PARTICLE PHYSICS DEPARTMENT

STATUS REPORT 2019

Science & Technology Facilities Council

UK Research and Innovation

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Front cover: Insertion of SCT into TRT Credit: © 2005-2019 CERN

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1 Foreword

This Status Report documents the work carried out in recent years within the RAL Particle Physics Department (PPD). Our staff are engaged in a wide and growing range of activities across the STFC particle physics and particle astrophysics programmes. As evidenced in this report, PPD expertise and capabilities, supported by those of other laboratory departments, are vital in enabling the STFC to engage in large-scale and cutting-edge science activities, and we support the whole UK community in these areas. We are also actively engaged in planning the next generation of experiments and technologies.

This document is the first in an ongoing series of Annual Reports, and will be complemented later in the year by a forward-looking Research Proposal detailing our strategy and plans for the coming years.

2 Introduction

2.1 Mission

The PPD mission is:

- To support the UK particle and particle astrophysics communities in all aspects of the current experimental programme, primarily through the design, construction and operation of experiments, and participation in experiment exploitation. PPD should lead in areas of work that would be beyond the scale of a university group, or which require specialised facilities present only at the national laboratories.
- To enable the future UK experimental programme through world-leading research and development in sensors, data-handling systems, software and computing, and engineering optimisation of instrumentation. This includes support and execution of small-scale projects aimed at new technology demonstration or evaluation.
- To ensure efficient use of resources allocated by STFC / UKRI, through effective project management and resource management on behalf of the UK community, and to facilitate interaction with UKRI corporate services.
- To provide facilities, expertise and talent in technical and professional areas relevant to particle and particle astrophysics, and to retain and support the careers of world-class researchers whose profile is oriented towards experiment design, construction and technology.
- To work directly with stakeholders in the UK and international community to develop the future particle and particle astrophysics programme, and to facilitate national and international discussions on strategy and collaboration.
- To promote societal, industrial and interdisciplinary impact from particle and particle astrophysics, both through internal activities, and through support for the UK communities.

These areas align directly with and support the STFC Strategic Delivery Plan [1], and are relevant across each of STFC's strategic themes. The work of PPD is essential in delivering the UK's particle physics (PP) and particle-astrophysics (PA) science programmes.

2.2 Strategic Context

The presence of a strong and well funded 'central' particle physics department at the national laboratory is essential in allowing the UK to undertake the widest range of PP and PA research, and to participate in the very large scale experiments at colliders and underground facilities that currently dominate the field. The activities undertaken by PPD are broadly comparable with analogous national lab groups in other countries, albeit at a somewhat smaller scale in recent times.

As part of the national laboratory, PPD has the important ability to collaborate with, and cross-fertilise between, other science and engineering areas within the STFC portfolio. In recent years, this has largely taken the form of cooperation with Technical Department (TD) for mechanical and electronic engineering, and Scientific Computing Department (SCD) for provision of large-scale PP computing. However, new collaborations with experts in Space, CLF, ISIS, and at the Hartree Centre are now taking shape. As an increasing fraction of UKRI funding is targeted at technology-oriented and interdisciplinary areas, these relationships will become essential as we seek to supplement the core PP / PA programme.

As the scale of new capital projects grows, the need for professional engineering, project management, logistics, and commercial and legal support is also increasing. We provide project management for STFC's largest PP / PA projects, including DUNE, ATLAS, CMS, LZ and AIT-WATCHMAN. Such activities require a pool of expert effort that we must maintain across the laboratory departments, with PPD both hosting trained individuals and acting as a liaison between STFC / UKRI professionals and the community. The requirement for a strong technical training activity has also become clear, in order that we maintain skills in instrumentation development, and in experimental hardware, software and firmware, in the long term and across activities. PPD aims to play an increasing role in all these areas.

2.3 Scientific and Technical Programme

Fulfilment of our mission requires us to engage in a wide area of PP and PA research, reflecting the breadth of the STFC programmes. We therefore undertake a larger range of activities than any other UK institution. Recent progress in each of our research areas, along with their scientific motivation and outcomes, is described throughout the rest of this document.

The core of PPD's activities for the last twenty years has been the Large Hadron Collider (LHC) at CERN, and this remains a focal point. PPD supports a wide range of operational activities for the ATLAS, CMS and LHCb experiments, typically supporting detectors that were originally designed or constructed at the laboratory. Although the LHC is currently in a shutdown phase, all experiments are engaged in maintenance or upgrade activities, and in preparations for LHC Run-3. In addition, ATLAS and CMS have recently entered the construction phase of their HL-LHC luminosity upgrade programmes. These projects are amongst STFC's largest capital commitments, and PPD leads the UK upgrade project in both experiments. We have also provided key project management support for the LHCb Phase-1 upgrade.

Neutrino research has recently expanded in scale and breadth in PPD, now encompassing accelerator- and reactor-driven experiments at long (DUNE), intermediate (T2K, Hyper-K) and short (SBND, SoLid) baselines. This represents a good mix of activities, from the currently-operational T2K, to DUNE and Hyper-K that have not yet begun construction. DUNE is the largest capital project in the PP programme, and the principal investigator and project manager are both PPD staff members.

PPD supports a range of low-background experiments, spanning the PP and PA areas. We designed and have recently installed key components of the LZ liquid xenon experiment in the USA, for which PPD provided the UK project manager. LZ is due to start science running later in 2019, with PPD support. Building upon technical capabilities built up during our previous involvement with neutron electric dipole moment experiments, we are a core partner in the new AION project, which aims to provide a new generation of ultra-sensitive gravitational wave and dark matter detectors based on atom interferometers.

Boulby Underground Laboratory is a unique environment for low-background research, and a key STFC asset. The facility supports a wide range of research, both within the PA programme and with an increasingly interdisciplinary focus. Boulby operates as a standalone division within PPD, but with ever-strengthening connections between their work and that of the rest of PPD. Key developments here are confirmed plans for a major new US-UK funded neutrino detector (AIT-WATCHMAN) to be installed at Boulby for nuclear security and fundamental science R&D. In addition, a feasibility study is being carried out, in conjunction with university partners, of the future potential of Boulby for large-scale next-generation dark matter experiments.

PPD continues its involvement in the preparation for new large-scale international facilities, both through scientific leadership and instrumentation R&D. Although this programme is currently limited in scale, due to the current prioritisation of the HL-LHC and long-baseline neutrino projects, PPD staff are engaged in a range of activities covering several possible future options. The MICE experiment, designed to demonstrate the feasibility of muon ionisation cooling in hydrogen, has reached the stage of science publications, thereby paving the way for further study of the potential of a future muon collider. PPD has access to extensive and high-quality research facilities and spaces, including well-equipped labs and experimental areas, which we place at the disposal of the whole UK community as funding allows.

Finally, PPD plays a direct role in supporting the community through financial administration of the PP programme, via organisation and hosting of community events, via the provision of the UK Liaison Office at CERN, and through provision of expert services in project management, technical management, procurement and purchasing. We anticipate all these aspects of our work increasing in scope and scale as major new STFC capital projects begin.

2.4 The PPD Group

The PPD group consists of approximately 50 'core' staff, plus additional staff and students funded within project grants, and a number of visitors and university joint appointees. We also benefit strongly from the active scientific engagement of several emeritus staff. Personnel numbers have stabilised in the last few years, after a long period of continuous decline, but this history is reflected by the presence of a relatively large number of senior staff compared to junior postdocs. Full details of the PPD organisation and staff profile are given in the Appendix. The majority of our staff are experienced particle physicists, and are fully engaged in science delivery from the experiments we are involved in, including data analysis and collaborative work with theorists where appropriate.

A new Director of PPD, Professor David Newbold, was appointed in October 2018, taking over from Interim Director Dr Stephen Haywood. A number of organisational changes have been put in place to ensure that the group's structure best matches its current activities. Staff are organised into three divisions, one of which comprises the Boulby team, plus a number of support staff working across the Department. The divisions are led by Dr Stephen Haywood, Professor Claire Shepherd-Themistocleous, and Professor Sean Paling, who are responsible for staff management and development within their areas. Scientific strategy and resourcing decisions are dealt with by a Management Board, comprising the senior staff leading research groups. Operational and administrative matters, and liaison with professional services within RAL, are the responsibility of Mr Chris Lowe, and are overseen by an Operations Board. Finally, we have recently put in place an external Advisory Board, which will provide input to the Director on scientific and technical strategy, and provide oversight of PPD on behalf of key stakeholders within and outside STFC.

As in other areas of STFC, the continuing 'flat cash' financial environment has put severe pressure on staffing levels and workload, and on our ability to recruit and retain new personnel. As an illustration, when the original LHC detectors were constructed, PPD staff numbered well over 200; at the current time, when we are constructing major new upgrades in parallel with operating and maintaining the original detectors, total staff numbers are around 80. We are actively working to identify routes to a sustainable and expanded programme within PPD, particular with respect to our R&D programme and the future facilities and experiments that will follow the LHC upgrade.

3 Energy Frontier

The Large Hadron Collider (LHC) is the largest particle accelerator in the world, and was commissioned in 2010 for proton–proton collisions at a centre-of-mass energy of 7 TeV. The collection of a greater quantity of data at a collision energy of 8 TeV in 2012 enabled the discovery of the Higgs boson, a tremendous success that completed the discovery of all predicted particles of the Standard Model (SM) of particle physics.

Since 2015 the LHC has been operating at the increased energy of 13 TeV (Run-2, 2015-2018), with a focus on increasingly precise measurements of the properties of the Higgs boson and uncovering fundamental particles and laws of physics beyond those predicted by the SM, which is known to be only an approximate and incomplete description of nature. Exploration of this energy scale has only just begun, and over the coming years the LHC will be upgraded to enlarge the data sample by a factor of 30. In the current two-year period of shutdown (LS2, 2019–20), the LHC will be upgraded to collide protons at greater energy (14 TeV) and about double the rate. After three years' more data-taking (Run-3, 2021–23), a subsequent 2.5-year shutdown (LS3, 2024–26) will complete the High Luminosity LHC (HL-LHC) upgrades, with a further tripling of the collision rate.

Two large, general purpose detectors (GPD) operate at the LHC: ATLAS and CMS. Although significant differences exist between the two detectors, both are designed to be highly efficient at detecting and reconstructing most of the known particles of the SM. The upgrade programme for the detectors is aligned with the LHC long shutdown (LS) periods, with the installation of Phase-1 and Phase-2 upgrades scheduled for LS2 and LS3, respectively. The primary objective of the upgrades is to maintain or improve on the present detector performance as the collision rate increases, which is imperative to ensure the full exploitation of the physics potential of the LHC.

The RAL PPD ATLAS and CMS groups were founding institutes at the start of both collaborations in 1992. Both groups have had substantial commitments in the construction and operation of the detectors and analysis of the data, and now for the Phase-1 and Phase-2 upgrades.

3.1 ATLAS

The ATLAS group is the largest in PPD, with 21 staff members and engagement from around ten members of TD. The group mostly concentrates on the upgrade programme for the HL-LHC, both Phase-1 (from 2021) and Phase-2 (from 2026). This accounts for three-quarters of our effort, with one-fifth in support of operations, and the small residual for physics analysis. Our current work is summarised in the sections below.

Haywood is the overall ATLAS Group Leader at RAL. PPD has in the past provided the ATLAS Physics Coordinator (Murray, 2013–14), and project leaders for the Semiconductor Tracker (SCT) (Tyndel, 1992–2006; McMahon, 2009–13), Inner Tracking Detector (ITk) (McMahon, 2013–19), Level-1 Calorimeter Trigger (L1Calo) (Middleton, 2015–19), and Computing (McCubbin, 1999–2003).

The Tracking Group is led by McMahon. The group was responsible for the development and construction of large parts of the SCT, which was installed into the ATLAS cryostat in 2006 and has been operational since 2008. The group was heavily involved in the design of the ATLAS tracker, in conjunction with TD, as well as the necessary performance studies. We assembled over 700 silicon modules, oversaw the installation of the services on the carbon-fibre support structures, played a substantial part in the creation of the DAQ (data acquisition) system and DCS (detector control system), and oversaw the subsequent installation and commissioning of the detector. The tracker has been enormously successful and has performed beyond expectations, at instantaneous luminosities up to twice the design limit.

Middleton leads the Level-1 Calorimeter Trigger group, which works seamlessly with TD electronic engineers led by Brawn (L1Calo Phase-1 Upgrade Project Engineer). For the original Level-1 e/γ and τ triggers for ATLAS, the group provided many custom hardware modules along with firmware and online software, and coordinated the UK and international L1Calo hardware development, installation and commissioning programme for Run-1 (2008–12) and Run-2 (2015–18). In the past, group members have held international Trigger & DAQ (TDAQ) management positions: TDAQ Upgrade Coordinator and Institute Board Chair (Gee), L1Calo Project Leader & Deputy (Middleton, Barnett). For many years, Gee was the Trigger Area Coordinator for the UK Upgrade activity.

The High-Level Trigger (HLT) Group is led by Baines. The group plays a major part in the ATLAS trigger software. Past leadership positions include Inner Detector Trigger Coordinator (Baines), and signature coordinators for the trigger, B-physics and e/γ. (Baines, Kirk, Wielers). The group had a major role in implementing the trigger tracking software used for data-taking in Run-1 and Run-2, and is developing fast tracking code for Run-3 (2021–24) and Phase-2. During ATLAS construction, the group provided oversight of the production of key parts of the hardware and the financial resources for the TDAQ (Wickens). Within the UK, PPD provided leadership of the UK-HLT group (Wickens, Baines).

All members of the group who are ATLAS authors contribute to service tasks required by ATLAS, including control room shifts, on-call shifts and the reviewing of ATLAS publications three or four times each year.

3.1.1 Tracking

The Tracking Group divide their efforts between the maintenance and operation of the existing Inner Tracking Detector, the development and preparation for the construction of the Phase-2 ITk and a small amount of blue-skies research into the next generation of tracking detectors.

The group continues to provide expertise and support on many aspects of day-to-day operation, including DAQ (Gallop is SCT DAQ coordinator) and DCS (Phillips is the designer of the DCS system, an on-call expert and is recognised as the go-to person for the DCS). This expertise has been called upon by several other experiments over the last ten years.

Ever since LHC start-up in 2008, the group has been engaged in development and preparation for the construction of the ITk, as part of a consortium of eleven UK universities and laboratories which will deliver the UK component of the tracker upgrade. The ITk has a total CORE (parts only) cost of 130 MCHF and is scheduled to be ready for LHC Run-4 in 2026. Construction of the tracker will start in 2020 and will be completed by 2024. The UK has taken on responsibility for fabrication of 50% of the barrel strip tracker staves and one of the pixel end-caps. PPD staff have both national and international ATLAS roles covering many aspects of the development.

We have also embedded colleagues from the Institute of High Energy Physics in Beijing into the RAL group. They will work with us on the bulk production of many of the parts. PPD staff will oversee the production of more than 750 silicon strip modules, with Sawyer coordinating the effort internationally. RAL will also mount 4500 UK modules and 1000 Chinese modules onto staves (local supports), shown in Figure 3.1. These are low-mass, high-value items. Within the UK, Dopke coordinates this effort; he also leads the international effort, where many of the developments coming from RAL are used. PPD staff have continued their success in the development of the DAQ and test-systems for the strips. This work is led nationally by Gallop and Phillips.

Building large-scale pixel detectors for ATLAS is a new venture for the UK. We will build one whole end-cap; Italy will build the other. At RAL, Matheson and Wielers, who act as the national work package leaders, are responsible for mounting 1200 modules on 60 half-rings with support from Zhang. Smart, a recent addition to the group, is working on the DAQ development for the pixel detector and preparation for bulk production. Wielers looks after the production database.

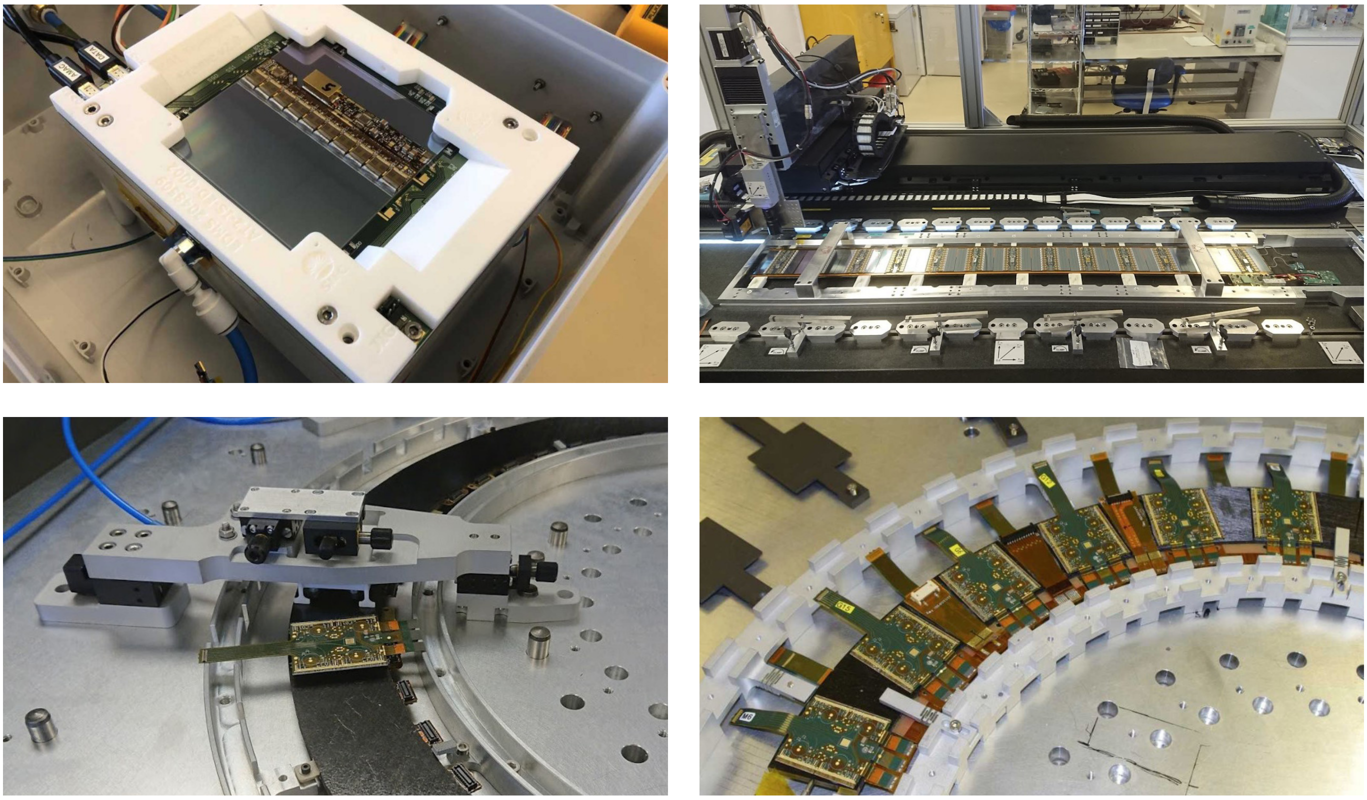


Figure 3.1: Clockwise from top left: Tracker strip module; Stave with modules mounted; Mounting pixel modules on a half-ring; Ring0, the first pixel half-ring.

PPD staff also work closely with staff from TD in the preparation for bulk component production, which will start around the end of 2019 and will make extensive use of the new RAL cleanroom facility. We have been at the forefront of many of the technical developments needed to realise the very demanding requirements of the ITk. One example has been the need to develop novel low-mass powering solutions. Villani has designed, developed, tested, and, with Zhang, qualified the use of radiation-tolerant high-voltage multiplexing. This has now been adopted by the silicon strip community as the standard for production.

