBC2 hybrid based pT mini-module and its associated interface board. These modules were designed, built and tested in the UK. Figure 4.2 shows two modules mounted in the Datura telescope at DESY, the upstream CNM module being mounted on a rotation stage.

The DESY test beam campaign was an international collaborative effort, with M.Pesaresi (UK) as the overall coordinator, and personnel from all of the UK WP2 institutes playing active roles. The control and DAQ was based on the CERN GLIB card emulating the GBT functionality. The DAQ firmware and software was the primary responsibility of Strasbourg, with significant contributions from the UK.

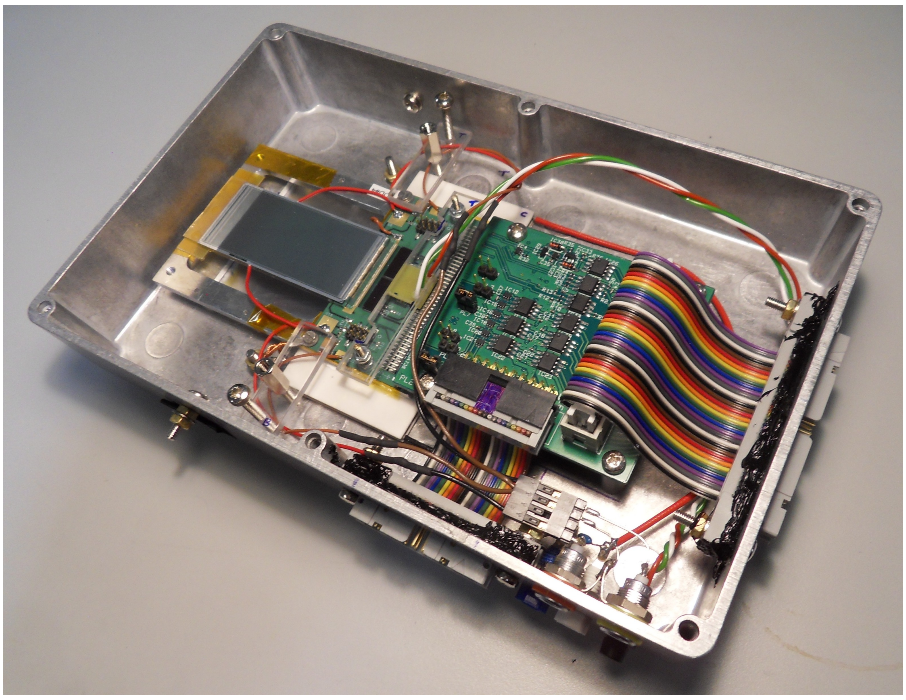

Figure 4.1. Beam test pT mini-module mounted in its box

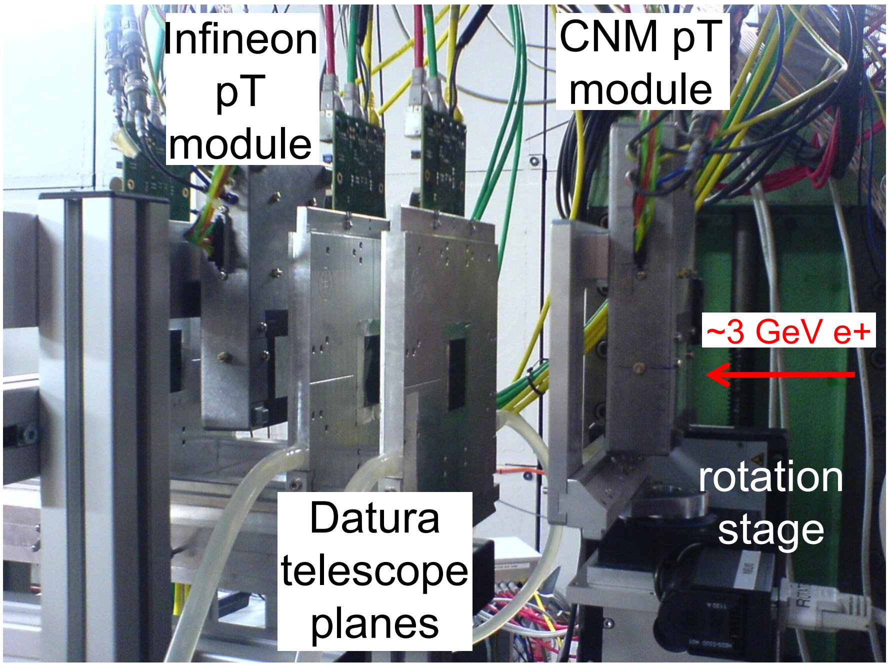

Figure 4.2. Mini-pT modules mounted in Datura telescope

Analysis of the test beam results is ongoing, and figure 4.3 shows some early results. Figure 4.3a shows the ~3GeV positron beam profile in one of the sensors in the CNM sensor module. Figure 4.3b shows the detection efficiency dependence on beam incident angle for the CNM module mounted on the rotating stage, which emulates the effect of magnetic field on the particle trajectory. Translating the incident angle scale into equivalent p_T for a particle traversing a 75 cm radius layer in the 4T CMS magnetic field gives the result in figure 4.3c, where the correlation logic operation can be seen to give rise to an effective p_T cut of 2.2 GeV/c.

