STFC Project Peer Review Panel

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

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[1] PI

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 in 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 deliver a new data acquisition system for the new pixel detector, and 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 consistent with proportionate sharing of construction responsibilities. We request appropriate resources to allow us to undertake these projects.

Request

In summary, our request is for a 73 month project commencing on 1 March 2013[2], for:

- 101.2 staff-years of new, project-funded effort, including students, at a cost of £4.811M, plus overheads, including £307k to support 3.7 FTE of management and administrative support effort,
- 61.0 staff-years of existing grant-funded or STFC (RAL PPD) supported effort at a total cost of £5.199M including overheads.
- Equipment and consumables costs totalling £2.887M, mainly at 100% under the Instrument Development exception,
- £390k 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 £11.486M of new funding, and £5.199M of existing resources via grants and RAL PPD funding, with a grand total of £16.685M

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

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[2] See comment in WP1 section. Only Imperial starts on 1 March. All others start 1 April.

luminosity of 5.2 fb^{-1} at end 2011, plus 140 μb^{-1} of Pb-Pb data, and 6.7 fb^{-1} by the June 2012 Technical Stop, with a target of 15 fb^{-1} before the end of year shutdown.

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.

It now seems certain that the LHC will discover or exclude the existence of the Standard Model Higgs during 2012, but this represents the beginning, not the end, of the programme which comprises searches for new physics and the detailed characterisation of any discoveries.

Either a major discovery or its absence requires more data, optimal selection of events at the Level-1 trigger and flexibility to adapt to the unexpected. In the case of a discovery, e.g. a light SM Higgs, the properties (mass, couplings, spin) must be measured to establish the identity of the new particle. 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 a Higgs sighting is the simplest SM object or, e.g., a SUSY version. Compiling evidence on the nature of a Higgs 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 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 to 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 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 latest CERN schedule (July 2011) 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} cm^{-2}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 the end of 2021 (LS3) for upgrade to very high intensity with an objective of a *levelled* peak luminosity of 5 x 10^{34} cm^{-2}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.

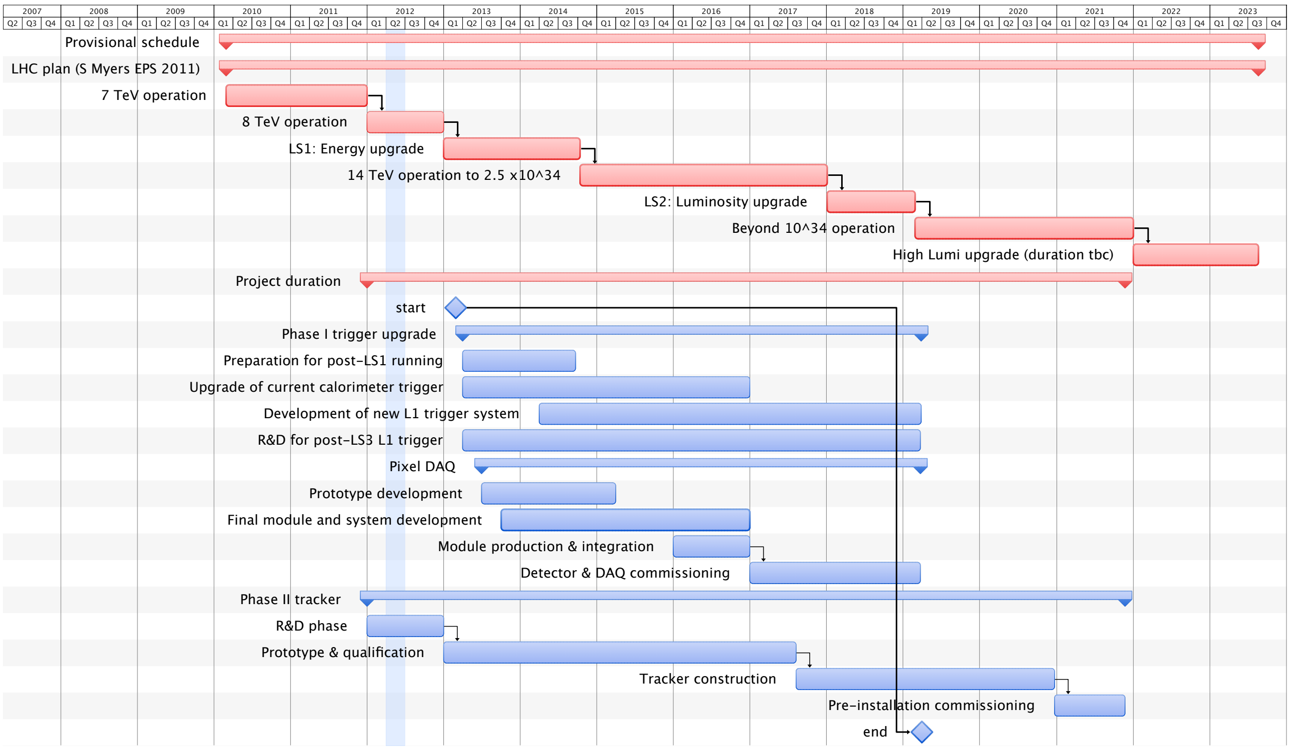

Fig. 1 Overall LHC schedule and the main elements of the UK projects to be undertaken

A second significant uncertainty is the 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 has been growing very fast during 7 and 8 TeV operation, and is expected to exceed the design value of 10^{34} cm^{-2}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 has already reached 6.6 x 10^{33} $cm^{-2}s^{-1}$; 50 ns bunch spacing doubles the pile-up (number of simultaneous events in a single bunch crossing), which is therefore 30% higher than nominal at this energy. The projected luminosity of 2.5 x 10^{34} $cm^{-2}s^{-1}$ 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. They are both areas of the detector where the UK has significant involvement and expertise, and is able to contribute original new ideas. 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 key 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 an alternative.

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. A new digital readout architecture is needed to cope with this, with 400 Mbps links. The off-detector readout must be adapted to cope, which requires a new front end data acquisition board (Front End Driver: FED, and Controller: FEC) integrated into a system with new links to the central DAQ. The UK groups are well placed to take responsibility for this because of our extensive contributions to delivery and operation of the present Tracker readout system, which included the design and provision of 500 FEDs, and much online software and firmware. The pixel DAQ proposal also profits considerably from the pioneering UK trigger R&D and the boards which have been developed.

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 5×10^{34} $cm^{-2}s^{-1}$ 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} $cm^{-2}s^{-1}$ 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 μTCA-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 μW/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, is due for submission in July. 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 mid-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 in manufacture. 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.

A proposal for a very innovative, time-multiplexed trigger architecture [2,3] which offers many benefits over a conventional system has evolved from this work and is under consideration in CMS. However, the MP7 can be used in any system and is far in advance of any alternative design.

An internal CMS review was held in October 2011 "*to evaluate the two systems [Time Multiplexed Trigger (UK) and Conventional Trigger (US)]*" The committee was unable to recommend the architecture to adopt, but noted that "*development of a common L1 trigger hardware platform, to be used by all trigger systems, is not only desirable but technically possible*" and that "*the trigger processing board should be based on the demonstrator board built by the UK group, which at this point is the only available prototype with performance approaching the requirements*". This remains the case.

More recently, as the pixel replacement became better defined, we began to see scope for building further on our successful R&D by contributing to the pixel detector upgrade, and a new work package, WP4, was formulated. A new FED is needed, and contributors were missing to provide it. It is natural to base it on the generic MP7 trigger board in a μTCA crate, optimised for cost and performance for a tracker application, and profit from the IPbus system and considerable firmware and software expertise which exists in the UK collaboration. RAL PPD began working closely with the designers of the pixel Readout Chip (ROC) to gain direct experience of the readout operation and the new features of the modified ROC. Meanwhile we have studied the requirements for the FED and will shortly begin the layout of an MP7-based pixel FED at Imperial now the MP7 has been submitted.

We have developed the system concept, proposed it to CMS – which was accepted – and have been preparing the case and detailed costing needed for the pixel Technical Design Report due for submission in August.

Proposed UK Activities

The three new Work Packages (numbered simply to avoid confusion with 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
- WP4: provision of a complete pixel DAQ readout system with hardware, firmware, online and offline software, including data quality monitoring.

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 and WP4 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 1.3μm 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 have begun 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 likely 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 concerns the architecture choice. The Time Multiplexed trigger is no longer considered to be technically risky but there are disputes about the latency penalty incurred, and firmware algorithms which can be deployed. These are the main arguments deployed in favour of the Conventional Trigger (CT) architecture, which is limited by boundaries in the system and consequent sharing of data between boards and crates. Our strongly held belief is that this more than wipes out any latency penalty incurred by the TMT, which in any case operates in a pipelined processing mode, and the CT is a more complex system design requiring reduced data resolution to remain within the achievable bandwidth, incurring avoidable risks. CT proponents do not yet concede this point and it will require more demonstrations to win the argument. We are hopeful of doing so in the coming year. However, whatever the decision, the MP7 hardware, software and much of the firmware can, and will, be used in any new trigger system.

In the pixel DAQ, there is strong support for the UK to take responsibility for FEDs and DAQ. It was previously the responsibility of a very small team who are now overcommitted and wish to relinquish this obligation. In addition, we expect to collaborate closely with Strasbourg, contributing to FEC and detector control work, which is both complementary and with whom we have excellent working relationships from our joint Tracker DAQ work.

Strategy and Organisation

Project Management Plan

The project has been divided into three 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.
4	M Pesaresi	Imperial	Based in London, with lead responsibility for pixel FED hardware design, developing test systems and firmware.
	K Harder	RAL PPD	Responsible for beam tests, including software, and interface to ROC and pixel team. Coordinate RAL engineers providing WP4 firmware, and supervising PPD staff.

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 (eg 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. Both WP3 and WP4 have 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 PPRP 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 March 2013. This is because extensions to the R&D project at Bristol and Brunel mean their grants now end on 31 March 2013, but Imperial College funding for the R&D project ends on 28 February 2013, hence the one month funding in financial year 2012/13 requested, otherwise staff posts are in jeopardy.

One small managerial challenge is formatting financial tables and Gantt charts in a readable form for this document. They can be provided in alternative formats, if needed.

Resource estimates

The resource estimates originate in WP work plans and have been developed by the WP managers (Raymond, Newbold, Pesaresi) 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 and WP4. 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.

