

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

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Table of Contents

Summary.....	2
Request.....	2
Scientific Objectives	2
Project Description.....	6
Strategy and Organisation	8
Work Package Descriptions	9
Deliverables Summary.....	21
Participants and Roles	22
References	24
Resource Request.....	25
Appendix A: Work Package Costs.....	26
Appendix B: Institute Costs.....	29
Appendix C: Gantt Charts	33
Appendix D: Risk Register.....	35

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Summary

To allow deeper investigations of the physics discoveries expected at the LHC, and the challenges presented by the very successful performance of the accelerator, upgrades to some key CMS sub-systems are required in the next few years. In addition, LHC operation is expected to continue for at least a decade longer than the experiments were designed for. Inevitable radiation damage to the tracking detector will require its replacement after 2022 and the new detector must be more granular and radiation hard. It must also perform better in an even harsher environment, with higher pileup of events in each beam crossing, to meet the required physics goals.

The LHC, which is the highest energy machine in the world, is the only accelerator capable of investigating some of the highest priority fundamental physics topics for the foreseeable future. In addition to the hoped for completion of the Standard Model by the discovery of the Higgs boson, it allows us to shed light on many other key questions in particle physics including the nature of dark matter, unification of forces, the existence of fundamental particles and their roles in the origin of the universe. The investment in the LHC programme has been significant and upgrades to the experiments will extend its working lifetime considerably, and improve their performance by taking advantage of technological progress in the last decade.

The most crucial sub-detectors to be modified are the tracker and trigger, in which UK groups have played significant roles and have undertaken successful R&D in recent years. We propose to build on this by delivering a significant part of the new calorimeter trigger system and continuing R&D to incorporate tracking data into the future Level 1 trigger. We will contribute to construction of detector modules for the future tracker by providing major parts of the front end electronics. In each case, the UK will be providing hardware, firmware and software with substantial intellectual input and leadership roles.

These represent substantial contributions to the overall CMS upgrade plan. We request appropriate resources to allow us to undertake these projects. This revised plan is based on provisional recommendations by the PPRP and Science Board.

Request

In summary, our request is for a 72 month project commencing on 1 April 2013, for:

- 61.9 staff-years of new, project-funded effort, including students, at a cost of £2.835M, plus overheads, including £304k to support 3.7 FTE of management and administrative support effort,
- 56.6 staff-years of existing grant-funded or STFC (RAL PPD) supported effort at a total cost of £4.597M including overheads.
- Equipment and consumables costs totalling £1.939M, mainly at 100% under the Instrument Development exception,
- £300k of travel funding, to be spent on travel to CERN, a few conferences and CMS meetings to present progress reports, and a number of Long Term Attachments in CERN to install, integrate and commission the systems in the CMS experiment.
- The total cost of the project amounts to £7.026M of new funding, and £4.597M of existing resources via grants and RAL PPD funding, with a grand total of £11.623M

Scientific Objectives

CMS Scientific Programme

CMS is a general purpose detector for high luminosity LHC operation optimised for Standard Model Higgs searches and a wide range of other physics. The experiment has operated extremely well and productively since LHC operations started in November 2009, accumulating an integrated p-p luminosity of 5.2 fb^{-1} at end 2011 (plus $140 \mu\text{b}^{-1}$ of Pb-Pb data) and 21.8 fb^{-1} by the December 2012 end of year shutdown. Data from p-Pb collisions are currently being taken until March 2013.

The UK delivered important CMS subsystems: parts of the ECAL, Tracker and the Calorimeter Trigger. We have a major role in software for reconstruction and analysis and in development of GRID-based computing, and important physics analysis activities. The UK has played notable roles in CMS and consistently taken leading positions in the overall scientific management.

CMS has an extensive publication list (summarised in the 2012 CMS grant request) with significant, highly cited, UK contributions to the highest profile physics studies, including the Higgs boson search, Supersymmetry and other Beyond Standard Model physics. CMS will shed light on the origin of mass and many objectives in the STFC Roadmap, including the nature of dark matter, unification of forces, the existence of fundamental particles and their roles in the origin of the universe.

As is now well known, in 2012 the LHC discovered a new boson with a mass of ~ 125 GeV which is consistent with the Standard Model Higgs, but this is the beginning, not the end, of the programme which comprises searches for new physics and the detailed characterisation of discoveries.

This major discovery certainly requires more data, optimal selection of events at the Level-1 trigger and flexibility to adapt to new conditions. The properties of the new particle (mass, couplings, spin) must be measured to establish its identity. This necessitates production and decay measurements in a variety of modes. Difficult but important signatures such as decays to bottom-quark and tau-lepton pairs or invisible decays require the analysis of Vector Boson Fusion (VBF) and associated production modes.

Thus, much further work is needed to verify whether the sighting is the simplest SM object or, e.g., a SUSY version. Compiling evidence on the nature of the signal will necessitate focused studies and careful design of trigger menus. SUSY observations, not so far evident, require similar detailed scrutiny to verify and begin spectroscopy studies. CMS is constantly extending the mass limits for new vector bosons and other objects. Absence of a clear indication of SUSY or other new physics, or ambiguity in its origin, will raise pressure to evaluate data even more carefully and ensure that no omissions have occurred at any stage of the L1 and higher level trigger.

From 2015 onwards we expect to approach and exceed the design luminosity of the LHC. A light Higgs boson requires the trigger to keep low enough thresholds to make accurate measurements of its properties. Thresholds must stay similar to current values to benefit from future higher luminosity running. The effect of pile-up on trigger rates for key channels will be very challenging, for example:

- For WH associated production, with a trigger on the W to examine Higgs properties without bias, a single lepton would be the simplest trigger. Thresholds will rise to at least 30 GeV/c transverse momentum, which cuts deeply into efficiency, at 8 TeV centre of mass energy.
- H to b-bar and to tau-tau measurements are needed to determine the Higgs couplings, which may only be possible with the help of the characteristic VBF production topology. This requires triggering on correlations between jets including forward jets, where pileup will be extreme.

In the even longer term, Standard Model predictions are expected to diverge from observations, and we expect thousands of fb^{-1} of data. Studies may include improvement of coupling measurements, determination of SUSY parameters and sparticle spectroscopy. Extension of current searches to higher masses for composite quarks, new heavy gauge bosons, multi-TeV squarks and gluinos, and extra dimensions will be possible. Searches for rare processes such as FCNC top decays, Higgs-pair production or multi gauge boson production will be improved. UK groups are currently playing very significant roles in highly topical physics areas including Higgs, SUSY and Exotica searches, and top physics, with multiple channels under study in each area.

A further challenge is the success of LHC accelerator operation. Presently, partly because of the machine operational constraints, the LHC is delivering data under much more demanding conditions than foreseen. The pileup of events in each beam crossing exceeds by more than a factor two what was designed for. The LHC is still operating at half its design energy and the luminosity is expected to grow beyond the design parameters within the next five years. This presents tremendous experimental challenges, in maintaining and operating the detector, withstanding radiation degradation in some crucial areas, and extracting high quality data and analysing it.

In short, the physics objectives and the experimental conditions motivate the need for upgrades. They are substantial and lengthy undertakings, comparable to the original detector construction.

LHC plans and the upgraded CMS detector

The CERN schedule foresees preparation for operation at full energy of 7 TeV per beam during a Long Shutdown (LS1) in 2013 and 2014. The second major shutdown (LS2), from December 2017, will prepare for higher luminosities beyond $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (Phase I upgrade) starting in early 2019. Although 25 ns bunch spacing is the baseline, it remains possible that LHC operation will be at 50 ns, with consequent impact on event pileup. The machine would run for a further three years and shut at, or after, the end of 2021 (LS3) for upgrade to very high intensity with an objective of a *levelled* peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, aiming to deliver up to 3000 fb^{-1} , the Phase II upgrade.

The main motivation for luminosity upgrades is to provide more statistics to improve physics studies. It is essential that detector performance remains as good as at LHC, but higher luminosity implies higher particle fluxes, detector occupancies, trigger rates, and radiation damage. Tracking detectors will have reached their design lifetime by LS3 and need complete replacement, adapted to the even harsher environment. However, much of the remainder of the CMS detector can remain intact and continue to operate well.

The overall machine schedule is indicated in fig. 1. It is important to note inevitable uncertainties in the long term plan, which is revised annually following a major LHC performance and prospects review each January. Input is provided by the experiments, focussing mainly on physics objectives and any detector performance and maintenance issues. Access to the experiments must be carefully planned, given the limited access to the underground caverns, and the radiation environment. From the machine perspective, maintenance and access issues are also crucial, as well as development of major new components, such as Linac4 and the collimation and machine protection system.

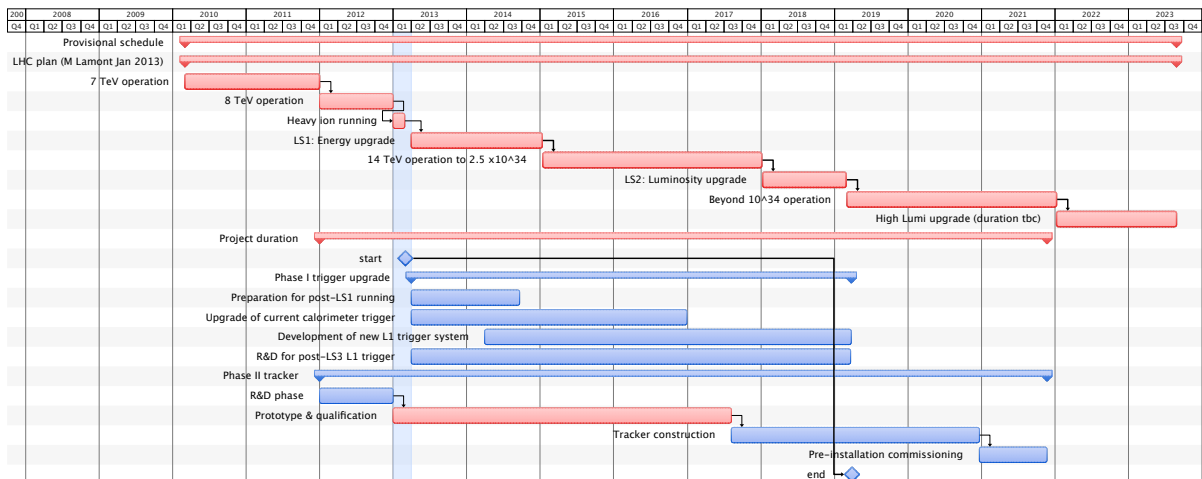


Fig. 1 Overall LHC schedule and the main elements of the UK projects to be undertaken

A second significant uncertainty is actual machine performance. Over the last two years, the CERN accelerator team has grown increasingly confident as they operate the LHC and are able to observe and measure key parameters. It now seems that some uncertainties were conservatively estimated and the luminosity grew very fast during 7 and 8 TeV operation, and is expected to exceed the design value of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the years between LS1 and LS2. Some challenges remain, including operation with 25 ns bunch spacing and at the full design energy, which is much more critical for the cryogenic components. However, it seems probable that the LHC will provide conditions which exceed those for which the experiments were designed by a significant factor.

In fact, during 8 TeV operation the peak luminosity reached $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$; 50 ns bunch spacing doubles the pile-up (number of simultaneous events in a single bunch crossing), which is therefore 50% higher than nominal at this energy. The projected luminosity of $2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will deliver 2.5x the design pileup and this could be a factor 2 larger if it is necessary to operate the LHC with 50 ns spacing, which might be required if electron cloud effects are hard to control. There are several major consequences for CMS:

- offline event reconstruction is more difficult, time consuming and CPU-intensive, especially in the tracker,
- some data are lost from the pixel detector, since on-detector buffers are insufficient to hold all the hits awaiting readout, exacerbating the previous problem, and weakening the ability to reconstruct short-lived decays from heavy quarks,
- the basic trigger objects (electrons, photons, muons, jets, event shape variables) are harder to identify cleanly because of pileup of particles in the calorimeters and muon detectors,
- Level-1 trigger rates will exceed the maximum practical level of 100kHz for acceptable object thresholds and efficiencies, owing to effects of pileup in the calorimeters and muon detectors.

All of these have important repercussions for the data quality and ability to discern rare signals in overwhelming backgrounds, as is the case for Higgs observation or SUSY searches. The impact on the trigger is a particular worry since the traditional method to control trigger rates, and one of the few available, is to increase energy thresholds in the online selection of trigger objects. However, this has significant impacts on searches, especially as the threshold changes required can be relatively large.

The proposed CMS upgrades up to LS3 were described in a Technical Proposal [1] submitted in 2010. They include improvements to the Hadron Calorimeter and Muon systems, in particular to install extra stations omitted for cost reasons from the present detector. However, the two upgrades which go well beyond maintenance, repair or extension of performance are replacement of the Level 1 trigger system and a new pixel detector. Both are driven by motivations described above, and are essential for CMS to maintain optimal physics performance. These upgrades should take place in the period between LS1 and LS2 and must be carefully organised so as not to degrade significantly the operational performance of CMS during a period when it should be producing data steadily. So both systems must be carefully commissioned and qualified prior to bringing them into full operation in the experiment so that there is no negative impact on performance.