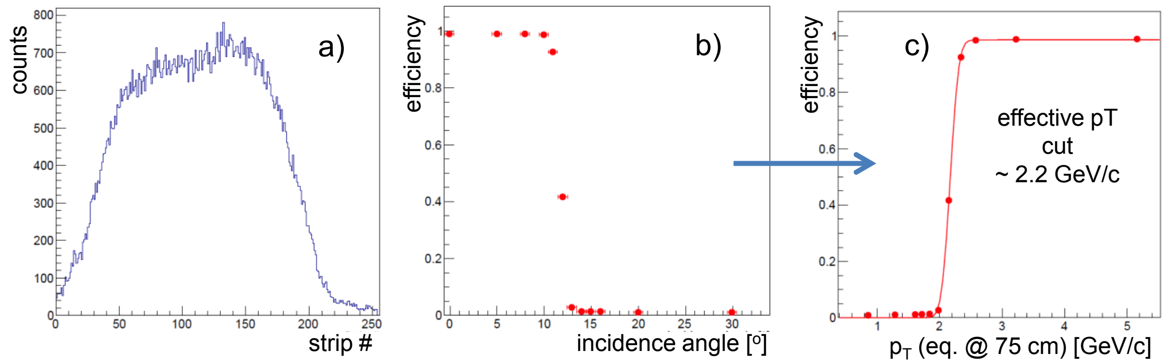

Figure 4.3. a) beam profile in CNM sensor. b) efficiency dependence on beam incidence angle CNM pT mini-module. c) incidence angle translated to equivalent p_T for a particle traversing a 75 cm radius layer

The flex-rigid 2-chip CBC2 hybrids are actually a lot more flexible than is desirable and it is to this that the problems of faulty and lost channels after module construction have been attributed. An alternative development using a fully flexible technology addresses this problem because the flex is glued to a carbon fibre support, achieving a fully rigid structure before the chips are mounted. The CBC inputs are tracked to two arrays of wire-bond pads, the further array appearing on the other side of the support piece when the hybrid is wrapped around the edge and glued. A significant advantage of this approach is that the carbon fibre thickness can be chosen to match the desired sensor spacing, which varies depending on where the module is located within the tracker.

The first populated prototypes of the 8-chip CBC2flex hybrid have recently been delivered (figure 4.4). With 8 CBC2 chips mounted, two of these hybrids can be used to construct a full-size prototype pT module. Electrical characterization of the hybrids has only just begun, but early results look promising.

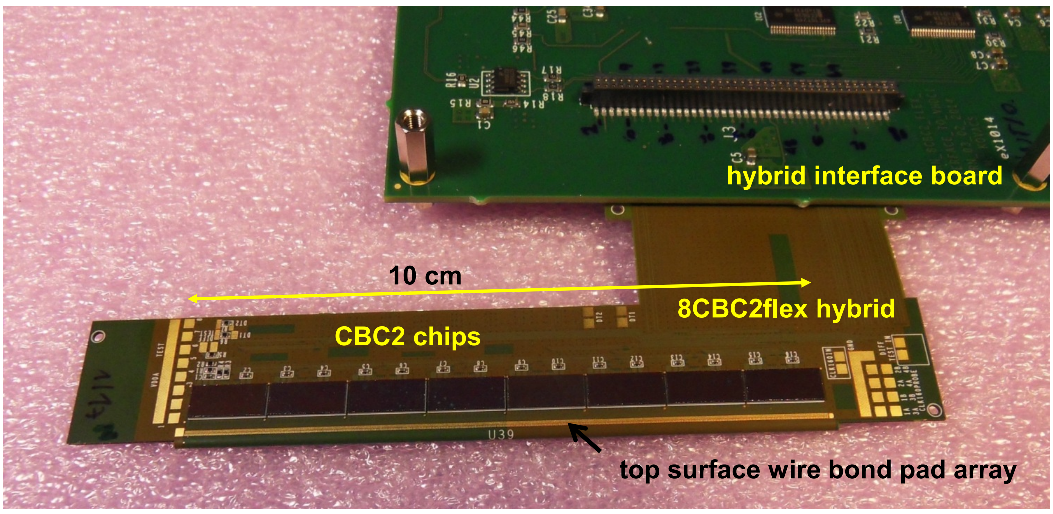

Figure 4.4. 8-chip CBC2flex hybrid under test

Hybrid and module testing has consumed more effort than expected, especially the investigations of the problem channels occurring for the 2-chip CBC2 hybrids. The ionizing and SEU effect irradiation tests of the chip have been delayed. We are still in the planning stage for an SEU study using a proton beam at Louvain which we hope to perform in the second half of this year. Ionizing radiation tests of the CBC2 have begun with a preliminary room temperature irradiation of one chip using an X-ray machine at the Diamond facility. Chip performance was constantly monitored and unaffected up to 10 Mrad, where irradiation stopped, but an unexpected increase in supply current was observed. The increase was affected by dose rate, and the total chip current was observed to fall to pre-irradiation levels a few hours after irradiation stopped, so may not be observable at HL-LHC dose rates. Nevertheless the cause of the current increase is not understood and a follow-up irradiation is planned where the chip will be operated cold (to see whether this affects the annealing behaviour) and extra diagnostics will be included to help isolate the origin of the effect.