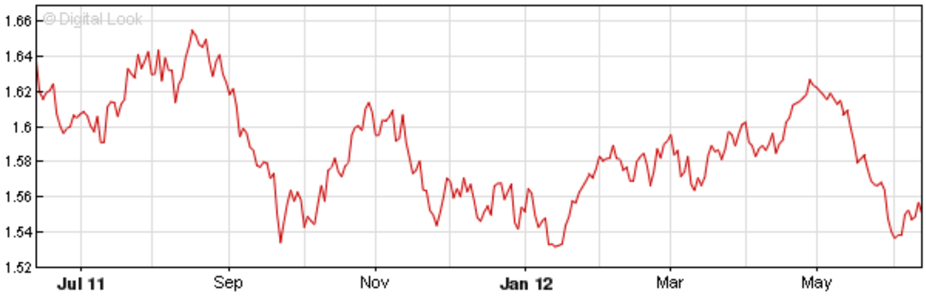

Fig. 2. Variation of the $ vs the £ over a recent one year period (source: BBC)

An allowance has been made for possible extra staff effort by including the last two years of RAL TD systems group engineering effort, amounting to 3.6 FTE years, in the Working Allowance. Although this could be used anywhere in the project, it has been assigned to WP4 in the tables. 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 been contributing to the MP7 design.

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 significant overlap between expertise and activities in each WP. WP3 and WP4 both have significant firmware and software tasks, where staff should be exchangeable in case of urgent need or, more likely, available to provide expert advice and support for short periods. This is already happening in the development of the WP4 project, following earlier work by WP3. Even in the case of WP2, which has a large ASIC design activity, part of the evaluation will require test beam activities, which will be based on hardware such as the pixel FED, adapted for the data acquisition required.

Five 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 (30cm< r <120cm and end-caps) instrumented as two regions. The outermost region (60cm < r < 120cm, 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 pixellated, 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.
- 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].

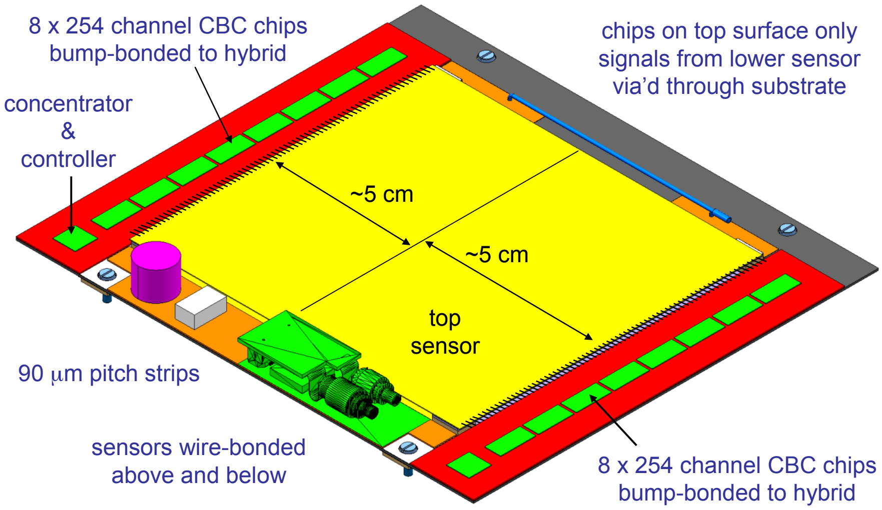

Figure 3. SS-Pt module

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 250μm 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.

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 five years up to production readiness status (0.4 SY/year Pesaresi, 0.6 SY/year RA_1). We also request project funding for a PG student. We request RA funding continue for production, integration and commissioning activities. 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).

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 - £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.

Risk

The work rests on production of 0.13μm 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 0.13μm 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, an essential step in preserving trigger selectivity at HL-LHC luminosities.

The objectives of WP3 are:

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

- Design of a track trigger architecture for HL-LHC running, and construction of a technology demonstrator.

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 1μs, 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 almost 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 (2013-14)

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. GCT improvements will involve definition and implementation of new algorithms, based on analysis of 2012 data, along with a rebalancing of the L1 trigger menu. We will also simplify and rationalise online and offline software for the current trigger system, in addition to introducing functionality to support the new hardware.

The move to a new trigger will optimally take place between LS1 and LS2, as the LHC luminosity reaches $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$, twice the design luminosity. The change can only take place after a significant commissioning and testing period, and when experience has been gained in operating the system with high reliability. 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, in preparation for the switchover. 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 must take place during LS1.

Work Plan: Stage 2 (2014-17)

The work package centres around implementation of a new calorimeter trigger. The system will be based on an advanced μTCA processor module, the MP7, developed at Imperial during the current R&D project. It uses the latest generation high-performance Xilinx Virtex-7 FPGA, coupled with an extremely high-throughput I/O system comprising 144 optical links running 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. The trigger system, along with 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.

The UK has proposed a novel, highly flexible processing architecture for the upgraded calorimeter trigger. In a traditional trigger, 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 proposed 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 μTCA module, allowing work towards the final MP7 module to proceed.

A TMT slice will be initially be constructed in prototype form during 2013/14, and integrated with the new fibre-optic input links during the first phase of post-LS1 running. Sign-off on construction of the full TMT is required by the end of 2014, with a target delivery date for the new system of early 2016. The final system will comprise up to 40 identical MP7 cards, divided between multiplexing and processor functions. After a period of parallel running, the TMT will be available for operation any time after late 2016, around the time the LHC begins operation at $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ luminosity.

Work Plan: Stage 3 (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 available position 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 will refine position estimates for trigger objects, add p_T information, improve charge assignments, and calculate 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 ASIC, 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 Stage 3 work programme will begin early in the project 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 next ASICs. This work will build upon the leading UK contribution within the CMS tracker upgrades simulation group.

From 2017, after 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 late 2018 of a hardware demonstrator comprising a small number of new modules, capable of receiving data from modules based on the CBC4 chip. A successful demonstration 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 at 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 an 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 46 staff-years of effort. The project has been planned against a relatively 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 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 two years of this project, and will oversee both RAL and Bristol contributions during this period.
- *Hardware development and core firmware* (17SY). Led by Iles (Imperial), effort from Imperial, Bristol and RAL TD – 17SY. 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* (11SY). Led by Frazier (Bristol), with effort from Imperial and RAL PPD. Frazier has been IPbus team leader to date, and has several years of experience on the current GCT. The 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. We will work closely with WP4 online software in, sharing modules wherever possible.
- *Trigger studies and offline software development* (14SY). Led by Brooke (Bristol), with effort from 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 an 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.

Our effort request includes new RA posts at Imperial, Bristol and RAL PPD. 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 £1475k, 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 30% 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. £65k 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.

In late 2011, CMS carried out a formal review of two alternative calorimeter trigger architectures: the TMT, and a traditional two-level trigger. The recommendation of this review was that a single hardware module be developed, which should be capable of supporting a range of possible architectures. The MP7 has been designed with this goal explicitly in mind, and is the only module under development in CMS with this capability. We therefore anticipate that the UK will play the leading role in the development of hardware and core firmware for the upgraded system. In addition, the UK will continue its leadership in online software. The trigger studies and commissioning efforts, and the development of algorithms, are likely to be collaborative efforts. The final choice of architecture would ideally be made after demonstration of a slice prototype in parallel with the existing trigger, which in turn depends upon a successful installation of the parallel trigger infrastructure, and the successful delivery of the MP7.

Work Breakdown Structure

WBS L1	WBS L2		Start	Finish	SY	Task description
3.1 LS1 infrastructure					**5.8**	**Preparation of CMS systems for the post-LS1 running, including parallel operations**
	3.1.1	Electronics devt	04/13	04/14	1.5	Installation and testing of parallel system infrastructure, modifications to GCT system
	3.1.2	Procurement	04/13	04/14	0.5	Procurement and acceptance tests of updated trigger / infrastructure components
	3.1.3	Online software	04/13	04/14	1.8	Completion of baseline IPbus / uHAL / trigger supervisor for post-LS1 running
	3.1.4	Integration	04/14	10/14	2.0	Shakedown and commissioning of the L1 trigger at end of LS1
3.2 Post-LS1 CALO trigger					**5.2**	**Optimisation and development of the current Level-1 system for operation to 2x 10^{34} $cm^{-2}s^{-1}$**
	3.2.1	Design studies	04/13	10/13	0.6	Studies of post-LS1 trigger based on 2012 data; development of pragmatic trigger strategy until new system is in place.
	3.2.2	Algorithm devt	10/13	04/14	0.8	Development of updated algorithms for GCT post-LS1
	3.2.3	Offline software	10/13	04/14	0.8	Development of updated offline software for GCT post-LS1
	3.2.4	Support	10/14	12/16	3.0	Expert support and optimisation of current L1 calo trigger
3.3 New L1 trigger					**20.2**	**Design, construction and integration of new L1 trigger for operation above 2x 10^{34} $cm^{-2}s^{-1}$**
	3.3.1	Design studies	04/14	04/15	1.3	Post-TDR design and performance studies for new L1 trigger architecture (TMT)
	3.3.2	Electronics devt	04/14	04/16	5.6	Development and construction of final version modules and infrastructure for new L1 trigger
	3.3.3	Procurement	10/14	04/16	0.8	Procurement and acceptance tests of updated trigger components
	3.3.4	Algorithm devt	04/15	04/16	1.6	Development of algorithms and associated firmware for new L1 trigger
	3.3.5	Online software	04/15	04/16	1.8	Development of online software for new L1 trigger (common project with other subsystems)
	3.3.6	Offline s/w	04/15	04/16	1.6	Development of offline software for new L1
	3.3.7	Integration	04/16	12/16	4.5	Integration and commissioning of hardware, firmware, software for new L1 trigger
	3.3.8	Support	01/17	04/19	3.0	Expert support and optimisation of new trigger
3.4 Post-LS3 R&D					**14.7**	**Studies, design and prototyping of post-LS3 L1 trigger, including track trigger**
	3.4.1	Conceptual design	04/13	04/15	3.2	Conceptual design for post-LS3 L1 trigger, including tracking input
	3.4.2	Dataflow design	04/16	04/17	1.6	Detailed design studies for prototype tracking trigger
	3.4.3	Algorithm devt	04/17	10/18	2.4	Design studies for prototype tracking trigger
	3.4.4	Hardware devt	01/17	10/18	4.5	Design & construction of track trigger prototype
	3.4.5	Integration	10/18	4/19	3.0	Testing of modules + track trigger prototypes
Totals					**45.8**	

Work Package 4: Pixel DAQ

Work package leaders: K. Harder, M. Pesaresi

Objectives

- develop and demonstrate a μTCA-based readout Front End Driver board (FED) with associated firmware and software for the CMS Phase I pixel detector

- design, produce, commission the off-detector data acquisition (DAQ) system including FEDs and associated firmware and software for the CMS Phase I pixel detector
- support and maintain the Phase I pixel DAQ system and contribute to the upgraded pixel detector performance studies

Description and work plan

The CMS pixel detector will be replaced, either in an extended year-end technical stop 2016/2017, or during the second planned long LHC shutdown (LS2) in 2018, in preparation for the Phase I LHC luminosity upgrade. The new pixel detector has been designed to cope with instantaneous luminosities of up to 2.5×10^{34} $cm^{-2}s^{-1}$ with 50 ns bunch separation, corresponding to a factor of 5 times the occupancy for which the current detector has been specified. In addition, in order to increase the overall track seeding efficiency, the new design will implement an extra pixel layer in both the barrel and endcap regions. The first barrel layer will also be placed closer to the interaction point, improving the impact parameter resolution and b-tagging efficiency, while the detector mass will be reduced significantly, increasing the overall tracking performance of the detector.