We have been involved in detector and physics performance studies for the design of the ITk. Wielers was one of those who showed the benefits for the Higgs physics programme of increasing the pseudorapidity coverage of the tracker. Murray co-convened the subgroup for tracking in dense environments, while Adye was one of the convenors of the group studying tracking performance at the HL-LHC, as well as playing a critical role in the tracking software validation. Most of the members of the group were involved in the preparation of the two volumes of Technical Design Reports which were published in 2016 and 2017 for the strip and pixel trackers, respectively. In these documents of over 1200 pages, the physics and technical justifications for the construction of the tracker were set out. The TDRs were successfully reviewed by the LHCC in 2017 and 2018 respectively.

3.1.2 L1Calo

The ATLAS L1Calo Trigger provides real-time event selection at the LHC rate of 40 MHz. The trigger is based on pipelined electromagnetic cluster and jet algorithms which are executed in custom hardware with a latency of a few microseconds. The PPD group had a major role in the development of the original calorimeter trigger, and is similarly involved in the Phase-1 Upgrade to this system.

Middleton is the international L1Calo Project Leader. He oversees contributions from fourteen institutes and is a member of the TDAQ Steering Group. Having built a significant part of the original L1Calo system, the UK has the responsibility to support operations at CERN. Barnett is the senior CERN-resident L1Calo physicist, and is responsible for many operational activities (e.g. software updates, calibration and test runs with calorimeters) and day-to-day run coordination, as well as providing on-call support for fault diagnosis, module repair and liaison with TD.

The principal UK deliverable for the Phase-1 Upgrade for Run-3 is the electron feature extractor system (eFEX) — see Figure 3.2. PPD has led the high-speed design, prototyping and production of the eFEX module and its testing programme (Qian, TD) and the specification of the system readout (Gee, Sankey). The group has been central in establishing the Surface Test Facility at CERN (Barnett, Middleton), which is needed by the L1Calo project and associated detector groups to integrate and test the new hardware in a controlled environment prior to installation in the experiment.

At RAL, the L1Calo Lab is becoming the principal UK L1Calo integration and testing centre. There are weekly visits by university colleagues, working on aspects of the Phase-1 upgrade, and by students, to train them in the use and testing of the complex hardware, firmware and software systems.

The Phase-2 upgrade work in the group is a lower-priority activity until the Phase-1 deliver.ables are complete. Sankey has contributed to the architectural design of the Level-0 Global system, and is the TDAQ Level-3 Global Project Co-leader. Middleton has led the initial specification of and planning for changes to the L1Calo system of FEXes which will form the new L0Calo system.

3.1.3 HLT

The ATLAS High-Level Trigger is crucial in selecting the datasets used for physics analysis. The trigger must decide in an average of 0.2 s whether to keep each event. Due to offline computing constraints, only 1% of events can be kept by the HLT; the rest are lost permanently.

For operations in the previous runs and for the Phase-1 Upgrade, a critical deliverable of the group has been the Core Software. Martin-Haugh is one of the two Trigger Core Software Coordinators, responsible for organising and tracking the work to maintain the software used for data-taking in Run-2, and for the development of the software for Run-3. The trigger software is being upgraded to exploit more efficiently multicore CPUs and hence reduce memory usage, which is a main driver of cost for the trigger processor farm. The trigger software consists of a framework which configures and controls the trigger operation and selection software which reconstructs features of the event data to form trigger decisions.
The upgrade requires the replacement of the framework and refactoring of the selection software algorithms.

Kirk is one of the two Release and Validation Coordinators responsible for the production and validation of trigger software releases. This includes quality assurance for all trigger software releases: those used for data-taking during Run-2 and those under development for Run-3. PPD is responsible for the production of the simulated datasets used for validation.

PPD delivered the upgraded fast-tracking algorithm used in the trigger in Run-2 and provided maintenance (Emeliyanov, Martin-Haugh) and validation (Kirk) of the Run-2 Trigger Tracking software. Baines is one of the two coordinators responsible for the integration of the Fast Tracker (FTK) into the HLT. The FTK is a hardware system using associative memory containing lookup tables to identify track candidates in the Inner Detector from hit patterns.
PPD implemented the software to support the FTK in the HLT (Baines, Kirk), is upgrading the tracking software for Run-3 (Emeliyanov), and developing the tracking software for Phase-2 (Emeliyanov, Baines).

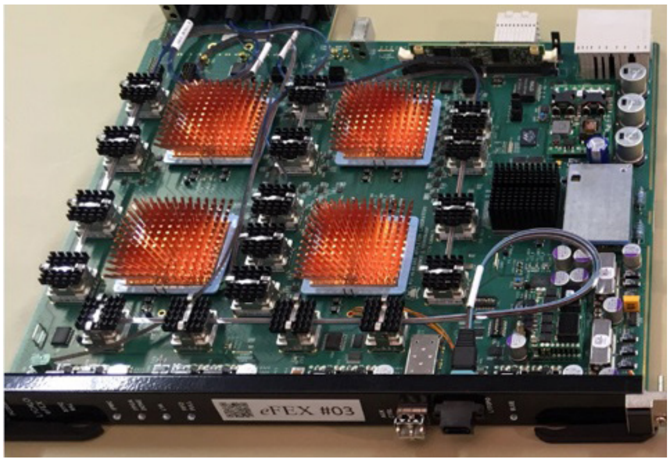


Figure 3.2: eFEX prototype, showing copper heatsinks on top of the large FPGAs, and sockets for the on-board optical connections.

Following a career break Julie Kirk joined PPD on a Daphne Jackson fellowship. Now a permanent staff member, she has taken senior roles in the ATLAS trigger, and is a member of the TDAQ Steering Group. She also organises the PPD annual Masterclass (see Section 12.3).

3.1.4 Physics Analysis

The principal activities of the group are currently operations and hardware activities. However, PPD physicists also make significant contributions to the ATLAS physics programme, contributing to physics analyses or studies of the detector performance. Leading roles have been or are held by members of the PPD group. Currently, Murray, who was Physics Coordinator in 2012–14, is one of the two convenors of one of the main ATLAS physics groups, for searches involving Higgs bosons and dibosons (HDBS), and thus remains a member of ATLAS Physics Coordination. Wielers was one of the two subgroup convenors of the Higgs Prospects group in 2016–17.

The group has been actively involved in Higgs physics (Adye, Murray, Song, Wielers), Standard Model measurements (Martin-Haugh), and searches for new particles in the exotic sector, in particular W' bosons (Kirk, Murray, Sawyer, Wielers). The group provides leading experts in areas crucial for these analyses: statistics, track and jet reconstruction, triggering, and electron and photon performance. Since the beginning of 2017, PPD members contributed to fourteen ATLAS papers, seven documents containing preliminary results, and four public documents containing results on physics prospects at the HL-LHC or detector performance. In the same time period, seven physics talks were given at international conferences. Group members (Adye, Haywood, McCubbin, Murray, Wielers) have been chairs of editorial boards; the chair's role is to scrutinise the analysis and ensure the production of a scientifically valid paper of good quality. Murray is frequently asked to give final sign-off of papers before journal submission on behalf of the ATLAS spokesperson.

In the coming years, Murray will continue his coordination role in the HDBS group and in Higgs boson precision measurements, together with other PPD members and Warwick University. The other main activity will be the search for long-lived heavy neutrinos that decay in the tracking detector. This activity ties in well with our expertise in tracking and triggering. This search will remain a key study at HL-LHC, as the discovery reach will be extended into unexplored regions thanks to the larger tracking volume of the ITk, which will provide sensitivity to longer neutrino lifetimes. Over the next few years we expect to increase our involvement in physics analyses, thanks to the resumption of the PPD PhD student programme.

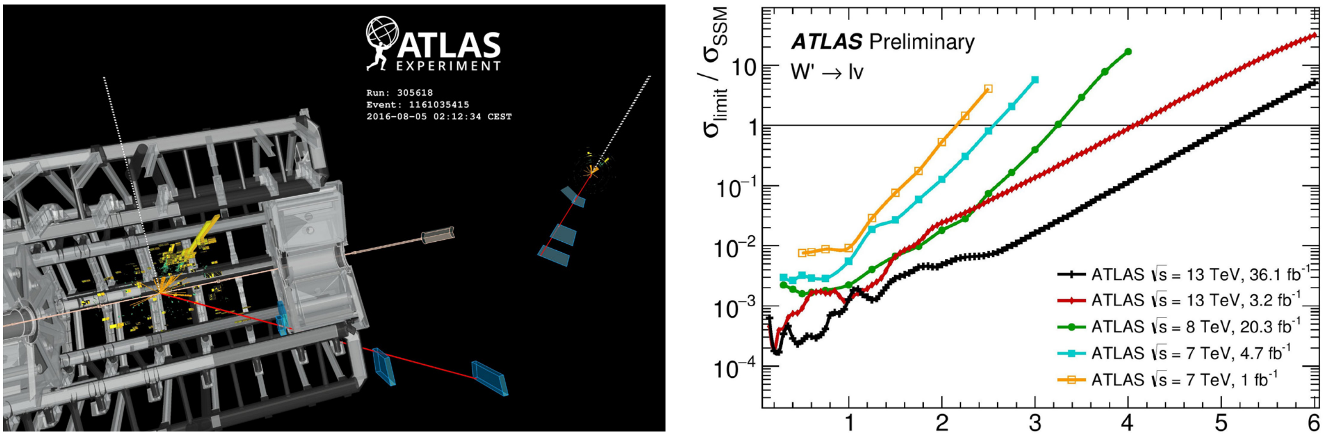


Figure 3.3: (left): Event display of a possible W' candidate found in the 2016 data. (right): Normalised W' cross-section limits. At the HL-LHC, W' bosons will be excluded up to masses of 8 TeV.

3.2 CMS

The PPD CMS group (led by Shepherd-Themistocleous) is active across computing, triggering and detector hardware, as well as in physics analysis. For the Run-1 CMS detector, the group designed and delivered the ECAL endcaps and contributed significantly to the tracker readout system. PPD played a key role in the design of the CMS computing system, and collaborates with SCD in the provision of Tier-1 and Tier-2 computer centres.

A first phase (Phase-1) of CMS detector upgrades was completed for Run-2, and considerable R&D for the HL-LHC upgrades has taken place. The construction project for the HL-LHC started in April 2019. The PPD group was a major player in the Phase-1 upgrade to the level-1 calorimeter trigger, and all of our HL-LHC upgrade activities are related to readout and triggering functions. The electronics systems being developed by UK institutes for the HL-LHC upgrades are based on a single common hardware-firmware-software platform, which the group plays a leading role in delivering, and expects to support in the long term. This coherence enables a broader involvement in the CMS upgrades than would otherwise be possible within the available resources.

The group is also highly active in physics analysis, and has strong connections with phenomenologists, primarily through the NExT Institute.

3.2.1 Level-1 Trigger

Harder, Harper, Linacre, Manolopoulos, Newbold, Olaiya, Shepherd-Themistocleous, Thea, Williams.

The CMS Level-1 trigger system provides real-time event selection at the LHC bunch-crossing rate of 40 MHz, with a latency of a few microseconds. The performance and robustness of the trigger system are vital for all aspects of the CMS physics programme, and the aspects PPD is involved in (calorimeter object identification) especially so. The last few years have seen the delivery of an upgraded trigger system, which involved a complete system redesign and deployment of new fast electronics centred on the capabilities of cutting-edge FPGAs. This was fully deployed in 2016 and has operated successfully for the duration of Run 2. The HL-LHC upgrade activity capitalizes on the novel technical developments, largely of UK origin, achieved in the Phase-1 upgrade. The CMS PPD group has a wide expertise and experience in trigger systems, firmware, online software, system control, software management, hardware debugging and testing, and production QA / QC, which has been further honed during the upgrade. In combination with physics analysis and detector operations experience, this breadth and depth of expertise enables the prominent role the group is playing in the CMS upgrades. Furthermore, this expertise is being exploited to broaden PPD's engagement with the UK Particle Physics programme, most notably in the construction of a strong group in the DUNE DAQ project (see Section 5.4).

3.2.2 Phase-1 Upgrade

Durkin, Harder, Harper, Newbold, Sankey, Shepherd-Themistocleous, Thea, Williams. Students: Aggleton, Taylor

The group made major contributions to the Phase-1 calorimeter trigger upgrade, working in close cooperation with other CMSUK institutes to implement a novel 'time-multiplexed' architecture that allows a complete event view in a single FPGA. This involved the construction of a custom-built dense fibre network between trigger layers, requiring the use of a new optical multiplexing technology. The completed system was successfully deployed in 2016, and allows CMS to trigger efficiently in the difficult pile-up conditions being experienced in 13 TeV running. PPD provided the UK Trigger Work Package Manager through a joint appointment. We have continued to develop many of the infrastructure and control elements of the system in light of running experience. All of these developments form the foundation for our Phase-2 work across several CMS electronics systems.

PPD took charge of the final assembly and acceptance testing of the common MP7 FPGA platfom used in the Phase-1 upgrade. A test centre was constructed at RAL for this purpose. PPD staff also led the design and implementation of the 'infrastructural' firmware and low-and mid-level control software. This framework (based on the IPbus system, see Section 10.3.1) implements all board functionality except for the particle reconstruction algorithms themselves, which can be 'plugged in' to specialise the platform for a range of purposes. The group also led the design and development of a new common framework for the control and monitoring 'upper-level' software. The wide scope of this framework ensured that a far greater fraction of common software was utilised across the trigger subsystems compared with the previous trigger system.

All electronics boards in the CMS Phase-I upgrades conform to the MicroTCA specification, which mandates the form factor, backplane connections, crate infrastructure and power/cooling management. The Phase-1 upgrades were the first systems to use the MicroTCA standard in CMS. Particle physics requirements push this standard significantly beyond its typical use in industry, and PPD staff played a central role in the development of a CERN MicroTCA standard requirements set, and in the debugging and deployment of commercial MicroTCA components.

This overall approach of providing flexible and adaptable components, with well-specified common interfaces, allowed a substantial saving in development, testing and commissioning time. Finishing the upgrade before Run-2 probably would not have been possible otherwise. Most of the upgraded trigger subsystems made use of this system of components, and the infrastructural firmware and software has been used even more widely throughout CMS. The same approach will be used in the Phase-2 upgrades. The group took a leading role in the final commissioning of the trigger, and provided the Level-1 trigger Technical Coordinator for Run-2. This period has seen a significant improvement in operational procedures and the efficiency of operations personnel. PPD staff have taken a substantial fraction of on-call expert duties for the system.

PPD developed key e/γ trigger algorithms for the Phase-1 upgrade, in particular adapting electron isolation requirements to high pile-up conditions. This has drawn on the group's expertise from activities on the ECAL and in physics analyses.

3.2.3 Phase-2 Upgrade: Common electronics platform

Harder, Newbold, Sankey, Thea, Williams

The success of the common platform approach in Phase-1 has informed our approach to the HL-LHC upgrade. However, the MicroTCA technology will not scale to the demands of the new system without difficulty, and the decision has been taken to adopt the ATCA form factor, which has greater power and cooling capacity. During the later part of the R&D phase, we have collaborated in the development of a standard ATCA platform using the latest generation of FPGA and optical links, with PPD focussing on the firmware and control software components.
We provide the UK work package manager for common electronics in the Phase-2 construction project, along with the lead developer of the infrastructural firmware / software components. These components will need to be updated and supported not only during the construction phase, but for up to another twenty years.

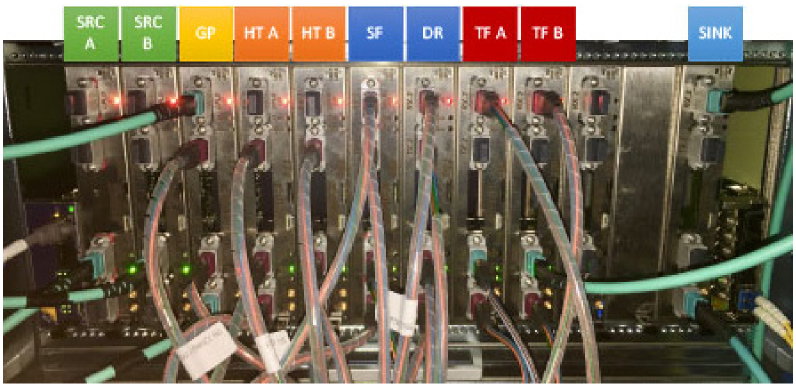
3.2.4 Phase-2 Upgrade: Level-1 Track Finder

Caligaris, Durkin, Harder, Manolopoulos, Newbold, Sankey, Schuh, Shepherd-Themistocleous, Thea, Tomalin, Williams. Students: Ardila, Cieri, Schuh

To maintain high trigger efficiency for interesting events during HL-LHC running, CMS will use charged particle tracks reconstructed using the silicon tracker as an additional input to the Level-1 trigger. The UK pioneered this approach within CMS, and developed the concept of a tracker structure that allows the prompt reconstruction of short track stubs from closely spaced silicon sensor layers. The work on this project has been supported by an STFC grant for R&D and an ERC ITN grant, and is now supported by the CMS STFC construction grant and a Rutherford International Fellowship. PPD provides the track-finder joint Project Manager within the UK and a convenor for the CMS algorithm development group.

The UK proposed an all-FPGA approach to online track reconstruction for use in the L1 trigger, as opposed to the use of expensive ASIC technology proposed by other groups. We were alone in providing a successful practical demonstration of our approach, meeting all CMS requirements, with the most efficient track-finding performance of any option, in time for a selection review in 2016. Our work in this area required us to rapidly put together a new UK team, with international partners, drawing upon our track reconstruction and silicon tracker expertise, as well as on the experience from the trigger. The necessary work encompassed: development of the track reconstruction algorithm, the core of which was a Hough transform followed by a fit to measure the track trajectory; the realization of the algorithm in firmware; and the implementation of a scalable demonstrator using the hardware available at the time, MP7 MicroTCA cards (see Figure 3.4). PPD staff were central to all these achievements. The selection of our approach as the baseline for system was a key milestone.

An improved algorithm has now been developed and optimized by PPD staff, in conjunction with international collaborators under our guidance. The firmware has been rewritten to use resources more effectively, exploit new FPGA features, and run at much higher clock speeds. The overall system design has also been improved. One notable development is the adoption of high-level synthesis as an algorithm development tool. The optimised algorithms have already been shown to work as a complete chain in the latest Ultrascale FPGAs and will be demonstrated on the new common platform during the remainder of 2019.



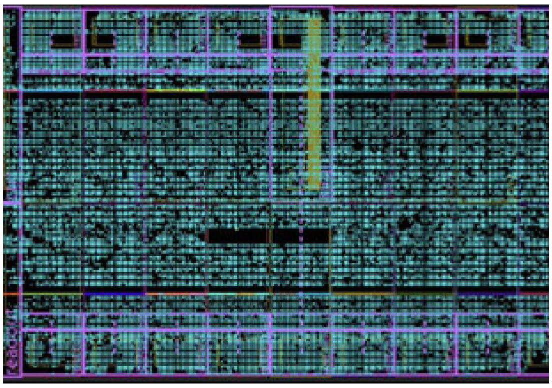


Figure 3.4: (left): CMS track-finder demonstration crate with MicroTCA MP7 cards interconnected by optical fibre ribbons; (right): Floorplan of CMS track-finder algorithm in a Xilinx FPGA.

3.2.5 Phase-2 Upgrade: Level-1 Trigger

Harder, Harper, Linacre, Manolopoulos, Olaiya, Shepherd-Themistocleous, Thea, Williams

The HL-LHC Level-1 trigger will make use of the information provided by the tracker, calorimeter and muon subdetectors. CMS is currently working towards the Level-1 trigger TDR and the consolidation of the overall architecture. Modern FPGAs provide vastly improved computational power compared even to the Phase-1 system, and with the addition of track information the upgraded Level-1 trigger will be able to reconstruct entire events at a level of complexity approaching that of the current high-level trigger. The UK will provide part of the new trigger hardware, based on our common platform.