Bristol agreed to take responsibility for provision of a test stand which could be adapted to different versions of the CBC hybrids. This could then be used for evaluation studies of the hybrids, and later for acceptance testing of pre-production and production hybrids and modules. It is essential that this requires minimal specialist software capabilities to allow its use by those non-expert in the CMS DAQ so a self-contained software suite is required with built-in test procedures, ideally compatible with wider Tracker DAQ developments which will be deployed in beam tests and full scale studies. Use of the GLIB initially and later the UK FC7 permits a flexible, adaptable system to be assembled.

The first version of the test stand has been commissioned at Bristol with 2-chip CBC2 hybrids, now also being used by CERN. An FMC for the 8-chip CBC2 test stand has been prototyped, and a revised version should be in hand imminently. Firmware and software for the 8-chip CBC2 stand should be commissioned shortly, and a new version of the test stand with improved interface and functionality is due soon.

As explained in the last report, the success of the CBC2 has allowed us to postpone the design and production of the next version of the chip until all requirements for HL-LHC CMS operation (e.g. level 1 latency and trigger rate) are defined. The latency will probably be fixed at 10 μs and we foresee that the trigger rate capability of the CBC3 can be increased to beyond 1 MHz, which are likely to be the CMS specifications. Readout data sparsification becomes unavoidable at high trigger rates, but this can be implemented in the concentrator ASIC which receives trigger and readout data from the CBC chips and assembles the data into packets which are then passed on to the GBT. Some advantages to this architecture are that the CBCs can remain synchronous (which can be verified by the concentrator), some functions are performed only once (e.g. time-stamping), and the purely digital functionality of the concentrator can be implemented in low power 65 nm technology. The concentrator functionality is under study and development at Universite Claude Bernard - Lyon, and is discussed in our regular system meetings.

Design of the CBC3 is beginning, with a view to submitting the chip for manufacture in the second half of 2015, thus we can expect to have chips in hand by the summer of 2016.

FC7 developments

The FC7 (FMC carrier - Xilinx Series 7) is based on the MP7 and CERN GLIB cards with the ability to host up to two FMC (FPGA Mezzanine Card) modules and support signaling rates up to 10 Gbps. It is a flexible, general purpose card allowing it to be deployed across many applications in CMS and its development has been shared with CERN-PH/ESE engineers who are now taking responsibility for distribution and support. The board will form the basis of a scalable DAQ system both for testing of the CBC2 and for readout of PT-module prototypes.

After a successful prototyping run in August 2013, the design was resubmitted to two different manufacturers (Exception-PCB [UK], Hapro [Norway]) with minor changes. This shared submission was intended to act as both as a pre-production run before production in 2014, but also as a means of surveying different manufacturers, which was especially desirable in view of the imminent MP7 production. Both pre-production runs have been successful, with an especially high manufacturing quality demonstrated by Hapro. As a result, CERN placed an order with them in February for the manufacture of 70 boards to satisfy the requirements of the CMS TCDS (Trigger Control and Distribution System: the CMS TTC upgrade) project.

In the meantime the pre-production boards have been used to develop a semi-automated test stand, including hardware (loopback cards, FMCs, GPIB oscilloscopes) and appropriate test firmware and software, so that cards from future production runs can be rapidly qualified for use. Firmware that encapsulates the board and system functionality has been written and documented, allowing casual developers to easily integrate their own user firmware to adapt the board for their own purposes. Basic software has been made available allowing users to take advantage of some of the more advanced features of the FC7, such as remote firmware loading over IPbus and remote configuration of the FMC power and clock distribution tree.

Some pre-production FC7 cards have now been distributed to selected users requiring priority access to the boards for their developments (CMS TCDS and Phase I pixel FED upgrades). These first users are also able to provide important feedback regarding the board functionality and system stability. In the UK, we plan to start development of the DAQ for CBC and module testing, eventually replacing the role of the GLIB.

The FC7 development has proved timely in another way, which has been to explore the manufacturing of such boards. Both the FC7 and MP7 rely on very high speed signal transmission, which requires special attention to signal delays across the board and the use of PCB materials with specific dielectric constants and care in the orientation of weave of the layers, and thickness and track dimensions. Several problems were encountered with MP7 manufacture and it was not always clear if they should be attributed to design or control of the manufacturing process. Some of the specifications are demanding, including great care in some mechanical tolerances so that boards fit into the µTCA crates; one particular area of the FC7 and MP7 requires cutting to better than 50µm precision.