A significant challenge for the new detector is the readout electronics. To keep hit losses in the readout chain below a few per cent, the current pixel readout chip (ROC) has modified data buffering and adds pulse-height digitisation and digital off-detector transmission at 400 Mbps. As a consequence, the current VME off-detector readout (FEDs) will not be suitable for this new transmission protocol and speed:

- the optical receiver is not suitable for 400 Mbps digital readout
- the bandwidth of the S-Link interface to the global DAQ is insufficient for data rates expected at instantaneous luminosities following LS2.

An additional problem with existing FEDs is that the complexity of the firmware has increased beyond expectations, to the point where ability to cope with detector occupancy and radiation related issues, including SEUs and beam gas events, is now severely limited by lack of FPGA resources.

Our objective is to deliver a replacement DAQ for the Phase I pixel detector, including FEDs suitable for high speed digital readout, and associated infrastructure. The pixel FED hardware will build on the success of UK trigger hardware developments undertaken in the UK CMS upgrade R&D programme. We also propose to develop, deliver and maintain firmware and software required to operate and monitor the performance of the new FEDs under high luminosity conditions and will provide a significant contribution to the commissioning effort of the new pixel detector both before and after installation.

We propose to base the new FEDs on the latest μTCA design developed for the calorimeter trigger, the MP7, which has a generic architecture centred on a high performance FPGA, high speed optical links and μTCA management. By replacing optical inputs and outputs with devices matching the pixel system requirements, we can build a fully functional pixel FED with a limited hardware design effort. For prototyping, we plan to implement the FED as an FMC carrier and locate optical links on mezzanine cards which will provide a modular and flexible approach to testing. It will also allow the use of specialised test input cards with electrical as well as optical links to read out chips or modules and give us the ability to evaluate optical transmitter/receiver options proposed.

A design based on μTCA is well matched to off-detector hardware upgrades for CMS which will see μTCA replacing VME as a standard in many applications including the trigger and, eventually, the outer tracker readout for Phase II. As part of the calorimeter work within the CMS-UK upgrade programme, we have already developed and tested firmware and software to control and read out μTCA modules through Gigabit Ethernet using a point-to-point protocol, IPbus, which was recently adopted as a CMS standard for μTCA communication and control. We will profit from and build on the expertise accumulated within the UK-CMS collaboration to develop common infrastructure and standards, both for the UK upgrade projects and for CMS.

Firmware development has a sound basis. In addition to substantial work on trigger hardware, RAL PPD has developed firmware to decode data from the new digital pixel ROCs, implemented in a commercial evaluation board for ROC beam test DAQ. RAL TD delivered much of the strip tracker FED firmware and has begun work on memory management firmware for data buffering.

Software development is at a similar stage and the UK has significant experience with building software for the strip tracker and FEDs. The C++ IPbus hardware access library is suitable for use with the new FEDs. New online and offline software will be based on existing pixel packages and CMS framework. A crucial element will be development of Data Quality Monitoring (DQM) tools for use during construction, commissioning and operation. This will ensure robust DQM during operations, as tools will be well tested, and allows quantitative evaluation of performance at all stages of the project.

Some elements of the DAQ are not yet fully specified and will require close coordination with other CMS groups. An optical receiver for the system has not yet been selected. However, mezzanine cards on the FED prototype will address this by providing flexibility and a testing platform for the receiver. Depending on the number of receivers a FED can host, the output bandwidth should be 10-20 Gbps, exceeding the maximum S-Link bandwidth possible. The replacement DAQ link is likely to be based on 10 Gigabit Ethernet. but has not yet been specified, and will be a focus of our initial testing plan.

The primary aim of this work package is to deliver a full pixel DAQ system on a timescale compatible with CMS planning. The work programme can be characterised into three distinct periods covering initial prototyping and testing; final system production and commissioning; and eventually DAQ operation and detector studies.

The initial prototyping period is subdivided into five main areas. The prototype FED will dominate work during the first year and a half. We will produce prototypes and mezzanines and make them available to collaborators. The majority of effort will then be dedicated to firmware and software development and electrical and optical link ROC testing in the lab. In parallel we plan to implement a prototype pixel FEC, using the same hardware as the FED and porting existing FEC software and firmware to reduce development time and effort. Replacement of the existing FECs is desirable due to performance limitations and age of the boards, and experienced French institutes have expressed interest in collaborating.

The first major system test will be part of the pixel pilot blade project, where prototype modules will be inserted into the existing detector and read out with a prototype FED and controlled by a prototype FEC. Testing in the period 2014-2016 will demonstrate readiness under realistic conditions and will be the proving ground for the majority of online software, firmware and algorithm development, and integration effort required. The final area of work in this period will be prototyping studies and definition of the replacement DAQ link requiring close collaboration with the CMS-central DAQ group.

The production and integration phase will follow on from successful prototype testing with pilot modules and the conclusion of the design study where the final system, including optical receiver, DAQ link and protocol and a decision on FED-FEC architecture, is defined. Effort is required to design and test the final board and integrate firmware and software from the DAQ link and pilot blade developments. The first final boards will replace pilot blade prototypes in the CMS service cavern to undergo integration testing with the global trigger and DAQ and timing systems where integration with the global DAQ and trigger and timing systems can take place. The full DAQ system will then be assembled at the Tracker Integration Facility (TIF) at CERN where construction of the Phase I pixel detector is expected to be completed. This allows DAQ slice tests with the pixel detector in situ and detector commissioning and characterisation studies before installation.

The earliest insertion of the pixel detector into CMS is during a possible extended technical stop at the end of 2016. This depends on overall CMS and LHC machine planning. If the detector cannot be installed then, everything will remain at the TIF until the long shutdown in 2018. Once installed in the CMS service cavern, re-commissioning the DAQ and pixel detector will commence. Additional resources will be required in the following years to support the DAQ system, including firmware and software maintenance during commissioning and operation. We expect to contribute effort towards detector performance studies and adapt the system to the evolving LHC environment as the luminosity is increased.

The proposed work requires effort from all four UK institutes. The µTCA boards will be designed at Imperial while Bristol and RAL will support mezzanine card development. The FED firmware will be the responsibility of RAL PPD with support from Imperial while RAL TD will coordinate DAQ link design and prototyping. RAL PPD will coordinate the FEC prototyping activity. Online and offline software, database integration and data quality monitoring effort will be concentrated at Bristol and Brunel with some support from RAL PPD and Imperial. Testing responsibilities, especially during the pilot blade project, will be shared across all institutes.

Work Breakdown Structure

WBS L1	WBS L2		Start	Finish	SY	Task Description
4.1 Prototype FED Development					**8.9**	**Development of the prototype FMC carrier FED including functional firmware and software for the pilot blade test**
	4.1.1	electronics development	04/13	10/13	1.3	design, submit prototype FMC-FED; design, produce FMC mezzanines
	4.1.2	software & firmware	04/13	10/14	5.4	multi-channel f/w development & system tests; design low level s/w and test suites
	4.1.3	testing and integration	10/13	10/14	0.9	assemble optical test system; ROC and opto link tests with prototype & IPbus r/o
	4.1.4	support	10/13	04/15	1.3	hardware board/mezzanine support
4.2 Prototype FEC Development					**4.6**	**R&D on implementing FEC functionality into FMC FED including preparations for testing with pilot modules and a design/feasibility study**
	4.2.1	design study	04/13	10/13	1.1	design study of FED/FEC prototype, design FMC
	4.2.2	software and firmware	04/13	04/14	2.7	integrate FEC f/w blocks, preliminary control s/w; integrate FEC f/w and s/w with prototype
	4.2.3	testing and integration	04/14	10/14	0.8	low level system tests with prototype FEC & mezzanine
4.3 Pilot Blade Testing					**7.9**	**Test readout and control of real phase I pixel modules in high luminosity conditions. Firmware and software developments and integration**
	4.3.1	FED/FEC testing and integration	04/14	04/15	0.5	assemble pixel module test systems at P5; crate tests with FED/FEC prototypes & pixel modules
	4.3.2	online software and firmware	10/14	04/15	2.7	FED & FEC independent f/w development; FED & FEC independent s/w development
	4.3.3	online software integration and algorithms	10/14	01/16	4.7	design and develop architecture for FED/FEC; commission algorithms with prototype; online s/w systems and database integration
4.4 DAQ Link & Architecture					**4.7**	**Design study, prototyping and evaluation of DAQ link to the central DAQ,**
	4.4.1	software and firmware	04/13	10/14	2.5	local crate DAQ prototyping, f/w and s/w; DAQ link prototyping and firmware; f/w and s/w integration
	4.4.2	testing and integration	04/14	04/15	2.0	single/multi link system tests with DAQ group
	4.4.3	design study	10/14	04/15	0.2	DAQ link definition, specifications & qualification
4.5 Final FED Development					**9.3**	**Design and production of final board and firmware/software with integration tests for qualification before production**
	4.5.1	design study, system defn	04/13	04/15	0.4	board specifications, interfaces with DAQ, GT, crate infrastructure
	4.5.2	electronics development	04/15	10/15	1.3	design final board; design final mezzanines
	4.5.3	testing and integration	10/15	07/16	2.1	final revision board qualification & testing; final board testing with pilot blade system; integration tests with global trigger system and DAQ4
	4.5.4	final software and firmware	04/15	07/16	4.2	f/w development, integration of DAQ f/w; s/w development, porting of online s/w; final board f/w and s/w development and integration
	4.5.5	support	10/15	01/17	1.3	hardware board/mezzanine support
4.6 FED Prodn & Integration Tests					**10.1**	**Production phase of DAQ, procurement of boards and infrastructure. Delivery to TIF for integration testing and development with pixel detector**
	4.6.1	contract tender, production, QA and assembly	10/14	01/17	3.9	preparation of contracts, tendering, negotiation & financial preparation; board production and QA testing; ship boards/crates, assemble DAQ at TIF
	4.6.2	testing and	01/16	01/17	1.0	TIF setup and crate tests with local and 10Gbps r/o;

		integration				board & slice tests with 10Gbps local DAQ & TTC
	4.6.3	software and firmware	07/16	01/17	3.8	f/w maintenance through pilot and TIF testing; online s/w integration and testing
	4.6.4	commissioning characterisation	07/16	01/17	1.4	tests & commissioning with Phase I Pixel detector at TIF; testing & detector performance studies
4.7 DAQ commissioning					**23.3**	**Commissioning DAQ and detector before running. DAQ & detector performance evaluation studies**
	4.7.1	commissioning and detector characterisation	01/17	04/19	17.3	commissioning of DAQ and detector; detector performance and tracking studies; recommissioning at P5 during LS2, maintenance, HL preparation
	4.7.2	support	01/17	04/19	6.0	hardware, f/w and online s/w and systems support
Totals		Project Effort			**68.6**	Plus working allowance of 3.6 FTE
		Management			**2.9**	
					71.5	

Collaboration

Our proposal has been accepted by CMS. The new pixel DAQ system will be a UK responsibility, subject to approval of funding, with optical components procured by the CERN optical links group where a close working relationship already exists. Specifications of the downstream DAQ interface are being negotiated in regular meetings with the central CMS DAQ team and groups developing DAQ electronics for other sub-detector upgrades. Consultation on the final system design and FED software and firmware capabilities will be required, with pixel experts and project management.