The upgraded calorimeter trigger is a particularly crucial part of the new system, where the UK has substantial expertise, arising in part from our experience in delivering the Global Calorimeter Trigger (GCT) in 2006. At this relatively late stage in CMS construction, the project was able to profit from the most advanced FPGAs of that era and the availability of high speed digital links, and the GCT remains the most technically advanced digital electronic system in CMS. The UK has proposed an innovative new architecture for the calorimeter trigger, and possibly other parts too, based on boards and test systems at an advanced stage of development, from several years of R&D. However, the board design is agnostic and could be used in a more conventional architecture, which is a now a backup.

The new pixel detector should offer significantly improved performance. The total material budget can be much reduced in a new design despite adding extra layers, achieving better track seeding and track reconstruction efficiency, whose impact will be felt across the full spectrum of physics, including the heavy ion programme. The number of pixels will double from 66 million to 125 million in the new system, yet must use existing cables, cooling and optical fibre infrastructure. The evolution of this system will have important repercussions for the rest of the tracker.

The other major change foreseen to CMS comes several years later, when the full tracker, including the new pixel detector, will be replaced in about 2022, during LS3. This will be required because the tracker will have largely reached the end of its life as a result of radiation damage from the high flux of secondary particles originating from collisions. A new, more granular, detector optimised for material, power and performance must replace the present system, and it must be made more robust against the high particle fluences to survive for about a decade of operation at $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity. It is also foreseen to contribute, for the first time, data which can be used in the Level-1 trigger decision.

The present CMS tracking system evolved (as fast as possible) over about 15 years. Although some of the technologies used, especially ASIC electronics and optical links, are now much more familiar and advanced, to deliver a new tracker in about ten years is still a very significant task. The new requirements for trigger data, lower mass, greater radiation tolerance and higher bandwidth and data volumes are highly challenging. There has been progress in R&D over the last few years but there is still some way to go.

Tracker modules under development in collaboration with CERN are based on readout electronics designed in the UK. Eventually, data from them must be used in a future trigger, once modules have been thoroughly studied and systematic studies on how the data can be used in the trigger have been completed. This work is included in the proposal and the R&D progress to date is described below.

The three elements of the UK proposal activities and the schedule are summarised at the top level in fig. 1. They have strong interconnections, both in hardware and expertise, and the UK has laid very solid foundations for contributions to CMS for the coming decade, and the next one, which will also contribute much to the highest priority physics objectives and ensure the UK can continue to play a leading role in influencing the future of CMS.

Project Description

Review of Current UK R&D

UK CMS groups have long standing interests in tracking and triggering and proposed an Upgrade R&D project in 2007, which was approved in Spring 2008, but effectively began in April 2009, delayed by STFC financial problems. There were three main work packages, with a fourth added in the last year. The overall LHC plans have changed considerably over the last few years, most notably by introducing the machine upgrade in two phases, as explained earlier. The original LHC plan was much more ambitious, aiming to reach $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ luminosity around 2017, in a single step.

WP1 aimed to develop software tools to contribute to design of the replacement detector and electronic systems for the CMS tracker and L1 trigger. The project is now focussed on the Phase-I upgrade; however, tools and ideas for Phase-II developed in the early part of the project have been valuable. The simulation studies and related software developments have been quite successful, resulting in important contributions to the CMS Upgrade Technical Proposal physics studies.

The second main objective of WP1 was provision of online software and firmware to support Phase-I electronic systems, including prototypes. This has been notably successful, resulting in Bristol and Imperial demonstrating during 2011 a new protocol, IPbus, and a complete online software and firmware suite to implement it, which has already been used extensively in μ TCA-based systems now in widespread use. Subsequently CMS adopted IPbus as its standard control system for all future systems.

There is more work under way: integrating IPbus with the CMS XDAQ online framework, release tools to allow easy deployment, a development system in the electronics integration centre at CERN to be used during hardware integration exercises. In addition, IPbus will be adapted for higher performance and robustness and to integrate IPbus components with the CMS Detector Control System. It is also spreading outside CMS, with the framework now in use by groups within ATLAS, LHCb and under study by the Daresbury and CERN accelerator controls groups, among others.

The second Work Package, WP2, aimed to develop a readout chip for the outer tracker, to study options for Level 1 trigger data from a new Tracker, and to share development of a complete readout system, including off-detector DAQ components. Substantial progress has been made, most notably the demonstration of the CBC (CMS Binary Chip) for short silicon microstrips, designed by RAL TD and Imperial College. It is a 128 channel wire-bonded 130nm CMOS ASIC delivered in March 2011. The main features include a fast front end amplifier, operable with either sensor polarity, high detector leakage current tolerance, 256 deep pipeline and 32 deep buffer for triggered events. The output provides binary non-zero-suppressed data using a low power signalling standard, and the chip has fast and slow control interfaces, and built-in DC-DC switched capacitor supply voltage regulation.

All features of the chip have now been evaluated and results presented regularly and published. For a sensor capacitance of 5 pF, a noise performance of less than 1000 r.m.s electrons is achieved for a power consumption of 300 μ W/channel. The CBC has been extensively tested in the laboratory with excellent results. A CBC-sensor module was operated successfully in a CERN test beam.

The next version of the chip, CBC2, was submitted in July 2012; wafers have only recently been received so not yet tested. Signals from two wire-bonded sensor layers are fed to chips mounted on only one side of the module through a substrate with very high density traces. Coincidences between

the two layers allow the selection of higher transverse momentum tracks for the trigger. The chip has expanded to 254 channels with triggering logic, laid out for bump-bonding on 250 μm pitch. The substrate design and technology studies are the responsibility of a CERN-led group, with whom we work closely. The module should be available from late-2013 and will require significant studies, including trigger functionality in test beams.

WP3, which is an Imperial College activity with support from WP1, has built a demonstrator system, equivalent to about 20% of the present trigger, and is studying new algorithms; it is the first prototype of a trigger system for HL-LHC, as well as the Phase I trigger. The goal was to provide a standard generic board in a μTCA format to minimise the number of future hardware variants, and thus simplify maintenance and firmware development. The first version, the Mini-T5, is in use. A more advanced final prototype, the MP7, is now in operation and working very well. It deploys very high speed optical links and a very powerful FPGA, with a 1.44 Tbps optical interface and a 64 Gbps electrical interface on the front panel with GbEthernet, DAQ, etc. supported on the backplane. The MP7 can be used in any system and is far in advance of any alternative design.

A proposal for a very innovative, time-multiplexed trigger architecture [2,3] which offers many benefits over a conventional system evolved from this work and was proposed to CMS. It was agreed in December 2012 that the future calorimeter trigger will use the TMT architecture, unless any unexpected insuperable difficulties emerge in the coming two years when a series of demonstrators will be constructed and evaluated.

Proposed UK Activities

The two Work Packages (numbered following the present R&D WPs) are:

- WP2: CBC2 ASIC and module development for the Phase II Tracker
- WP3: Level-1 trigger development, primarily aimed at the calorimeter trigger for Phase I upgrades but also to carry out R&D for the future track-trigger required by CMS

They build heavily on R&D to date and, in some cases, are a straightforward continuation of it but up-scoped to extend the deliverables in WP3 to be those for a construction project matching the CMS schedule. The technical Work Packages are supplemented by a management activity, WP1.

Context, Collaboration and Competition

Within CMS, there is a high degree of collaboration in most projects and little duplication of activities. RAL TD and Imperial have a high standing in the Tracker project, based on delivery of much of the electronic readout system, contributions to Tracker management and many other CMS contributions over many years. Similarly in the L1 trigger, Imperial and Bristol delivered the GCT and have operated it for several years without major problems. We considerably extended our skills in board design, use of multi-Gbps signal transmission and firmware, and online software during and since the GCT project. These are much in demand and will remain so. RAL PPD and Brunel have contributed mainly to Tracker offline software activities in the past (and RAL PPD also had a leading role in the Endcap ECAL construction where they and Brunel, on VPTs, continue to have maintenance and operation responsibilities).

We work closely in WP2 with CERN, who delivered CMS optical links using 1.3 μm single mode telecomms components and who provided the team which carried out much of the tracker integration and outer tracker assembly. More recently Lyon and Strasbourg began to contribute to the R&D. Strasbourg worked closely with us on Tracker DAQ software, while Lyon have ASIC design engineers who wish to contribute to some ancillary chip design and eventually Phase II tracker construction. A group from Aachen, in collaboration with CERN, has been successfully developing DC-DC power conversion, which will be needed to provide current at 12V and minimise cable heat losses. Over time, it is certain that additional groups will contribute to the Phase II activities, particularly once modules exist and are available for studies in test beams and detector integration develops further. Although the tracker collaboration is large, there is little or no overlap with UK electronic activities but good collaboration on online DAQ software with French and US groups.

The trigger project involves a wide range of groups and detectors. UK interests to date are mainly in the calorimeter trigger where we have worked closely with the University of Wisconsin, who provided the Regional Calorimeter Trigger (RCT) hardware, and Vienna, who provided the Global Trigger (GT). Up to now, unlike the Tracker for example, individual groups in the trigger have specialised in particular hardware into which the trigger is sub-divided (thus RCT-GCT-GT, etc.). There is consensus that more common hardware will be used in future, leaving groups more free to concentrate on firmware and software developments, since these are lengthy undertakings and subject to change as trigger algorithms and physics objectives evolve. Reliability and impact on physics dictates caution and extensive testing in operating with new firmware, as well as good record keeping and repositories. There is also growing ability, and will, to share firmware and software and avoid unnecessary duplication, and the UK groups have taken a lead in promoting this.

The outstanding area of competition in the trigger concerned the architecture choice. This was resolved at the end of 2012 with a decision in favour of the TMT.

Strategy and Organisation

Project Management Plan

The project has been divided into two main work packages as explained earlier. Each WP has two managers, listed in the table below. One main reason for this is the need for hardware design and layout to be closely supervised by an Imperial College team member, but it also has the merit of distributing responsibilities between institutes and providing continuity and sharing of information and duties. There is a significant level of interaction regularly required with CMS, and it is essential that the WP managers do not become overloaded with reporting and budget management duties, and are able to actively supervise others working on the project in their direct vicinity.

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	CMS Upgrade Trigger Project Manager, currently 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.

As the construction project has evolved recently, approximately monthly UK meetings have been held, organised by the PI, which have monitored progress and generated actions. It is envisaged that these will continue, generating progress reports and actions. In each of the sub-projects there are regular meetings with collaborators, typically in CERN.

WP managers will be (are already) the frontline mediators with our external collaborators, in some cases holding significant responsibilities in CMS (e.g. Tapper, as Trigger Upgrade PM). Although this adds to their workload, it is effective in ensuring our role in the CMS projects, maintaining communications (which is vital in large international activities) and influencing both decisions and our input and reactions to them, keeping the overall project on track. The PI has been, and will continue to be, closely involved in much of this. The WP managers also have significant responsibilities in delivering the projects. WP3 has hardware, firmware and software roles to manage and we believe that this is another good reason to share the overall management of each WP.

We expect to be reporting regularly to an Oversight Committee, which has already been following our progress during the R&D phase at six-monthly intervals.

Resource Management

The cost breakdown and sharing between institutes is given in tables in appendices. Apart from staff costs, the two major items are travel and capital, which is requested under the Instrument Development exception, since almost all of the costs will result in equipment delivered to CERN, and will remain there. The travel budget will be managed like other particle physics travel budgets; it will be held in RAL and allocated to groups proportionately to need, who will submit quarterly invoices to the Shared Service Centre to recover their expenditure. A small fraction of the funds are consumables and small expenses for preparing test equipment, purchasing computers and other materials. These have been distributed to the groups, as indicated in the tables. The largest part of the capital budget will be held at Imperial College, where most of the hardware will be developed and procured, since it will be used to purchase prototypes and production versions of the trigger and DAQ boards, or purchase ASIC processing via CERN.

Work Package Descriptions

In this section, we give further detail on each of the work packages. Later sections summarise the deliverables, explain roles of participants, contain resource tables of and risks.

Work Package 1: Management

Work package leader: G. Hall

Objectives

There is a significant management load in steering the entire project, including resource usage reporting, and it is anticipated that this will grow further from the level experienced during the R&D project, in view of the several large scale procurements which will be required, as well as the increased number and scale of activities. For the R&D project, a fraction of the research time of the PI was bought out by STFC (in addition to effort allocated through the Imperial rolling grant) to ensure sufficient time was available to manage the project. This was requested by the PRRP review panel, and proved to be wise. The load has grown as the project progressed. Therefore a similar request for the PI is included in the financial resources requested.

A fraction of time is also requested for two administrative support staff (C Barlow and P Brambilla) to provide help in collecting information for regular reports, predicting staff expenditure, interfacing to college administration (Barlow) and monitoring expenditure and placing orders (Brambilla), both of which tasks are expected to grow. This has also proven to be essential in the R&D project to date. The PI is also responsible for UK CMS reporting and in the last grant round (2009) no additional STFC support, other than available research time was provided for these duties.

The start date for the project is requested to be 1 April 2013.

Resource estimates

The resource estimates originate in WP work plans and have been developed by the WP managers (Raymond, Newbold) in collaboration with the PI. Staff cost estimates result from assessment of effort required for individual tasks. Although a full resource-loaded costing has not been attempted, the Gantt plans have been used to estimate the required effort, with task estimates in most cases based on realistic appraisal of the effort needed, since many of the tasks are similar to those already underway either in the R&D activities or CMS construction and exploitation.

The material costs have been estimated using a bottom-up approach to cost the modules required for WP3. The estimates have been developed over a period of time during the R&D project by G Iles and are largely based on quotations and procurements already undertaken for board fabrication. Detailed Excel spreadsheet breakdowns exist, which are available if needed.