The PPD group's algorithm studies are focussed on the use of track information, profiting from the track finder expertise within the group. The greatest challenge in developing trigger algorithms at the HL-LHC is dealing with the very high pile-up. Being able to reconstruct primary vertices and select the one associated with a hard scattering will be a powerful means of rejecting background. We performed a study of possible reconstruction algorithms, and selected one providing very good performance with a structure amenable to firmware implementation. We are also studying the performance of algorithms for reconstructing jets only using tracks. While the energy resolution of such algorithms is worse than if one includes calorimeter information, the ability to reject pile-up track through vertex association results in very robust trigger candidates.

Sam Harper, who is resident at CERN, was appointed CMS Trigger Coordinator in 2019. This is a senior management role within the experiment, with responsibility for all aspects of online event selection and for balancing the competing needs of analysis groups.

3.2.6 ECAL

Bell, Cockerill, Durkin, Petyt, Reis, Shepherd-Themistocleous

The PPD group is a prominent player in the CMS ECAL. RAL designed and delivered the ECAL endcaps (EE), providing both the project manager and project engineer, and produced the mechanical design for the entire ECAL. The specialised photodetectors, vacuum phototriodes (VPTs), were developed and delivered by the group, along with the HV system required to operate them (RAL invented VPTs in the 1980s for use in OPAL). The ECAL endcaps are complex objects, the delivery of which drew on a large team of people from PPD and TD.

PPD covers a wide range of ECAL responsibilities and activities, including operation, performance monitoring and optimization of the detector, and the HL-LHC ECAL upgrade. During Run-2, a PPD staff member was ECAL System Manager, with overall responsibility for all day-to-day aspects of ECAL operation and performance. A major responsibility during this time was overseeing and driving the definition of the ECAL upgrade programme, and its documentation in the upgrade TDR. Working with PPD, RAL TD provided a key technical contribution to the TDR, in the form of a redesign of the current front-end ASIC to incorporate the increased functionality required for the HL-LHC. This work, which was built on expertise gained during the design of the original ASIC for ECAL, was included as a backup solution to the baseline HL-LHC ECAL front-end ASIC design.

PPD maintains a strong presence at CERN to support ECAL operations. A particular responsibility is the high voltage system for the endcaps, designed and delivered in collaboration with TD. PPD is responsible for its operation including providing 24h on-call cover whenever the system is active. Understanding the performance of the ECAL is of particular importance for CMS, since the crystal behaviour continuously evolves with radiation damage. PPD organised and largely performed the analysis of the performance of the EE crystal plus VPT system under running conditions, including the contributions of several final year students from Southampton University on 9-month placements at CERN. The work has provided predictions for the evolution of the performance of the endcaps that are critical for the ECAL trigger calibrations and energy resolution estimates. PPD provided the ECAL Technical Coordinator for many years. This entails responsibilities for the planning and direction of all ECAL infrastructure, hardware, and detector-integrity-related activity at the experiment since its installation and commissioning, including on-call responsibility for over half of each year. As part of planning for any eventuality, PPD and

TD have undertaken a thorough maintenance programme at CERN for all the EE handling equipment, should there be a need for an EE dismount / remount occur prior to LS3 (including the need to gain access to other subdetectors).

PPD has played central roles in ensuring optimal detector performance, providing the detector performance convenor, responsible for organising the data analysis to monitor and understand the detector behaviour and finally calibrating the data. This was a crucial contribution to the discovery of the Higgs boson in the two-gamma decay mode in 2012. A particular speciality is the detailed examination and understanding of ECAL data for interesting events, undertaken at the request of physics analysis teams.

For the Phase-2 ECAL upgrade, the available funding does not allow a continued particip.ation in the on-detector parts of the calorimeter. However, we are exploiting our detailed knowledge of the ECAL performance to develop the off-detector processing of the readout of the barrel crystals. The primary objective is to provide optimal information to the L1 trigger. This is part of the overall strategy of utilizing the CMS group's expertise in readout systems that exploit the power of processing in FPGAs. High-luminosity running presents a particular difficulty in the barrel ECAL, as the occurence of anomalously large signals from the APDs would, without mitigation, swamp the L1 trigger. The range of expertise within PPD, encompassing both the ECAL and fast electronics, ideally places the group to develop methods to combat this challenge. The complete redesign of the ECAL backend electonics requires a complex optical-fibre routing system to share crystal data between boards, permitting the use of more advanced energy clustering algorithms. PPD is designing this system and will produce and deploy it.

Members of PPD hold and have held numerous and prominent roles in the ECAL, including ECAL Endcap Project Manager, Chair of the ECAL Finance Scrutiny Group and ECAL Field Technical Coordinator.

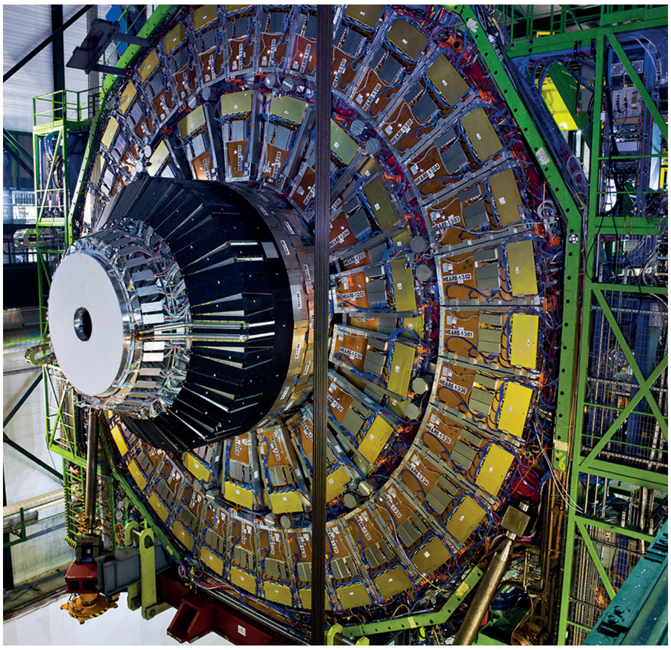


Figure 3.5: The CMS ECAL endcap (the frontmost silver-coloured assembly)

3.2.7 Physics Analysis

Brown, Delle Rose, Harper, Linacre, Olaiya, Shepherd-Themistocleous, Tomalin, Waltari, Williams. Students: Aggleton, Day-Hall, Fiashi, Ford, Taylor, Titterton

The PPD group leads a number of key analyses on CMS, many of which were originally conceived by PPD members. The focus of analysis work is on searches for new physics phenomena beyond the SM. The group has created strong connections with theorists, particularly through the NExT Institute. A common theme in the analyses is making full use of the group's strong expertise in the ECAL and silicon tracker.

PPD staff have led the CMS 'flagship' vector-boson search analysis (Z' search) since 2006. At high energy, electrons are measured with better resolution than muons. PPD has focused on the Z' decay to electrons, which provides the greatest sensitivity to new physics. This analysis exploits the extensive expertise in PPD on the ECAL, electron reconstruction and triggering. There have been CMS publications at 8 and 13 TeV, nearly all written by PPD physicists, and a number of related phenomenology papers written by PPD staff in collaboration with theorists. The techniques were also adapted for quantum black hole searches and general searches for new physics using Z bosons.

PPD proposed and carried out the first searches in CMS for long-lived exotica decaying to displaced leptons or jets, also implementing the displaced track reconstruction needed for such studies. This has since developed into a major field and PPD now focusses on lepton channels. The capability for such studies followed naturally from our involvement in the tracker.

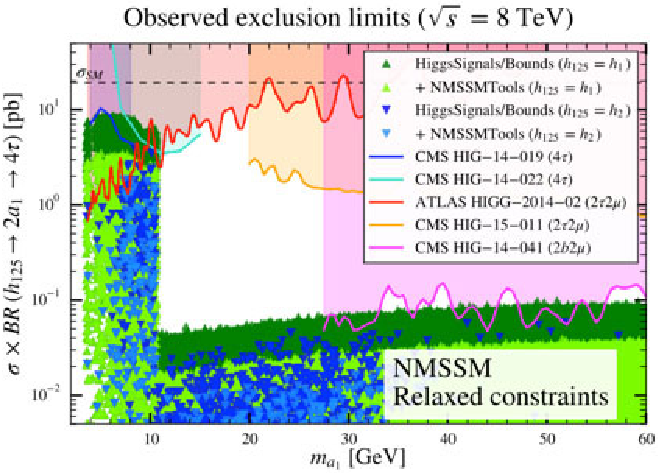


Figure 3.6: Using all LHC results available at the time this plot illustrates how many different searches for a SM-like Higgs decaying to two light neutral Higgs boson are further constraining the allowed parameter space for NMSSM supersymmetry. The points show allowed parameter space before considering the searches for light Higgs bosons.

The group is currently working on a new physics search involving Higgs bosons lighter than the discovered SM-like Higgs, along with other supersymmetric particles. Collaboration with theorists to identify interesting scenarios was very important in the search process. A related phenomenological study has also been published.

Through Rutherford International Fellowship Programme (RIFP) and Marie Curie fellowships, the physics activities of PPD have broadened to encompass top physics. The top quark is the heaviest quark, with properties that make it a key tool in new physics searches. The group has also been successful in attracting two phenomenologists as RIFP fellows, who are working on searches for new particles in plausible theoretical scenarios so far not excluded by CMS data.

The NExT Institute was conceived and set up by physicists in PPD and at Southampton. It has been highly successful and now encompasses five UK institutes. The objective is to encourage interactions between theorists and experimentalists. This has proved to be effective, with the production of numerous joint papers where the work has inspired, improved and helped to interpret analyses. The RIFP fellows work within this mechanism.

Machine learning is of growing interest within particle physics. The CMS group is exploring this technique in collaboration with computer scientists from Southampton University. Our GPU facility has been of considerable use in this activity. Two joint students are developing b-tagging and jet reconstruction techniques and the methodology has been applied to the vertexing being developed for use in the L1 trigger upgrade. We are also exploring other, more profound, applications of ML techniques for triggering.

The PPD group has built on its ECAL knowledge to develop considerable expertise in electron identification and e/γ High Level Triggers. PPD has provided the sub-convenor of the e/γ HLT and Reconstruction group, the convenor of the e/γ Physics Object Group and most recently has provided the Trigger Coordinator, a top-level management position in CMS. Through these roles, PPD has been responsible for significantly improved performance in the e/γ triggers, notably performing the work to exploit the upgraded CMS pixel detector. This extensive expertise has proved to be critical for many analyses that are more demanding of e/γ identification and the support and advice provided have increased the physics capability of the CMS experiment.

3.2.8 Computing

Brew, Ellis, Lahiff, Olaiya

Computing is vital to the work of CMS. It underpins every aspect of the experiment, from data-taking to final analysis. The group is active in computing support, development, and operations.

The CMS Computing Model is constantly being developed and refined as increasing data rates and volumes mandate the use of more resources more efficiently. In the future, cloud technologies and coprocessing platforms such as GPUs will be increasingly important. PPD is actively investigating and exploiting these exciting areas, with a recent proposal to STFC to inaugurate a new national project in this area. PPD made significant contributions to the original CMS computing model and to the development of services deployed at both the RAL Tier-1 and 2. The most recent PPD work includes:

- Testing and bringing into production the use of Tier-3 sites that provide no disk or services to CMS other than running jobs using the storage of nearby CMS Tier-2 sites
- Tuning access to the disk storage at the RAL Tier-1 to better support CMS data access patterns both for local jobs and for access from WLCG
- Replacing CMS's current data management tool, which will not scale to the data volumes and rates required for HL-LHC, with Rucio, a joint ATLAS-CMS project
- Improving data analysis software for the challenging requirements of Run-4, including the use of GPUs and modern software including industry-standard tools for big data. As well as being used in CMS, some of our software is now used in other experiments such as LUX-ZEPLIN, and builds against both HEP and industry-standard 'big data' libraries.

4 Precision Physics

The Standard Model of particle physics is an impressively precise description of the universe. Improvements in theoretical precision and experimental techniques, as well as the absence of signs of new physics in direct searches, have led to an increasing focus on more precise measurements to find tiny deviations from the Standard Model, which may explain the matter / antimatter asymmetry in the Universe, the properties of the strong nuclear force, or provide indirect evidence for new particles or interactions. The search for these deviations is complementary to the direct searches for new physics, for instance those at the ATLAS and CMS detectors. Our efforts at the precision frontier focus on the operation and upgrade of the LHCb detector and ultra cold neutron experiments.

4.1 LHCb

4.1.1 Overview

The LHCb experiment is one of the four major detectors at the CERN LHC [2]. The collaboration consists of 850 scientists, plus 450 engineers and technicians, from 79 institutes and 18 countries, and has been taking data since 2008.

The experiment is currently undergoing a major upgrade during Long Shutdown 2 (LS2) to enable it to take data with five times the current instantaneous luminosity [3]. The collaboration and the UK have ambitious plans for futher important upgrades in 2024–25 (LS3) and 2029–30 (LS4) to extend the LHCb physics programme into the HL-LHC era [4].

The main physics goals of LHCb are the study of the properties of quarks and leptons ('flavour physics'). The LHCb detector is optimised to record the decays of particles containing beauty and charm quarks produced by the colliding proton beams of the LHC. Differences between matter (quarks) and antimatter (antiquarks) can be explained in the Standard Model of particle physics by the phenomenon of CP violation in weak interactions. However, the strength of this violation is about one billion times too small to explain the almost total absence of antimatter in the Universe. It is therefore a fertile ground for searching for new particles or new interactions that could explain the discrepancy. Beyond this, LHCb has a broad physics programmes in many areas, including Standard Model measurements, fixed-target physics and searches for new particles.

Physics highlights so far in 2019 include the discovery of CP violation in charmed meson decays, a phenomenon first predicted 60 years ago; the observation of new pentaquark states, P_c^+ (see Figure 4.1); the observation of an excited charmed beauty particle, B_c^+; and the observation of a new charmonium state, $X(3842)$.

The Belle II detector in Japan will start taking physics data in 2019. The total Belle II data sample collected by 2029/30 is expected to be superior to that of LHCb in some areas (mainly final states with neutral particles, photons, or electrons), and comparable in some others, allowing for important cross-checks. However, the nature of the particle production at the LHC means that there are many areas where LHCb will continue to dominate (e.g. production of B mesons). Currently Belle II is not expected to be extended beyond 2030, and further future upgrades to LHCb will ensure that LHCb remains at the core of flavour physics for the next twenty years.

4.1.2 Responsibilities

The LHCb group is led by Wilson and consists of five members (including the GridPP Tier-1 liaison) with a total FTE count of 3.7. For the last ~10 years, two members were based at CERN but this has now reduced to one. During the design

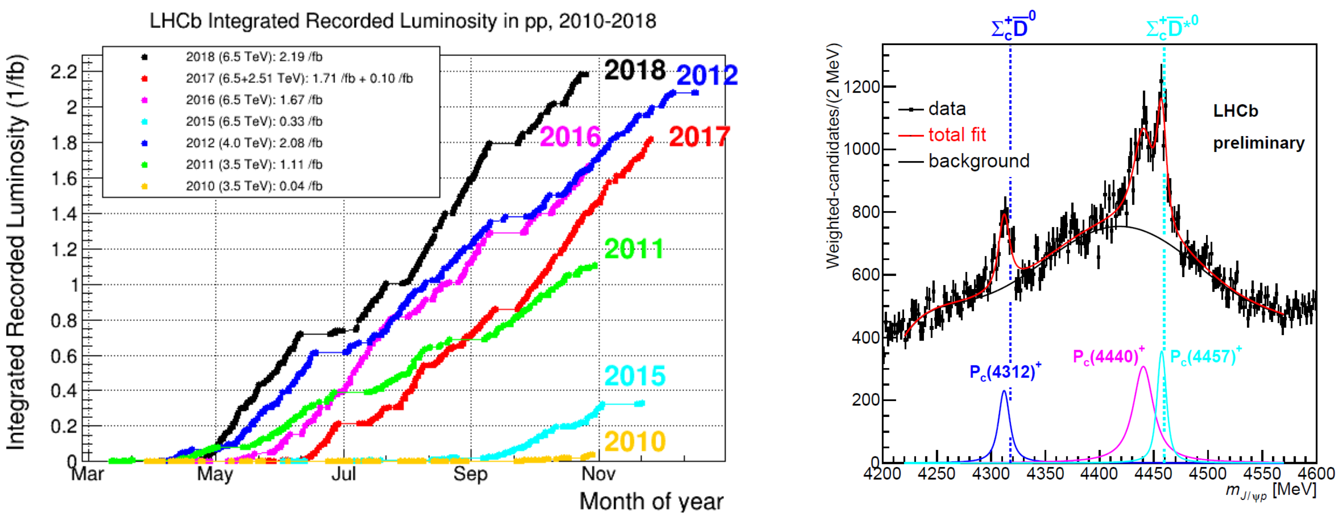


Figure 4.1: (left): LHCb recorded luminosity by year. (right): Observation of new pentaquarks in 2019.

and installation phase of the LHCb upgrade (2016-2021), an average of 2.1 FTE was dedicated to LHCb operations and 1.6 to the upgrade.

PPD and TD were involved in the design, construction and installation of the two Ring Imaging Cerenkov subdetectors (RICH 1 and 2). Our current activities are: optimisation and calibration of the RICH subdetectors; RICH simulation; RICH pattern recognition and reconstruction; RICH subdetector and experiment control systems; RICH front-end digital board maintenance; RICH 1 mechanics and operation; 24-hour on-call shifts (both RICH and computing); grid computing support; and physics analysis. We also provide engineering support for the RICH 2 subdetector.

For the period of this report, the group provided the RICH Project Leader (Papanestis), responsible for all aspects of the RICH 1 and 2 operations. The group also contributed the RICH simulation and calibration coordinator (Easo). The simulation is constantly being improved and must follow data-taking conditions, while the calibration occurs for every run and must be propagated to the real-time data-taking system and event reconstruction. The RICH simulation and calibration coordinator also covers the task of improving the accuracy and speed of the pattern recognition and reconstruction. We have also been involved in the RICH laser mirror alignment system. We ensure that the control systems, safety sensors, and front-end digital boards for the RICH are operating correctly, replacing them as necessary. In collaboration with TD, we provide engineering support as needed for the RICH 1 and 2 mechanics.

The group hosts the LHCb UK GridPP Tier-1 and Tier-2 liaison (Nandakumar), responsible for ensuring that the requirements and requests of the LHCb experiment are understood by the UK Tier-1 and 2 centres, and monitoring LHCb computing across the whole Grid.

All members of the group take data-quality and RICH monitoring shifts; for the last nine years our group has provided the fourth-largest number of shifts. As a result, the UK is a major and reliable contributor to the data-taking and computing of LHCb.

Over the last five years, four members of the group (Easo, Ricciardi, Wilson, Nandakumar) have contributed to the physics programme of LHCb. The main topics have been: suppressed charmless three-body decays; lepton-number and baryon-number violation in Λ_c decays; lepton universality in Λ_b decays; charm polarisation and CP violation in Λ_c decays; and lepton-flavour violation in *B* meson decays (see for example [5]). In addition, in 2019 Wilson published papers on the rare leptonic decays of the D^0 meson [6], and lepton-flavour and lepton-number violation in D^0 meson decays [7], using data from the BaBar experiment. Members of the group have been chairs or members of several physics review groups.

Recent major collaboration roles held by group members include: LHCb Editorial Board chair (Wilson); RICH Project Leader (Papanestis); RICH Simulation and Calibration coordinator (Easo); Deputy chair of the LHCb Speakers' Bureau (Ricciardi); and LHCb UK computing coordinator (Nandakumar). The group manages the LHCb UK budgets on behalf of the community: Wilson manages the LHCb UK operating budgets, while Wilson and Ricciardi manage the LHCb UK upgrade budget.

4.1.3 Upgrade

The UK has two major roles in the LS2 upgrade of the LHCb detector. These are the replacement of the existing vertex detector (VELO) [8] and of one of the RICH detectors (RICH 1) [9]. PPD works on the RICH 1 upgrade. The RICH upgrade consists of a complete refurbishment of the detector including the gas enclosure (required to generate Cerenkov light), mirrors (to direct photons to the photon detectors), photon detectors (to cope with the five-fold increase in luminosity), front-end electronics (upgrade to 40 MHz readout), and all associated mechanics.