The costs are listed in the financial tables. In addition to staff, we estimate a total cost of £651k constituting the hardware, including prototypes and spares, to be deployed in CMS. £99k will be incurred in the construction of prototype systems and hardware and software costs within the institutes.

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	Updated algorithms and software ready for current L1 calo trigger
M3.2	PM15	CMS L1 Calo trigger ready for post-LS1 running
M3.3	PM24	Design studies for > 2x 10^{34} $cm^{-2}s^{-1}$ trigger ready; architectural choices made by CMS; sign-off point on > 2x 10^{34} $cm^{-2}s^{-1}$hardware production
M3.4	PM40	Hardware systems ready for > 2x 10^{34} $cm^{-2}s^{-1}$ trigger
M3.5	PM48	> 2x 10^{34} $cm^{-2}s^{-1}$ trigger in operation
M3.6	PM60	Technical design of post-LS3 trigger complete; sign-off point on LS3 prototype production
M3.7	PM72	Delivery of track trigger prototype

M4.1	PM6	prototype FMC-FED hardware available
M4.2	PM18	standalone prototype FED, multi ROC readout
M4.3	PM18	standalone prototype FEC, multi-module control
M4.4	PM24	demonstrator FED & FEC with readout & control of pilot blades
M4.5	PM24	demonstrator fast link integrated with central DAQ hardware
M4.6	PM33	final FED hardware ready for production
M4.7	PM39	final firmware & software for full system ready for deployment
M4.8	PM45	delivery of full Pixel DAQ

Participants and Roles

Institute	Name	Project support?	Category	WP1	WP2	WP3	WP4	
	Newbold		CG Acad			1.2		
	Goldstein		CG Acad		0.6		0.6	
	Brooke		CG Ph			1.5		
	Cussans		CG PE		1.5			
	Nash		CG T		1.5		1.5	
	Frazier	Y	Proj PP			6.0		
	Grimes	Y	Proj Ph				6.0	
	Kolya	Y	Proj PE				3.0	
	New RA WP3	Y	Proj Ph			6.0		
	New RA WP4	Y	Proj PP				6.0	
	Student 1	Y				1.8	1.8	
	Student 1	Y				1.8	1.8	42.4
Brunel	Cole		CG Acad				0.9	
	Hobson		CG Acad				0.6	
	Powell		CG Ph				1.1	
	New_RA1_CORE		CG AP				1.8	
	Reid	Y	Proj AP				3.0	7.4
Imperial	Hall	Y	CG Acad	3.0				
	Tapper		CG Acad			2.2		
	Fulcher		CG Ph				3.0	
	Raymond		CG AP		4.9			
	Iles		CG E			4.0	0.6	
	Rose		CG E			4.3	1.2	
	Pioppi		CG Ph			1.5		
	Clark, I		CG T		0.6			
	Kasey, V		CG T		1.2			
	Pesaresi	Y	Proj Ph		2.4		3.7	
	RA_1	Y	Proj Ph		3.6		2.4	
	RA_2	Y	Proj Ph			6.0		
	RA_3	Y	Proj Ph			3.0		
	Barlow	Y	Proj O	0.6				
	Greenwood	Y	Proj T			1.5	1.5	
	Khaleeq	Y	Proj T		1.2			
	Brambilla	Y	Proj T	1.2				
	Student 1	Y			3.5			
	Student 2	Y				3.5		
	Student 3	Y					3.5	64.2
RAL PPD	Shepherd-T					0.9	0.5	
	Harder						6.0	
	Durkin						6.0	
	Newbold					0.7		
	Tomalin					1.6		
	Sankey					3.0		

	Petyt					1.8		
	Zhang						3.0	
	RA 1	Y				6.0		
	RA 2	Y					6.0	35.5
RAL TD	Prydderch	Y	Proj E		0.5			
	Braga	Y	Proj E		4.5			
	Bell	Y	Proj E		1.5			
	Coughlan	Y	Proj E				2.2	
	Siyad	Y	Proj E				4.0	12.7
	Coughlan W All	Y	Proj E				1.6	
	Siyad W All	Y	Proj E				2.0	3.6
Total FTE				4.9	27.5	58.2	75.2	165.8

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 R. Frazier (Project physicist programmer): Responsible for online software components of current CMS L1 GCT since 2006. Principal designer of CMS ipbus / uHAL common online system.

Dr M. Grimes (Project physicist): Currently responsible for physics performance studies of proposed upgraded pixel detector; software integration / production manager for pixel and trigger upgrades.

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 S. Kolya (Project physicist engineer): Detector and electronic development engineer, with experience on tracking and trigger systems from major past experiments (H1, ATLAS, BaBar, D0)

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 R Powell (Academic) background control and instrumentation, software, state estimation, Kalman filters, detection and rejection of bad data. Significant experience of databases and XML schema for large-scale systems. WP4 DQM and conditions database design and implementation.

Dr I Reid (Project 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.

New_RA1_CORE (CG applied physicist) Lead online and offline software at Brunel with academics, contribute to M&O of the detector. WP4 support development of online pixel FED software.

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) Imperial since 2008, physics data analysis (SUSY, W asymmetry), extensive Tracker experience, a developer of particle flow algorithm, electron reconstruction and identification. Modelling trigger performance via simulations in high pileup.

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 μHAL development.

Dr G Zhang (Engineer): Development of Si detectors for a linear collider and for LHCb. Experienced in board design and laboratory test systems. WP4 design of input mezzanine board and FED testing.

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.

M Siyad (TD engineer) >15 years experience PCB design, advanced FPGA firmware VHDL design for DAQ and Trigger systems, e.g. T2K readout. DAQ link hardware and FPGA firmware design, implementation and test.

J Coughlan (TD engineer) PhD Particle Physics, >15 years experience design, implementation of DAQ systems, embedded software, FPGA firmware design. PM for CMS Tracker FED system. DAQ link system design, FPGA firmware development and test, management of board production.

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Resource Request

Institution			Cost to STFC													
	FY 12/13		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	Cost	FTE
New staff																
Bristol	£0	0	£156,962	5	£170,173	5.5	£183,529	6	£197,046	6.5	£184,565	5.5	£189,624	5.5	£1,081,899	34.0
Brunel	£0	0	£23,003	0.5	£23,462	0.5	£23,932	0.5	£24,410	0.5	£24,899	0.5	£25,396	0.5	£145,103	3.0
Imperial	£8,275	0.2	£176,344	4.8	£199,852	5.8	£223,491	6.8	£271,595	8.3	£257,517	7.3	£243,489	6.3	£1,380,564	39.5
RAL PPD	£0	0	£138,400	2	£138,400	2	£138,400	2	£138,400	2	£138,400	2	£138,400	2	£830,400	12.0
RAL TD	£0	0	£362,754	3.5	£256,240	2.5	£357,600	3.2	£330,434	2.9	£66,302	0.6	£0	0	£1,373,331	12.7
Total new staff	**£8,275**	**0.2**	**£857,463**	**15.8**	**£788,127**	**16.3**	**£926,953**	**18.5**	**£961,886**	**20.2**	**£671,684**	**15.9**	**£596,909**	**14.3**	**£4,811,297**	**101.2**
Equipment			£508,554		£806,902		£618,723		£663,632		£139,213		£150,182		**£2,887,206**	
Travel			£40,000		£50,000		£60,000		£75,000		£90,000		£75,000		**£390,000**	
Other costs																
Other DI																
Other DA	£106		£3,586		£3,586		£3,586		£4,543		£4,543		£4,543		**£24,493**	
Indirect costs	£3,397		£262,111		£262,120		£262,120		£292,889		£292,889		£292,889		**£1,668,415**	
Estates costs	£1,422		£114,653		£114,644		£114,644		£127,522		£127,522		£127,522		**£727,929**	
Working allowance			£245,411	0.0	£45,995	0.0	£33,764	0.0	£36,682	0.0	£396,411	1.8	£219,059	1.8	**£977,322**	**3.6**
Total 'new' cost	£13,200		£2,031,778		£2,071,374		£2,019,790		£2,162,154		£1,722,261		£1,466,104		**£11,486,662**	
Existing grant resources	£30,935	0.4	£871,995	10.4	£866,285	10.4	£839,899	9.9	£869,668	10.1	£864,565	10.0	£855,677	9.9	**£5,199,025**	**61.0**
Grand total	**£44,135**	**0.5**	**£2,903,773**	**26.2**	**£2,937,659**	**26.7**	**£2,859,689**	**28.4**	**£3,031,822**	**30.3**	**£2,586,827**	**27.7**	**£2,321,781**	**26.0**	**£16,685,687**	**165.8**