The first pair of FC7s made by Exception PCB appeared to be very successful in July 2013, but a subsequent order experienced significant problems, both in assembly quality and the PCB itself. The special material, NELCO, is known by now to require attention to moisture control and baking times, and can be subject to blistering or delamination whose precise causes can be hard to isolate later if they occur.

Because of the manufacturing problems, CERN placed an order with a Norwegian company, Hapro, in December 2013, who sub-contracted their PCBs to a Chinese company. Initially it appeared that meeting the lay-up requirements in China would be difficult, so another order was placed with Exception by us using an alternative PCB material when it seemed that their manufacturing issues had been addressed, in view of the urgency of constructing successful boards for the TCDS project, as well as the later production contracts for the MP7 which were due in early 2014.

When the FC7 deliveries arrived, which were within a week of one another in late January, both manufacturers had succeeded. A few very minor issues were identified with the FC7 but the board production was generally of very high quality. This then allowed us to place contracts for MP7 production with the leading bidders which were, by good fortune in a competitive tender, the two companies with whom we had the most experience.

4.3 Deliverables

One of our milestones is to provide documented CBC2 detailed test results, which is achieved by presentations at CMS collaboration meetings[1] including the recent ATLAS/CMS Electronics Workshop for LHC Upgrades (ACES 2014). Also the CBC2 test results paper presented at TWEPP 2013 is now published[2]. There continues to be progress in defining the system specifications, which becomes more important as the delayed design phase of the next version of the chip commences.

The LHC upgrade schedule has evolved since the time of the proposal and the shutdown period LS3 is now scheduled to commence in 2023, one year later than originally foreseen. CMS tracker front end chip requirements have also evolved requiring extra features in the CBC3 beyond those originally envisaged. A longer pipeline is now proposed and the trigger rate capability requirement has increased from 100 kHz to 0.5-1MHz. While successful bump-bonding to hybrids has been demonstrated it has become clear that the bonding pitch is sufficiently fine that the demands on tracking and via pitches are at the limit of what can be achieved, and so we are considering increasing the pad pitch for the CBC3, which is a significant change to the layout. With these developments in mind the Work Breakdown Structure prepared at the time of the proposal has been reviewed and modified to accommodate these changes.

The WBS shown below includes the original dates together with revised dates shown in red. The main changes are:

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[1] http://www.hep.ph.ic.ac.uk/~dmray/CBC_documentation
[2] http://iopscience.iop.org/1748-0221/9/03/C03001/pdf/1748-0221/9/03/C03001.pdf

- The final deliverable is a chip ready for mass production by end 2018. Production phase activities now commence beyond the period of this proposal.
- The CBC3 design phase begins later and lasts 6 months longer to accommodate the extra features required.
- The CBC3 test phase has been shortened by 6 months, and the final CBC4 design phase has been shortened from 6 to 3 months. We will keep the durations and scope of these activities under review as developments progress, and the overall CMS and LHC schedules evolve. If necessary, we can seek help from our external collaborators to expedite the test activities.

4.4 Staff on project

Unchanged since the last report.

4.5 Expenditure

The major expenditure in the last period has been staff costs at RAL, as usual, and on FC7 manufacture.

WBS	WBS L2	Start	Finish	Months	Task Description
2	Phase II tracker Readout	04/13	09/21	102	
2.1	**system**	04/13	03/14	12	**definition of the CBC-based SS-Pt module readout**
	2.1.1 specification definition	04/13	03/14	12	regular meetings with CMS collaborators to define overall system specification and interfaces
2.2	**CBC2 test**	04/13	03/15	24	**CBC2 is final deliverable of the UK upgrade R&D**
	2.2.1 CBC2 ongoing testing	04/13	03/14	12	complete the detailed studies of the CBC2 chip, including irradiation and SEU tests
	2.2.2 CBC2 SS-Pt module prototype studies	04/13	03/15	24	a programme of SS-Pt module studies, in collaboration with CMS, including test beam
2.3	**CBC3**	04/13	09/14	18	**CBC3 is specified for the final system**
		04/14	**03/16**	**24**	**extra 6 months**
	2.3.1 CBC3 design	04/13	03/14	12	design period
		04/14	**09/15**	**18**	**extra 6 months design period**
	2.3.2 CBC3 production	03/14	09/14	6	production period
		09/15	**03/16**		
	2.3.3 test setup preparation	03/14	09/14	6	wafer and chip test setup preparation
		09/15	**03/16**		
2.4	**CBC3 test**	09/14	03/17	30	**CBC3 chip and module testing**
		03/16	**03/18**	**24**	**6 month shorter overall test period**
	2.4.1 early tests	09/14	03/15	6	chip verification tests to prior to module tests
		03/16	**09/16**		
	2.4.2 ongoing testing	03/15	09/15	6	complete characterization, including irradiation and SEU tests
		09/16	**03/17**		
	2.4.3 CBC3 SS-Pt module studies	03/15	03/17	24	CBC3 based module studies in collaboration
		09/16	**03/18**	**18**	with CMS in lab and test beam (**shorter test phase**)
2.5	**CBC4 design and test**	03/15	09/16	18	**CBC4 is the final version of the chip, fixing any**
		09/16	**12/17**	**15**	**remaining bugs found in the CBC3**
	2.5.1 CBC4 design	03/15	09/15	6	design period
		09/16	**12/16**	**3**	**shorter design period**
	2.5.2 CBC4 production	09/15	03/16	6	production period
		01/17	**06/17**	6	
	2.5.3 testing	03/16	09/16	6	tests to verify full and final functionality
		07/17	**12/17**	6	
2.6	**CBC4 mass production preparations**	09/16	12/17	15	**a full wafer engineering run is required for**
		01/18	**12/18**	**12**	**CBC4 in preparation for mass production**
	2.6.1 CBC4 final masks	09/16	03/17	6	mask preparation for full wafer engineering run
		12/18	**03/18**	**3**	**reduce mask preparation period by 3 months**
	2.6.2 CBC4 engineering run	03/17	09/17	6	production period
		03/18	**09/18**	6	
	2.6.3 CBC4 final production readiness verification tests	09/17	12/17	3	final functionality check
		09/18	**12/18**	3	
	2.6.4 procurement planning	01/17	12/17	12	detailed financial plans for mass production
		01/18	**12/18**	12	