For WP2, the major component of the material costs are for ASIC submissions, so the estimates are based on current actual prices, which are well known. For all WPs, modest estimates have been made for annual provision of consumables, replacement of computers, test system construction and software licences, which are distributed to the individual institutes.

An estimate of a working allowance has been made, taking account of the two major factors influencing material costs, namely currency fluctuations and manufacturing success. Most material transactions originate in dollar purchases, for electronics. Although major exchange rate variations belong in contingency, there is a more modest quasi-random fluctuation of the £ (or CHF) against the dollar, illustrated in fig. 2, which over the last year has varied by 6.5%. This has been applied to equipment costings, all of which are based on an exchange rate of \$1.55/£. For manufacturing risk, an allowance has been made based on the cost of a few prototype runs, or a 50% share of an ASIC production run. The total is listed in the Working Allowance for each WP. VAT has not been included on production orders, since delivery should be to CERN, where systems will remain.

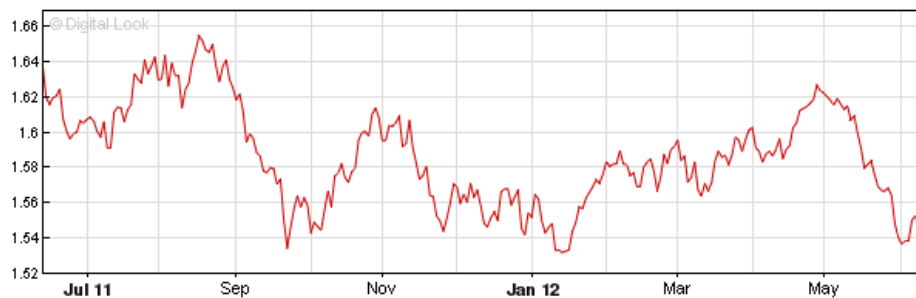


Fig. 2. Variation of the \$ vs the £ over a recent one year period (source: BBC)

We make no specific provision for staff Working Allowance, because the project has been reconfigured from the original proposal with extra staff effort in RAL PPD, and to a lesser extent Imperial, Bristol and Brunel, being allocated to the WP2 and, particularly, WP3 activities.

We also request funding for sub-contracts to a small UK company (Iceberg Technology) run by an outstanding ex-Imperial student, John Jones, who worked on stacked tracking ideas, the GCT project and was an originator of the Time Multiplexed Trigger (TMT) concept. He is an exceptional firmware and hardware designer, who has already contributed to MP7 design and evaluation. However, recently it has become clear his availability for this project will be less than hoped, in view of development of his own business, so much of the originally foreseen funding has been committed to extending the duration of an Imperial RA post.

An estimate of the travel budget required has been made by using our experience of expenditure during the R&D project, which has been steadily increasing in the last two years as progress has been made. It is expected to increase further, then level, but in the last few years of the project a number of LTAs in CERN have been added at an average cost of £15k/year each.

One favourable feature of the project is the overlap between expertise and activities in each WP. WP3 has significant firmware and software tasks, and staff should be available to provide expert advice and support for short periods. This will help WP2, which has a large ASIC design activity, since part of the evaluation will require test beam activities, which will be based on MP7-like and other FPGA hardware, adapted for the data acquisition. Although simulation activities have been assigned to WP3, we expect the effort used to be distributed to both WP2 and WP3, in view of the focus on real module performance.

Three project studentships are requested. We regard them as essential; excellent training opportunities are provided, with highly transferable skills gained; in addition it ensures throughput of trained, skilled candidates for posts during the subsequent operational period.

In the even longer term, the future tracker and trigger will benefit from the developments in the coming few years and it should be possible to ensure a very significant leading role in any future project in the next decade.

Work Package 2: Phase-II Tracker

Work package leaders: M. Raymond (Imperial), M. Prydderch (RAL TD)

Objectives

The phase II high luminosity LHC upgrade requires complete replacement of the present tracker with a higher granularity detector which must also contribute information to the Level 1 trigger to maintain the current 100 kHz rate. The working design for a new tracker contains a pixel detector at small radii and an outer tracker ($30\text{cm} < r < 120\text{cm}$ and end-caps) instrumented as two regions. The outermost region ($60\text{cm} < r < 120\text{cm}$, and outer end-cap disks) will be populated by modules with two closely spaced microstrip sensor layers, providing L1 triggering information by correlating hits in the two layers [4-6]. Fig. 3 illustrates the proposed construction of these SS-Pt modules, where the SS designation refers to the 2 strip-sensor layers. The inner region of the outer tracker requires increased precision for z information and a similar approach is proposed, but where one of the sensor layers is pixelated, hence the PS-Pt designation for these modules.

The objectives of work package 2 are:

- To complete development of a readout and triggering chip suitable for the SS-Pt module depicted in fig. 3, 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, including the development and operation of data acquisition for beam tests.
- To contribute to development of ancillary chips required for the SS-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.

Description and work plan

The work proposed here follows from successful front end chip development in WP2 in the current CMS UK Upgrade R&D project, which targeted a triggered readout chip for short microstrips in the outer tracker. Originally it was not envisaged that the readout chip would provide trigger information (it was thought trigger data would originate from a few dedicated layers). The first CBC (CMS Binary Chip) prototype was therefore a triggered, readout-only circuit, a 128 channel wire-bond chip in 130nm CMOS technology. Results from detailed studies of the performance of the CBC prototype in the lab and test beam can be found in [7, 8].

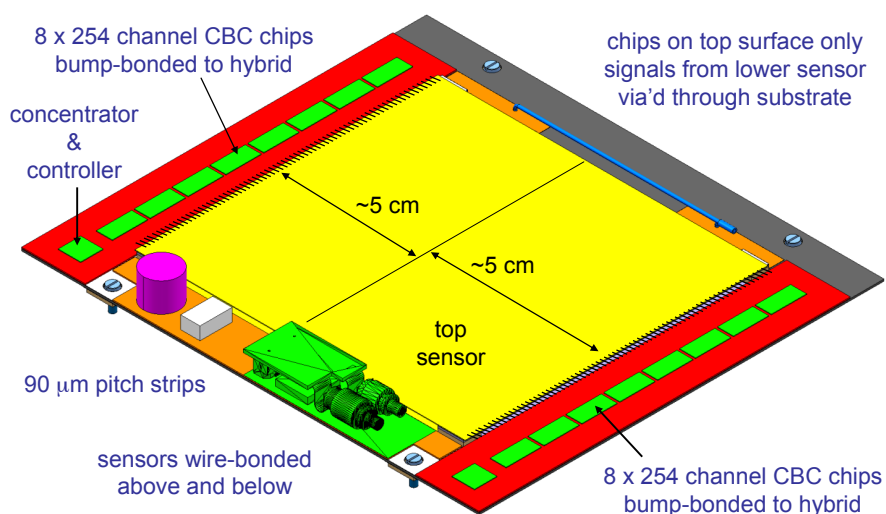


Figure 3. SS-Pt module

During the course of our work a tracker design based on the module concept of fig. 3 has been developed. Signals from both sensors are fed to readout chips which are bump-bonded face-down on a substrate to allow high density interconnection to be made with commercial substrate technologies used in system-on-chip applications. The module design places several additional requirements on the front end chip not envisaged in the original proposal. The chip layout must be adapted for bump-bonding, configurable triggering logic is required to perform the correlation operation between the two sensor layers, and the coordinates of high P_T stubs must be transferred off-chip to the concentrator and controller chip at high speed. A successor to the CBC, the CBC2, will be submitted (July 2012) to address the correlation and bump-bonding criteria. The CBC2 has been laid out for C4 bump-bonding on 250 μ m pitch and will be a final deliverable of the current upgrade project.

We propose to bring the outer tracker front end triggering and readout chip to a mature state so that full-scale production can be launched. To achieve this we propose a four to five year programme of chip development and chip and module evaluation studies, finishing in 2017. Such a timescale is compatible with current CMS planning. The chip development will naturally lead to a large scale production phase where the UK should take responsibility for delivering the front end chip, and play a major role in integration, commissioning and operation activities, as for the present CMS Tracker.

The CBC2 will facilitate prototyping studies of the SS-Pt module concept, where detailed performance issues can be studied. More important will be the proof-of-principle that modules can be constructed in the proposed way. For example, it will be essential to verify that fully functioning large area multi-chip substrates can be produced with high yield, where bump-bonding has not been previously demonstrated over such large areas, as well as validate the PT concept in practice.

Two further iterations of the CBC will be required. The first (CBC3) will be a prototyping stage of all the required system functionalities, including the high speed communication interface and other system features such as an on-chip ADC for the setup and monitoring of bias levels. The second and final iteration (CBC4) will be required for minor changes and to correct any remaining bugs found in the CBC3. Once verified, the production masks for the CBC4 will be prepared, where the whole wafer is dedicated to the CBC4 and for which a full wafer engineering run is required before mass production can be launched.

There are components in the SS-Pt system not yet fully specified. A controller and concentrator ASIC is required where it would be natural, and important, for us to play a part, particularly in aspects related to the CBC such as the definition of the high speed communication interface. We are also participating closely in the definition of the PS-Pt system, which is still at an early stage. The system definition will converge within the first year of the programme.

Apart from the extremely important design effort required, there will be a heavy load of chip and module test and evaluation studies required, starting immediately since it should follow on seamlessly from current upgrade R&D. Test setups will need to be constructed for lab, irradiation (ionising and single-event) and test-beam studies. Multi-chip modules can only be manufactured with high yield if known good die are used, so a wafer probe test system will also need to be developed.

In addition to laboratory studies, careful evaluation in beam tests will be required. This will also be based on μ TCA hardware, where we are sharing the responsibility for development of the FC7, an FPGA Carrier board which uses a Virtex 7 FPGA. It hosts FPGA Mezzanine Cards (FMC) which carry optical transceivers and some local processing. It will be integrated into the Tracker DAQ systems we have used during recent years and become a CMS Tracker standard; we expect CERN to take responsibility for manufacturing and distributing the final board to other users, especially in the pixel system. The fraction of funding which was recommended from the original, non-approved, WP4 for transitional arrangements will be used to free some of M Pesaresi's time for the FC7 activity, by means of the third Imperial RA post, formally accounted in WP3, which should help the transfer of the FED task in the pixel project and ensure backup μ TCA expertise is provided.

The work will be spread across the institutions, with RAL concentrating on integrated circuit design under the direction of M. Prydderch, with Imperial focusing on chip and module evaluation studies coordinated by M. Raymond, and Bristol collaborating on the development of the chip and module readout systems.

Work Breakdown Structure

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
	2.3.1 CBC3 design	04/13	03/14	12	design period
	2.3.2 CBC3 production	03/14	09/14	6	production period
	2.3.3 test setup preparation	03/14	09/14	6	wafer and chip test setup preparation
2.4	CBC3 test	09/14	03/17	30	CBC3 chip and module testing
	2.4.1 early tests	09/14	03/15	6	chip verification tests to prior to module tests
	2.4.2 ongoing testing	03/15	09/15	6	complete characterization, including irradiation and SEU tests
	2.4.3 CBC3 SS-Pt module studies	03/15	03/17	24	CBC3 based module studies in collaboration with CMS in lab and test beam
2.5	CBC4 design and test	03/15	09/16	18	CBC4 is the final version of the chip, fixing any remaining bugs found in the CBC3
	2.5.1 CBC4 design	03/15	09/15	6	design period
	2.5.2 CBC4 production	09/15	03/16	6	production period
	2.5.3 testing	03/16	09/16	6	tests to verify full and final functionality
2.6	CBC4 mass production preparations	09/16	12/17	15	a full wafer engineering run is required for CBC4 in preparation for mass production
	2.6.1 CBC4 final masks	09/16	03/17	6	mask preparation for full wafer engineering run
	2.6.2 CBC4 engineering run	03/17	09/17	6	production period
	2.6.3 CBC4 final production readiness verification tests	09/17	12/17	3	final functionality check
	2.6.4 procurement planning	01/17	12/17	12	detailed financial plans for mass production
2.7	Production phase activities	12/17	09/21	45	wafer production, testing, modules assembly, integration and commissioning
	2.7.1 mass production	12/17	06/20	30	wafer production
	2.7.2 production test	01/18	06/20	30	wafer testing
	2.7.3 modules assembly	01/18	06/20	30	module assembly
	2.7.4 integration activities	04/18	09/21	42	integration

Staff effort

The success of the CMS chip development has resulted from close collaboration between microelectronics design engineers at RAL and university staff and students, who perform the detailed studies on chip and module performance.

The tables in appendices A and B list existing university effort available, and new staff requests for six years: the four year development period and the first two years of production.

Based on experience of developing the CBC we request 6 SY of micro-electronics design and test effort (Braga, Bell) from RAL TD in the first five years: 2 SY for the CBC3 design, 1 SY for the CBC4 design, 0.5 SY for the final full wafer production mask preparations, and 2.5 SY (Braga) for documentation and chip evaluation studies. We further request 0.5 SY (0.1 SY per year for the first five years, Prydderch) to cover RAL TD management, supervising design, submission and wafer production.

To provide chip and module testing effort at Imperial we request project funding for an RA for the six years up to production readiness status (1 SY/year Pesaresi); the task includes test beam evaluations, which requires data acquisition hardware development. We also request project funding for a PG student. Test effort and production will need mechanical and electronics technician support

throughout. Imperial HEP group technical support is only partly Consolidated Grant funded and we therefore request support for half the electronics technical effort (0.2 SY/year, Khaleeq).