PPD provide the work package leader for the simulation of the upgraded RICH detector, including the simulation and optimisation of the reconstruction for all the design variants over the last four years (Easo). Through the RICH Project Leader, we provided project management expertise (Papanestis). On the RICH mechanics side, PPD are responsible for the replacing the entrance and exit windows and beam pipe seals. We also provide the installation engineer and are responsible for the design and construction of the installation equipment, including project management, scheduling, safety, and mechanics design and construction (Ricciardi, TD engineers). We have a supporting role in the upgrade of the Detector Control System (DCS), as we were responsible for the original installation (Papanestis). There are currently six STFC engineers working on the project with varying fractions of their time, and they are overseen by Ricciardi. At the time of writing, we have just finished the dismantling phase of the existing RICH subdetector on schedule and on budget.

The installation of the upgraded RICH 1 components is scheduled to happen over the next eighteen months. This will involve extensive work at CERN by PPD and TD staff. We will then move onto commissioning, monitoring, calibration, and operation of the new RICH detector, building on our existing expertise in running the current RICH detector. We expect to maintain many of the roles we already hold into the operations phase, including: RICH optimisation and calibration; RICH detector and experiment control systems; RICH front-end digital board maintenance; RICH 1 mechanics and operation; and 24-hour on-call shifts. We will also provide support for the RICH 2 mechanics for data-taking after LS2.

We are building on our existing physics work to exploit the data from the upgraded LHCb detector, where we will be concentrating on lepton-flavour and lepton-number violation in B and D meson and baryon decays.

4.2 Neutron EDM

The PPD group has historically played a leading role in the neutron electric dipole moment (nEDM) experiments at ILL in Grenoble, including the room temperature experiments that set the world limit on the nEDM and the cryogenic experiment that pioneered a number of technologies for the next generation of projects. The fact that the world limit on the nEDM set by us in 2006 is still world leading, despite intense international competition, illustrates the complexity of such experiments.

It is generally accepted that a next-generation nEDM experiment, capable of providing an order of magnitude improvement in sensitivity, would have to be based on a fully cryogenic experimental set-up, and PPD has been working to advance ultra-cold neutron (UCN) technologies. Higher densities of UCN can be generated in a super-thermal source and substantially higher electric fields can be sustained within a cryogenic medium. Following the withdrawal of STFC from the nEDM project, our group has applied its expertise to a large extent to support the dark matter activity in PPD whilst maintaining a low-level effort on related R&D for the benefit of next-generation nEDM experiments.

Balashov, van der Grinten and Khazov developed a novel way to produce UCN guides with complex geometries, to mitigate losses when guiding neutrons through bends and changing confinement geometries when transferring UCN between different sections of the experiment. This technology will allow improved UCN numbers, and hence improved sensitivities, in UCN based experiments such as nEDM and neutron lifetime measurements.

We are one of the founding institutes of PanEDM, a nEDM experiment under construction to run at ILL. This is a room temperature experiment coupled to a super-thermal UCN source (PanEDM), but our future interest focusses on the next-generation fully cryogenic experiment. Tucker and van der Grinten designed the cryogenic ^{3}He filter system that will be integrated in the super-thermal UCN source. Our involvement with this project provides a potential pathway for the UK in a next-generation nEDM experiment.

Tucker and van der Grinten were involved in the cryogenic neutron lifetime experiment, providing cryogenic expertise and technologies. Although our involvement has been at a minimal level, our contributions to the experiment have allowed for enhanced monitoring and control of the cryogenics parameters of the experiment, and have led to a new lifetime measurement published by our group. The neutron lifetime and nEDM data both provide input to constraints on low-mass dark matter, which is now a key topic of interest for the UK particle-astrophysics community.

For the work at ILL, which is a partly STFC-funded facility, the group has been successful in obtaining beam time over several proposal rounds via a peer review process, also providing the group with on-site support, travel and accommodation funds. Although current funding does not allow a full UK scientific participation in this area, such experiments may in the future form a key route for detection and exploration of physics beyond the SM, without the use of colliders. Our R&D efforts are therefore a cost-effective means of preserving UK capability in this area, and preserving the opportunity for a future UK engagement at the heart of the next-generation nEDM experiment.

Figure 4.2: The completed room-temperature nEDM experiment: ultra-cold neutrons are stored in a quartz cylinder in an electric and magnetic field. A Hg co-magnetometer probes the storage volume for magnetic field fluctuations to a precision of 1 nGauss that enabled the most precise nEDM measurement to date to be made.

5 Neutrino Physics

Neutrinos are the most abundant matter particles in the universe, but are also the particles we know least about. The Standard Model predicts that neutrinos should be massless, but the Nobel Prize for physics 2015 was awarded to Profs Kajita and McDonald in recognition of the discovery that neutrinos oscillate and therefore must have mass. Over the last decades, a variety of experiments have studied the properties of neutrinos, at an increasing level of detail, trying to understand their secrets. Are neutrinos their own anti-particles (Majorana neutrinos) or are they like the other fermions in the SM (Dirac neutrinos)? What are the neutrino masses? What are the parameters governing neutrino oscillation (PMNS neutrino mixing matrix)? Are there more than the three types of neutrinos known in the SM (electron-, muon- and tau-neutrinos)?

Neutrino physics is a vibrant and expanding field and PPD is at the centre of the UK's neutrino activities. We are involved in the exploitation of T2K, the most sensitive long-baseline experiment so far, and its planned successor HyperK. We are providing leadership for the world's future premier neutrino observatory DUNE. Additionally, we are investigating long-standing anomalies seen by previous neutrino experiments (LSND, MicroBooNE), which could potentially be explained by additional sterile neutrinos not predicted in the SM, with the SBND and SoLid experiments.

5.1 T2K

T2K [10] is a neutrino experiment designed to investigate how neutrinos change from one flavour to another as they travel (neutrino oscillations). An intense beam of muon neutrinos is generated at the J-PARC nuclear physics site on the East coast of Japan and directed across the country to the Super-Kamiokande (Super-K) neutrino detector in the mountains of western Japan. The beam is measured once before it leaves the J-PARC site, using the near detector ND280, and again at Super-K: the change in the measured intensity and composition of the beam is used to infer information on the properties of neutrinos.

PPD was one of the original UK T2K institutions. Wark identified RAL Technology Department (TD) as having key skills in designing and fabricating components for the T2K beam line that were critical to the delivery of the experiment. This further developed into a close partnership between PPD physicists and their university collaborators with TD engineers in electronics and DAQ providing two more of the major components for the UK contributions to T2K (with further major contributions, including the largest elements of the electromagnetic calorimeter and the basket to hold it, being built at Daresbury in close cooperation with physicists from T2K's other UK university collaborators). Wark leads the T2K group within PPD, is the UK PI for T2K and the UK country representative.

5.1.1 Near Detector DAQ

Weber leads the T2K Near Detector DAQ group at RAL, as well as overseeing the Electronics Group within T2K as a whole. PPD is instrumental in operating, maintaining, and upgrading the DAQ system and near detector electronics. This has enabled T2K to take high-quality data that is used both for the oscillation analyses, as well as the neutrino-interaction cross-section measurements. The other members of the DAQ / electronics group in PPD, providing expert operational support for the experiment, are Nova and Koch.

5.1.2 Grid Data Management

RAL provides the primary tape archive for the T2K near-detector data, which is accessed nationally and internationally via Grid software. This is one of two Tier-1 sites of T2K, the other being located in Canada. Furthermore, PPD provides a Tier-2 site with disk storage and computing resources. Koch is in charge of the distribution of T2K data on the Grid, making sure that it is available for processing and backed-up at the designated Tier-1 sites. He works together with the computing groups in PPD and SCD and the T2K members in charge of data processing.

5.1.3 Neutrino Cross-Section Measurements

Koch is working on neutrino cross-section measurements using the T2K near detectors. His own research focusses on measurements using the gaseous TPCs in the ND280 detector as active targets for the neutrinos. This promises an unprecedentedly low threshold for the detection of hadrons produced in the interaction. To facilitate these measurements he is investigating 'forward-folding' statistical methods that should also prove useful for the wider cross-section measurement community. His contributions were recognised by the cross-section group leaders and in early 2019 he was made a cross-section sub-group convener. In this position he supports other analysers in their measurements and is involved in the review process of official T2K results.

5.1.4 Oscillation Analysis

Andreopoulos is the lead author and coordinator of the VALOR neutrino fit group [11]. Since 2010, the VALOR group has underpinned the overall T2K oscillation analysis effort. Andreopoulos has contributed to seventeen oscillation analysis cycles, co-authored a similar number of reviewed T2K technical notes, and contributed to ten published T2K oscillation papers. He has co-supervised five PhD students working on the flagship T2K oscillation analysis.

5.1.5 Neutrino Event Generators

Andreopoulos is a co-spokesperson of the GENIE Collaboration [12] and he is one of the main authors of the corresponding neutrino interaction Monte Carlo simulation, that is one of the main physics simulations used in T2K and a number of other experiments.

5.2 HyperKamiokande

HyperKamiokande (HK) is a future international experiment in neutrino physics that will build on the successful experiences of Kamiokande (1983–96) and SuperKamiokande (1996–) to investigate a wide range neutrino properties and phenomena with unprecedented precision. The apparatus includes a beamline (J-PARC) to produce an artificial beam of neutrinos and antineutrinos; a suite of near and intermediate detectors to characterize the beam before oscillations and help reduce the systematic errors; and the signature far detector, an underground tank containing 250 kt of ultra-pure water monitored by 40 000 large PMTs. The detection principle consists of measuring rings of light emitted through the Cherenkov effect by charged particles moving in the water. The experiment aims to measure the beam neutrinos (thus constraining several unknowns of the SM, including the leptonic CP-violating phase), as well as solar neutrinos, atmospheric neutrinos, geo-neutrinos, cosmic neutrinos from supernova explosions and the not-yet-observed effects of proton decay. The HK experiment will begin taking data around 2026.

5.2.1 DAQ System

PPD is primarily involved in designing and building the Data Acquisition (DAQ) system for the HK experiment. The HK DAQ has to be extremely flexible in order to be able to identify in real time interesting physics events which take place at very different energy and time scales. These events have an enormous background from dark noise, radioactivity, cosmic rays, spallation events, and other sources. Beam events happen at high energy (around 600 MeV) at known times (as controlled by the source accelerator). Atmospheric events have even higher energies (above 1 GeV) but occur randomly, and nucleon decay is presumed to happen at similarly large energies but with negligible rate. On the other hand, solar neutrinos are characterised by very small energies (1 to 5 MeV), where background radioactivity is a competing channel. Finally, a supernova explosion poses the challenge of detecting a small number of low-energy (10 to 20 MeV) interactions that take place over a long time interval (about 10 s) and then go silent.

The DAQ group has been involved in designing several low-energy triggers whose job is to distinguish in real time electrons generated by a neutrino from those generated by random dark hits and radioactivity. Nova has created a high-performance Test Vertices algorithm that reconstructs the interaction vertex with a 2.5 m standard deviation at the trigger level. A high speed of execution is attained by running parallel computations on GPUs. The system has now been test-benched at RAL. Koch has further adapted this algorithm to identify in real time the direction of an exploding supernova. Other efforts include the possibility to reconstruct not only the interaction vertex but also the direction of motion of the charged lepton at trigger level, as well as the capability to differentiate radioactive decays from neutrino-induced Cherenkov light based on the pulse height. Each of these achievements directly ehances the performance of the HK experiment, and opens up new areas of physics sensitivity.

5.2.2 Detector Design

Other efforts have gone in the direction of optimising the detector design. To this end, GEANT4 simulations of the HK tank have been prepared to study the effect of different design choices. Nova has studied the possibility of using light concentrators around each PMT to increase its effective area. Another area of development has been that of the photosensor design; Wark and Nova have proposed a new design in which large PMTs (that are expensive, slow and background-rich) are replaced by smaller PMTs (cheap, fast and clean) coupled to wavelength-shifting plate to augment the light acceptance. We have also produced simulations to optimise the design of the Outer Detector, a region of water instrumented with outwards-looking PMTs to be used as a veto shield against cosmic radiation.

5.2.3 Background Characterisation

Another essential task for HK is to understand the background. Particular attention has been paid by PPD staff to reducing the relevance of dark noise in the phototubes (this is accomplished by the Test Vertices trigger) and to characterizing the radioactivity of different elements. Extensive work has been performed by Nova to allow the simulation of radioactive decays in the detector and to study the impact of all natural radioactivity isotopes that may contaminate the glass of the photomultiplier bulb.

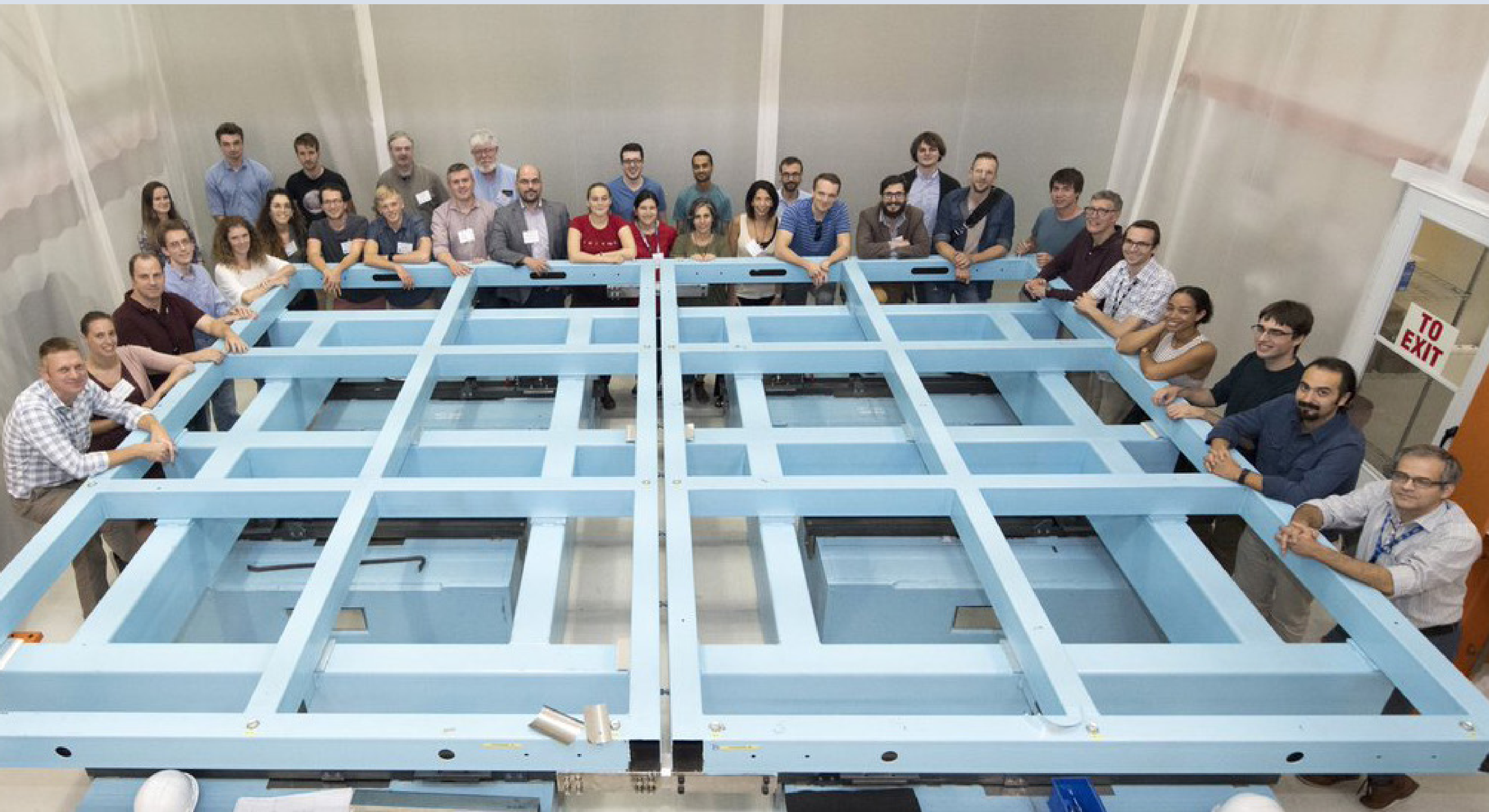
5.3 SBND

The Short-Baseline Neutrino programme (SBN) is a phased international experimental programme in the Booster neutrino beam at Fermilab in the USA. The facility was designed to reach a >5σ sensitivity test of the currently allowed oscillation parameter region associated with a series of statistically-significant anomalous results in neutrino physics that may be an indication of unknown phenomena or new physics. The superb SBN sensitivity to electron-neutrino appearance, characterised by the mixing parameter $\sin^2 2\theta_{\mu e} \approx 10^{-3}$ is enabled by the combination of three Liquid Argon Time Projection Chamber (LArTPC) detectors, with excellent imaging capabilities, positioned at different baselines in the same neutrino beam: SBND (112 t active mass) at a distance of 110 m from the neutrino production target; MicroBooNE (89 t) at a distance of 470 m; and ICARUS (476 t) at a baseline of 600 m. This multi-detector configuration also allows a sensitive search for muon-neutrino disappearance in the same experiment, a powerful cross-check of any new physics interpretation of an observed signal in the electron channel.

In addition to its unique oscillation physics potential, the SBN programme and, in particular the SBND experiment, will bring a generational advance in neutrino interaction studies. The extensive SBND neutrino-argon cross-section measurement programme is crucial forthe future neutrino programme and for DUNE in particular. Finally, SBND offers unique opportunities for exotics searches, in particular by probing vector, neutrino and Higgs portal models via the direct production and detection of sub-GeV dark matter candidates. Physics data-taking with all SBN detectors commissioned is expected to begin in 2021.

The SBN / SBND activities in PPD are led by Andreopoulos, who is also the physics co-coordinator for the SBND experiment and co-coordinator of the Systematics and Oscillation Sensitivity Working Group for the overall SBN programme. Andreopoulos also led the development of the GENIE neutrino interaction physics simulation [12], and the development of the VALOR neutrino oscillation fit [11].

Costas Andreopoulos is a joint appointee with the University of Liverpool, and leads SBN / SBND activities in PPD. He is currently physics co-ordinator of SBND, and is seen here with other collaboration members in front of a mock SBND Anode Plane Assembly (APA) frame sitting on the alignment fixture.



5.4 DUNE

The Deep Underground Neutrino Experiment (DUNE) is a long-baseline neutrino oscillation experiment. It is the flagship particle physics experiment in the USA, pursued by an international collaboration of more than 1000 physicists from around the world. The DUNE Experiment will use state-of-the-art Liquid Argon Time-Projection Chamber (LArTPC) technology for the massive neutrino detectors planned at the Sanford Underground Research Facility (SURF) in South Dakota. This facility currently hosts the LZ experiment (see Section 6.1), and a large new underground cavern for DUNE will begin construction in 2021, with physics data-taking expected in 2026. DUNE has a wide physics programme across PP, PA and astrophysics, ranging from studying the CP asymmetry in the lepton sector to observing the creation of a black hole.

- Neutrinos are the most abundant form of matter in the universe, but only interact very weakly and little is known about them. In particular, it was discovered only in 2000 that neutrinos have mass and oscillate between three flavours. DUNE will study neutrino properties with unprecedented precision.
- In addition to neutrinos, DUNE could detect proton decay, a process predicted by many models of new physics but not so far observed.
- When a star implodes in a supernova (SN), 99% of the energy produced is emitted in the form of neutrinos. DUNE is a unique detector sensitive to both the neutrinos and anti-neutrinos generated by a galactic SN implosion.