Appendix A: Work Package Costs

WP1					Cost to STFC													
			FY 12/13		FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
	Institution		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff	Imperial	Hall	£1,897	0.03	£22,331	0.30	£22,331	0.30	£22,331	0.30	£22,331	0.30	£22,331	0.30	£22,331	0.30	£135,883	1.8
	Imperial	Barlow	£476	0.01	£5,683	0.10	£5,849	0.10	£6,020	0.10	£6,202	0.10	£6,296	0.10	£6,296	0.10	£36,822	0.6
	Imperial	Brambilla	£677	0.02	£8,086	0.20	£8,321	0.20	£8,563	0.20	£8,812	0.20	£9,067	0.20	9,332	0.20	£52,858	1.2
Total			**£3,050**	**0.05**	**£36,100**	**0.60**	**£36,501**	**0.60**	**£36,914**	**0.60**	**£37,345**	**0.60**	**£37,694**	**0.60**	**£37,959**	**0.60**	**£225,562**	**3.7**
Equipment																		
Travel																		
Other costs	Imperial	DA	£24	0.03	£287	0.30	£287	0.30	£287	0.30	£287	0.30	£287	0.30	£287	0.30	£1,747	
Indirects	Imperial		£784	0.03	£9,231	0.30	£9,231	0.30	£9,231	0.30	£9,231	0.30	£9,231	0.30	£9,231	0.30	£56,168	
Estates	Imperial		£328	0.03	£3,864	0.30	£3,864	0.30	£3,864	0.30	£3,864	0.30	£3,864	0.30	£3,864	0.30	£23,509	
Working allowance																	£0	
Total non-staff			£1,137		£13,381		£13,381		£13,381		£13,381		£13,381		£13,381		£81,424	
Total 'new' cost			£4,186	0.05	£49,481	0.60	£49,882	0.60	£50,295	0.60	£50,726	0.60	£51,075	0.60	£51,340	0.60	£306,986	3.7
Existing resource			£1,473	0.02	£17,415	0.20	£16,798	0.20	£17,879	0.20	£18,133	0.20	£18,401	0.20	£18,628	0.20	£108,727	1.2
Grand total (exc travel)			**£5,659**	**0.07**	**£66,896**	**0.80**	**£66,680**	**0.80**	**£68,174**	**0.80**	**£68,858**	**0.80**	**£69,476**	**0.80**	**£69,969**	**0.80**	**£415,713**	**4.9**

WP2					Cost to STFC													
			FY 12/13		FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
	Institution		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff	Imperial	Pesaresi	£1,142	0.03	£13,631	0.4	£14,013	0.4	£14,408	0.4	£14,810	0.4	£15,229	0.4	£15,658	0.4	£88,892	2.4
	Imperial	RA_1			£20,447	0.6	£21,020	0.6	£21,612	0.6	£22,215	0.6	£22,844	0.6	£23,486	0.6	£131,625	3.6
	Imperial	Khaleeq	£677	0.02	£8,086	0.2	£8,321	0.2	£8,563	0.2	£8,812	0.2	£9,067	0.2	£9,332	0.2	£52,858	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
	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			£106,513	1.0	£0	0.0	£53,257	0.5	£0	0.0	£0	0.0	£0	0.0	£159,770	1.5
Total			**£1,819**	**0.05**	**£255,932**	**3.8**	**£160,318**	**3.3**	**£236,816**	**3.8**	**£184,814**	**3.3**	**£113,442**	**1.8**	**£48,476**	**1.2**	**£1,001,618**	**17.3**
Equipment	Test stands & consumables				£10,000		£10,000		£10,000		£10,000		£10,000		£10,000		£60,000	
	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	
Total equipment					**£24,286**		**£202,351**		**£202,351**		**£202,351**		**£24,286**		**£24,286**		**£679,911**	
Travel																		
Other costs	Imperial	DA	£33	0.03	£957	1.0	£957	1.0	£957	1.0	£957	1.00	£957	1.0	£957	1.0	£5,773	
Indirects	Imperial		£1,045	0.03	£30,769	1.0	£30,769	1.0	£30,769	1.0	£30,769	1.00	£30,769	1.0	£30,769	1.0	£185,658	
Estates	Imperial		£438	0.03	£12,878	1.0	£12,878	1.0	£12,878	1.0	£12,878	1.00	£12,878	1.0	£12,878	1.0	£77,708	
Working allowance							£11,574		£11,574		£11,574		£178,065				**£212,787**	
Total non-staff			£1,515		£68,890		£258,529		£258,529		£258,529		£246,955		£68,890		**£1,161,837**	
Total 'new' cost			£3,335	0.05	£324,822	3.8	£418,847	3.3	£495,345	3.8	£443,343	3.3	£360,397	1.8	£117,366	1.2	**£2,163,455**	17.3
Existing resource			£8,102	0.09	£136,989	1.7	£133,883	1.7	£139,882	1.7	£141,278	1.7	£142,753	1.7	£144,005	1.7	**£846,892**	10.3
Grand total (exc travel)			**£11,437**	**0.14**	**£461,811**	**5.5**	**£552,730**	**5**	**£635,227**	**5.5**	**£584,621**	**5**	**£503,149**	**3.5**	**£261,371**	**2.9**	**£3,010,347**	**27.5**

WP3					**Cost to STFC**													
			FY 12/13		**FY 13/14**		**FY 14/15**		**FY 15/16**		**FY 16/17**		**FY 17/18**		**FY 18/19**		**Total**	
	Institution		**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**
New staff	Bristol	Frazier			£34,587	1.0	£35,638	1.0	£36,722	1.0	£37,860	1	£38,987	1.0	£40,182	1.0	£223,976	6.0
	Bristol	RA 1			£31,615	1.0	£32,575	1.0	£33,566	1.0	£34,586	1	£35,638	1.0	£36,722	1.0	£204,702	6.0
	Bristol	Student			£4,355	0.3	£8,709	0.5	£8,709	0.5	£8,709	0.5					£30,482	1.8
	Bristol	Student							£4,355	0.3	£8,709	0.5	£8,709	0.5	£8,709	0.5	£30,482	1.8
	Imperial	RA_2			£34,078	1.0	£35,034	1.0	£36,020	1.0	£37,026	1.00	£38,073	1.0	£39,144	1.0	£219,374	6.0
	Imperial	RA_3									£34,078	1.00	£35,034	1.0	£36,020	1.0	£105,132	3.0
	Imperial	Greenwood	£846	0.02	£10,107	0.3	£10,401	0.3	£10,704	0.3	£11,015	0.25	£11,334	0.3	£11,664	0.3	£66,072	1.5
	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			**£846**	**0.02**	**£183,942**	**4.5**	**£201,266**	**5.3**	**£218,694**	**6.0**	**£260,601**	**7.25**	**£256,392**	**6.8**	**£241,641**	**5.8**	**£1,363,382**	**35.5**
Equipment	PreProduction				£54,573												£54,573	
	Infrastructure				£100,000												£100,000	
	Production				£143,887		£431,661		£143,887								£719,435	
	Subcontracts				£75,000		£75,000		£75,000		£75,000						£300,000	
	Next generation										£54,573		£54,573		£109,146		£218,292	
	Institute support				£15,000		£15,000		£10,000		£10,000		£10,000		£5,000		£65,000	
Total equipment					**£388,460**		**£521,661**		**£228,887**		**£139,573**		**£64,573**		**£114,146**		**£1,457,300**	
Travel																		
Other costs	Bristol	DA															£0	
	Imperial	DA	£0	0.00	£957	1	£957	1	£957	1	£1,913	2	£1,913	2	£1,913	2	£8,610	
Indirects	Bristol				£64,496		£64,500		£64,500		£64,500		£64,500		£64,500		£386,996	
	Imperial		£0	0.00	£30,769	1	£30,769	1	£30,769	1	£61,538	2	£61,538	2	£61,538	2	£276,919	
Estates	Bristol				£30,072		£30,068		£30,068		£30,068		£30,068		£30,068		£180,412	
	Imperial		£0	0.00	£12,878	1	£12,878	1	£12,878	1	£25,757	2	£25,757	2	£25,757	2	£115,906	
Working allowance					£129,521		£29,033		£10,003		£4,197		£4,197		£7,419		£184,370	
Total non-staff			£0		£657,153		£689,866		£378,062		£327,546		£252,546		£305,341		£2,610,514	
Total 'new' cost			£846	0.02	£841,095	4.5	£891,132	5.25	£596,756	6	£588,147	7.25	£508,938	6.75	£546,982	5.75	£3,973,896	35.5
Existing resource			£15,468	0.18	£351,559	3.9	£356,465	4	£323,228	3.55	£350,085	3.75	£341,917	3.65	£344,081	3.65	£2,082,802	22.7
Grand total (exc travel)			**£16,314**	**0.20**	**£1,192,654**	**8.4**	**£1,247,596**	**9.25**	**£919,984**	**9.55**	**£938,232**	**11**	**£850,855**	**10.4**	**£891,063**	**9.4**	**£6,056,698**	**58.2**