In view of the outcome of the Imperial Consolidated Grant, which anticipated support for this post from the Upgrade project grant but before it had been agreed, we request 50% funding for J Fulcher for three years at an approximate cost of £138k.

Financial resources requested

- Funds for chip production – engineering run cost x 1.5 – £534k

The full cost of a run with C4 processing is \$552k, based on the cost of the CBC2 run. We hope to share costs of the CBC3 and CBC4 pre-prototype runs with other designs, but it is not possible to predict in advance how wafer area will be shared. The final production requires a dedicated engineering run where the CBC will be the sole design on the wafer. We request half the cost of a dedicated run for each submission, where we will seek to make up any shortfall for the full wafer run costs from a CMS common fund.

- FE chip test setup custom hardware and components - £60k (£10k / year)

We request funds for manufacture of test systems hardware, including fine-line printed circuit board (PCB) production, interface PCBs and components, prototype hybrid manufacture, wafer test probe card manufacture, custom mechanical assemblies and electronic circuits associated with test structure, prototype and final module testing and integration and commissioning. It is difficult to estimate exact costs for any particular year so we request £10k per year.

- Module assembly costs/DAQ development - £86k (£14.3k / year)

The costs of the other components of the SS-Pt module will be shared with our collaborators at an estimated cost of 20kCHF/year, based on quotations for commercial fabrication and assembly, or these funds will be allocated to DAQ development since it seems likely that the module assembly costs can largely be met by CERN.

Risk

The work rests on production of 0.13 μ m CMOS circuits by IBM. A CERN frame contract exists so there is minimal risk of our programme being compromised by a loss of foundry access. The UK micro-electronics design team has considerable experience and a proven track record.

Design is an open-ended process, and prototype development must match submission schedules for 0.13 μ m MPW runs. Prototype designs can be submitted through MOSIS or through CERN-organised MPW runs, so there should not be significant scheduling problems.

Collaboration

The module concept of fig. 3 has evolved over several years within the international CMS upgrade R&D programme. We have been closely involved in the module definition, and the front end readout is based on the CBC. We hold regular (every 6 - 8 weeks) “systems” meetings with our CMS colleagues, which involve relatively small numbers of physicists and engineers closely involved with, and actively engaged in work on, design, production and test of one or more of the module components. These meetings are in addition to regular Tracker and CMS meetings where plans and progress are presented to, and discussed with, a wider audience. The working meetings will continue for some time until the system (including readout data format) is fully defined, and also to monitor progress in the individual components from which the overall module is constructed, including sensors, substrates, CBC and ancillary chips, off-detector links, DC-DC powering circuitry, mechanics and cooling.

Work Package 3: Level-1 Trigger

Work package leaders: A. Tapper, D. Newbold

Objectives

The physics reach of a high-luminosity hadron collider experiment is dictated by the performance of its trigger system. The CMS high-level trigger will be continuously re-optimized as LHC delivers up to 2.5 times design luminosity in the next decade. However, the hardware-based Level-1 trigger is less flexible, and will require replacement to maintain optimal performance. A similar strategy of Level-1 upgrade was successfully employed at previous generations of experiments at the Tevatron, HERA and SppS. We propose to replace the current Level-1 system with more flexible and higher-performance hardware, capable of implementing an evolving set of algorithms up to LS3. In the long term, this technology will also allow incorporation of tracking information into the Level-1 decision, believed to be an essential step in preserving trigger selectivity at HL-LHC luminosities.

The objectives of WP3 are:

- Short-term improvement of the current CMS calorimeter trigger in preparation for above-design-luminosity conditions from the start of running in 2015.
- Provision of infrastructure to operate an entirely new calorimeter trigger in parallel with the existing system.
- Design, construction and commissioning of a time-multiplexed calorimeter trigger for CMS, capable of implementing new and more selective algorithms.
- Design of a track trigger architecture for HL-LHC running, building initially on the module and ASIC developments of WP2, and construction of a technology demonstrator.

Trigger Requirements

The purpose of the Level-1 trigger system is to select, in real time, a subsample of LHC collisions for further analysis. Collisions which are not selected for readout are entirely discarded. The rate of selected collisions cannot exceed 100kHz, in order to reduce the recorded data volume to a feasible level. The trigger must have a very high acceptance for 'important' physics signals, whilst suppressing up to 10GHz rate (at HL-LHC) of uninteresting QCD scattering events. The trigger operates in pipelined mode with a processing latency of around 1 μ s, making implementation of complex selection algorithms extremely challenging.

The future trigger must be optimised for maximum acceptance of any newly-discovered phenomena, whilst maintaining sensitivity to further signs of new physics. Rate control in the presence of increasing levels of background is challenging. Since the natural transverse energy scale of final state objects is set by the W, Z and top masses, and eventually by the EWSB scale, it cannot be accomplished simply through increased thresholds. It is likely to require use of increasingly exclusive selections compared to today's 'inclusive' trigger menu, along with use of topological and kinematic information. This in turn will require trigger objects to be identified with improved position and momentum resolution. The trigger must be capable of implementing a wide range of possible algorithms in order to maintain performance, regardless of the unfolding physics scenario.

The technical requirements on the Level-1 trigger are demanding. The system, comprising a large number of custom electronics modules and interconnections, must operate continuously during several month data-taking periods, with practically 100% reliability. Since a detailed knowledge of trigger acceptance is important for analysis, monitoring takes place continuously. Tools must be provided to allow design, simulation, verification and monitoring of event selection algorithms implemented in firmware. The trigger hardware is controlled and monitored via a distributed online software system, which must also function with extremely high reliability.

The UK was responsible for the CMS Global Calorimeter Trigger (GCT) component of the Level-1 trigger. We therefore have a detailed understanding of the trigger system, and a realistic appreciation of the resources required for trigger development. The GCT project pioneered several new technologies, including use of very large FPGAs and fast fibre-optic serial links. The system has operated successfully and reliably during the first years of LHC running. We propose to build upon our

successful delivery of the GCT by implementing a new trigger architecture using similar technologies, but capable of much higher event selectivity, and with much greater flexibility.

The detailed plan for the CMS Level-1 upgrade, including physics requirements, will be documented in an Upgrade Technical Design Report due for completion in early 2013.

Work Plan: Stage 1 upgrade (Operation from 2014-15)

During the LS1 shutdown period, we will incrementally upgrade the current Level-1 system, and make arrangements to allow parallel operation of a new calorimeter trigger. The current GCT system will be replaced with an initial version of a new advanced μ TCA processor module, the MP7, developed at Imperial during the current R&D project. The current Regional Calorimeter Trigger (RCT) will be augmented by US collaborators with a new final output board, in order to allow optical transmission of data to the MP7 modules at sufficiently high rates. These changes are intended to provide a significant improvement in the performance of the CMS calorimeter trigger for the first physics run in 2015, whilst requiring relatively modest resources from the UK project, and disrupting the existing CMS trigger system to the minimum possible extent. We refer to this intermediate upgrade solution as 'Stage 1'.

In parallel with the installation and commissioning of the new hardware, new software and firmware for the control and monitoring of μ TCA hardware, and for interfacing to the upgraded CMS DAQ and TTC systems, will be developed. This work will also directly support the final calorimeter trigger upgrade from 2016, and must be tested during the LS1 shutdown period. The trigger system, along with all other upgraded CMS electronics, will be controlled via the UK-developed IPbus system, now accepted as the common CMS standard. This replaces the traditional VME backplane with a distributed Ethernet-based system for control and local readout.

Finally, the new calorimeter trigger algorithms made possible by the more powerful FPGAs on the MP7 module must be optimised and commissioned during the first global runs of CMS in 2014, ensuring a smooth startup for physics. The current GCT hardware will be maintained during LS1, and will act as a fallback in case of issues with any of the Stage 1 developments.

Work Plan: Stage 2 upgrade (Operation from 2016 onwards)

The work package centres around implementation of a new calorimeter trigger. The move to entirely new trigger hardware ('Stage 2') will take place between LS1 and LS2, as the LHC luminosity reaches $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, twice the design luminosity. Parallel operation of the new and existing systems will allow a significant commissioning and testing period, with switch-over when experience has been gained in operating the new system with high reliability. This is currently foreseen to take place in the year-end technical stop in winter 2015/6. Our strategy is therefore to make provision for operating the new and old trigger systems in parallel, with data from both held in the event record. The performance of the new system will be analysed in detail, and HLT software adapted to use seed information from the new system, when required. In order to provide calorimeter data to the new trigger system, we will replace existing copper serial links, which transfer energy information from ECAL and HCAL to the calorimeter trigger, with fibre-optic links. The fibres will either be duplicated (ECAL) or split via passive optics (HCAL), to provide identical input data to both new and old trigger hardware without interference between the two systems. This disruptive modification to the CMS systems will take considerable time, and must take place during 2013.

The new system will be based on the final version of the MP7 module. This module uses the latest generation high-performance Xilinx Virtex-7 FPGA, coupled with an extremely high-throughput I/O system comprising 144 optical links each operating at over 10Gbps. A variety of trigger architectures may be implemented by interconnecting identical MP7s, and the module is also under study by other groups as a basis for the new Global Trigger and muon drift tube track finder.

The UK has proposed a novel, highly flexible processing architecture for the upgraded calorimeter trigger, which has been accepted as the baseline architecture for the upgrade. In a traditional trigger system, each module processes data from a small part of the detector using pipelined logic. Seamless coverage of the detector requires many cross-links between modules, and the dataflow architecture is fixed in the system design, for instance by the routing on crate backplanes. In the Time-Multiplexed

Trigger (TMT), the system instead transfers all data corresponding to a given bunch-crossing into a single hardware module, with many identical modules working in parallel on different bunch-crossings. This approach is similar to that used by the CMS event builder / HLT system. The new architecture has several advantages: the dataflow is specified in firmware, and may be altered at any time; complex algorithms may be implemented to use data in unforeseen ways, including global event variables; and the system will include redundant hardware modules, allowing it to remain fully functional despite the failure of any single component. The additional latency incurred by the multiplexing system is compensated by the lack of cross-connections between modules. The architecture was successfully demonstrated [9, 10] using a lower-specification μ TCA module, allowing work towards the final MP7 module to proceed.

A TMT slice will initially be constructed in prototype form during early 2013, and the full system hardware built up during 2014. The final system will comprise two layers, with the physics algorithm processing taking place in the UK-provided second layer, consisting of 12 MP7 modules. The first layer, responsible for data concentration and multiplexing, will be provided by US collaborators. Since the MP7 is significantly more technically advanced than any other development in CMS, the option remains to use the UK hardware for all stages of the system if required. The full upgraded calorimeter system will be in place in time for first global running in the autumn of 2014, albeit without full-optimised physics algorithms. Experience during the first physics run in 2015 will allow optimal algorithms and effective operational strategies to be put in place well before the switchover to the new trigger system in 2016.

The adoption of a TMT architecture will require a significant effort in the provision of new online and offline software, both for the new L1 system, and for some parts of the HLT. The task will be undertaken during 2014/5, with the parallel architecture allowing system tests without disruption to CMS data-taking.

Work Plan: Post-LS3 R&D (2013-19)

In parallel with the calorimeter trigger upgrade, we will continue our R&D towards a tracking trigger for CMS. The current Level-1 system uses coarse-grained information from the calorimeter and muon systems only, and the rate reduction capability of the trigger at very high luminosities is compromised by the limited position and momentum resolution. A large improvement in rate reduction is achieved in the first stages of the high-level trigger by the use of minimal information from the inner tracking systems. This information allows refined position estimates for trigger objects, additional p_T information, improved charge assignments, and the calculation of robust isolation variables. This motivates inclusion of tracking information at Level-1 as a means of maintaining reasonable rates and signal efficiencies at up to ten times design luminosity at the HL-LHC. Use of tracking information at Level-1 will be technically challenging. The key issues include: incorporation of sufficiently flexible trigger logic into the low-power front end ASICs being developed in WP2; compression of data to limit the number of output links from the tracker; and track reconstruction in hardware within the limited latency budget.

The baseline track triggering concept under study by CMS is the 'stacked module', consisting of two closely-spaced silicon sensors coupled to an ASIC which identifies 'straight' high- p_T tracks through hit correlations between the two layers. The UK developed this concept, and first demonstrated its feasibility by simulation. Since we propose to take responsibility for both the outer tracker readout system, and the upgraded trigger architecture, there is a clear opportunity for the UK to make a decisive intellectual and practical contribution in the long term.

The track trigger work programme will commence with the development of a conceptual design for the track trigger, based upon detailed simulations of HL-LHC conditions and on the results of tracker module prototype tests by WP2. Physics requirements will be identified, and options for trigger data compression explored. This will in turn inform the specification of the new versions of the on-detector ASICs. This work will build upon the leading UK contribution within the CMS tracker upgrade simulation group.

From 2016, after successful delivery of the TMT system, we will begin development of a new generic trigger module based upon the next generation FPGA technologies. It will be specified with

sufficient processing capacity to form the building block of an upgraded TMT capable of integrating calorimeter, muon and tracking information. We anticipate that use of next-generation FPGA devices, probably using multi-die technology, will pose new challenges for hardware and firmware design. Along with the development of corresponding software, this programme will culminate with construction in 2018 of a hardware demonstrator comprising a number of the new modules, capable of receiving data from modules based on the CBC4 chip. A successful demonstration of on and off-detector hardware, firmware and algorithm ideas will allow work to progress towards the construction of the HL-LHC Level-1 trigger by 2022, in a successor project.