DUNE is the largest neutrino experiment to date, and the UK is the largest international partner after the USA. The UK is making essential contributions to the experiment. We are providing the DAQ system for the far detector and the readout planes to record the signatures generated by the neutrino interactions. Additionally, we are taking the lead in developing the event reconstruction software and contributing to the computing infrastructure and organisation of the experiment. PPD is at the heart of this effort, with a technical focus on DAQ and computing, complementing work by TD at Daresbury Laboratory on detector construction.

5.4.1 Management

PPD provides senior leadership for the national and international DUNE effort. Weber is the Principal Investigator of the overall UK LBNF / DUNE grant (costed at around £80M), as well as the co-leader of the near detector effort, and Papanestis is the DUNE UK project manager. Newbold was until 2019 the leader of the international DAQ project, in the critical phase leading to the creation of the Technical Design Report. He has now stepped down from this role upon taking over as PPD Director, but continues as the chair of the DAQ consortium resource board. Thea (previously CMS) has taken over as the Technical Lead in the DAQ consortium, a good example of the use of PPD expertise gained on LHC projects in new initiatives. Durkin is responsible within DUNE Technical Coordination for the design of underground infrastructure. The PPD DUNE technical effort is overseen by Shepherd-Themistocleous.

5.4.2 DAQ

Durkin, Harder, Manolopoulos, Newbold, Shepherd-Themistocleous, Thea

The DUNE DAQ system is the largest and most complex that a neutrino experiment has ever required, and is similar to an LHC system in cost and scope. The DUNE Far Detector consists of four liquid argon modules, with 10 kt fiducial mass and up to 400 000 electronics channels apiece. These modules are housed 1.5 km underground in a remote location with stringent access and power constraints.

The number of channels and total data rates are lower than at LHC detectors, but there are different challenges to overcome. The DAQ system has to be capable of responding to beam-induced events, with a known time of arrival, as well as non-beam induced events such as supernova bursts. This provides one of the key DAQ challenges. A self-triggered system is required that is capable, for SN, of streaming data to a memory store capable of recording 10-100 seconds of unfiltered continuous data. Furthermore, a triggered system is required for beam-initiated events since it would not be possible or sensible to record data from all channels for all beam live time.

The data processing stream broadly consists of frontend processing in FPGAs of input from the on-detector ADCs, data buffering pending trigger decisions, followed by data processing to build events and finally the transmission of data to permanent storage at FermiLab. PPD has considerable experience in all of these areas, and this has been leveraged to construct a DUNE DAQ and Computing group.

Our expertise in the use of FPGAs and signal processing has been deployed to address the frontend processing element of the DAQ chain. The data arriving at the frontend FPGAs is processed to generate trigger primitive objects used for making a trigger decision, and this requires complex digital signal processing for noise suppression and data reduction. PPD expertise in firmware and data handling in FPGAs has been utilised both to implement specific processing algorithms and to construct dataflow procedures in FPGAs capable of exploiting high operating frequencies. The expertise developed for LHC DAQ and trigger requirements has been deployed to do this.

TD has considerable board design and construction expertise and this, through PPD, has been used to review the design of the current UK co-processor card. The neutrino platform at CERN is currently being used to test the first implementation of the complete data processing chain in an FPGA. The exact data handling model beyond the frontend boards, where the data is first passed to the PCs that host the board supporting the FPGAs, is evolving within DUNE. PPD is well placed to influence the ultimate design through the newly appointed DAQ Technical Lead, who provides a wealth of online software experience from previous work on the CMS trigger system. The UK and PPD activity in this area will ramp up strongly over the next year as the DUNE construction project begins.

The housing of the DAQ underground within a mine is one of the major challenges for the system. This means that there is limited space, power and cooling available, and that the system must be designed with the expectation that only infrequent human intervention is possible to replace components or fix problems. The DAQ consortium is provided with a cavern and basic infrastructure. The design of the services and layout of the physical structure, such as the electronics racks, must be provided by the consortium. PPD is providing the technical expertise to accomplish this task. This has already encompassed designing the room layout to accommodate the DAQ components, designing the power, cooling and signal cable distribution systems and designing fire safety systems (see Figure 5.1). This work is being done in concert with the DUNE technical coordination team at FermiLab, and builds upon previous work at CERN and on the MINOS and T2K experiments.

5.4.3 Computing

Brew, Nandakumar, Wilson

DUNE expects to use around 30 PB of offline storage per year. Typical event sizes are very large (order of 100 MB) and the electric field map and electron lifetime calibration alone, as currently implemented, requires several GB of memory. The challenge is to reuse as much of the existing current LHC software and expertise as possible while taking into account the unique features of DUNE.

The DUNE construction proposal assigns two main work packages to PPD. The first is the offline production management and monitoring. The DUNE production system must support complex work-flows, communicate with data catalogues, and optimise the submission and execution of production jobs across the available resources. The development of a production system for DUNE will begin with the testing and evaluation of existing (LHC) workload management systems. Having chosen a candidate system, DUNE-specific adaptations will be implemented, including the integration with RUCIO. The final system will then be deployed into production.

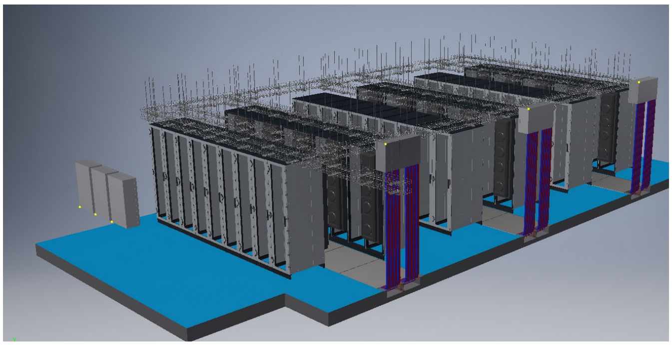


Figure 5.1: Mechanical design of the DUNE underground data centre.

The second work package requires a similar production system to be deployed at SURF (in effect a small remote data centre) to support the management and processing of the Far Detector raw data. A full prototype system will first be constructed at FermiLab, and will be benchmarked using simulated data. The full production system will then be installed at SURF ready for data-taking. The deployment of the SURF production system will transition into a long-term online coordination role (Brew), expected to form one of the UK's common fund in-kind contributions to the DUNE experiment.

The DUNE computing model is currently being designed. PPD aims to be involved in both the data and computing model design, using our expertise from running computing production on ATLAS, CMS and LHCb. In the meantime, we have been supporting ProtoDUNE data analysis and DUNE simulation production. 1 PB of disk and 0.5 PB of tape have been assigned at the RAL Tier-1 for ProtoDUNE data and DUNE simulation production. Data from ProtoDUNE can now be transferred to the RAL Tier-1 site from CERN. We have run the DUNE simulation production system to gain hands-on experience with the current system. We provide a Tier-1 Liaison post for DUNE.

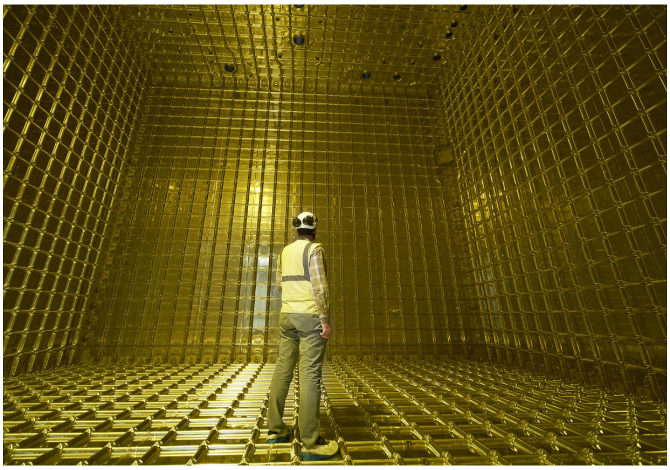


Figure 5.2: Interior view of one of the ProtoDUNE cryostats at CERN, before filling with liquid argon.

5.4.4 ProtoDUNE

Newbold, Thea

The DUNE technology is currently being tested at scale in a pair of dedicated 5% scale cryostats (see Figure 5.2) at the CERN Neutrino Platform, a new facility based in the EHN1 extension to the SPS North Area. This experiment has allowed the engineering feasibility, stability and physics performance of the LAr TPC technology to be studied in detail, including the study of low-energy interactions of a variety of incident beam particles.

PPD staff played a key role in the design and development of the central trigger and timing system for ProtoDUNE-SP, along with colleagues from Bristol and Oxford Universities. This system, at the heart of the ProtoDUNE DAQ, is responsible for distributing precisely-aligned timing, control and trigger signals to electronics modules distributed throughout the LAr volume, as well as for enabling test runs while the beam line was being installed. The system makes use of a novel bi-directional optical fanout network to allow continuous alignment and calibration of the detector timing, as well as a high level of reliability. The system operated to specification during the 2018 beam run, and has continued to support test running for detector and DAQ development during 2019.

The basic technology of the timing system is now considered proven, and will be adopted at large scale for the first DUNE module. The construction and operation of the timing system is a joint responsibility with Bristol.

Tim Durkin, seen here preparing a component of the SoLid detector, is an engineer specialising in electronic and mechanical design of particle detectors, and experience on both collider and neutrino experiments. He has recently been appointed as liaison between the DUNE DAQ and Technical Coordination teams, with responsibility for the specification and design of the underground counting room.

5.5 SoLid

The SoLid experiment aims to measure the flux and energy spectrum of reactor anti-neutrinos on a ultra-short 5 to 10 m baseline. The apparatus is now taking data adjacent to the 50 MW BR2 reactor at the SCK-CEN laboratory in Belgium. Previous reactor neutrino experiments have indicated a significant deviation at low L/E from the expected flux under a conventional three-neutrino model. This may be due to source or detector mis-modelling, but this is also an expected signature of a ~1 MeV sterile neutrino. SoLid aims to make detailed measurements in order to resolve this question.

The experiment operates on the surface, with no significant overburden, and makes use of novel composite scintillator technology and a very high-performance trigger and readout system in order to suppress backgrounds. By employing a very finely divided scintillator mass, with pulse-shape discrimination to detect neutrons, we can cleanly observe inverse beta-decay (IBD) interactions of neutrinos against a cosmogenic, radiological and reactor-driven backgrounds.

PPD members were responsible for the design and construction of both the mechanical infrastructure of the experiment and the trigger and readout system. The experiment is not easily accessible at BR2, and so these systems must be designed for exceptional robustness and reliability. The mechanical support structure for the experiment, along with the cooling and power subsystems, was constructed at RAL (Durkin, Weber, along with Bristol and Oxford colleagues) within a self-contained shipping unit, and then transported to BR2 as a whole (Figure 5.3). The complex firmware and software for the trigger and readout system was designed by Newbold, along with Imperial College colleagues.

SoLid has been operating smoothly at BR2 for over a year, and has accumulated a substantial dataset. Work currently focusses on the understanding of backgrounds, and on optimisation of flux and energy measurements for IBD events. First physics results are expected within the next twelve months.

Figure 5.3: The SoLiD experiment in its shipping container.

6 Particle Astrophysics

6.1 Dark Matter

Over the last seven years, PPD has played a leading role in the LUX-ZEPLIN (LZ) project [13], a 7 t liquid-xenon detector that will search for dark matter with unprecedented sensitivity in the Sanford Underground Research Facility (SURF), South Dakota. The PPD group has had a leading involvement in the project throughout its R&D (2012–15), construction (2015–19) and exploitation (2019–) stages. Today the LZ collaboration consists of around 250 scientists from 37 institutions in the US, UK, Portugal, Russia and South Korea.

PPD was one of the founding institutes of the LZ collaboration and our staff have held several roles of responsibility through the various stages of the project. The group has made substantial technical contributions to the LZ design, as published in its Technical Design Report [14]. We currently provide project management for the LZ-UK project (Preece 2015–18, Majewski 2018–), where the task list includes: reporting to the LZ Oversight Committee (OsC), liaising with and reporting to the LZ project office at LBNL, chairing project management meetings, oversight of the project progress and budget, chairing the project risk board, conducting internal reviews, and chairing of the cryostat fabricator selection committee.

Majewski has been an L2 manager (in the DOE structure) responsible for the delivery of the ultra-radiopure cryostat (Figure 6.1). This involved coordinating the design and development effort between RAL and LBNL engineers, overseeing the procurement and fabrication in the US and Italy, testing, transportation and final delivery to SURF.

The group also undertook modelling and simulations of the electroluminescence (EL) region responsible for the secondary (S2) scintillation in the LZ detector, which included: optimisation of the electrostatic field between woven meshes with various geometries, and estimation of the electroluminescence scintillation yield and evaluation of the anode woven mesh deflection and its impact on the S2 signal size and the radial dependence. This work was performed with a PhD student from Imperial College (Bayle) and a PPD summer student from RHUL (Baker).

PPD leads the LZ-UK calibrations effort, with van der Grinten acting as an L3 manager in the collaboration. Energy, position and timing calibration of the experiment is achieved through the calibration source deployment (CSD) system and the optical calibration system (OCS). These systems were provided by the UK, which undertook the design, prototyping, manufacture and extensive testing of each.

The CSD system has been entirely developed by PPD (Balashov, Khazov) with support from TD (Barclay) and included: a stepper-motor assembly, in-house designed electronics control unit, and deployment mechanics and support structure. The system consists of three identical subsystems operating within calibration tubes inside the cryostat. Gamma and neutron sources can be delivered to any position along the 6 m long tubes to a precision better than ±1 mm (compared with the experimental requirement of a precision of ±5 mm). This has been made possible by a laser position feedback mechanism incorporated into the CSD system and the use of a suspension filament identified and characterised by us. We have made use of several test locations at the RAL site allowing full-scale (6 m vertical displacement) testing of the systems. This system will be installed and commissioned at SURF in the autumn of 2019. The OCS design and fabrication were performed by the University of Liverpool with a joint Liverpool / PPD PhD student (Boxer) pursuing the construction and testing of the system. Joint appointee from RHUL, Kaboth, has been supporting the LZ-UK calibration effort with detector simulations and in 2018 he became an LZ calibration convener.

Figure 6.1: The LZ Inner and Outer Cryostat Vessels in the cleanroom at SURF.

The UK provides one of the two global data centres for the storage and processing of LZ data. This makes use of GridPP infrastructure to connect storage at Imperial College with data processing resources at a number of UK Tier-2 centres, including PPD. Brew is supporting this by integrating the LZ data transfer software (SPADE) with the GridPP Infrastructure.

The group is fully engaged in preparations for the future of the field. In early 2019, we participated in the preparation of two key proposals to STFC: 'Xenon Futures: R&D for a global rare event observatory' and 'Feasibility Study for Developing the Boulby Underground Laboratory into a Facility for Major International Projects'. The latter project will pave the way for a possible major proposal for a third-generation dark matter experiment under UK soil, representing a substantial expansion of these activities in PPD and the UK as a whole.

6.2 AION

RAL is one of the core institutes in the UK Atom Interferometer Observatory and Network (AION) project [15]. Three departments will contribute to AION: PPD, RAL Space and TD. AION is part of the Quantum Sensors for Fundamental Physics initiative, which recently won support from the UKRI Strategic Priorities Fund, and was identified by PAAP as a high priority for the UK community.

The AION interferometer will be based on cold atomic beam fountains, and uses laser excitation to drive atomic beams through separate trajectories in the interferometer, recording any phase difference built up between the two trajectories. This phase difference can be generated by interactions with fields related to gravitational waves or dark matter. The sensitivity of the interferometric sensor includes signals from ultralight dark matter (10^{-13} to 10^{-16} eV mass) and gravitational waves in the mid-band frequency range (0.01 to 10 Hz). The mid-band frequency that the detector can access is not covered by current or planned detectors and would thus be complementary to the LISA and LIGO detectors with a discovery potential for new astrophysical sources (e.g. black hole and neutron star binaries) in addition to the searches for dark matter.

The AION project covers several stages scaling up the interferometer stepwise from 10 m (AION-10) to 100 m (AION-100) in the first instance, with the long-term objective of a terrestrial (km scale) and a satellite-based (thousands of km) detector. The PPD group is involved in two work packages:

- The AION-10 interferometer: This will operate at the Beecroft Centre in Oxford. Control over the magnetic field stability and homogeneity is of crucial importance to the successful operation of the interferometer. The PPD group has extensive expertise in this area through its past activities in nEDM experiments. Magnetic field simulations and modelling are being carried out by our group, and we are leading the design and manufacture of the magnetic screening required for the interferometer.
- AION-100: The PPD group is leading the design of the 100 m long interferometer together with its support structure. The site identification for the AION-100 experiment also forms part of this work package, and PPD will be actively involved in this.

Our early involvement in the AION project has allowed us to bring relevant and vital expertise to the collaboration, and to secure leadership roles in this project (van der Grinten, Majewski). The staged approach of the project underpins the potential for this project not only to be delivering science in the short and medium term, but also in the long term. We anticipate this exciting new area of science to be a major future focus for the group.

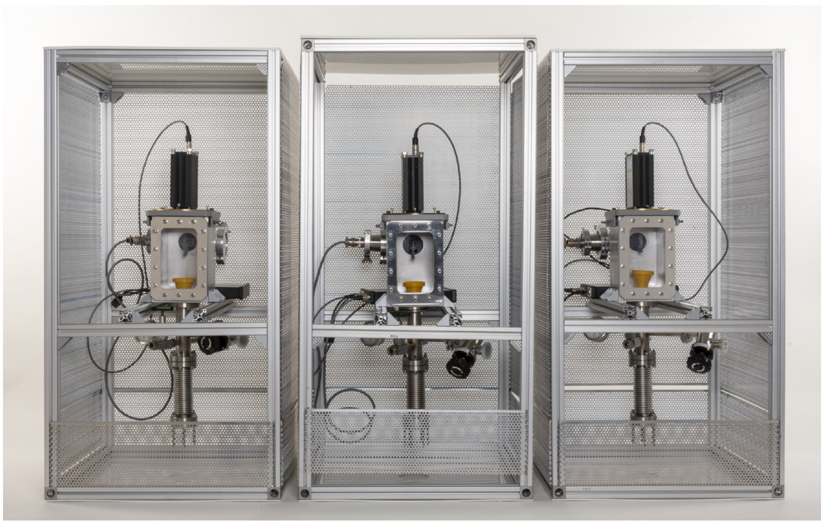


Figure 6.2: A complete set of three LZ calibration source deployment systems ready for shipment to SURF.

7 Preparation for Future Facilities

The future of collider physics is at a crossroads, with the discovery of the Higgs boson a triumph which completes the Standard Model, but which leaves few pointers to the answers to further deep questions. These include: the source of the observed matter-antimatter asymmetry; the nature of dark matter; and the mechanism for stabilisation of the Higgs potential. It is possible the answers to these questions lie beyond the direct production reach of even HL-LHC, and the preparation for future collider projects is underway.

7.1 MICE

The international Muon Ionisation Cooling Experiment (MICE) was constructed in Building 5.2 (the MICE Hall) to prove the principle of the technique by which it is proposed to cool the muon beam at the Neutrino Factory and Muon Collider.

The RAL PPD group has played important roles in the experiment since its inception. Over the reporting period, Long (Imperial College) served as international spokesperson. Preece served as international Project Manager until the summer of 2015 and delivered the experiment in the 'Step IV' configuration.

Whyte, seconded from Strathclyde to PPD, took over from Preece, and managed the completion of the liquid-hydrogen system and its installation in the MICE Hall. Whyte (Strathclyde) also managed the commissioning of the experiment. This complex programme included the training and operation of three large-bore superconducting magnets, the commissioning of the liquid-hydrogen absorber system in situ, and the commissioning of beam-line diagnostics and the MICE instrumentation. Whyte also played a major role in the design and testing of the high-power, 201 MHz RF system that was not eventually deployed.

Tucker designed and implemented the vacuum system on which the experiment relied. The system served the superconducting magnets, and the liquid-hydrogen system. Tucker also made substantial contributions to the development and implementation of the liquid-hydrogen system itself. His analysis was used to identify heat leaks in the hydrogen-refrigeration system. With others, Tucker designed and implemented the modifications required for the system to reach specification. Following the successful deployment of the system, Tucker was the lead author on the publication describing the system and its performance [16]. Tucker was a key player in all aspects of the operation of the experiment.