WP4					Cost to STFC													
			FY 12/13		FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
	Institution		Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
New staff	Bristol	Grimes			£33,568	1.0	£34,586	1.0	£35,638	1.0	£36,722	1.0	£37,860	1.0	£38,987	1.0	£217,361	6.0
	Bristol	Kolya			£16,868	0.5	£17,381	0.5	£17,910	0.5	£18,456	0.5	£19,024	0.5	£19,593	0.5	£109,232	3.0
	Bristol	RA 2			£31,615	1.0	£32,575	1.0	£33,566	1.0	£34,586	1.0	£35,638	1.0	£36,722	1.0	£204,702	6.0
	Bristol	Student			£4,355	0.3	£8,709	0.5	£8,709	0.5	£8,709	0.5					£30,482	1.8
	Bristol	Student							£4,355	0.3	£8,709	0.5	£8,709	0.5	£8,709	0.5	£30,482	1.8
	Brunel	Reid			£23,003	0.5	£23,462	0.5	£23,932	0.5	£24,410	0.5	£24,899	0.5	£25,396	0.5	£145,103	3.0
	Imperial	Pesaresi	£1,714	0.05	£20,447	0.6	£21,020	0.6	£21,612	0.6	£22,215	0.6	£22,844	0.6	£23,486	0.6	£133,338	3.7
	Imperial	RA_1			£13,631	0.4	£14,013	0.4	£14,408	0.4	£14,810	0.4	£15,229	0.4	£15,658	0.4	£87,750	2.4
	Imperial	Greenwood	£846	0.02	£10,107	0.3	£10,401	0.3	£10,704	0.3	£11,015	0.3	£11,334	0.3	£11,664	0.3	£66,072	1.5
	Imperial	Student 3							£9,709	0.5	£19,418	1.0	£19,418	1.0	£19,418	1.0	£67,963	3.5
	RAL PPD	RA 2			£69,200	1.0	£69,200	1.0	£69,200	1.0	£69,200	1.0	£69,200	1.0	£69,200	1.0	£415,200	6.0
	RAL TD	Coughlan			£52,181	0.4	£52,181	0.4	£78,272	0.6	£104,363	0.8	£0	0.0	£0	0.0	£286,997	2.2
	RAL TD	Siyad			£106,513	1.0	£106,513	1.0	£106,513	1.0	£106,513	1.0	£0	0.0	£0	0.0	£426,053	4.0
Total			**£2,560**	**0.07**	**£381,489**	**6.9**	**£390,043**	**7.2**	**£434,528**	**8.1**	**£479,127**	**9.1**	**£264,155**	**6.8**	**£268,833**	**6.8**	**£2,220,734**	**44.8**
Equipment	Prototypes				£72,663		£42,189										£114,852	
	Preproduction								£22,256								£22,256	
	Production						£17,556		£150,479		£306,958		£38,604				£513,597	
	Institute support				£23,145		£23,145		£14,750		£14,750		£11,750		£11,750		£99,290	
Total equipment					**£95,808**		**£82,890**		**£187,485**		**£321,708**		**£50,354**		**£11,750**		**£749,995**	
Travel																		
Other costs	Bristol	DA															£0	
	Brunel	DA	£0		£429		£429		£429		£429		£429		£429		£2,574	
	Imperial	DA	£49	0.05	£957	1	£957	1	£957	1	£957	1	£957	1	£957	1	£5,789	
Indirects	Bristol				£80,620		£80,625		£80,625		£80,625		£80,625		£80,625		£483,745	
	Brunel		£0		£15,458		£15,458		£15,458		£15,458		£15,458		£15,458		£92,748	
	Imperial		£1,568	0.05	£30,769	1	£30,769	1	£30,769	1	£30,769	1	£30,769	1	£30,769	1	£186,181	
Estates	Bristol				£37,590		£37,585		£37,585		£37,585		£37,585		£37,585		£225,515	
	Brunel		£0		£4,492		£4,492		£4,492		£4,492		£4,492		£4,492		£26,952	
	Imperial		£656	0.05	£12,878	1	£12,878	1	£12,878	1	£12,878	1	£12,878	1	£12,878	1	£77,927	
Working allowance		Equipment			£115,890		£5,388		£12,187		£20,911		£3,273		£764		£158,413	
		Staff			£0	0	£0	0	£0	0	£0	0	£210,876	1.8	£210,876	1.8	£421,752	3.6
Total W. Allowance					£115,890	0	£5,388	0	£12,187	0	£20,911	0	£214,149	1.8	£211,640	1.8	£580,165	3.6
Total non-staff			£2,273		£394,891		£271,471		£382,865		£525,812		£447,696		£406,583		£2,431,590	
Total 'new' cost			£4,833	0.07	£776,380	6.9	£661,514	7.2	£817,393	8.1	£1,004,939	9.1	£711,851	8.6	£675,416	8.6	£4,652,325	48.4
Existing resource			£5,892	0.07	£366,038	4.55	£359,138	4.5	£358,910	4.5	£360,171	4.5	£361,494	4.5	£348,961	4.4	£2,160,605	26.8
Grand total (exc travel)			**£10,725**	**0.14**	**£1,142,417**	**11.5**	**£1,020,652**	**11.7**	**£1,176,303**	**12.6**	**£1,365,110**	**13.5**	**£1,073,345**	**13.0**	**£1,024,377**	**12.9**	**£6,812,929**	**75.2**

Appendix B: Institute Costs

N: New post or new funding
S: STFC internally-funded post
R: Rolling grant funded post

Brunel					**Cost to STFC**													
Staff name	**WP**	**Type**	**FY 12/13**		**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**	**Cost**	**FTE**
Cole	4	R			£7,100	0.15	£7,100	0.15	£7,100	0.15	£7,100	0.15	£7,100	0.15	£7,100	0.15	£42,600	0.9
Hobson	4	R			£7,910	0.1	£7,910	0.1	£7,910	0.1	£7,910	0.1	£7,910	0.1	£7,910	0.1	£47,462	0.6
Powell	4	R			£14,050	0.25	£11,239	0.20	£8,430	0.15	£8,430	0.15	£8,430	0.15	£8,430	0.15	£59,007	1.1
New_RA1_CORE	4	R			£11,797	0.3	£12,046	0.3	£12,288	0.3	£12,534	0.3	£12,784	0.3	£13,040	0.3	£74,489	1.8
Reid	4	N			£23,003	0.5	£23,462	0.5	£23,932	0.5	£24,410	0.5	£24,899	0.5	£25,396	0.5	£145,103	3.0
Total new posts					£23,003	0.5	£23,462	0.5	£23,932	0.5	£24,410	0.5	£24,899	0.5	£25,396	0.5	£145,103	3.0
Total RG posts					£40,857	0.80	£38,296	0.75	£35,728	0.70	£35,974	0.70	£36,224	0.70	£36,480	0.70	£223,558	4.4
Equipment					£3,000		£3,000		£3,000		£3,000		£3,000		£3,000		£18,000	
Travel																	£0	
Other DI																	£0	
Other DA					£429		£429		£429		£429		£429		£429		£2,574	
Indirect costs					£15,458		£15,458		£15,458		£15,458		£15,458		£15,458		£92,748	
Estate costs					£4,492		£4,492		£4,492		£4,492		£4,492		£4,492		£26,952	
Total 'new' costs					£46,382		£46,841		£47,311		£47,789		£48,278		£48,775		£285,377	
RG resource					£73,469		£68,870		£64,263		£64,508		£64,759		£65,015		£400,883	
Grand total					**£119,851**		**£115,711**		**£111,574**		**£112,298**		**£113,037**		**£113,790**		**£686,260**	**7.4**

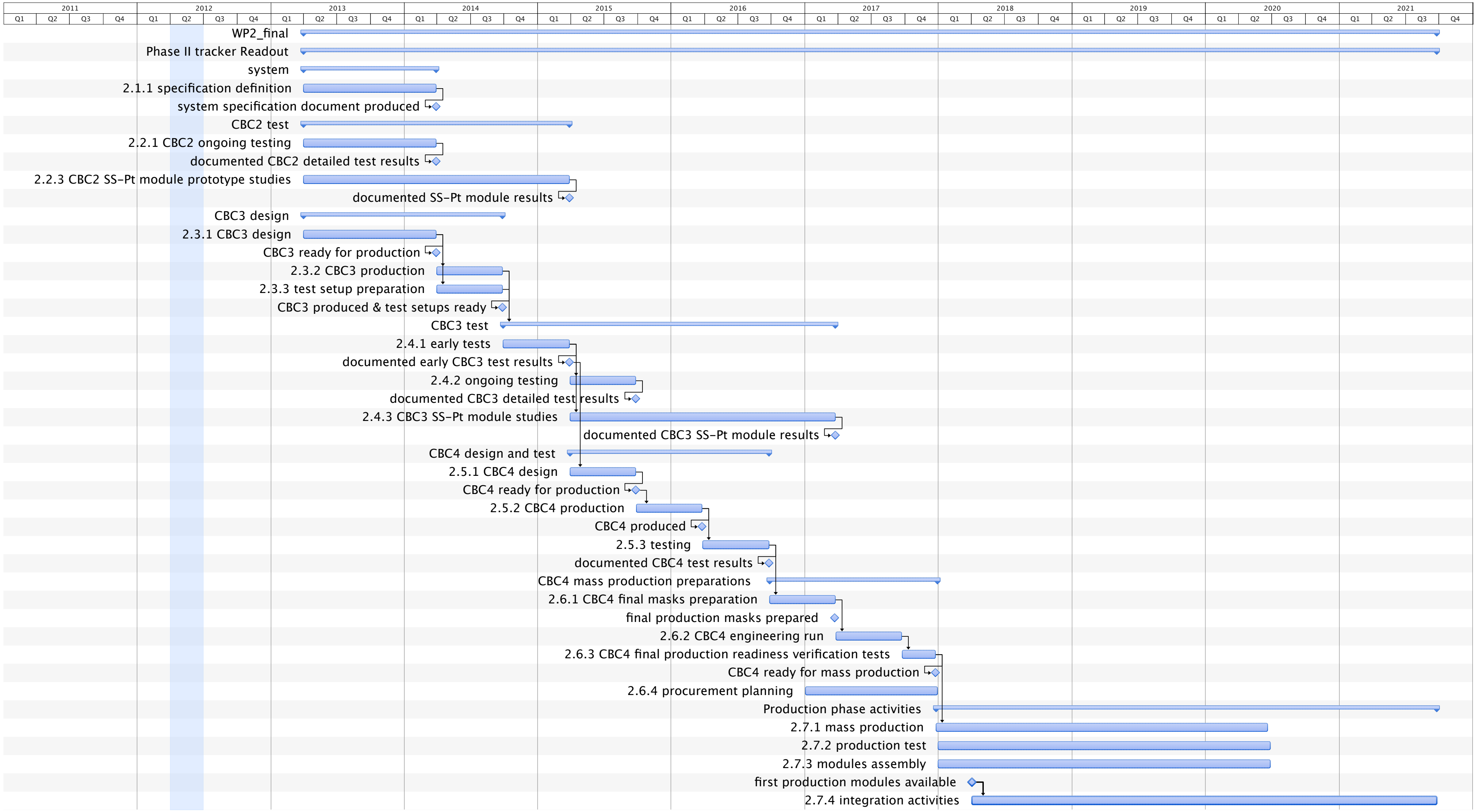
Bristol					**Cost to STFC**													
Staff name	**WP**	**Type**	**FY 12/13**		**FY 13/14**		**FY 14/15**		**FY 15/16**		**FY 16/17**		**FY 17/18**		**FY 18/19**		**Total**	
			Cost	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**	**Cost**	**FTE**
Newbold	3	R			£11,140	0.2	£11,482	0.2	£11,598	0.2	£11,598	0.2	£11,598	0.2	£11,598	0.2	£69,014	1.2
Goldstein	2/4	R			£11,140	0.2	£11,482	0.2	£11,598	0.2	£11,598	0.2	£11,598	0.2	£11,598	0.2	£69,014	1.2
Brooke	3	R			£9,749	0.25	£10,045	0.25	£10,045	0.25	£10,045	0.25	£10,045	0.25	£10,045	0.25	£59,974	1.5
Cussans	2	R			£11,593	0.25	£11,711	0.25	£11,711	0.25	£11,711	0.25	£11,711	0.25	£11,711	0.25	£70,148	1.5
Nash	2/4	R			£14,978	0.5	£14,979	0.5	£14,979	0.5	£14,979	0.5	£14,979	0.5	£14,979	0.5	£89,873	3.0
Frazier	3	N			£34,587	1	£35,638	1	£36,722	1	£37,860	1	£38,987	1	£40,182	1	£223,976	6.0
Grimes	4	N			£33,568	1	£34,586	1	£35,638	1	£36,722	1	£37,860	1	£38,987	1	£217,361	6.0
Kolya	4	N			£16,868	0.5	£17,381	0.5	£17,910	0.5	£18,456	0.5	£19,024	0.5	£19,593	0.5	£109,232	3.0
RA 1	3	N			£31,615	1	£32,575	1	£33,566	1	£34,586	1	£35,638	1	£36,722	1	£204,702	6.0
RA 2	4	N			£31,615	1	£32,575	1	£33,566	1	£34,586	1	£35,638	1	£36,722	1	£204,702	6.0
Student 1	3/4	N			£8,709	0.5	£17,418	1	£17,418	1	£17,418	1					£60,963	3.5
Student 2	3/4	N							£8,709	0.5	£17,418	1	£17,418	1	£17,418	1	£60,963	3.5
Total new posts					£156,962	5	£170,173	5.5	£183,529	6	£197,046	6.5	£184,565	5.5	£189,624	5.5	£1,081,899	34.0
Total RG posts					£58,600	1.4	£59,699	1.4	£59,931	1.4	£59,931	1.4	£59,931	1.4	£59,931	1.4	£358,023	8.4
Equipment					£15,000		£20,000		£15,000		£10,000		£10,000		£10,000		£80,000	
Travel																	£0	
Other DI																	£0	
Other DA																	£0	
Indirect costs					£145,116		£145,125		£145,125		£145,125		£145,125		£145,125		£870,741	
Estate costs					£67,662		£67,653		£67,653		£67,653		£67,653		£67,653		£405,927	
Total 'new' costs					£384,740		£402,951		£411,307		£419,824		£407,343		£412,402		£2,438,567	
RG resource					£101,154		£102,255		£102,487		£102,487		£102,487		£102,487		£613,357	
Grand total					**£485,894**		**£505,206**		**£513,794**		**£522,311**		**£509,830**		**£514,889**		**£3,051,924**	**42.4**