Strategy

A key lesson learnt during the design, delivery and commissioning of the current GCT is that a single tightly-integrated team is required, comprising individuals with skills in hardware, firmware, and online and offline software systems. Whilst the first version of the MP7 board is about to enter production, it is likely that one or more design revisions of the board will be necessary to include all the necessary functionality, and the final specification can only be developed through construction of prototype systems of increasing levels of complexity. We therefore plan to carry out the development of hardware, firmware and software in parallel, with close communication between all members of the team, and regular integration tests with well-defined goals.

Of particular importance is a strong link between trigger performance studies, event selection algorithm design, and trigger monitoring through comparison with software emulation. This was a crucial step in commissioning the current CMS trigger system, and will continue to be vital both in achieving the correct specification for the TMT, and in commissioning the new system on a more compressed time scale than for the original trigger.

The breakdown of the work package into three stages, with most project personnel contributing to all three, will help to achieve a continuity of expertise from re-commissioning of the current trigger, through delivery of a new system, into the specification and prototyping of a highly challenging new trigger concept. We do not request resources for the ongoing operation of the trigger systems, since M&O activities are supported within the consolidated grants. We do, however, request resource for expert support of the trigger to allow modifications to firmware, software or even hardware as required by the CMS programme. Our experience with the GCT is that such requirements occur regularly, and our estimate of the required effort is based upon our current experience.

Resources and Personnel

We estimate that the work package deliverables will require around 65 staff-years of effort (not counting students). The project has been planned against a roughly flat effort profile, and most team members will contribute to multiple deliverables across the course of the project. The effort will be divided into four activities:

- *Management* (4SY), led by Newbold, Tapper. The project requires strong management at each institute. Both work package managers are highly experienced in triggers and electronic systems, and have significant CMS management experience. Tapper is CMS Level-1 upgrade manager, and Newbold chairs the CMS TriDAS institution board. Newbold will take a 50% secondment to RAL PPD during the first three years of this project, and will oversee both RAL and Bristol contributions during this period.
- *Hardware development and system firmware* (18SY). Led by Iles (Imperial), with effort from Imperial, Bristol. Iles is a highly-experienced hardware and firmware designer, who led development of the GCT and the MP7 module. Support of Iles by a team of engineers, technicians and detector physicists is essential. This request is based directly upon our experience of similar projects over several years, and key hardware work leading to the TMT delivery consists of iterations on an existing module design. We will share, as far as possible, a common module design with the pixel FED developed in WP4. A major task in this area is the development of firmware designs; this will be supported by further developing the firmware versioning and build system used in the design of the GCT.

- *Online software development and integration (18SY)*. Led by Harder (RAL), with effort from RAL PPD, Bristol and Imperial. Harder has significant experience from the CMS pixel upgrade project. Online software is critical to ensure system reliability and robustness. Our efforts will firstly be spent on the 'core' online system (IPbus) which will support not only the trigger, but as a common CMS standard, also the new readout system for pixels and HCAL. Secondly, we will build on top of IPbus a new trigger control framework, integrated with existing online software. This work package will also cover the practical commissioning of the trigger system, in conjunction with effort from elsewhere in the WP.
- *Algorithms and offline software development (27SY)*. Led by Brooke (Bristol), with effort from Brunel, Bristol, Imperial and RAL PPD. Brooke has significant experience of trigger offline software and performance studies. He was chair of the CMS Level-1 software group, and convened the CMS Level-1 Performance Group during commissioning in 2008–10. A strong trigger studies effort is essential. A detailed set of specifications for each trigger upgrade stage is required, to ensure the systems meet requirements with sufficient margin and low risk. This activity encompasses studies before system design; input to algorithm design, engineering trade-offs; comparison with expectation during integration and commissioning; and verification of correct trigger operation. These tasks depend upon a well-validated offline software framework, to be used for subsequent algorithm validation throughout the running period. The requested new RAs at Imperial and Bristol will bridge the trigger studies and firmware development activities, ensuring maximum interaction between the two areas. The majority of the track-trigger development work during the first half of the project will take place within this work package, jointly with WP2.

Our effort request includes new RA posts at Imperial, Bristol and RAL PPD and modest support for an existing RA at Brunel which will be matched by local non-STFC funding. (A fraction of the third RA Imperial post, now extended to the full six years by reducing consultancy costs, will also provide support for WP2 DAQ.) Availability of full-time researchers on the project, bridging firmware and software tasks, is essential. The current R&D project has provided opportunities to train several students in relevant areas, providing a pool of effort. New staff will be closely supervised by experienced researchers. We also propose to engage project-funded postgraduate students at Imperial and Bristol in the work package. The design and delivery of a trigger system, from conceptual design, through construction, to final commissioning represents a truly excellent training opportunity, which is heavily interlinked with the CMS physics programme.

In addition to human resources, we estimate a total cost for materials of £1243k, including sub-contracts, of which £774k will constitute the hardware, including prototypes and spares, to be deployed within the CMS experiment. £100k will be a 20% pro-rata contribution by the UK in 2013 towards the cost of common infrastructure (optical links) to support the parallel trigger development, without which the overall trigger upgrade project cannot proceed. £121k will be incurred in the construction of prototype systems and hardware and software costs within the institutes, including a small fraction for general support of new project staff.

Collaboration

The current Level-1 trigger system was constructed over several years by a core group of 5-6 CMS European and US institutes who now support trigger operations and will contribute to the upgrade. The development of a new trigger system and its commissioning for physics is a substantial task, which can only be carried out through the combined efforts of several partners. In particular, the delivery of the new calorimeter trigger is likely to be a joint enterprise between the UK institutes and the University of Wisconsin, subject to project approval in both cases.

Work Breakdown Structure

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 Summary

The deliverables from each work package are listed. Progress towards them will be used to monitor project progress.

Deliverable	Date	Description
M2.1	PM12	System specification document produced
M2.2.1	PM12	Documented CBC2 detailed test results
M2.2.2	PM24	Documented SS-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 SS-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

Participants and Roles

Institute	Name	Support reqd?	Category	WP1	WP2	WP3	
Bristol	Newbold		CG Acad			0.5	
	Goldstein		CG Acad		0.4		
	Brooke		CG Ph			1.5	
	Cussans		CG PE		1.5		
	Nash		CG T		3.0		
	Core RA		CG Ph			3.0	
	Frazier repl	Y	Proj PP			6.0	
	New RA WP3	Y	Proj Ph			6.0	
	Student 1	Y				3.5	25.4
Brunel	Cole		CG Acad			0.9	
	Hobson		CG Acad			0.6	
	Powell		CG Ph			0.9	
	Reid	Y	Proj Ph			1.5	3.9
Imperial	Hall	Y	CG Acad	3.0			
	Tapper		CG Acad			2.2	
	Fulcher	50% 3yr	CG Ph		3.0		
	Raymond		CG AP		4.8		
	Iles		CG E			4.5	
	Rose		CG E			5.4	
	Pioppi		CG Ph			1.5	
	Clark, I		CG T		0.6		
	Kasey, V		CG T		1.2		
	Pesaresi	Y	Proj Ph		6.0		
	RA_2	Y	Proj Ph			6.0	
	RA_3	Y	Proj Ph			6.0	
	Barlow	Y	Proj O	0.6			
	Greenwood	Y	Proj T			2.0	
	Khaleeq	Y	Proj T		1.2		
	Brambilla	Y	Proj T	1.2			
	Student 1	Y			3.5		
Student 2	Y				3.5	56.2	
RAL PPD	Shepherd-T					1.4	
	Harder					6.0	
	Durkin					6.0	
	Newbold					0.7	
	Tomalin					1.6	
	Sankey					3.0	
	Petyt					1.8	
	RA 1	Y				6.0	26.5
RAL TD	Prydderch	Y	Proj E		0.5		
	Braga	Y	Proj E		4.5		
	Bell	Y	Proj E		1.5		6.5
Total FTE			4.8	31.7	81.0	118.5	

Dr D. Newbold (Academic): WP3 manager; Bristol PI. CMS collaborator since 1993, current chair of Trigger and Data Acquisition Institution Board. Project and resource management experience in CMS computing, ECAL and trigger systems.

Dr J. Brooke (CG physicist) Leader of offline activity in WP3. Key contributor to development of current CMS L1 trigger. Past convenor of L1 offline software group; past convenor of L1 Detector Performance Group.

Dr D. Cussans (CG physicist engineer): Experience in high speed digital and analogue design, and detector / readout integration. Contributor to CMS trigger, ECAL. Co-leader of EU AIDA DAQ project.

Dr J. Goldstein (Academic): Expert in silicon detector system integration, readout and commissioning, with experience on CDF Run-II and LC R&D projects.

Dr M. Grimes (Project physicist): Experience with detailed tracking system simulation and optimisation, and development of tracking algorithms.

Mr S. Nash (CG technician): Expert in high-speed PCB layout, fabrication and test. Experience of hardware design for CMS, BaBar, ZEUS, WA89 experiments.

Prof P Hobson (Academic) Brunel group leader, CMS member since 1995. Tracker DQM via new computationally efficient non-parametric tests. Local management of R&D and in WP4, to contribute to DQM techniques and offline software design and documentation.

Dr J Cole (Academic) CMS Tracker since 2005, online software for FEDs. Significant experience of Tracker commissioning, software deployment, shifter training and documentation, led development of software for DCS data to offline calibration database, used in event reconstruction. WP4 DQM.

Dr I Reid (Applied physicist) considerable software skills, track-reconstruction, Tracker DQM, track reconstruction algorithm development for high pile-up environment. Support WP4 effort in DQM and offline software design, implementation and documentation.

Prof G Hall, (Academic) PI. CMS since inception, UK CMS PI and CMS MB/FB representative. Many roles in CMS management, including leader of Tracker readout system, and PI of current UK R&D project.

Dr J Fulcher (CG physicist) based CERN, manages all UK Tracker electronic hardware, software expert and key contributor to CMS Tracker DAQ, responsible for online software and firmware.

Dr G Iles (CG engineer) based CERN. Responsible GCT hardware and firmware, leads trigger upgrade R&D. Designer Mini-T5, MP7, parts of GCT, pioneered optical and backplane technology, CMS firmware coordinator. Time Multiplexed trigger architecture originator.

Dr A Tapper (Academic) WP3 manager. Trigger and SUSY physics expert. CMS Trigger Upgrade Project Manager, ex-SUSY convenor. Coordinated commissioning of GCT. Led analysis of LHC data using jet and energy sum triggers. Based in CERN, responsible for continued GCT operation.

Dr M Pesaresi (Project physicist). WP4 manager, PhD on track-trigger, hardware responsibilities on tracker APV emulator, trigger rate control, R&D on upgrades with responsibility for DAQ software and analysis. Excellent electronic hardware skills. Lead designer of pixel FED.

Dr M Pioppi (CG physicist) left Imperial December 2012, and in the process of recruiting a replacement with similar skills in physics data analysis and simulations.

Dr M Raymond (CG applied physicist) WP manager, experienced analogue ASIC designer (Tracker APV25 and ECAL MGPA), detector physicist building systems for lab and beam tests, expert on radiation tolerance studies. Lead scientist for CBC and CBC2, designed analogue stages.

Dr A. Rose (CG engineer) CMS trigger, PhD on GCT, extensive simulation studies of future calorimeter trigger performance, expert in online and offline software, excellent firmware and hardware skills. Design work on Mini-T5 & MP7. Originator of much of IPbus, and TMT concept.

Dr C Shepherd-Themistocleous (Academic): RAL group leader, PPD Division Head. Expertise data analysis and requirements imposed on triggers (CMS & LHCb), ECAL and electron ID. Management of WP3 and WP4 at RAL. Development of strategies and algorithms for a track trigger.

Dr K Harder (Physicist): WP4 manager. D0 Si det operations group leader. Experience: firmware, hardware, control software, data integrity monitoring and software for simulation and reconstruction, Linear Collider detectors, D0, CMS. Leads CMS pixel upgrade DAQ test systems at RAL.

Dr D Petyt (Physicist): CMS since 2008. ECAL DPG convenor (2012-13): In depth knowledge of ECAL detector and performance. Particular expertise on ECAL input to L1 trigger and corrections of problems encountered during CM running. WP3 work on emulation of trigger and algorithm design.

Dr I Tomalin (Academic): Convenor Tracker software (simulation and reconstruction), Tracker readout (CMS & ALEPH). CMS physics analyses and development of dedicated triggers. WP3 definition of requirements of track trigger and development of algorithms.

Mr T Durkin (Engineer): 12 yrs hardware for HEP, 4 yrs FPGA firmware. Installation, testing and operations (MINOS, T2K). MSc telecoms elec. WP4 FED front-end firmware and hardware integration.

Dr D Sankey (Physicist): extensive experience systems integration, tracking software, triggering, real-time programming in software and VHDL, on H1, LC R&D and ATLAS. Previously UK Project Manager for H1 Fast Track Trigger. WP3 IPbus and μ HAL development.

M Prydderch (TD engineer) WP2 manager, leader ASIC Design Group. 21 years microelectronics design experience, project management, responsible for MS Sharepoint system for ISO9001 Quality Management. Managing and participating in the CBC2 design at RAL.