Substantial support for the operation of the experiment and the management of its data was provided by PPD staff. Brew made it possible for MICE personnel to access the PPD computing resources both on-site and off-site. In addition, he made substantial contributions to the implementation of the data persistency model for the experiment. Ricciardi made contributions to the simulation and the geometrical description of the experiment. Substantial contributions to the day-to-day management of the experiment and the international collaboration was provided by the PPD administrative team (Birch, Hayes, Loader, Shand). Senior personnel (Haywood) also played key roles in the oversight and management of the activity. This valuable support will be essential for the collaboration to complete its scientific programme.

The MICE collaboration has published five papers in refereed journals [17–21]. The first documented the design and performance of the MICE Muon Beam and the second documented the characteristics of the muon beams delivered to the experiment. The third and fourth publications quantified the degree to which a pure muon beam can be selected entering and leaving the experiment. The first particle-by-particle measurement of emittance was described in the fifth publication.

MICE data taking ended on the 18th December 2017, 24 hours before the end of ISIS User Cycle 2017/03. The final User Cycle included 35 days of continuous data taking that involved daily changes of magnetic configuration and regular absorber changes. The goals set out for the extended operation of the experiment were more than achieved. Full data sets were recorded with lithium-hydride and liquid-hydrogen absorbers, in solenoid and flip mode, over a range of input beam momentum and emittance and for a variety of optical settings of the superconducting-magnet channel. In addition to the planned programme, it was possible to take data with a wedge absorber to allow the first studies of emittance exchange to be made. This success is testament to the hard work and dedication of the international MICE collaboration, the STFC laboratory staff and the strong support the collaboration received from personnel from the ISIS, Particle Physics and Technology Departments.

The analysis of the data is now in full swing. One paper describing the techniques by which emittance may be calculated from an ensemble of muons selected from the flux incident on the upstream spectrometer has been published [21]. The collaboration is now preparing its observation of ionisation cooling for submission to Nature. This publication will present the first evidence for an increase in the phase-space density in the core of the beam in the presence of both liquid-hydrogen and lithium-hydride absorbers for input beams with initial emittance above equilibrium. The results are therefore the seminal observation of ionisation cooling (Figure 7.1).

The wealth of data accumulated during operation will allow the collaboration to bring forward the following publications:

- The multiple Coulomb scattering of muons in lithium hydride
- The study of the evolution of normalised transverse emittance in the Step IV lattice and its dependence on the focusing at the absorber and the emittance and momentum of the initial muon beam
- The measurement of the material properties of lithium hydride and liquid-hydrogen that determine the ionisation cooling effect
- Reverse emittance exchange introduced by the presence of a polyethylene wedge absorber.

The first of these is at an advanced stage of preparation. The continued support of PPD personnel and the computing resources managed by PPD are essential in the delivery of the scientific legacy of the experiment.

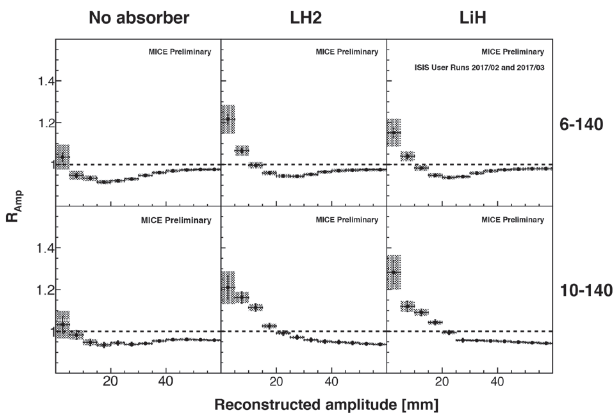


Figure 7.1: MICE results obtained using liquid-hydrogen (LH2) and lithium-hydride (LiH) absorbers exposed to beams with a nominal momentum of 140 MeV/c and nominal initial normalised transverse emittance of 6 mm (top row) and 10 mm (bottom row). The results obtained with no absorber are also shown. The ratio of the cumulative amplitude distribution downstream of the absorber to that upstream of the absorber (R_{Amp}) is shown as a function of the reconstructed amplitude. The value of R_{Amp} for a particular bin will be greater than one if muons have been caused to migrate there by their passage through the absorber. R_{Amp} is observed to be greater than one for low-amplitude bins for both liquid-hydrogen and lithium-hydride absorbers, implying that the population of muons at low amplitude in the core of the beam has increased and therefore that the beam has been cooled.

7.2 Future e^+e^- and pp Colliders

There are several current proposals for future e^+e^- colliders, each offering a different optimisation between construction and operation cost, schedule, and physics potential. In past years, PPD made a major contribution to studies for machine elements and detectors for the International Linear Collider (ILC) in Japan. PPD was also a member of the Silicon Pixel Detector R&D collaboration (SPiDeR) that investigated the viability of monolithic silicon active pixel sensors (MAPS) for use in vertexing, tracking and digital calorimetry.

The future of the ILC is uncertain, and there is currently no UK programme in this area. However, much of the basic technology development is relevant to other machines, and PPD staff are following developments across the board.

Interest currently centres on circular machines, operating initially at around 250 GeV centre-of-mass energy, close to the peak of the ZH coupling, and focussed on precision measurements of Higgs boson properties. The clean environment will allow a large factor of improvement in all the common Higgs coupling modes compared to HL-LHC precision, with particular strong points being the $c\bar{c}$ decay and the ZZH coupling strength from production. In addition, the tagging of the Higgs production from the Z recoil mass allows the width to be determined in a model-independent way and gives access to a plethora of potentially very rare decay modes, where those involving missing energy typically gain three orders of magnitude in sensitivity over the LHC. One particular target is the possibility that a strong first-order phase transition in the mechanism of electro-weak symmetry breaking, which could have produced the observed CP asymmetry, might be revealed.

CEPC [22, 23] is a proposed 100 km-circumference collider in China, proposed to break ground in 2022, with the intention of first collisions in 2030. This machine has the potential to be operational on a time-scale commensurate with maintaining a vibrant collider community. Two PPD members, Dopke and McMahon, signed the CEPC CDR. Dopke has strong silicon expertise and an active interest in future colliders, while McMahon's systems knowledge is naturally in demand. In the context of the ATLAS upgrade project, a strong collaboration with IHEP Beijing is already in place, with IHEP and PPD staff members planned to carry out construction work at each site in the coming years. Murray is a world leader in Higgs boson physics, and his expertise was sought out as reviewer of the CEPC detector CDR.

The proto-collaboration which produced the CEPC Conceptual Design Report (CDR) is keen to profit from the silicon strip and data acquisition expertise at PPD. We have the opportunity to play a leading role in either or both of these areas. The work is scheduled to peak in the mid to late 2020s, which allows for a natural progression for the staff currently focussing on the HL-LHC upgrades.

The Future Circular Collider (FCC) [24] is a proposed new machine at CERN [25], which will allow high-energy, high-luminosity collisions in a 100 km tunnel in the Geneva area. The time scale for this machine is uncertain, but detailed planning and construction clearly could not start until well after the current HL-LHC upgrade in 2026. The machine is proposed to have a staged programme of e^+e^- collisions at up to 350 GeV energy ('FCCee'), and subsequent pp collisions at up to 100 TeV ('FCChh'), thus allowing both precision measurements of Higgs properties and exploration of the energy frontier.

Together with Birmingham and Sussex Universities, Wilson received funding to investigate the design and performance of a fast, low-noise, reconfigurable, radiation-hard MAPS sensor ('DECAL') for use either as part of an FCChh outer tracker or a digital calorimeter [26]. Aspects of the sensor also targetted the ILC and CEPC tracking requirements.

Building on his experience with trigger and readout systems for CMS, Newbold instigated studies of the requirements of an FCChh detector in these areas, subsequently working with colleagues at Bristol and CERN on contributions to the FCC CDR [27]. It has become clear that triggering under FCChh conditions, whilst maintaining a simple and low-power detector design, will be extremely challenging compared to the LHC, and that implementation of detector readout is beyond today's technology. Since many years of further development will be possible before a final detector design is established, the emphasis for FCChh work will be on understanding the technology requirements as motivation for ongoing R&D. Detector development for FCCee can for the immediate future be in common with the CEPC effort.

8 Boulby Underground Laboratory

8.1 Introduction

The STFC Boulby Underground Laboratory is the UK's deep-underground science facility operating 1.1 km below ground in Boulby mine, a working polyhalite and rock-salt mine in the North-East of England (see Figure 8.1). Boulby is one of the few special facilities in the world in which science studies can be carried out with vastly reduced levels of interference from natural background radiation and cosmic-ray particles. It is also a place where researchers can gain safe and supported access to the scientifically interesting deep underground geology and environment.

Boulby has hosted science from early 1990s when the site was initially dedicated to supporting UK dark matter search studies (including the world-leading NAIAD, ZEPLIN and DRIFT dark matter search programmes). In recent years the science programme at Boulby has dramatically grown and diversified, with new, multi-disciplinary, pure and applied studies taking place. These range from particle physics and particle-astrophysics (continued dark matter search studies) through to studies of geology and geophysics, climate, life in extreme environments, robotics, and technology development for planetary exploration. The science portfolio at Boulby is still growing, with various new projects planned or in preparation, including a confirmed major new US / UK-funded antineutrino detector (AIT-WATCHMAN) for applied nuclear security and fundamental science R&D.

The current laboratory facilities consist of a fully supported 4000 m^3 underground laboratory, operated with class 100k and 1k experimental clean room spaces. It has a 3000 m^3 Outside Experimentation Area (OEA) for science projects requiring wider access to the deep underground environment. The facility also has a 2000 m^3 surface building for administration, project staging and support. Boulby is of moderate size and depth compared to other world underground laboratories. However the facilities are truly world-class in quality, the local backgrounds are relatively low (Boulby has the lowest radon background of all the world's underground laboratories), and the local geology is scientifically interesting, enabling Boulby to host a rich and diverse science programme.

The laboratory itself is run by a small on-site team of seven staff, with additional remote administrative support from Harwell-based staff, and some on-site support from the mine owners and operators (ICL-UK). The responsibilities of the facility team are to develop and support the science programme, manage and maintain the laboratory infrastructure, manage the operations and HSE regime for hosted projects and visiting scientists, and to liaise with the many facility stakeholders. With the laboratory working with and alongside the commercial mine operators, Boulby is a prime example of science and industry working in a close and successful partnership.

The Boulby facility is currently involved in nine active collaborative research projects, involving more than 70 scientists from over 20 universities and research institutes around the world. For each project Boulby provides experimental space, in addition to scientific, technical and on-site operations support.

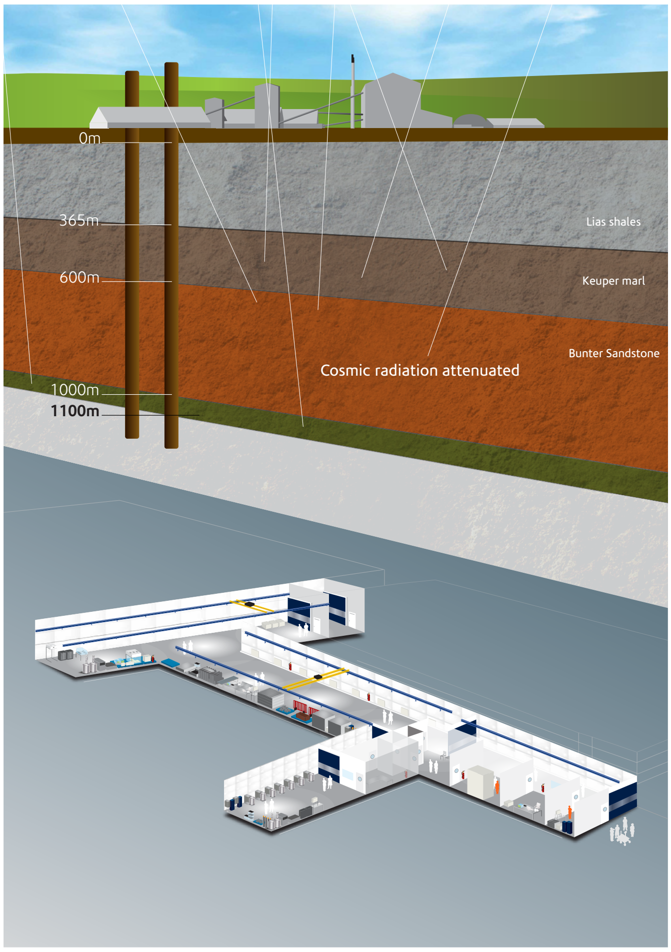


Figure 8.1: Schematic Diagram of the STFC Boulby Underground Laboratory: one of the World's deep underground science facilities enabling projects requiring ultra-low background experimental space and/or access to the scientifically interesting deep underground environment.

8.2 Dark Matter, 'Rare Event' and Low Background Studies

Boulby continues to lead in international dark matter and 'rare event' science. The facility hosts and operates one of the world's best germanium detector suites, the 'BUGS' facility, which is in increasing demand internationally for the selection of ultra-low activity materials for building future low-background / rare-event detectors (including dark matter searches and neutrino studies). The BUGS facility has seven world-class, ultra-low-background germanium detectors (see Figure 8.2) capable of screening down to <50ppt (U/Th) per sample, enabling the UK to play an important and active role in the construction of: the LUX-ZEPLIN (LZ) dark matter detector, one of the world's most sensitive detectors, currently under construction in the USA; the Super-K detector, a world leading neutrino observatory in Japan, currently being upgraded by addition of gadolinium to its target to give more sensitivity / discrimination; and several other UK and international ultra-low-background projects.

Boulby hosts and supports the internationally-important CYGNUS programme, a collaboration developing gas TPC (and other) technologies for directional dark-matter detection. This is a a capability that will greatly enhance signal verification in future dark-matter search efforts. Boulby also hosts a wide range of other projects requiring an ultra-low-background environment. Current activitites include: AWEGe, an MOD / AWE project using ultra-low background gamma-spectroscopy atmospheric-monitoring systems to improve international nuclear test-ban treaty verification; SELLR, a study of the effects of low and ultra-low radiation levels on microbial life; and ERSAB, multiple ultra-low background environmental gamma spectroscopy studies including material provenance studies and the exploration of ^{210}Pb radio-dating capabilities.

8.3 Multi-Disciplinary Underground Science Studies

Boulby also hosts a number of other important projects seeking access to the scientifically interesting geology and underground environment of the site. These projects are commonly multi-disciplinary and / or interdisciplinary and have applications beyond fundamental science, in industry and in engineering and environmental fields. One of these projects is MINAR (Mine Analogue Research), an exciting and world-leading programme of work in which the facility supports the work of astrobiologists and planetary exploration engineers from around the world. These researchers study the microbial life found underground at Boulby, and use the site to test and develop equipment for future exploration of life beyond Earth. Ongoing since 2012, MINAR is led by the UK Centre for Astrobiology (UKCA, Edinburgh) and has included more than 70 scientists from international research institutes, including NASA and ESA. This has resulted in numerous scientific reports and papers and the successful development of three instruments (to date) that are confirmed for deployment on the ExoMars rover, see Figure 8.3. This work on planetary exploration instrumentation also has significant potential benefit for technical challenges in industrial mining, and various crossover technology opportunities are being considered.

The MINAR programme and the underground facilities supporting it are also of interest and importance for general robotics development. Boulby has growing links with the UK's AI and Robotics Hubs, targetting robotics in extreme environments in the mining and space industries.

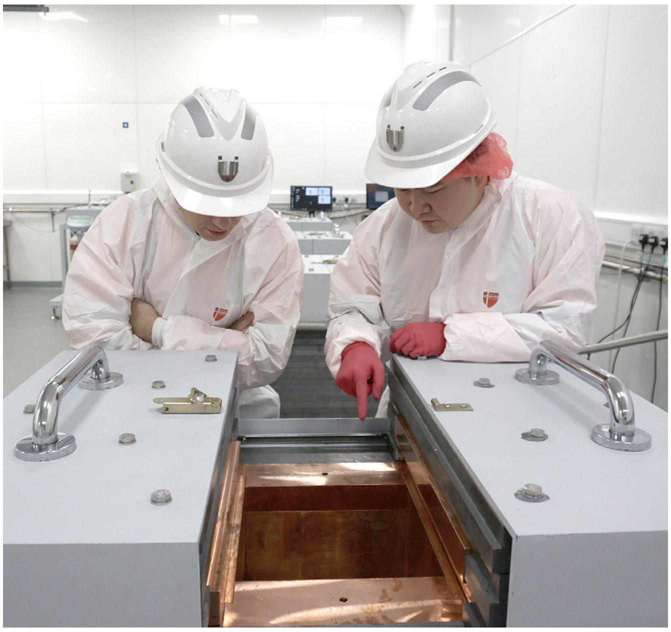


Figure 8.2: The BUGS facility (Boulby Underground Germanium Suite), STFC's world-class ultra-low background screening facility.

8.4 Future Studies

Boulby is well positioned and suited to host a wide range of major future deep-underground studies, both in the low-background / rare-event and multidisciplinary sectors. A number of internationally important new studies are being considered and proposed.

We are currently planning for the installation and operation of a major new detector, AIT-WATCHMAN. This will enable us to explore and develop the capabilities of antineutrino detector technology for remote reactor monitoring in global nuclear security and nonproliferation initiatives. A US–UK collaboration will construct a 6 kt Gd-loaded water detector, requiring significant new excavations at Boulby (see Figure 8.3). Over $60M funding for the project has been secured, and cavity and detector designs are now being developed. Full installation and operation are expected in 2024. Once in operation, AIT-WATCHMAN will be one of the largest neutrino detectors in the world, enabling internationally important nuclear security study and future particle physics and fundamental science R&D.

Figure 8.3: The MINAR programme at Boulby, studying astrobiology and the development of technologies for beyond-Earth planetary exploration.

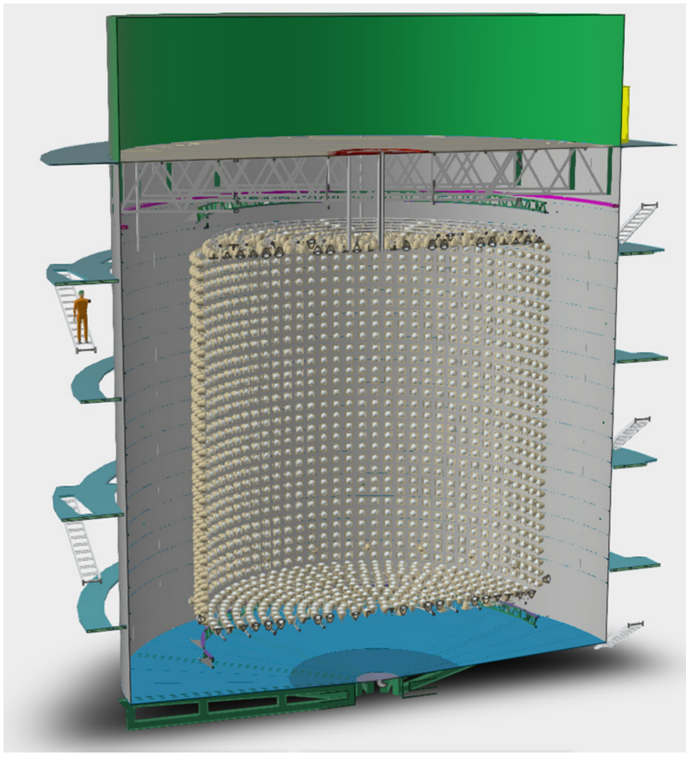


Figure 8.4: Schematic of the upcoming AIT-WATCHMAN neutrino detector at Boulby.