5. Work Package 3: Level-1 Trigger

5.1 Objectives

- Improvement of the current CMS calorimeter trigger in preparation for above-design-luminosity conditions.
- Provision of infrastructure to allow testing of an entirely new calorimeter trigger in parallel with the existing system.
- Design, construction and testing of a time-multiplexed hardware trigger for CMS, capable of implementing new and more selective algorithms.
- Design of a track trigger architecture for HL-LHC running, and construction of a technology demonstrator.

5.2 Progress to date

Building on the successful test of the time-multiplexed calorimeter trigger in September 2013 the focus has been on preparations for the production trigger system.

Orders have been placed with two companies, following a CERN tender procedure, for the MP7 cards required for the final trigger system. Two companies were chosen to mitigate risk, given the quality control problems observed in the manufacture of the pre-production cards, and partly because the two leading bids were within less than 3% of each other, while the rest were significantly higher. To further mitigate risk the MP7 cards will be delivered in batches of two, then four and finally 10 cards from each supplier, with a testing sign-off before the production of each subsequent batch. The first of these batches has been received and is under test (see Fig 5.1). A comprehensive bench-top test system has been developed with hardware, software and firmware components to allow thorough and prompt testing as the cards arrive.

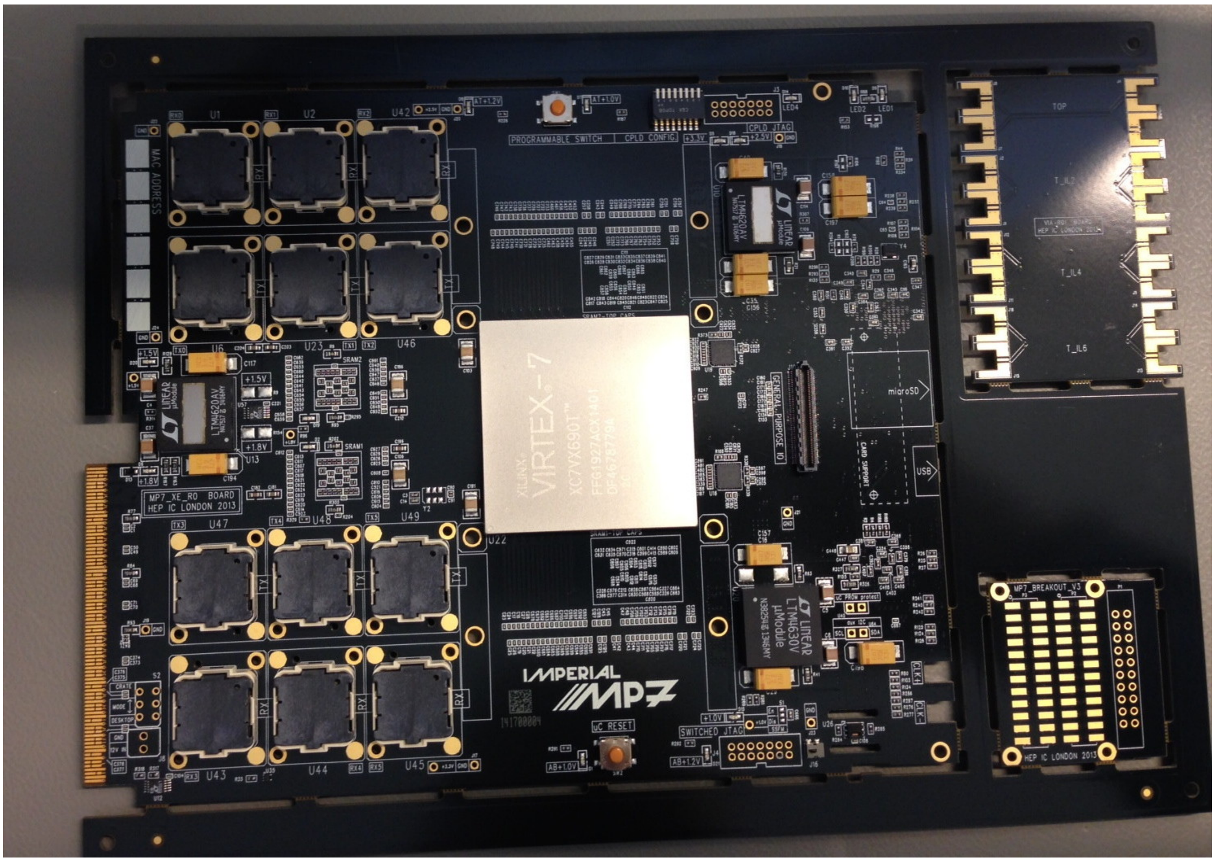

Fig. 5.1. The top side of the first production version of the MP7

The optical patch panel required to connect the two layers of the calorimeter trigger has been designed by Tim Durkin at RAL and prototype components procured and tested. In a change to the anticipated design, custom components organised in standard cassettes have been chosen to reduce the complexity of installation and improve the robustness of the many connections. Rack space in the CMS electronics cavern has been allocated and we expect to place orders for the patch panel components and the required µTCA crates very soon.

Pre-production MP7 cards have been distributed to our close collaborators at LLR and Vienna. They have also been provided with supporting documentation and core software and firmware to control the cards. In addition we have built up a facility in the CMS electronics integration lab in Prevessin where other collaborators may use shared MP7 cards for their own development. Groups from the US, Austria and Greece are amongst the users of this facility.

Updates to the UK-developed IPbus control system for µTCA have been released. This is the CMS-wide standard for upgraded systems, and has also been adopted by other collaborations and experiments (including ATLAS). Work has continued at a modest level on optimisation of the system to achieve higher bandwidths and bug fixing. A stress test of the IPbus system was performed under realistic conditions at CERN, with a full crate of µTCA cards. Results showed good performance and indicated areas where improvement may be possible.

A noteworthy point is that the UK is at the forefront of using µTCA in CMS. This means that a number of general issues are being confronted in addition to items which are specific to the MP7 and the calorimeter trigger. Examples are the evaluation of µTCA infrastructure at RAL using the facilities set up for this purpose, which allows many combinations of hardware to be tested which is important to anticipate potential problems which would otherwise emerge only during implementation at Point 5.