D Braga (TD engineer) ASIC designer, >5 years experience includes ASIC for AIDA, measuring unstable nuclei decays for FAIR at GSI, ASIC for the Large Pixel Detector for XFEL. Lead designer on CBC2 design. Working on PhD under supervision of Prof G. Hall.

Dr S Bell (TD engineer) 15 years Microelectronics Support, moved to ASIC Group to focus on design. Experience design flows and techniques, training academics and researchers. PhD on high-resolution position-sensitive two-dimensional charged particle detector.

References

1. The CMS Collaboration, J.Nash and A.Ball (eds), *Technical Proposal for the Upgrade of the CMS detector through 2020* (2011) CERN-LHCC-2011-006
2. J Jones, C Foudas, G Iles, M Hansen, *The GCT Matrix Card and its Applications*, Proc TWEPP-09: Topical Workshop on Electronics for Particle Physics (2009) pp.259-264
3. G. Iles & A. Rose et al., *A Time-Multiplexed Calorimeter Trigger for CMS with Addendum*, 2011 CMS-IN-2011-008.
4. J Jones, A Rose, B Constance, C Foudas, G Hall, M Raymond, K Zhu *Stacked Tracking for CMS at Super-LHC* 12th Workshop on Electronics for LHC Experiments, 2006. CERN Report CERN-2007-001, 130-134
5. G Hall, M Raymond and A Rose *2-D PT module concept for the SLHC CMS tracker* 2010 *JINST* **5** C07012
6. M Pesaresi and G Hall *Simulating the performance of a p_T tracking trigger for CMS* 2010 *JINST* **5** C08003
7. http://www.hep.ph.ic.ac.uk/~dmray/CBC_documentation/
8. M Raymond, D Braga, W Ferguson, J Fulcher, G Hall, J Jacob, L Jones, M Pesaresi, M Prydderch *The CMS binary chip for microstrip tracker readout at the SLHC*, 2012 *JINST* **7** C01033.
9. C Foudas, R Frazier, G Hall, G Iles, J Jones, J Marrouche, D Newbold and A Rose *A demonstrator for a level-1 trigger system based on MicroTCA technology and 5Gb/s optical links* 2010 *JINST* **5** C11015
10. R Frazier, S Fayer, G Hall, C Hunt, G Iles, D Newbold and A Rose *A demonstration of a time multiplexed trigger for the CMS experiment*. 2012 *JINST* **7** C01060

Resource Request

Institution	Cost to STFC												Total	
	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19			
	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff														
Bristol	£76,571	2.5	£87,344	3	£89,478	3	£91,670	3	£76,556	2	£78,836	2	£500,455	15.5
Brunel	£6,669	0.15	£6,962	0.15	£7,265	0.15	£7,586	0.15	£0	0	£0	0	£28,482	0.6
Imperial	£199,050	5.3	£223,100	6.3	£226,995	6.55	£209,241	6.05	£193,953	5.05	£178,703	4.05	£1,231,041	33.3
RAL PPD	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£415,200	6.0
RAL TD	£177,431	1.85	£124,174	1.35	£172,815	1.6	£119,559	1.1	£66,302	0.6	£0	0	£660,280	6.5
Total new	£528,920	10.8	£510,780	11.8	£565,753	12.3	£497,256	11.3	£406,011	8.65	£326,739	7.05	£2,835,459	61.9
Equipment	£374,746		£684,012		£394,508		£276,351		£88,286		£121,286		£1,939,189	
Travel	£50,000		£60,000		£60,000		£50,000		£40,000		£40,000		£300,000	
Other costs														
Other DI														
Other DA	£3,662		£3,662		£3,662		£3,662		£3,540		£3,540		£21,729	
Indirect costs	£190,836		£190,836		£190,836		£175,174		£170,431		£170,431		£1,088,544	
Estates costs	£76,300		£76,300		£76,300		£76,300		£74,706		£74,706		£454,610	
W allowance	£130,301	0.0	£41,062	0.0	£22,357	0.0	£13,004	0.0	£178,975	0.0	£910	0.0	£386,609	0.0
Total 'new'	£1,354,765		£1,566,652		£1,313,416		£1,091,747		£961,948		£737,612		£7,026,140	
Existing	£770,265	9.9	£769,155	10.0	£747,376	9.5	£776,899	9.2	£771,546	9.1	£762,402	9.0	£4,597,643	56.6
Grand	£2,125,031	20.7	£2,335,807	21.8	£2,060,792	21.8	£1,868,646	20.5	£1,733,494	17.8	£1,500,014	16.1	£11,623,784	118.5

Appendix A: Work Package Costs

WP1	Institution		Cost to STFC												Total	
			FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19			
			Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff	Imperial	Hall	£22,434	0.30	£22,434	0.30	£22,434	0.30	£22,434	0.30	£22,434	0.30	£22,434	0.30	£134,601	1.8
	Imperial	Barlow	£5,605	0.10	£5,767	0.10	£5,932	0.10	£6,103	0.10	£6,285	0.10	£6,379	0.10	£36,070	0.6
	Imperial	Brambilla	£8,021	0.20	£8,248	0.20	£8,483	0.20	£8,726	0.20	£8,974	0.20	£9,230	0.20	£51,682	1.2
Total			£36,059	0.60	£36,448	0.60	£36,849	0.60	£37,262	0.60	£37,692	0.60	£38,042	0.60	£222,353	3.6
Equipment																
Travel																
Other costs	Imperial	DA	£279	0.30	£279	0.30	£279	0.30	£322	0.30	£322	0.30	£322	0.30	£1,804	
Indirects	Imperial		£9,397	0.30	£9,397	0.30	£9,397	0.30	£9,397	0.30	£9,397	0.30	£9,397	0.30	£56,385	
Estates	Imperial		£3,616	0.30	£3,616	0.30	£3,616	0.30	£4,164	0.30	£4,164	0.30	£4,164	0.30	£23,342	
Working allowance															£0	
Total non-staff			£13,293		£13,293		£13,293		£13,884		£13,884		£13,884		£81,530	
Total 'new' cost			£49,352	0.60	£49,741	0.60	£50,142	0.60	£51,146	0.60	£51,576	0.60	£51,926	0.60	£303,883	3.6
Existing resource			£19,769	0.20	£19,069	0.20	£20,433	0.20	£18,133	0.20	£18,401	0.20	£18,628	0.20	£114,432	1.2
Grand total (exc travel)			£69,121	0.80	£68,810	0.80	£70,575	0.80	£69,278	0.80	£69,977	0.80	£70,554	0.80	£418,315	4.8

WP2			Cost to STFC													
			FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
			Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff	Imperial	Pesaresi	£34,887	1.0	£35,843	1.0	£36,829	1.0	£37,835	1.0	£38,881	1.0	£39,963	1.0	£224,238	6.0
	Imperial	Fulcher	£20,547	0.5	£21,129	0.5	£21,731	0.5	£0	0	£0	0	£0	0	£63,406	1.5
	Imperial	Khaleeq	£8,021	0.2	£8,248	0.2	£8,483	0.2	£8,726	0.2	£8,974	0.2	£9,230	0.2	£51,682	1.2
	Imperial	Student 1	£9,709	0.5	£19,418	1.0	£19,418	1.0	£19,418	1.0		0.0			£67,963	3.5
	Bristol	RA 1	£16,966	0.5	£17,482	0.5	£18,015	0.5	£18,563	0.5	£19,139	0.5	£19,709	0.5	£109,873	3.0
	RAL TD	Prydderch	£13,045	0.1	£13,045	0.1	£13,045	0.1	£13,045	0.1	£13,045	0.1	£0	0.0	£65,227	0.5
	RAL TD	Braga	£84,500	1.0	£84,500	1.0	£106,513	1.0	£106,513	1.0	£53,257	0.5	£0	0.0	£435,284	4.5
	RAL TD	Bell	£79,885	0.8	£26,628	0.3	£53,257	0.5	£0	0.0	£0	0.0	£0	0.0	£159,770	1.5
	Total			£267,560	4.6	£226,293	4.55	£277,291	4.8	£204,100	3.8	£133,297	2.3	£68,901	1.7	£1,177,442
Equipment	Test stands & consumabl		£12,000		£15,000		£10,000		£10,000		£10,000		£8,000		£65,000	
	ASIC manufacture				£178,065		£178,065		£178,065						£534,195	
	Module assembly		£14,286		£14,286		£14,286		£14,286		£14,286		£14,286		£85,716	
	Institute support		£3,000		£3,000		£3,000		£2,000		£0		£0		£11,000	
	Total equipment		£29,286		£210,351		£205,351		£204,351		£24,286		£22,286		£695,911	
Travel																
Other costs	Bristol	DA													£0	
	Brunel	DA													£0	
	Imperial	DA	£1,397	1.5	£1,397	1.5	£1,397	1.5	£1,073	1.0	£1,073	1.0	£1,073	1.0	£7,411	
Indirects	Bristol		£16,765	0.50	£16,765	0.50	£16,765	0.50	£16,765	0.50	£16,765	0.50	£16,765	0.50	£100,589	
	Brunel														£0	
	Imperial		£46,987	1.5	£46,987	1.5	£46,987	1.5	£31,325	1.0	£31,325	1.0	£31,325	1.0	£234,936	
Estates	Bristol		£7,225	0.50	£7,225	0.50	£7,225	0.50	£7,225	0.50	£7,225	0.50	£7,225	0.50	£43,349	
	Brunel														£0	
	Imperial		£18,082	1.5	£18,082	1.5	£18,082	1.5	£13,881	1.0	£13,881	1.0	£13,881	1.0	£95,887	
Working allowance					£11,574		£11,574		£11,574		£178,065				£212,787	
Total non-staff			£119,742		£312,381		£307,381		£286,193		£272,619		£92,554		£1,390,869	
Total 'new' cost			£387,302	4.6	£538,674	4.55	£584,672	4.8	£490,293	3.8	£405,915	2.3	£161,455	1.7	£2,568,311	21.7
Existing resource			£192,154	2.17	£189,210	2.17	£196,905	2.17	£223,171	2.17	£225,315	2.17	£227,137	2.17	£1,253,893	13.0
Grand total (exc travel)			£579,457	6.72	£727,884	6.72	£781,577	6.97	£713,464	5.97	£631,230	4.47	£388,593	3.87	£3,822,204	34.7

WP3			Cost to STFC												Total	
			FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19			
			Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE		
New staff	Bristol	Frazier repl	£33,931	1.0	£34,963	1.0	£36,030	1.0	£37,126	1.0	£38,278	1.0	£39,418	1.0	£219,746	6.0
	Bristol	RA 1	£16,966	0.5	£17,482	0.5	£18,015	0.5	£18,563	0.5	£19,139	0.5	£19,709	0.5	£109,873	3.0
	Bristol	Student	£8,709	0.5	£17,418	1.0	£17,418	1.0	£17,418	1.0					£60,963	3.5
	Brunel	Reid	£6,669	0.15	£6,962	0.15	£7,265	0.15	£7,586	0.15	£0	0.0	£0	0.0	£28,482	0.6
	Imperial	RA_2	£34,887	1.0	£35,843	1.0	£36,829	1.0	£37,835	1.0	£38,881	1.0	£39,963	1.0	£224,238	6.0
	Imperial	RA_3	£34,887	1.0	£35,843	1.0	£36,829	1.0	£37,835	1.0	£38,881	1.0	£39,963	1.0	£224,238	6.0
	Imperial	Greenwood	£20,052	0.5	£20,620	0.5	£10,610	0.25	£10,913	0.25	£11,224	0.25	£11,543	0.25	£84,961	2.0
	Imperial	Student 2			£9,709	0.5	£19,418	1.0	£19,418	1	£19,418	1.0			£67,963	3.5
	RAL PPD	RA 1	£69,200	1.0	£69,200	1.0	£69,200	1.0	£69,200	1	£69,200	1.0	£69,200	1.0	£415,200	6.0
Total			£225,301	5.7	£248,039	6.7	£251,613	6.9	£255,893	6.9	£235,021	5.8	£219,795	4.8	£1,435,663	36.6
Equipment	PreProduction		£54,573												£54,573	
	Infrastructure		£100,000												£100,000	
	Production		£143,887		£431,661		£143,887								£719,435	
	Subcontracts		£20,000		£20,000		£23,270								£63,270	
	Next generation							£50,000		£50,000		£85,000			£185,000	
	Institute support		£27,000		£22,000		£22,000		£22,000		£14,000		£14,000		£121,000	
Total equipment			£345,460		£473,661		£189,157		£72,000		£64,000		£99,000		£1,243,278	
Travel																
Other costs	Bristol	DA													£0	
	Brunel	DA	£122		£122		£122		£122		£0		£0		£488	
	Imperial	DA	£1,863	2.0	£1,863	2.0	£1,863	2.0	£2,146	2.0	£2,146	2.0	£2,146	2.0	£12,027	
Indirects	Bristol		£50,294	1.5	£50,294	1.5	£50,294	1.5	£50,294	1.5	£50,294	1.5	£50,294	1.5	£301,766	
	Brunel		£4,743		£4,743		£4,743		£4,743		£0		£0		£18,972	
	Imperial		£62,650	2.0	£62,650	2.0	£62,650	2.0	£62,650	2.0	£62,650	2.0	£62,650	2.0	£375,898	
Estates	Bristol		£21,674	1.5	£21,674	1.5	£21,674	1.5	£21,674	1.5	£21,674	1.5	£21,674	1.5	£130,046	
	Brunel		£1,594		£1,594		£1,594		£1,594		£0		£0		£6,376	
	Imperial		£24,109	2.0	£24,109	2.0	£24,109	2.0	£27,762	2.0	£27,762	2.0	£27,762	2.0	£155,611	
Working allowance			£130,301		£29,488		£10,783		£1,430		£910		£910		£173,822	
Total non-staff			£642,810		£670,198		£366,989		£244,414		£229,435		£264,435		£2,418,282	
Total 'new' cost			£868,111	5.7	£918,237	6.7	£618,602	6.9	£500,308	6.9	£464,457	5.8	£484,231	4.8	£3,853,946	36.6
Existing resource			£558,342	7.48	£560,876	7.58	£530,038	7.1	£535,596	6.8	£527,830	6.7	£516,636	6.6	£3,229,319	42.4
Grand total (exc travel)			£1,426,453	13.1	£1,479,113	14.2	£1,148,640	14	£1,035,904	13.7	£992,287	12.5	£1,000,867	11.4	£7,083,264	79.0