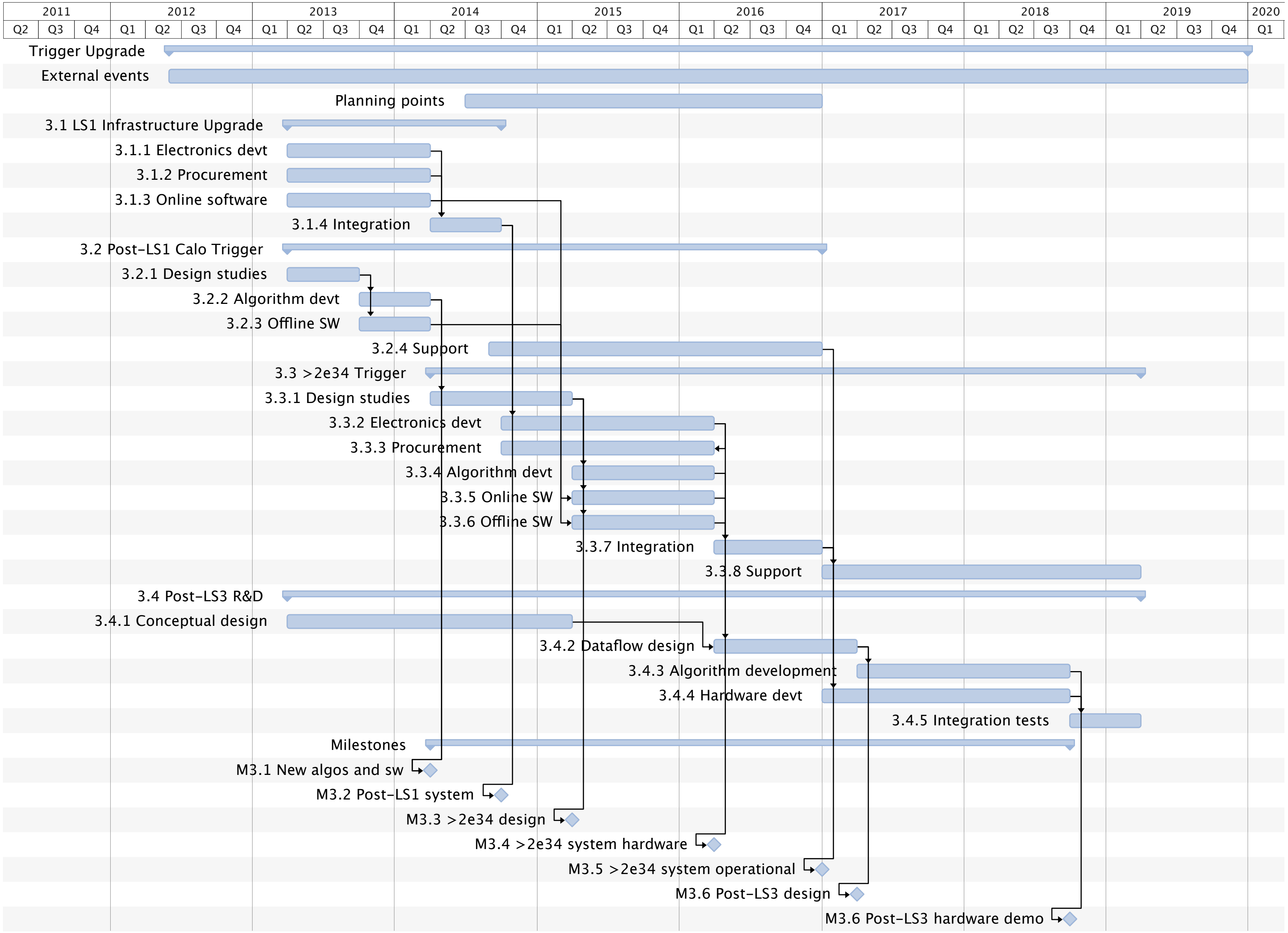
Imperial					Cost to STFC													
Staff name	WP	Type	FY 12/13		FY 13/14		FY 14/15		FY 15/16		FY 16/17		FY 17/18		FY 18/19		Total	
			Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE	Cost	FTE
Hall	1	R	£1,264	0.02	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£14,887	0.2	£90,589	1.2
Tapper	3	R	£1,857	0.04	£21,868	0.5	£13,121	0.5	£13,121	0.3	£13,121	0.3	£13,121	0.3	£13,121	0.3	£89,328	2.2
Fulcher	4	R	£1,734	0.04	£20,713	0.5	£21,315	0.5	£21,936	0.5	£22,572	0.5	£23,226	0.5	£23,901	0.5	£135,398	3.0
Raymond	2	R	£3,534	0.07	£42,337	0.8	£43,793	0.8	£45,250	0.8	£46,888	0.8	£48,709	0.8	£49,622	0.8	£280,134	4.9
Iles	3/4	R	£3,272	0.06	£39,094	0.75	£40,243	0.75	£41,419	0.75	£42,634	0.75	£43,876	0.75	£45,158	0.75	£255,696	4.6
Rose	3/4	R	£2,570	0.08	£30,671	0.9	£31,530	0.9	£32,418	0.9	£33,323	0.9	£34,265	0.9	£35,230	0.9	£200,007	5.5
Pioppi	3	R	£843	0.02	£10,071	0.25	£10,362	0.25	£10,663	0.25	£10,974	0.25	£11,292	0.25	£11,619	0.25	£65,824	1.5
Clark, I	2	R	£339	0.01	£4,043	0.1	£4,160	0.1	£4,282	0.1	£4,406	0.1	£4,534	0.1	£4,666	0.1	£26,429	0.6
Kasey, V	2	R	£677	0.02	£8,086	0.2	£8,321	0.2	£8,563	0.2	£8,812	0.2	£9,068	0.2	£9,331	0.2	£52,858	1.2
Hall	1	N	£1,897	0.03	£22,331	0.3	£22,331	0.30	£22,331	0.3	£22,331	0.3	£22,331	0.3	£22,331	0.3	£135,883	1.8
Pesaresi	2/4	N	£2,856	0.08	£34,078	1	£35,034	1.00	£36,020	1	£37,026	1	£38,073	1	£39,144	1	£222,230	6.1
RA_1	2/4	N			£34,078	1	£35,034	1.00	£36,020	1	£37,026	1	£38,073	1	£39,144	1	£219,374	6.0
RA_2	3	N			£34,078	1	£35,034	1.00	£36,020	1	£37,026	1	£38,073	1	£39,144	1	£219,374	6.0
RA_3	3	N									£34,078	1	£35,034	1	£36,020	1	£105,132	3.0
Barlow	1	N	£476	0.01	£5,683	0.1	£5,849	0.10	£6,020	0.1	£6,202	0.1	£6,296	0.1	£6,296	0.1	£36,822	0.6
Greenwood	3/4	N	£1,693	0.04	£20,214	0.5	£20,802	0.50	£21,409	0.5	£22,030	0.5	£22,668	0.5	£23,328	0.5	£132,144	3.0
Khaleeq	2	N	£677	0.02	£8,086	0.2	£8,321	0.20	£8,563	0.2	£8,812	0.2	£9,067	0.2	£9,332	0.2	£52,858	1.2
Brambilla	1	N	£677	0.02	£8,086	0.2	£8,321	0.20	£8,563	0.2	£8,812	0.2	£9,067	0.2	£9,332	0.2	£52,858	1.2
Student 1	2	N			£9,709	0.5	£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
Student 3	4	N							£9,709	0.5	£19,418	1	£19,418	1	£19,418	1	£67,963	3.5
Total new posts			£8,275	0.19	£176,344	4.8	£199,852	5.8	£223,491	6.8	£271,595	8.3	£257,517	7.3	£243,489	6.3	£1,380,564	39.5
Total RG posts			£16,091	0.35	£191,769	4.2	£187,734	4.2	£192,539	4	£197,617	4	£202,978	4	£207,534	4	£1,196,262	24.8
Equipment	Expenses				£15,000		£15,000		£15,000		£10,000		£10,000		£10,000		£75,000	
	Procuremer				£455,554		£755,902		£572,723		£627,632		£108,213		£122,182		£2,642,206	
Equipment	W All.				£245,411		£45,995		£33,764		£36,682		£185,535		£8,183		£555,570	
Travel																	£0	
Other DI																	£0	
Other DA			£106		£3,157		£3,157		£3,157		£4,114		£4,114		£4,114		£21,919	
Indirect costs			£3,397		£101,537		£101,537		£101,537		£132,306		£132,306		£132,306		£704,926	
Estate costs			£1,422		£42,499		£42,499		£42,499		£55,377		£55,377		£55,377		£295,050	
Total 'new' costs			£13,200		£1,039,502		£1,163,942		£992,171		£1,137,706		£753,062		£575,651		£5,675,235	
RG resource			£30,935		£365,725		£352,768		£357,574		£362,652		£368,013		£372,569		£2,210,236	
Grand total			**£44,135**		**£1,405,227**		**£1,516,710**		**£1,349,745**		**£1,500,358**		**£1,121,075**		**£948,220**		**£7,885,471**	**64.2**