Since the LHC has been out of operation, the computers used for trigger control had been replaced and several key software packages changed. The GCT, the current UK commitment to the "legacy" CMS Calorimeter Trigger, ran successfully in the first CMS cosmic-ray muon run for a week in April. This is the initial baseline for the L1 trigger in 2015 when, until luminosity rises above the level reached in 2012 improvements in the trigger performance are not essential but the highest priority is to have a reliable, well understood trigger while commissioning an upgraded trigger in parallel, as explained in the Trigger Upgrade TDR.

The Imperial group has continued development, now in collaboration with the CERN group, on jet-finding algorithm studies to enable the estimation of the energy contributed by pile-up interactions, on an event-by-event basis, and subtract this from the trigger objects. This gives very significant improvements in performance for multi-jet and H_T triggers. Baseline versions of the algorithm have been implemented in software and firmware and testing and debugging work is currently the focus.

The RAL group are developing improved trigger algorithms for electrons and photons in collaboration with LLR. The focus of the RAL work is on isolation criteria, requiring pile-up subtraction to allow robust identification of electrons and photons in high luminosity running conditions. Studies prove that using such an algorithm high efficiency for electron and photon triggers can be maintained despite the high levels of pile-up expected in future running. A baseline version of the algorithm has been implemented in software and implementation in firmware is in progress.

The Bristol and Imperial groups, working with the Ohio State group, are studying expected rates and thresholds for different trigger objects under different LHC operating conditions. The aim of this work is to study LHC scenarios after the Phase II upgrades, and in particular to study the benefits of increased trigger bandwidth and a tracking trigger for CMS. The studies were presented at the CMS Upgrades Meeting in Karlsruhe in March and will be included in the CMS Technical Proposal for Phase II upgrades expected to be released this Summer.

Activity is underway on planning the next phase of the trigger upgrade, including tracking information. The UK groups are working closely with other CMS groups, for example, FNAL and CERN, to make detailed studies of the data volume and bandwidth requirements. An initial outline of an architecture and a hardware demonstrator system based on the time-multiplexed trigger design has been presented to CMS and studies continue. As this work is everywhere at an early stage and there is plenty of room for ideas and technological progress, e.g. in FPGAs and high speed links it is unlikely that this will be described in detail in the CMS Technical Proposal, but it is essential to validate many of the ideas relatively soon, since this is crucial element of the CMS trigger strategy and alternatives based on custom hardware, such as Associative Memories, could require significant investment if they are shown to be essential.

5.3 Overview of CMS plans

The trigger upgrade project had an internal CMS Engineering Design Review (EDR) in November at CERN. The report from the review committee was extremely positive about all UK parts of the project.