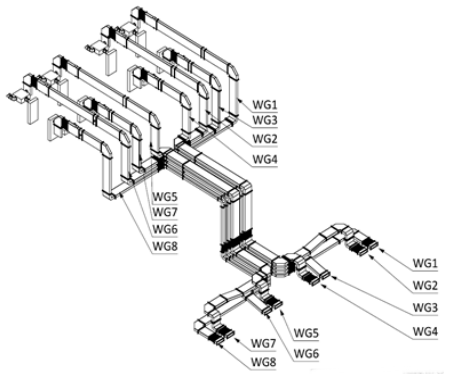
9 Accelerator Science

The PPD Accelerator Science Group was formed originally to study the design of the accelerator complex for a Neutrino Factory. Following the demise of this project, it has moved into several other areas, including the medical and environmental applications of accelerators. Much of this work is currently done in conjunction with a postdoc and PhD students at the University of Huddersfield (UoH).

9.1 ESS RF Distribution System (RFDS)

The RFDS for the European Spallation Source distributes the RF power from the power sources (klystrons and tetrodes) to the RF cavities. Given the high peak / average powers of 1.5 MW / 75 kW, this is must be done in a way that avoids damage to any of the components in the chain, allows monitoring and testing, and is safe for personnel. The RFDS for the superconducting cavities is one of the UK's 'large' ESS in-kind contributions, with a total equipment cost of about £16M. Initially, this was for 146 cavities, but was reduced to 106 after an ESS Value Engineering Exercise. Each cavity has its own distribution system and, on average, these are around 30 m long. They are split into three sections: the gallery on the surface, the accelerator tunnel below ground, and the stub that joins them. The RFDS is formed into groups of eight which pass through a stub. The layout is shown in Figure 9.1.
The UK contribution is all the components in the RFDS, plus the support system.

The PPD / UoH contribution has been to identify the RFDS as a possible UK in-kind contribution, obtain approval and funding to go ahead, help create the UK team, do most of the major tenders, and verify that the equipment meets the requirements. The work is done in collaboration with the project management and engineering team at Daresbury Laboratory (DL). The project is one of the most advanced major in-kind contributions to the ESS, with most of the equipment delivered and installation underway. However, as it is far ahead of most other contributions and there is a lot of it, much of our equipment is now in three storage locations: the ESS site, the ESS off-site storage (Figure 9.2), and a storage facility in Malmö docks. Our main current activity is devising a system for detecting arcs in the RF couplers into the cavities to avoid damage to the vacuum window protecting the cavity.



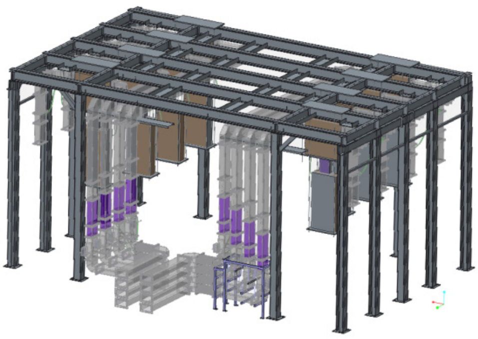


Figure 9.1: (left): Schematic of a group of 8 waveguide runs, gallery at the top left and tunnel at the bottom right. (right): Engineering drawing of the gallery section, showing the support system.

Figure 9.2: Equipment deliveries in the ESS off-site storage

9.2 ISIS Front End Test Stand (FETS)

FETS has been designed and built as a prototype for possible future high-power proton facilities such as an ISIS upgrade, a neutrino factory or a muon collider. It consists of an H-ion source, a low-energy beam-transport system, a radio-frequency quadrupole (RFQ), and a medium-energy beam-transport system incorporating a chopper. The RFQ provides focussing, efficient bunching, and beam acceleration from 65 keV to 3 MeV, thus providing a beam which can be further accelerated in a standard RF structure.

The FETS RFQ is 4 m long and constructed from four sections (Figure 9.3). All the components are bolted together rather than using the standard vacuum brazing technique. Due to the complexity of the structure, it needs to be tuned before use to make sure that it is resonating at the correct frequency, 324 MHz, and that the accelerating field is the same throughout the structure, i.e. ‘flat’. This is done via 62 tuners (Figure 9.3), 16 in each quadrant, except for two locations which are used for RF power couplers.

The PPD / UoH role is to undertake the tuning of the RFQ. This is done by using a bead-pull technique in which a bead is passed through the structure. The bead modifies the local resonance frequency and the modification depends on the local field strength. Measuring the frequency as a function of length determines the field flatness. A novel iterative numerical technique is then employed to determine the tuner positions.

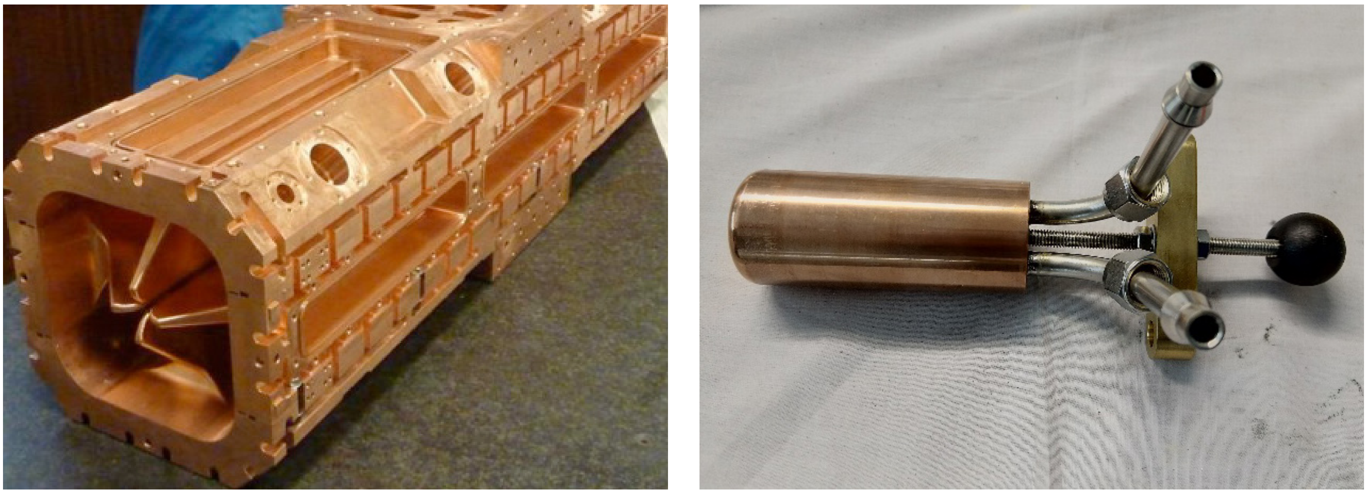


Figure 9.3: (left): First section of the RFQ. (right): An RFQ tuner.

9.3 Accelerator Applications

Over the last four years, the PPD / UoH team have undertaken a number of accelerator application studies. In particular, we have provided leadership for the Accelerator Applications work package in the EuCARD2 WP7 project, and the Industrial and Societal Applications work package in the current ARIES FP7 project. Under our leadership, EuCARD2 produced the ‘Applications of Particle Accelerators in Europe’ document, which describes current applications and identifies possible future uses and the developments needed to achieve them.

Studies have been made of a number of medical applications. A target system has been designed to produce a sufficient neutron flux using an accelerator for trials of a novel form of cancer therapy for particularly aggressive forms of cancer, Boron Neutron Capture Therapy (BNCT). A complete optics design has also been done for two compact FFAG accelerators to produce helium ion beams for cancer therapy. Another optics design has been done for a very high beam-current FFAG to produce radioisotopes for therapy and for imaging. All three of these projects are now stalled due to lack of sufficient funding to proceed further.

Our current activity is focussed on the use of low-energy, high-current electron beams, around 3 MeV and 100 mA, for treating sewage sludge. Trials indicate that this can increase bio-gas production in anaerobic digestion by a factor of about three, turn contaminated waste into clean, organic fertiliser, treat anti-microbial resistant bacteria, and break up other contaminants. First measurements of treating micro-plastics have also produced encouraging results.

10 Technology and Instrumentation

10.1 Research and Development

PPD's Research and Development programme falls into three main areas. The first is the R&D necessary for the existing projects and their upgrades. This primarily involves the ATLAS, CMS and LHCb experiments at the LHC. Details of their R&D programs are given in their respective sections (see Sections 3.1, 3.2, and 4.1).

The second category covers R&D for experiments that are either in their initial planning stages or just beginning their design. These experiments require design and feasibility studies but do not yet have their own funding streams. This category also includes speculative experiments far in the future, blue-skies projects, and R&D that tackles fundamental problems not specifically associated with a particular experiment.

The final category covers our commitment to STFC facilities and STFC strategic priorities. In particular, this involves repurposing technological solutions found for particle physics experiments for STFC facilities such as CLF and ISIS. We also have projects involving the humanities and a number of projects tackling health care.

Funding for these efforts come from three main sources. Project-based R&D is typically funded through STFC grants and core staff effort. Non-project-based proposals are overseen by the New Detector Initiatives (NDI) group, led by Wilson. Some funding from the NDI group has been provided for existing experiments when their requests benefit PPD in general or have cross-cutting potential. For projects not yet funded, PPD allows researchers to dedicate part of their 'academic time' to non-project-based research. Researchers are encouraged to apply forexternal grants. Examples of successful bids in recent years include funding from the Centre for Instrumentation [28] (CfI), STFC Innovations (CLASP), STFC PPRP PRD, and Arts and Humanities Research Council. Researchers can also apply for financing through a PPD fund that supports any research related activity, apart from capital items Researchers can apply for money anytime during the year through a light-touch review process. This style of support was a key discussion point at the STFC Leadership Conference in February 2019.

In the last few years, non-project-based NDI research has included:

- CMOS, HVCMOS
- HRCMOS prototypes, including reconfigurable devices for FCC / CEPC and designs created for CERN
- Development of a laboratory for testing SiPM and other photon sensors
- Development of detectors based on photonic crystals
- Sensors for in-vivo health monitoring
- Next-generation dark matter detection technology
- Outreach projects

It is clear from the number and variety of proposals submitted each year that the group has the expertise and willingness to do much more, though staff time on these projects is in tension with core experimental activities.

10.1.1 Silicon Sensors

PPD has significant experience in the design, simulation, production and testing of silicon sensors. In recent times, most effort has been concentrated on the ATLAS ITk construction. However, there have been a number of projects aimed at pushing the technology and deepening the expertise in the group, in preparation for future projects.

The group (Wilson, McMahon, Villani, Zhang, Dopke, Phillips, Sawyer) has concentrated primarily on variants of monolithic active pixel sensors (MAPS) using CMOS technology [29]. We worked extensively with ALICE in the early design stages of the sensors for the inner tracking system (ITS) and the Technical Design Report [30]. Although ultimately STFC did not join this part of the upgrade, many of the ideas were incorporated in the ALPIDE chip [31].

Since 2013, we have secured three PRD grants to develop MAPS technology. The first allowed us to test the CHERWELL sensor [32], which had been designed for the Linear Collider vertex detector and for digital calorimetry. CHERWELL was partly based on TPAC, a tera-pixel sensor for digital calorimetry [33, 34]. After two successful beam tests at CERN, we were able to show that the sensor could achieve a 3 μm resolution and that the digital calorimeter concept worked [35]. The second project involved the OverMOS chip [36, 37], designed to test the ability of High Resistivity CMOS (HRCMOS) to sustain high radiation doses. This device allowed us to develop TCAD simulations of the performance as a function of radiation dose [38]. We were also able to secure a second tranche of funding from the CfI to complete fabrication of the OverMOS sensor. The third device was DECAL, a configurable HRCMOS sensor for an outer tracker or a digital calorimeter for the FCC or CEPC. This has been irradiated at Ljubljana and is currently undergoing testing; initial results have been presented at workshops [26, 39, 40] and formed part of the FCC design study [27].

We have been involved in the development of HVCMOS and HRCMOS pixel sensors for the ATLAS Phase-2 upgrade. This included the characterization of prototype sensors HVStripV1 [41], CHESS-1 [42], and CHESS-2 [43–45]. Although this is not being adopted for the ATLAS upgrades, a number of spin-off designs are being considered for other experiments. We worked with CERN to enable our designs to be part of the 2018 engineering run for the Investigator chip with the goal of improving charge collection time; our design is called RadEcal and is currently being tested.

TCAD simulations are a speciality of the group. Using our success in designing, testing and simulating silicon sensors, we joined both the CERN RD50 radiation-hard sensor collaboration and the AIDA-2020 infrastructure project [46]. On RD50 we have presented work on our Cherwell, OverMOS, and DECAL chips and are one of the major groups specialising in TCAD simulation [38]. We have a similar role in AIDA-2020 [47].

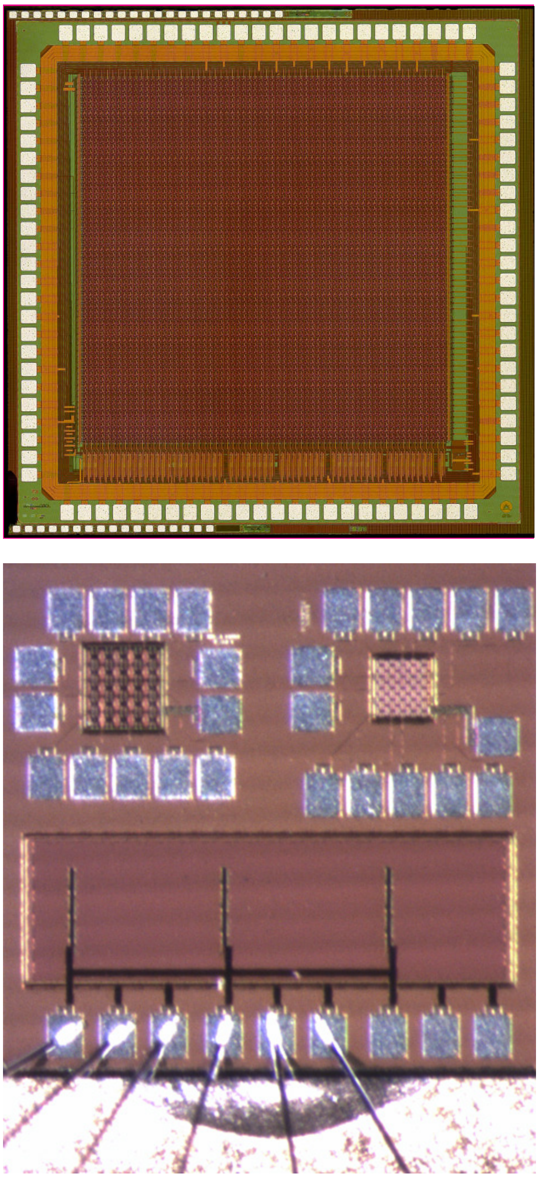


Figure 10.1: (left): DECAL sensor. (right): RadEcal sensor.

10.1.2 Photon Detection

Photonic crystals are used in solar cells, fibre optics, and astronomy, and have the potential to allow for small, tuneable particle identification (PID) detectors that could replace large devices such as the LHCb RICH or be used in Cherenkov Luminescence Tomography (CLT) for tumour detection. We have purchased photonic crystals, created 1D and 2D structures, built a DAQ system, and successfully tested the photon response of the crystals (Easo). The response was compatible with our GEANT4 simulations. The results appeared in Nature Physics [48].

In preparation for further work on photon sensors, in particular fast timing sensors, we invested in a laboratory space for the testing of photon detectors such as MaPMT's, SiPM's, and LAPPD's. The space includes temperature controlled areas, LED and laser light sources, and high-speed readout capabilities for multiple channels (Papanestis, Durkin, Easo).

10.1.3 nEDM and Dark Matter

Experiments to measure the neutron EDM have been carried out by PPD and the University of Sussex at the Institut Laue Langevin (ILL) in Grenoble (France) and set the tightest limit ever on the magnitude of the neutron EDM using a room temperature experiment (as described in Section 4.2). PPD is helping to develop an ultra-cold neutron (UCN) source. The NDI group has helped fund an ADC and multichannel analyser system (ADC/MCS) and R&D development work on neutron guides for UCN research.

In the field of Dark Matter, PPD has a track record in advanced radiopurity control techniques. In preparation for work on third generation detectors, PPD has invested in simulation software for magnetic shielding, electrostatic fields and mechanical deflections due to electrostatic forces (COMSOL) and is currently looking at investing in a radon detector, a neutron generator and a fast low-noise CMOS camera.

10.1.4 Trigger and DAQ

As emphasised in past reviews of PPD, our work on Trigger and DAQ spans across many activities, and our R&D programme has been designed to be relevant to as wide a cross-section of potential experiments as possible. This is exemplified by the work on DUNE which relies on input from PPD trigger and DAQ experts from both ATLAS and CMS. The NDI group helped support the DUNE trigger and DAQ work in the period before STFC funding was secured. See Sections 3.2 and 5.4 for more details.

10.1.5 Mechanical Workshop and Additive Manufacturing

Most PPD detector designs can be built by the RAL Central Workshops. However, there is a minimum of a three-week lead time and the effort must be paid for. For small jobs we have developed our own mechanical workshop. As well as traditional devices such as lathes and mills, the workshop has three 3-D printers, a laser cutter, and a CNC machine. This enables us to quickly develop prototypes and final designs (Zhang, Matheson, Preece, Balashov).

10.1.6 Advanced Computing

In the field of computing, we have made two main long-term investments. Building on our in-house TCAD expertise and close ties with the TD Sensor Group, we continually invest in TCAD servers, capable of compute-intensive simulation of silicon sensors. This has enabled us to contribute to both the CERN RD50 collaboration [49] and AIDA-2020 [46] (Villani, Wilson, Dopke).

With the increasing use of Machine Learning, Deep Learning, and Artificial Intelligence in particle physics [50], we have invested in a GPU farm with a number of modern GPUs (Djaoui, Brew). The farm contains both low-end and high-end GPU's to allow for performance comparisons. The goal is to allow easy testing of ideas without the need to book time on external systems (such as at the Alan Turing Institute). The farm could potentially form the basis for a national resource for particle physics. The system is configured to allow access to Root, Tensorflow, fast.ai, and Microsoft's Cognitive Toolkit (CNTK), together with Python packages. Other packages can be easily installed using containers. The system has simple access to LHC and WLCG code and is integrated into the local Tier-2 batch system. Access is also possible to Cloud resources such as Amazon Web Services (AWS). Some examples of current work include testing ideas for software acceleration for ATLAS (tracking), LHCb (physics analysis), CMS (physics analysis), and DUNE (event categorisation) (Djaoui, Nandakumar, Olaiya, Wilson). See Section 11.1 for more details.

10.1.7 Health Care and Society

Health care is one of STFC's strategic priorities and a challenge area of the Global Challenges Research Fund. The CMOS silicon senors developed by PPD with a view to high radiation tolerance (Section 10.1.2) have the potential to revolutionise imaging in health care, as they can be cheaper, larger and faster than existing designs. They can be used (and in some cases already are) in ultra-fast cameras, mass spectroscopy, hadron therapy, X-ray imaging, and Transmission Electron Microscopy. Working with TD, PPD has investigated combining the existing wafer-scale designs with radiation-hardness techniques for next generation sensors (Wilson, Dopke, Villani, Zhang).

The group developed in-vivo sensors for monitoring radiation dosages in real-time. Designed to be implanted under the skin, the sensors can record the radiation dose delivered, rather than having to rely on pre- and post-calibration (which can be inaccurate at the 25% level). A second stage involved floating gate sensors. These have been subjected to protons and neutrons at PSI, Pavia Hospital, and ISIS and qualification work is on-going (Villani, Zhang).

The group is working in the field of Molecular Radiotherapy (MRT), in which large doses of radioactive elements are ingested and selectively destroy cancer cells. However, the exact dose delivered is almost unknown. The group, together with NPL, Leicester University and the Royal Surrey County Hospital, is investigating using directional Hexitec sensors to detect secondary X-rays or gammas from α-emitting radiopharmaceuticals as a way of measuring the actual dose (Matheson).