RAL PPD					**Cost to STFC**													
Staff name	**WP**	**Type**	**FY 12/13**		**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**	**Cost**	**FTE**
Shepherd-T	3/4	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	4	S			£87,567	1	£87,567	1	£87,567	1	£87,567	1	£87,567	1	£87,567	1	£525,400	6.0
Durkin	4	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
Zhang	4	S			£34,617	0.5	£34,617	0.5	£34,617	0.5	£34,617	0.5	£34,617	0.5	£34,617	0.5	£207,700	3.0
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
RA 2	4	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					£138,400	2	£138,400	2	£138,400	2	£138,400	2	£138,400	2	£138,400	2	£830,400	12.0
Total RG posts					£331,647	3.95	£342,392	4.05	£315,576	3.8	£340,021	4	£329,307	3.9	£315,607	3.8	£1,974,549	23.5
Equipment					£15,000		£8,000		£8,000		£8,000		£8,000		£5,000		£52,000	
Travel					£40,000		£50,000		£60,000		£75,000		£90,000		£75,000		£390,000	
Other DI																	£0	
Other DA																	£0	
Indirect costs																	£0	
Estate costs																	£0	
Total 'new' costs					£193,400		£196,400		£206,400		£221,400		£236,400		£218,400		£1,272,400	
RG resource					£331,647		£342,392		£315,576		£340,021		£329,307		£315,607		£1,974,549	
Grand total					**£525,047**		**£538,792**		**£521,976**		**£561,421**		**£565,707**		**£534,007**		**£3,246,949**	**35.5**

RAL TD					**Cost to STFC**													
Staff name	**WP**	**Type**	**FY 12/13**		**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**	**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			£106,513	1	£0	0	£53,257	0.5	£0	0	£0	0	£0	0	£159,770	1.5
Coughlan	4	N			£52,181	0.4	£52,181	0.4	£78,272	0.6	£104,363	0.8	£0		£0		£286,997	2.2
Siyad	4	N			£106,513	1.0	£106,513	1.0	£106,513	1.0	£106,513	1.0	£0		£0		£426,053	4.0
Total new posts					**£362,754**	**3.5**	**£256,240**	**2.5**	**£357,600**	**3.2**	**£330,434**	**2.9**	**£66,302**	**0.6**	**£0**	**0**	**£1,373,331**	**12.7**
W All. Coughlan		N			£0		£0		£0		£0		£104,363	0.8	£104,363	0.8	£208,725	1.6
W All. Siyad		N			£0		£0		£0		£0		£106,513	1.0	£106,513	1.0	£213,027	2.0
Total W. All.					**£0**	**0.0**	**£0**	**0.0**	**£0**	**0.0**	**£0**	**0.0**	**£210,876**	**1.8**	**£210,876**	**1.8**	**£421,752**	**3.6**
Total RG posts																	£0	0.0
Equipment					£5,000		£5,000		£5,000		£5,000						£20,000	
Travel																		
Other DI																	£0	
Other DA																	£0	
Indirect costs																	£0	
Estate costs																	£0	
Total 'new' costs					£367,754		£261,240		£362,600		£335,434		£66,302		£0		£1,393,331	
RG resource																	£0	
Grand total					**£367,754**		**£261,240**		**£362,600**		**£335,434**		**£66,302**		**£0**		**£1,393,331**	**12.7**

Appendix C: Gantt Charts




2011
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2013
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2016
2017
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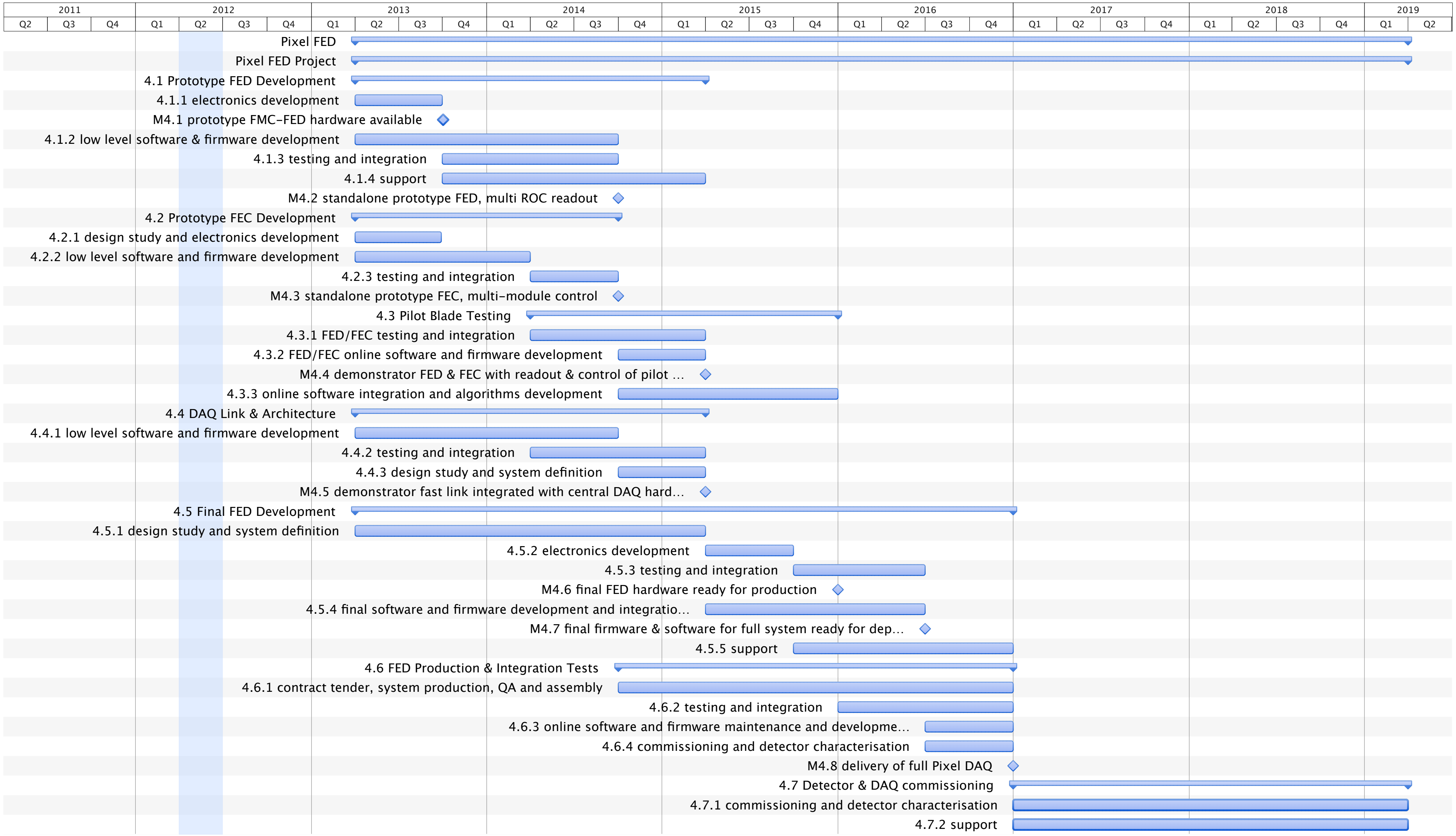
2019
2020
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1
Trigger Upgrade
External events
Planning points
3.1 LS1 Infrastructure Upgrade
3.1.1 Electronics devt
3.1.2 Procurement
3.1.3 Online software
3.1.4 Integration
3.2 Post-LS1 Calo Trigger
3.2.1 Design studies
3.2.2 Algorithm devt
3.2.3 Offline SW
3.2.4 Support
3.3 >2e34 Trigger
3.3.1 Design studies
3.3.2 Electronics devt
3.3.3 Procurement
3.3.4 Algorithm devt
3.3.5 Online SW
3.3.6 Offline SW
3.3.7 Integration
3.3.8 Support
3.4 Post-LS3 R&D
3.4.1 Conceptual design
3.4.2 Dataflow design
3.4.3 Algorithm development
3.4.4 Hardware devt
3.4.5 Integration tests
Milestones
M3.1 New algos and sw
M3.2 Post-LS1 system
M3.3 >2e34 design
M3.4 >2e34 system hardware
M3.5 >2e34 system operational
M3.6 Post-LS3 design
M3.6 Post-LS3 hardware demo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Q1
Pixel FED
Pixel FED Project
4.1 Prototype FED Development
4.1.1 electronics development
M4.1 prototype FMC-FED hardware available
4.1.2 low level software & firmware development
4.1.3 testing and integration
4.1.4 support
M4.2 standalone prototype FED, multi ROC readout
4.2 Prototype FEC Development
4.2.1 design study and electronics development
4.2.2 low level software and firmware development
4.2.3 testing and integration
M4.3 standalone prototype FEC, multi-module control
4.3 Pilot Blade Testing
4.3.1 FED/FEC testing and integration
4.3.2 FED/FEC online software and firmware development
M4.4 demonstrator FED & FEC with readout & control of pilot …
4.3.3 online software integration and algorithms development
4.4 DAQ Link & Architecture
4.4.1 low level software and firmware development
4.4.2 testing and integration
4.4.3 design study and system definition
M4.5 demonstrator fast link integrated with central DAQ hard…
4.5 Final FED Development
4.5.1 design study and system definition
4.5.2 electronics development
4.5.3 testing and integration
M4.6 final FED hardware ready for production
4.5.4 final software and firmware development and integratio…
M4.7 final firmware & software for full system ready for dep…
4.5.5 support
4.6 FED Production & Integration Tests
4.6.1 contract tender, system production, QA and assembly
4.6.2 testing and integration
4.6.3 online software and firmware maintenance and developme…
4.6.4 commissioning and detector characterisation
M4.8 delivery of full Pixel DAQ
4.7 Detector & DAQ commissioning
4.7.1 commissioning and detector characterisation
4.7.2 support

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
2.8	Staff for FED design or layout not available	Delay in completion of the project. Affects WP4.	PI & WP4 managers	0.1	70	7	Monitor staff availability	Ensure sub-contracts are in place. Redistribute some work to RAL TD.
2.9	Significant change in FED specification	Delay in reaching objectives. Costs to revise design	PI & WP4 managers	0.3	80	24	Well designed specification, endorsed by CMS	Organise in-depth review with appropriate experts
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	FED does not meet requirements	Delay in schedule. Affects WP4.	PI & WP4 managers	0.2	80	16	Work with collaborators on system design & influence decisions	Negotiate with CMS Tracker management. Working allowance
4.2	Delay in specification of DAQ link by CMS	Delay in WP4 schedule.	WP4 managers	0.5	50	25	Participate in the process of specifying the DAQ link.	Negotiate with CMS is schedule becomes a concern.
4.3	Failure of the pixel pilot project	Reduced ability to test pixel FED prior to installation	WP4 managers	0.25	50	12.5	Monitor progress with external deliverables	Alternative testing programme. Emphasis on TIF testing
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