One of the recommendations of the committee was to review the schedule for the project and determine what changes might be necessary based on current actual progress. The schedule for the UK work was unaffected by the review, however an interim trigger ("Stage 1") proposed for the 2015 LHC run by the US has been reduced in scope and a new schedule developed in reaction to significant delays in the delivery of components from the US. A dedicated project manager, J. Berryhill (FNAL) has been appointed to lead this part of the project, following an internal US review of the Stage 1 project.

Stage 1 was included in the final description of the UK CMS upgrade project work plan which we were asked to submit following approval by the PPRP and prior to endorsement from STFC; it had not been part of the original proposal as the ideas for it were only developed after the proposal had been submitted and essentially only by the US in response to their expected local budgetary constraints. The milestones for Stage 1 were therefore included in our list (M3.1 and M3.3); neither of them has been met by the US although the UK has been ready to carry out our parts of the tests and provided much intellectual property, such as firmware, to allow US deliverables to be validated. Hence the US internal review in January.

The trigger project budget and schedule were reviewed by the LHCC Upgrade Cost Group review in December 2013. The committee recommended approval to the full LHCC committee.

The new CMS management have appointed C. Foudas (Ioannina, Greece) as joint project manager of the CMS L1 trigger project, alongside the incumbent D. Acosta (Florida). Foudas has been instrumental in developing the new trigger plan and schedule. This foresees Stage 1 being completed in March 2015, provided the UK delivers the jet algorithm firmware, which should be possible once the July integration test is complete. The critical path items for both Stage 1 and for the final TDR trigger are US responsibilities; the UK can either mitigate difficulties (for Stage 1) or provide alternatives (MP7s for Layer 1 of the TDR trigger). The UK has also taken leading roles in the improvement of online software and much assistance in all aspects of the project, including links to the Global Trigger.

Work to duplicate the input to the L1 trigger from the ECAL and HCAL, which can only realistically be done during the current shutdown period, is proceeding well with installation currently underway. This was a critical path item. A subset of the trigger using the newly installed links was run without problems in the April cosmic-ray muon run.

The availability of the interface to the CMS data acquisition system, the AMC13 which is to be provided by Boston University, is a source of concern to CMS. Production of the necessary boards is under way after delays due to long component procurement lead times. However the necessary software and firmware is in an immature state. The situation is being monitored carefully and there are various possible workarounds if necessary.

The next major milestone in the project is to test the interconnection of all components of the calorimeter trigger in July. We do not expect problems for the UK deliverables. Data should be sent from the ECAL and HCAL through a full slice of the calorimeter trigger and received by a prototype of the Global Trigger.

5.4 Staff on project

Reported in accompanying tables. A. Thea (RAL) has been appointed online software coordinator for the CMS L1 trigger project. E. Olaiya (RAL) has been appointed CMS L1 trigger simulation contact. A project studentship at Imperial remains open.

5.5 Expenditure

Most of the expenditure to date continues to be committed to MP7 manufacture and component purchases. Overall spending is well within the budget foreseen at this stage.

5.6 Deliverables

The MP7 remains ahead of other comparable developments in both CMS and ATLAS. There are now other prototype electronics boards operating at 10 Gbps from other groups but in small numbers and under initial testing.

The first layer of the calorimeter trigger is planned to be built by the University of Wisconsin, based on cards with the same FPGA as the MP7 but fewer optical links. A prototype is currently under test. The EDR committee report considered this a significant schedule risk.

The deliverable list is appended below. Blue font means complete. Red font is delayed.

L1	L2		Start	Finish	PM	Task description
3.1		**Stage-1 calorimeter trigger upgrade**				
	3.1.1	Hardware development		07/13	6	Finalisation of production hardware module (48-link version)
	3.1.2	Procurement and testing	07/13	10/13	3	Procurement, production and acceptance tests of hardware
	3.1.3	uTCA infrastructure		07/13	6	Completion of baseline IPbus / uHAL
	3.1.4	Online software development	04/13	10/13	6	Development of system-specific and trigger-wide online software (control, monitoring, DAQ)
	3.1.5	Algorithms and offline software	04/13	04/14	12	Development of stage-1 algorithms and corresponding emulator and DQM software
	3.1.6	Integration	07/13	01/14	6	Integration tests with other trigger components, DAQ, TTC
	3.1.7	Commissioning	09/14	03/15	6	Commissioning with cosmics and beam
	3.1.8	Support	03/15	01/16	9	Ongoing expert support and optimisation of Stage-1 system
3.2		**Stage-2 calorimeter trigger (TMT) upgrade**				
	3.2.1	Hardware development	10/13	04/14	6	Development and finalisation of production hardware module (72-link version)
	3.2.2	Procurement and testing	04/14	10/14	6	Procurement, production and acceptance tests of hardware
	3.2.3	Online software development	10/13	04/14	6	Development of system-specific and trigger-wide online software (control, monitoring, DAQ)
	3.2.4	Algorithms and offline software	04/14	04/15	12	Development of stage-2 algorithms and corresponding emulator and DQM software
	3.2.5	Integration	04/14	10/14	6	Integration tests with other trigger components, DAQ, TTC
	3.2.6	Commissioning	04/15	04/16	12	Commissioning with cosmics and beam
	3.2.7	Support	04/16	04/19	36	Ongoing expert support and optimisation of stage-2 system
3.3		**Post-LS3 trigger R&D**				
	3.3.1	Design studies	04/13	10/14	18	Simulation studies of track trigger performance, and decision on final concept
	3.3.2	Dataflow design	10/14	10/15	12	Detailed simulation, architecture design and technology choices for track trigger
	3.3.3	Hardware development	04/16	10/17	18	Development of next-generation hardware modules for integrated L1 trigger
	3.3.4	Algorithms and offline software	10/15	04/17	18	Development of algorithms and firmware for integrated L1 trigger
	3.3.5	Integration and demonstration	10/17	10/18	12	Hardware slice test of integrated L1 trigger
	3.3.6	Final system design	10/18	04/19	6	Production planning for final version of integrated L1 trigger