Appendix B: Institute Costs

Brunel		Cost to STFC													
Staff name	WP Type	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
Cole	3 R	£1,683	0.15	£1,683	0.15	£1,683	0.15	£1,683	0.15	£1,683	0.15	£1,683	0.15	£10,098	0.9
Hobson	3 R	£2,043	0.1	£2,043	0.1	£2,043	0.1	£2,043	0.1	£2,043	0.1	£2,043	0.1	£12,258	0.6
Powell	3 R	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.9
Reid	3 O	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.15	£0	0.9
Reid	3 N	£6,669	0.15	£6,962	0.15	£7,265	0.15	£7,586	0.15	£0	0	£0	0	£28,482	0.6
Total new posts		£6,669	0.15	£6,962	0.15	£7,265	0.15	£7,586	0.15	£0	0.00	£0	0.00	£28,482	0.6
Total RG posts		£3,726	0.55	£3,726	0.55	£3,726	0.55	£3,726	0.55	£3,726	0.55	£3,726	0.55	£22,356	3.3
Equipment		£2,000		£2,000		£2,000		£2,000		£0		£0		£8,000	
Travel														£0	
Other DI														£0	
Other DA		£122		£122		£122		£122		£0		£0		£488	
Indirect costs		£4,743		£4,743		£4,743		£4,743		£0		£0		£18,972	
Estate costs		£1,594		£1,594		£1,594		£1,594		£0		£0		£6,376	
Total 'new' costs		£15,128		£15,421		£15,724		£16,045		£0		£0		£62,318	
RG resource		£6,356		£6,356		£6,356		£6,356		£6,356		£6,356		£38,136	
Grand total		£21,484		£21,777		£22,080		£22,401		£6,356		£6,356		£100,454	3.9

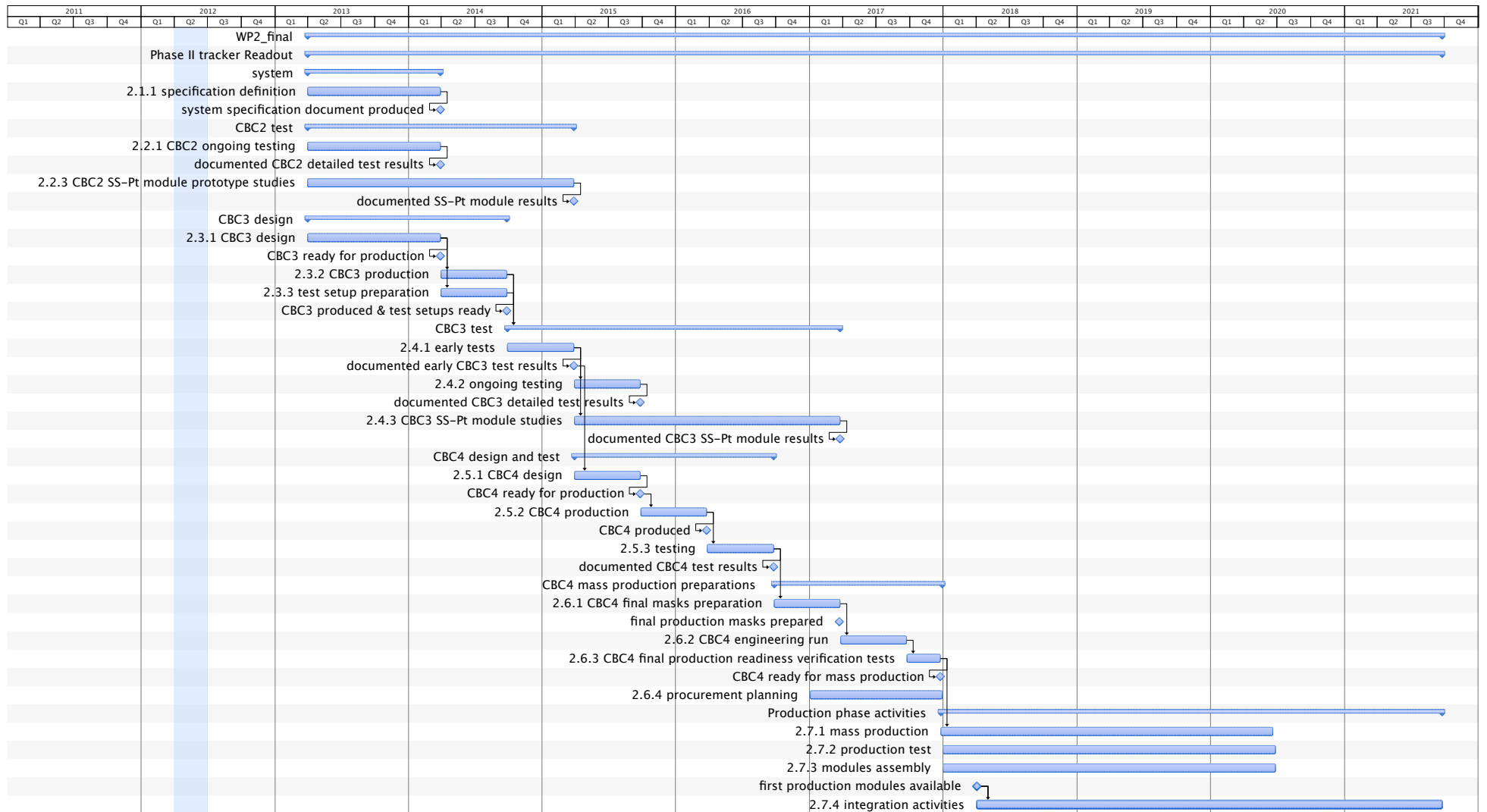
Bristol		Cost to STFC													
Staff name	WP Type	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
Newbold	3 R	£4,550	0.083	£4,690	0.08	£4,834	0.083	£4,883	0.08	£4,883	0.083	£4,883	0.083	£28,723	0.5
Goldstein	2 R	£3,643	0.067	£3,755	0.07	£3,871	0.067	£3,910	0.07	£3,910	0.067	£3,910	0.067	£22,999	0.4
Brooke	3 R	£9,855	0.25	£10,159	0.25	£10,159	0.25	£10,159	0.25	£10,159	0.25	£10,159	0.25	£60,650	1.5
Cussans	2 R	£11,370	0.25	£11,723	0.25	£11,841	0.25	£11,841	0.25	£11,841	0.25	£11,841	0.25	£70,457	1.5
Nash	2 R	£15,140	0.5	£15,140	0.5	£15,140	0.5	£15,140	0.5	£15,140	0.5	£15,140	0.5	£90,840	3.0
Core RA	3 R	£27,843	0.75	£28,708	0.75	£29,563	0.75	£20,319	0.25	£20,319	0.25	£20,319	0.25	£147,071	3.0
Frazier replacem.	3 N	£33,931	1	£34,963	1	£36,030	1	£37,126	1	£38,278	1	£39,418	1	£219,746	6.0
RA 1 (Grimes)	2&3 N	£33,931	1	£34,963	1	£36,030	1	£37,126	1	£38,278	1	£39,418	1	£219,746	6.0
Student 1	3 N	£8,709	0.5	£17,418	1	£17,418	1	£17,418	1					£60,963	3.5
Total new posts		£76,571	2.5	£87,344	3	£89,478	3	£91,670	3	£76,556	2	£78,836	2	£500,455	15.5
Total RG posts		£72,401	1.9	£74,175	1.9	£75,408	1.9	£66,252	1.4	£66,252	1.4	£66,252	1.4	£420,740	9.9
Equipment		£15,000		£13,000		£13,000		£13,000		£10,000		£10,000		£74,000	
Travel														£0	
Other DI														£0	
Other DA														£0	
Indirect costs		£67,059		£67,059		£67,059		£67,059		£67,059		£67,059		£402,354	
Estate costs		£28,899		£28,899		£28,899		£28,899		£28,899		£28,899		£173,394	
Total 'new' costs		£187,529		£196,302		£198,436		£200,628		£182,514		£184,794		£1,150,203	
RG resource		£101,154		£102,255		£102,487		£102,487		£102,487		£102,487		£613,357	
Grand total		£288,683		£298,557		£300,923		£303,115		£285,001		£287,281		£1,763,560	25.4

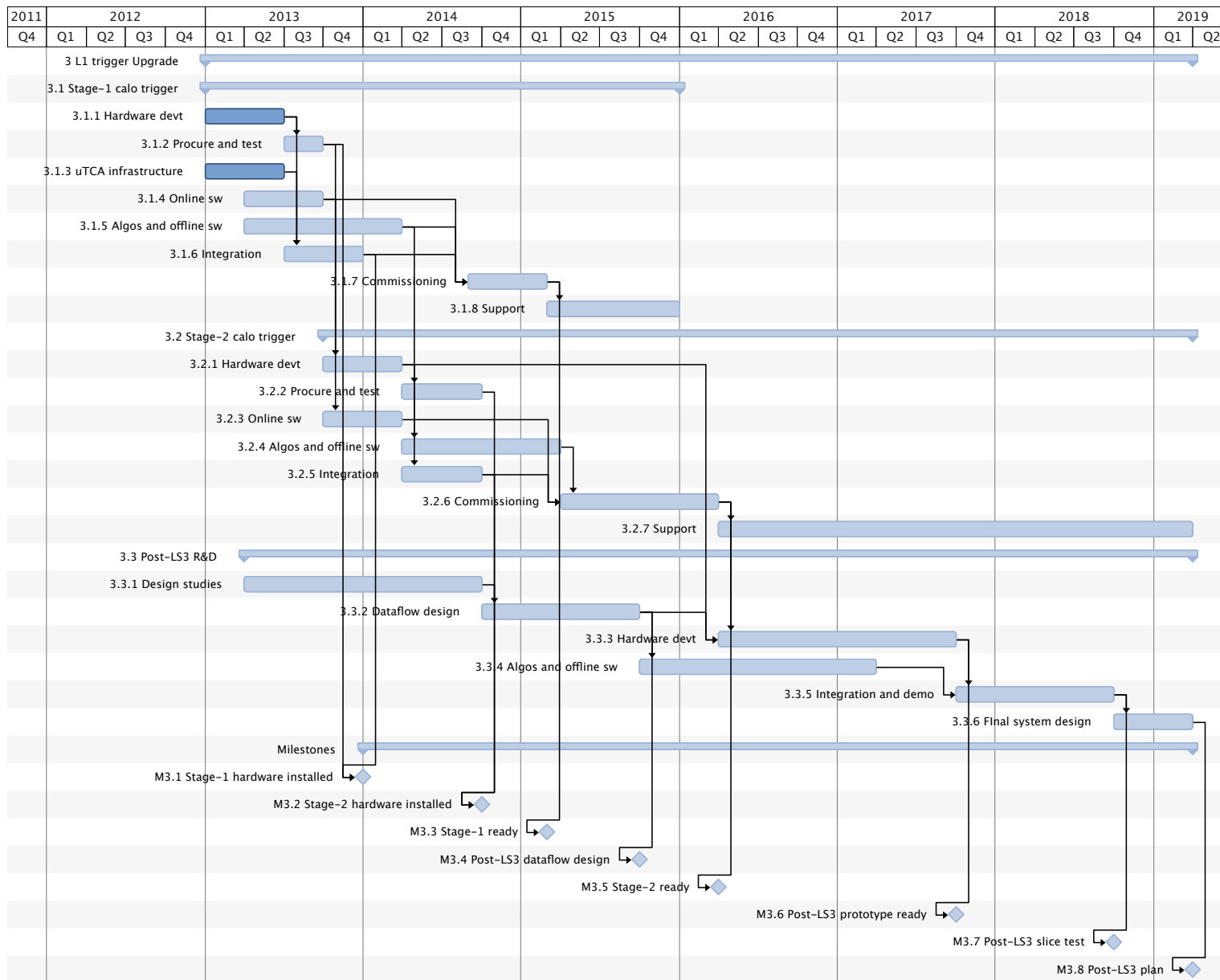
Imperial			Cost to STFC												Total	
Staff name	WP	Type	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Cost	FTE
			Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE		
Hall	1	R	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£89,324	1.2
Tapper	3	R	£21,868	0.5	£13,121	0.5	£13,121	0.3	£13,121	0.3	£13,121	0.3	£13,121	0.3	£87,470	2.2
Raymond	2	R	£42,337	0.8	£43,793	0.8	£45,250	0.8	£46,888	0.8	£48,709	0.8	£49,622	0.8	£276,600	4.8
Fulcher	2	R							£22,572	0.5	£23,226	0.5	£23,901	0.5	£69,699	1.5
Iles	3	R	£39,094	0.75	£40,243	0.75	£41,419	0.75	£42,634	0.75	£43,876	0.75	£45,158	0.75	£252,424	4.5
Rose	3	R	£30,671	0.9	£31,530	0.9	£32,418	0.9	£33,323	0.9	£34,265	0.9	£35,230	0.9	£197,437	5.4
Pioppi replacmt.	3	R	£10,071	0.25	£10,362	0.25	£10,663	0.25	£10,974	0.25	£11,292	0.25	£11,619	0.25	£64,981	1.5
Clark, I	2	R	£4,043	0.1	£4,160	0.1	£4,282	0.1	£4,406	0.1	£4,534	0.1	£4,666	0.1	£26,090	0.6
Kasey, V	2	R	£8,086	0.2	£8,321	0.2	£8,563	0.2	£8,812	0.2	£9,068	0.2	£9,331	0.2	£52,181	1.2
Hall	1	N	£22,434	0.3	£22,434	0.3	£22,434	0.3	£22,434	0.3	£22,434	0.3	£22,434	0.3	£134,601	1.8
Fulcher	2	N	£20,547	0.5	£21,129	0.5	£21,731	0.5	0	0	0	0	0	0	£63,406	1.5
RA_1 (Pesaresi)	2	N	£34,887	1	£35,843	1.00	£36,829	1	£37,835	1	£38,881	1	£39,963	1	£224,238	6.0
RA_2	3	N	£34,887	1	£35,843	1.00	£36,829	1	£37,835	1	£38,881	1	£39,963	1	£224,238	6.0
RA_3	3	N	£34,887	1	£35,843	1.00	£36,829	1	£37,835	1	£38,881	1	£39,963	1	£224,238	6.0
Barlow	1	N	£5,605	0.1	£5,767	0.10	£5,932	0.1	£6,103	0.1	£6,285	0.1	£6,379	0.1	£36,070	0.6
Greenwood	3	N	£20,052	0.5	£20,620	0.50	£10,610	0.25	£10,913	0.25	£11,224	0.25	£11,543	0.25	£84,961	2.0
Khaleeq	2	N	£8,021	0.2	£8,248	0.20	£8,483	0.2	£8,726	0.2	£8,974	0.2	£9,230	0.2	£51,682	1.2
Brambilla	1	N	£8,021	0.2	£8,248	0.20	£8,483	0.2	£8,726	0.2	£8,974	0.2	£9,230	0.2	£51,682	1.2
Student 1	2	N	£9,709	0.5	£19,418	1	£19,418	1	£19,418	1	£19,418	1			£67,963	3.5
Student 2	3	N			£9,709	0.5	£19,418	1	£19,418	1	£19,418	1			£67,963	3.5
Total new posts			£199,050	5.3	£223,100	6.3	£226,995	6.6	£209,241	6.1	£193,953	5.1	£178,703	4.1	£1,231,041	33.3
Total RG posts			£171,056	3.7	£166,418	3.7	£170,603	3.5	£197,617	4	£202,978	4	£207,534	4	£1,116,207	22.9
Equipment	Expenses		£12,000		£15,000		£10,000		£10,000		£10,000		£8,000		£65,000	
	Subcontract		£20,000		£20,000		£23,270		£0		£0		£0		£63,270	
	Procurement		£312,746		£624,012		£336,238		£242,351		£64,286		£99,286		£1,678,919	
Equipment	W All.		£130,301		£41,062		£22,357		£13,004		£178,975		£910		£386,609	
Travel																
Other DI															£0	
Other DA			£3,540		£3,540		£3,540		£3,540		£3,540		£3,540		£21,241	
Indirect costs			£119,034		£119,034		£119,034		£103,372		£103,372		£103,372		£667,218	
Estate costs			£45,807		£45,807		£45,807		£45,807		£45,807		£45,807		£274,840	
Total 'new' costs			£842,478		£1,091,555		£787,241		£627,315		£599,932		£439,618		£4,388,139	
RG resource			£365,725		£352,768		£357,574		£362,652		£368,013		£372,569		£2,179,301	
Grand total			£1,208,203		£1,444,323		£1,144,815		£989,967		£967,945		£812,187		£6,567,440	56.2

RAL PPD		Cost to STFC													
Staff name	WP Type	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
Shepherd-T	3 S	£27,400	0.2	£27,400	0.2	£27,400	0.2	£41,100	0.3	£41,100	0.3	£27,400	0.2	£191,800	1.4
Harder	3 S	£87,567	1	£87,567	1	£87,567	1	£87,567	1	£87,567	1	£87,567	1	£525,400	6.0
Durkin	3 S	£69,233	1	£69,233	1	£69,233	1	£69,233	1	£69,233	1	£69,233	1	£415,400	6.0
Newbold	3 S	£26,786	0.25	£26,786	0.25	£10,714	0.1	£10,714	0.1					£75,000	0.7
Tomalin	3 S	£21,495	0.2	£32,240	0.3	£21,495	0.2	£32,240	0.3	£32,240	0.3	£32,240	0.3	£171,949	1.6
Sankey	3 S	£43,783	0.5	£43,783	0.5	£43,783	0.5	£43,783	0.5	£43,783	0.5	£43,783	0.5	£262,700	3.0
Petyt	3 S	£20,767	0.3	£20,767	0.3	£20,767	0.3	£20,767	0.3	£20,767	0.3	£20,767	0.3	£124,600	1.8
RA 1	3 N	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£415,200	6.0
Total new posts		£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£69,200	1	£415,200	6.0
Total RG posts		£297,030	3.45	£307,776	3.55	£280,959	3.3	£305,404	3.5	£294,690	3.4	£280,990	3.3	£1,766,849	20.5
Equipment		£10,000		£7,000		£7,000		£7,000		£4,000		£4,000		£39,000	
Travel		£50,000		£60,000		£60,000		£50,000		£40,000		£40,000		£300,000	
Other DI														£0	
Other DA														£0	
Indirect costs														£0	
Estate costs														£0	
Total 'new' costs		£129,200		£136,200		£136,200		£126,200		£113,200		£113,200		£754,200	
RG resource		£297,030		£307,776		£280,959		£305,404		£294,690		£280,990		£1,766,849	
Grand total		£426,230		£443,976		£417,159		£431,604		£407,890		£394,190		£2,521,049	26.5

RAL TD		Cost to STFC													
Staff name	WP Type	FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
Prydderch	2 N	£13,045	0.1	£13,045	0.1	£13,045	0.1	£13,045	0.1	£13,045	0.1	£0	0	£65,227	0.5
Braga	2 N	£84,500	1	£84,500	1	£106,513	1	£106,513	1	£53,257	0.5	£0	0	£435,284	4.5
Bell	2 N	£79,885	0.75	£26,628	0.25	£53,257	0.5	£0	0	£0	0	£0	0	£159,770	1.5
Total new posts		£177,431	1.85	£124,174	1.35	£172,815	1.6	£119,559	1.1	£66,302	0.6	£0	0	£660,280	6.5
	N	£0		£0		£0		£0						£0	0.0
Total W. All.		£0	0.0	£0	0.0	£0	0.0	£0	0.0	£0	0.0	£0	0.0	£0	0.0
Total RG posts														£0	0.0
Equipment		£3,000		£3,000		£3,000		£2,000						£11,000	
Travel															
Other DI														£0	
Other DA														£0	
Indirect costs														£0	
Estate costs														£0	
Total 'new' costs		£180,431		£127,174		£175,815		£121,559		£66,302		£0		£671,280	
RG resource														£0	
Grand total		£180,431		£127,174		£175,815		£121,559		£66,302		£0		£671,280	6.5

Appendix C: Gantt Charts





Appendix D: Risk Register

(Abbreviated from the Excel master copy to fit the available space)

Ref	Description	Impact	Owner	L	I	L*I	Controls	Mitigation
1.1	Reduced STFC funding	Delay completing, reduced travel, posts loss	PI & STFC	0.25	60	15	Costs scrutinised; Cash flow management.	Preserve Working Allowance as long as possible
1.2	Reduced university funding	Delay in completion of projects due to lack of staff	PI & Group leaders	0.1	30	3	Ensure adequate STFC funding for key posts	Preserve Working Allowance as long as possible
1.3	CERN funding shortfall	Delays to SLHC project, significant STFC cost to adapt	PI and STFC	0.1	70	7	Monitor progress of SLHC.	An issue for contingency
1.4	Shortfall in or CERN collaborator funding	Overall delay in tracker or trigger projects	PI & STFC	0.3	50	15	RRB monitoring of SLHC project	Preserve Working Allowance as long as possible. STFC contingency
1.5	Insufficient project funding	Delay in completion of project	PI	0.1	90	9	Cautious budgeting with adequate working allowance	Preserve Working Allowance as long as possible
1.6	Unfavourable currency variation	Shortfall in fabrication funds	PI & STFC	0.3	50	15	Mainly affects the US\$. Some provision in Working Allowance.	Preserve Working Allowance. STFC contingency.
1.7	Loss of key non-UK collaboration members	Delay in completion of the project. Could affect any WP	PI	0.1	50	5	Ensure collaborator responsibilities compatible with resources	Negotiate with CMS collaboration
2.1	Extended absence of senior managers	Risk of project failing to meet deadlines/deliverables	PI	0.2	50	10	Distribute management and share information.	Identify deputies and share information
2.2	Loss of staff in Bristol	Delay in completion of the project. Affects mainly WP3	Group leader	0.2	40	8	Monitor deliverables and staff provided	Redistribute work load and draw on Working Allowance
2.3	Loss of staff in Brunel	Delay in completion of the project. Affects only WP4	Group leader	0.2	20	4	Monitor deliverables and staff provided	Redistribute work load and draw on Working Allowance
2.4	Loss of staff at Imperial	Delay in completion of the project. Affects all WPs.	Group leader	0.1	80	8	Monitor deliverables and staff provided	Redistribute work load and draw on Working Allowance
2.5	Loss of staff in RAL PPD	Delay in completion of the project. Affects mainly WP4.	Group leader	0.2	40	8	Monitor deliverables and staff provided	Redistribute work load and draw on Working Allowance
2.6	Required staff in RAL TD unavailable for any reason	Delay in completion of project. Affects WP2 and WP4	PI and TD managers	0.2	90	18	Monitor staff availability, but particularly ASIC design team	Redistribute load, use Working Allowance. Well documented designs, to ISO9001 QM standards
3.1	Loss of foundry access	Delay to WP2.	PI & WP2 managers	0.1	90	9	CERN frame contract already in place. Remain vigilant	Would affect many projects, so negotiate with CERN and CMS
3.2	Technical problems with 130 nm CMOS	Delay to WP2.	PI & WP2 managers	0.2	60	12	Anticipate contingency requirements	Work closely with foundry to monitor and remedial actions.
3.3	Access to radiation tolerant technology	Delay completion of Phase II Tracker	PI & WP2 managers	0.1	90	9	Remain vigilant to changes in regulations.	Negotiate with CERN and CMS. Preserve Working Allowance.

3.4	ASIC design failure or flaw	Schedule delay, cost of additional MPW submission	PI & WP2 managers	0.25	50	12.5	Design reviews at regular intervals during design phase	Evaluation of ASICs delivered. Preserve working allowance
3.5	ASIC slowed by external decisions	Delay in schedule	PI & WP2 managers	0.3	70	21	Work with collaborators on system design & influence decisions	Negotiate with CMS Tracker management. Working allowance
4.1	Absence of DAQ for module evaluation	Delay in schedule	PI & WP2 managers	0.1	50	5	Work with collaborators to ensure development proceeds	Slow subsequent ASIC development until modules studied
5.1	10 Gbps PCB design layout	Delay to the project or links at lower speed	WP3 managers	0.1	80	8	Careful attention during R&D.	Prototype test boards. Work with manufacturers to solve problems
5.2	Supply of components for trigger boards	Delay in WP3 schedule	WP3 managers	0.3	60	18	Identify alternative suppliers for appropriate parts	Anticipate purchases of key parts where possible
5.3	Trigger objectives more difficult than anticipated	Delay in WP3 schedule	PI & WP3 managers	0.2	70	14	R&D phase has limited the risk, but remain vigilant	Move extra staff to WP3 from other parts of project
6.1	FPGA firmware more complex than expected	Delay in WP3 and WP4 schedules	WP3 & WP4 managers	0.3	50	15	Early development of critical firmware, evaluation and test.	Expert sub-contractors or move engineering effort from other WPs
6.2	Software development problems	Delay to deliverables or reduced scope	WP3 & WP4 managers	0.2	50	10	Early development of critical software.	Revise sharing of effort across WPs
7.1	Significant change in HL-LHC specifications	Revision of UK project to meet new requirements	PI	0.25	80	20	Monitor status of SLHC project	Negotiate with CERN and CMS
7.2	CERN schedule for accelerator	Delays, cost to STFC, need for longer R&D.	PI & STFC	0.5	80	40	Monitor status of SLHC project. Ensure effort matches need.	Negotiate with CERN and CMS
8.1	Destruction of Laboratory/Test area.	Delay to project. Impact will depend on lab affected.	PI & group leaders	0.01	70	0.7	Maintain security and fire protection systems	Transfer work to another institute
8.2	Loss of dedicated data disks	Delay to project.	WP managers	0.1	15	1.5	Ensure critical data is replicated and/or archived	Maintain multiple copies of all designs in several places