Deliverables 3.1.1-3.1.3 are complete. We have made substantial contributions to 3.1.4 but do not regard it as complete. 3.1.5 is not a UK responsibility, but we have agreed to deliver the jet algorithms

once the July integration test is complete; it is expected to require up to 3 months from G. Iles. 3.1.5 relies on the US part to be completed; it should be done by the end of May unless new problems emerge with oRSC firmware. The remaining milestones are approximately consistent with the new overall trigger schedule.

Deliverable 3.2.1 is complete and the others remain on schedule, including those for longer term R&D.

7 Risk register

There has not been a recent review of the risk register. The issues which cause concern have been described in the report and are not inconsistent with risks in the register. UK funds are sufficient to address the issues of timely delivery but can only be deployed if CMS chooses.

8 Finances

At the time of writing, the financial information is being prepared and inserted into a modified spreadsheet, as proposed by STFC. The question of how to account the "existing project costs" which is Consolidated Grant or existing RAL PPD staff effort correctly is still causing a little concern. However, the effort being delivered to the project from those resources is essentially what was foreseen; the issue is computing its numerical value correctly. There is also a minor question about the proportion of RAL staff costs reported in SBS which is overheads.

In addition to invoiced expenditure, there are outstanding commitments made via CERN orders, which are proving to be the largest part of the costs, unsurprisingly, as the developments are intended to be installed in CERN, and the lead engineer on the trigger project, G. Iles, is based in CERN on LTA to operate and maintain the present GCT, and to develop, install and commission the new trigger within this project. The second major item of expenditure routed through CERN has been the ASIC fabrication runs, none of which have yet been repeated in the present grant period.

Until recently the CERN orders were paid from the CMS team account and routed via RAL to SBS. The costs were then invoiced to Imperial College where the grant funds are held and repaid at regular intervals. In future, from this financial year onwards, it is planned for Imperial College to pay CERN invoices directly. This will be discussed with the OSC.

9 Gantt charts

The most recent Gantt chart for the trigger project is included. There is no update on the Phase II tracker planning.

10 Milestones

The deliverables from each work package are listed below. The milestones which were due have been highlighted in red font, or met in blue, and further comments on their status follows below.

Deliverable	Date	Description
M2.1	PM12	System specification document produced
M2.2.1	PM12	Documented CBC2 detailed test results
M2.2.2	PM24	Documented 2S-Pt module results
M2.3.1	PM12	CBC3 ready for production
M2.3.2	PM18	CBC3 produced & test setups ready
M2.4.1	PM24	Documented early CBC3 test results
M2.4.2	PM30	Documented CBC3 detailed test results
M2.4.3	PM60	Documented CBC3 2S-Pt module results
M2.5.1	PM42	CBC4 ready for production
M2.5.2	PM48	CBC4 produced
M2.5.3	PM54	Documented CBC4 test results
M2.6.1	PM60	Final production masks prepared
M2.6.3	PM69	CBC4 ready for mass production
M2.7.3	PM72	First production modules available
M3.1	PM9	Stage-1 calorimeter trigger hardware tested and installed
M3.2	PM18	Stage-2 calorimeter trigger hardware tested and installed
M3.3	PM23	Stage-1 calorimeter trigger commissioned & system ready for physics
M3.4	PM30	Post-LS3 trigger dataflow design completed
M3.5	PM35	Stage-2 calorimeter trigger commissioned & system ready for physics
M3.6	PM54	Post-LS3 trigger prototype trigger modules produced and tested
M3.7	PM66	Demonstration of post-LS3 trigger slice
M3.8	PM72	Post-LS3 trigger construction plan delivered

Milestone 2.1 is not complete but is tied to the overall CMS and LHC schedule; however, there has been substantial progress, including many internal documents, and the CMS Technical Proposal in September should allow to sign this off. Milestone 2.2.1 is complete.

Milestone 3.1 is not met and should be due later this year. But other milestones remain intact.