The group recently agreed to help the Centre for the Clinical Application of Particles (CCAP) at Imperial College to develop a scintillating-fibre-based dosimeter for use in hadron therapy to measure dose distributions in real time (Long).

10.1.8 Laboratory Infrastructure

An important aspect of the R&D program is timely and proactive investment in laboratory equipment and space. The NDI group has targeted silicon sensors, photon detection, Dark Matter, MICE, and Boulby as areas where we have provided support. In particular we have made sure we can do comprehensive silicon sensor testing in-house using lasers (including new pulsed lasers and edge TCT systems), radiation sources, and X-ray machines. We have have built up excellent personal contacts with beamlines around the world (Birmingham, CERN, DESY, SLAC and Ljubljana).

The PPD development laboratories are strategically located close to the PPD offices and the RAL conference rooms. They are dedicated to: silicon sensor testing (ATLAS and generic); Trigger and DAQ development, including a dedicated computing room (mainly CMS and DUNE); ATLAS Level-1 calorimeter trigger; mechanical workshop, with additive manufacturing; photon sensor testing; a machine room for GPUs and other PPD-specific computing; cryogenics (Dark

Matter); and a general purpose lab for development and testing (including radioactive sources and other access-controlled requirements). All the laboratories were refurbished in 2015, except for the general purpose laboratory that is now showing its age, and will be the target of future investment. The group also has access to Technology Department facilities, in particular the R12 clean-room (now replaced by new building R115) for production of ATLAS staves and modules. It is our intention to increase collaborative use of our facilities in support of the overall UK detector development community.

10.1.9 Outreach and Public Engagement

In the area of outreach and public engagement, we invested in a number of exhibits for our display room, open days and road shows. We refurbished a large spark chamber and created designs for a smaller, portable version for use on the road (Durkin, Dopke). Effort over some years from Dopke culminated in an AHRC grant to develop techniques for reading burnt papyri from Herculaneum using X-rays; this work was featured in the Smithsonian magazine [51]. We designed and built cooled camera systems for use on telescopes for Global Jet Watch in India (Durkin), as discussed in Section 10.4. NDI also funded the technology that drives the PPD corridor displays (Brew).

We have used the NDI fund to enable collaborators to attend conferences and to invite experts to PPD. We used the NDI fund to support the March 2016 national meeting on UK silicon sensor strategy at Cosener's House [52] and the follow-up July 2017 meeting at Birmingham University [53]; we also paid for CERN colleagues to come and present their work at the meetings. We have used NDI funds to support PPD work on SHiP [54] and to send people to help at annual CERN Masterclasses.

10.2 Radon Emanation Facility

The PPD group is constructing a cold radon emanation facility that will serve the UK particle-astrophysics community through its ability to perform studies on radon emanation processes and materials characterisation for rare-event experiments. This will provide an entirely new technical capability for the UK, benefiting our dark matter and neutrinoless double beta decay communities.

Radon is emerging as the dominant background in current generation dark matter and neutrinoless double beta decay experiments, and it represents the greatest challenge to future experiments, regardless of the underlying detector technology. Many of these experiments are performed under cryogenic conditions. The cold radon emanation facility, with its 200l volume main emanation chamber, will be able to perform assays on large samples and in a temperature range between room temperature and 77K. PPD has, together with UCL, been awarded a STFC capital equipment grant to kick-start the facility incorporating existing cryogenic equipment in PPD, a new clean-room facility, components for a so-called radon concentration line and radon detector.

The expertise from the PPD group in large-scale cryogenics and instrumentation along with the low background technologies brought in by our collaborators from UCL are at the basis of the operation of the facility.

This facility will be central to the development of the design and technologies of next-generation rare-event experiments. The experimental hall R5.2 at ISIS (previously used for MICE) has been prepared to host this facility and the installation and commissioning of the apparatus will start in August 2019.

10.3 Software and Firmware

10.3.1 IPbus

PPD is the originator and maintainer of the IPbus ethernet-based control system for FPGAs [55], which underpins the control, trigger and readout systems of a large number of experiments around the world. The system is currently in use by, amongst others, ATLAS, CMS, LHCb, ALICE, DUNE, JUNO, SoLid, FNAL g-2, mu2e, COMET, COMPASS, many test beam DAQ instances, and various subsystems in the CERN accelerator chain.

The IPbus software and firmware provide a simple, reliable and standardised means of allowing online software to control a large distributed system of FPGAs. Construction of relatively complex system-on-chip designs for FPGAs is enabled by a simple bus fabric connecting a number of slave blocks. The system is supported by an automated firmware build system, ipbb. All software and firmware components are open source and free for use in any project.

Recent IPbus developments, by Williams, Sankey, Thea, Harder, and Newbold, have included: addition of a PCI express transport layer; performance enhancement via expansion to arbitrary data bus widths; porting to new FPGA architectures; and a new lightweight simulation interface to software testbenches.

10.3.2 SMI++

SMI++ is a software package for online control written and supported by Franek, which has been selected by JCOP group at CERN as the Finite State Machine (FSM) component to complement the commercial supervisory control and data acquisition (SCADA) system that provides the basis for implementing the Common Control Framework.

SMI++ merges the concept of object modelling and FSM concepts. This allows the implementation of a homogenous, integrated control system by providing a standardized approach to the control of devices, from hardware equipment to software tasks.

All four major LHC experiments are using SMI++ as part of their control framework, but to a different degree. ATLAS and CMS use it for the monitoring and control of their detector, while LHCb and ALICE are also using it for controlling the data acquisition system and for the automation of the complete experiment.

10.3.3 RooUnfold

RooUnfold is a software framework for unfolding (also known as 'deconvolution' or 'unsmearing') in one, two or three dimensions, using a number of methods [56]. The project was initiated by PPD and is now maintained by PPD on behalf of the community [57]. It forms the basis for the unfolding packages for many experiments, including ATLAS, CMS. ALICE, LHCb, IceCube, PHENIX, MinERvA, ANTARES, AlCap, JUNO, MICE, T2K, Super-Kamiokande, Fermi-LAT, Daya Bay, CDF, COMET, FaNS, RHIC, STAR, CALET (International Space Station), and DANCE (Detector for Advanced Neutron Capture Experiments) [58] (Adye, Wilson).

10.4 Global Jet Watch

The Global Jet Watch project is designed to study transient astrophysical phenomena on a timescale of hours to days. Using a global network of 0.5 m telescopes, mostly located in schools, the key science goal is to study the behaviour of matter near black holes. Building on our collaborative connections to Oxford University, a PPD engineer (Durkin) has worked to modify a high-end amateur astronomy camera, Atik 490EX, for use in hot and humid conditions, and allowing the project to equip schools in a wider range of climates.

A stock Peltier cooler and heatsink did not provide adequate cooling power to bring the camera CCD down to a required –20^{o}C. By re-engineering the part of the camera housing that provided the CCD mount and heatsink to accommodate a larger Peltier device and water cooling (Figure 10.2), sufficiently low temperatures were achieved. This approach allowed the low thermally resistive heatsink, necessary for the required heat load in the target environment, to be sited away from the telescope mount. The cameras will now be deployed in developing countries, allowing the students access to astronomical equipment.

Building on this work, we will continue to explore where PPD skills may be relevant and useful for astronomy instrumentation projects.

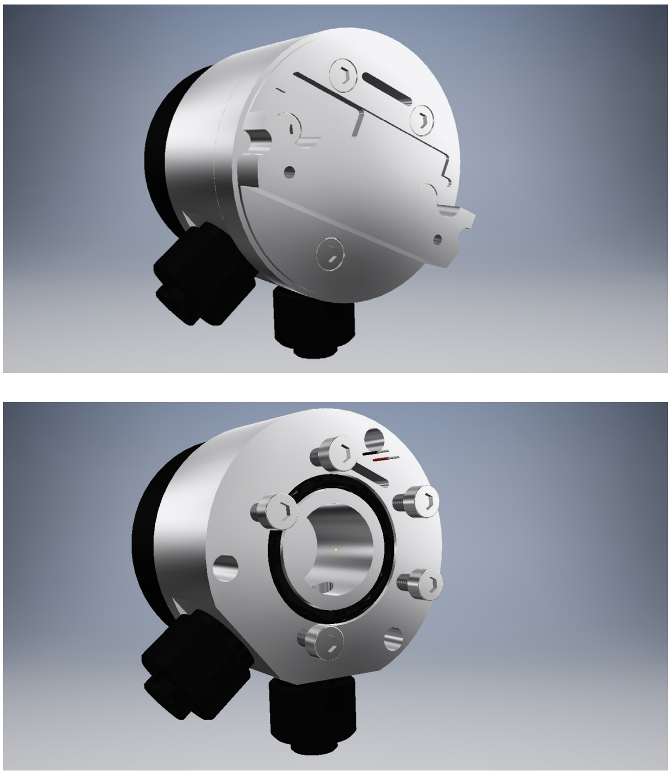


Figure 10.2 : CAD models of the modified CCD mount and heatsink used in the Global Jet Watch telescope cameras.

11 Computing

Computing underpins the entire programme of PPD, including complex simulations on dedicated machines, video conferencing to work with collaborators worldwide, specialised DAQ systems in laboratories and interfaces to access huge worldwide resources via WLCG.

Computing in PPD can be divided into three broad areas both within Computing Group and in the wider department.

11.1 Computing Services

The Computing Services Team, which supports all computing activities in the department, is led by Brew. The team is composed of two sub teams: Brew also leads scientific computing services; Loader and Dunford lead for Windows server infrastructure. Their work in supporting the users and user devices is assisted by Pilcher, joined annually by a Year in Industry student. However, there is a large overlap in competencies and responsibilities between the two teams. Together they run the main departmental computing infrastructure; with Dunford leading on maintaining the resilient service and storage infrastructure based on Microsoft Failover Cluster distributed across two different STFC computer rooms at RAL, underpinning many of the departmental and scientific computing services.
Brew is the main network architect, working closely with the STFC network team to provide high performance reliable networking for scientific and geneal computing.

The group operates an open-door policy as the first point of call for PPD staff and visitors in resolving IT issues, be it software, services, operating system, hardware, networking or purchasing. They liaise with STFC Computing Support units as necessary while remaining the single point of contact for the user. The team supports a wide variety of operating systems for users and visitors including Windows, MacOS and Linux machines, allowing, within reason, users to get on with their work on their preferred platform rather than imposing one solution on them. The team works closely with the wider STFC support network to ensure that we use common services and solutions wherever possible.

The major scientific computing infrastructure in PPD is the Tier-2 / Tier-3 facility, comprising a high throughput batch facility with more than five thousand CPU cores. Approximately 80% of the CPU capacity and 90% of the storage space is allocated to the GridPP Tier-2, which in addition to supporting three of the four large LHC virtual organisations (ATLAS, CMS and LHCb) supports over 30 other small VOs including several, such as LSST and SKA, outside of HEP. The Tier-3 services for local users are completely integrated with the Tier-2, significantly reducing duplication of services and management load. With no hard boundary between the compute nodes for the Tier-2 and Tier-3, the base load of Grid jobs can fill unused Tier-3 capacity during quiet times but users can make use of several times the nominal capacity during peaks.

The other major facility run in PPD is the Mercury Fast Interactive Analysis Facility which couples nodes with CPU, memory and disk together using fast networking and a cluster file system to allow users to interactively analyse large datasets quickly.

PPD supports the wider UK particle physics community, running a number of web servers for UK workgroups / collaborations, and as the hosting institute supporting many services for the MICE experiment.

As the computing landscape continues to evolve towards heterogeneous architectures with different devices optimized for specific dedicated workflows, there is a need to provide early access to these new technologies in order to identify best solutions, and to develop corresponding expertise within the group and the PP community. Over the last few years Djaoui has procured a number of platforms incorporating various accelerator processors, built and tested the required software and supported users with early access for the purposes of prototyping, development and analysis. As a result, we have now an expanding accelerated computing facility and user base, supporting current and future experiments. This has now evolved into small production service with a number of GPU-equiped nodes available in the batch system for interactive and batch work alongside the existing test boxes. In PPD, this initiative has been the catalyst and enabler of the current accelerated computing in general, and Deep Learning R&D in particular, and we are well positioned to take it to the next stage.

As part of our remit as the national laboratory we offer access to our scientific computing services to all UK particle physicists on demand, including support to all visitors to PPD.

11.2 Trust, Security and Other Activities

GridPP is the STFC-funded UK collaboration of 19 UK Universities, RAL and CERN to provide the UK's contribution to the Worldwide LHC Computing Grid (WLCG) to facilitate the storage and analysis of all data produced by the four LHC Experiments at CERN. Kelsey is the budget holder for all GridPP funds spent through RAL, including the Tier-1 and Tier-2 computing centres, 22 RAL staff and travel funds for the whole UK GridPP Collaboration.

An important activity carried out by Kelsey and Cornwall since the beginning of GridPP back in 2001 has been the ongoing establishment, leadership and evolution of the necessary international bodies to coordinate Trust, Security and Identity Management for GridPP, WLCG and many EU-funded Grid infrastructures, including DataGrid, EGEE, EGI, and now EOSC-hub. This work started with the coordination of X.509 Certificate Authorities across Europe, in turn leading to the formation of EUGridPMA and the International Global Trust Federation, the creation of the WLCG/EGEE Joint Security Policy Group, the first Grid operational security group in EGEE, leading to the formation of the EGEE/EGI Software Vulnerability Group and the creation of the EGI CSIRT, the computer security incident response team.

GridPP, as a major partner in WLCG, operates key elements of the global trust infrastructure. A vital UK responsibility, led by Kelsey, is in the area of Security Policy and Trust, including international policy and the creation and maintenance of international trust groups. Without this work the WLCG could not function. Much of the security work concerns the prevention of security incidents. One aspect of this is to minimise the risk posed from vulnerabilities in the software used to enable services. The 'Software Vulnerability Group' (SVG), led by Cornwall, handles all vulnerabilities reported to the group and assesses the risk to the infrastructure. The infrastructure is monitored for higher risk vulnerabilities, and sites are required to patch urgently when serious vulnerabilities are exposed. Ongoing work includes evolving the process to cope with a less homogeneous infrastructure and wider variety of services.

During the last six years all of these activities have been expanded to include distributed IT Infrastructures provided for many different research communities across the world. Kelsey created the Security for Collaborating Infrastructures (SCI) activity to define a Trust framework and policy standards for Infrastructures to collaborate. By including the European e-infrastructure network (GEANT) and the national network security officers, this in turn was used to form the Wise

Figure 11.1: The signatories of the endorsement of WISE/SCI during the TNC17 Networking Conference in Lin Austria on 1st June 2017. Representatives of SURF, GEANT, EGI, EUDAT, WLCG, HBP and PRACE and David Kelsey -far right.

Information Security for e-Infrastructures (WISE) Community in 2015. WISE builds trust between IT Infrastructures and defines policy templates and best practices. WISE and the new version 2 of the SCI Trust Framework, with Kelsey as leader, was endorsed by many major Infrastructures in 2017 as shown in the photograph 11.1.

Kelsey was a founder member of the “Federated Identity Management for Reasearch” community, a collaboration of approximately fifteen global research communities, including HEP, to discuss and specify their requirements for their combined use of federated identity. Together with his participation in the EU H2020 projects AARC and AARC2, this led to the publication in 2018 of the FIM4R version 2 paper [59]. This paper has been used as important input into strategic planning by the various stakeholders, including funding bodies and the identity federation operators. Kelsey is also a member of the HEPiX Board and chairs the HEPiX IPv6 Working Group, leading the transition of WLCG to the use of this new networking protocol.

11.3 Experiment Support on the RAL Tier-1

The RAL Tier-1 computing facility is a key part of the World LHC Computing Grid, providing high-availability, high-throughput computing, persistent storage of important experiment data and a direct private network link to CERN. The full exploitation of the facility requires a combination of engineering and scientific expertise. PPD physicists have a long history of working closely with the RAL Tier-1, to enhance its capabilities and to support their experiments. In addition to informal links, there are currently three Experimental Tier-1 Liaison posts, for ATLAS (jobshare between Adye and Martin-Haugh), CMS (Ellis) and LHCb (Nandakumar).

Typical liaison duties include diagnosing problems with experiment jobs and data transfers at the Tier-1 and adjusting experiment-specific software to upgrades and changes on the infrastructure. Since these staff are experts in both their experiment’s computing model and in supporting Grid services, they have played a major role in the success of LHC computing as a whole.

A key recent success for the team was the migration from the CASTOR Tier-1 disk storage system to Echo, a novel storage system based on Red Hat Ceph. The Liaisons ensured that the new system was fully tested and integrated with their experiment software during the migration. The Liaisons also provide support and coordination for smaller UK Tier-2 sites. Additionally, they support smaller experiments and projects (including DUNE, LIGO, LSST and SKA), both with help using the RAL Tier-1 and passing on the experience of years of operating distributed computing systems.

12 Impact

12.1 Industrial and Interdisciplinary Engagement

PPD industrial engagement takes place in three strands:

- Companies with whom we have a long-standing commercial relationship, sometimes via TD
- Companies with whom we are engaged in co-development or commercialisation of technology
- Companies with whom we cooperate in the training of students and staff

Examples of the former category include Stevenage Circuits, who have provided printed circuit boards for many PP projects, and Xilinx Corp., suppliers of FPGA devices.

PPD staff are collaborating with an increasing number of UK and international companies to co-develop technology for current or future projects. Examples include:

- ATLAS have interacted heavily with a US aerospace company, PCI, to fabricate carbonfibre support structures for the SCT endcap. The engagement was via staff from PPD, TD and Liverpool University. This enabled the company to later develop support structures for space-based telescopes.
- We collaborated with Molex Corp. to test and demonstrate a very high density optical interconnect fabric for use in the CMS trigger system.
- We are collaborating with uSystems, a UK company specialising in high efficiency computer cooling, in the design of the underground counting room for DUNE.
- We have an ongoing relationship with TowerJazz in the development of deep p-well technology for CMOS sensors, with the aim of improving radiation tolerance.
- We have recently begun a new collaboration with e2v-Teledyne on the development of low-gain avalanche detectors for fast timing.
- We have won a European Space Agency tender, in collaboration with GMV Innovations Ltd., for a preliminary exploration of an innovative and disruptive technological concept for positioning, navigation and timing applications, based on neutrinos.
- We are collaborating with the Atomic Weapons Establishment on technologies for the nuclear anti-proliferation effort.
- Along with CERN, we have worked with vendors of MicroTCA format hardware to establish a standard sub-specification for interoperability in PP experiments.

We have increasingly sought to cooperate with industry in the training of students. Examples here include:

- We have worked with Lenovo Group Ltd. through our participation with the UCL Centre for Doctoral Training in Data-Intensive Science.
- A number of staff have participated in Google's Summer of Code, resulting in training of students.
- As a key partner in the EU INFIERI ITN, we collaborated with Philips N.V., Teradyne Inc., and Thales Group, in the training of students and postdocs in high performance electronics for PP, medicine and remote sensing.
- We are a training partner within the STFC Centre for Doctoral Training in Data Intensive Science, led by Cardiff University, and involving a range of industrial partners.

Much of our interdisciplinary work currently centres on Boulby. Past and current projects have included advanced technologies and knowledge in the fields of environmental / atmospheric science and climate change, practical atmospheric CO_2 mitigation (carbon capture and storage), the effects of radiation on life, astrobiology and life in extreme environments, robotics and planetary exploration techniques for fundamental science (searches for life beyond Earth) and industry. The upcoming major US-UK AIT-WATCHMAN detector at Boulby will have significant impact in both the international nuclear security and fundamental science R&D sectors.

At RAL, Villani is supported by EPSRC in his work on dosimetry to molecular radiotherapy, and also holds patents related to the development of in-vivo dosimetry. Dopke has won grants to read ancient burned scrolls from Herculaneum, applying HEP silicon detector techniques and obtaining beamtime at Diamond and DESY. Our accelerator activity also has several industrial applications, though is currently at a low level due to lack of funding priority.

12.2 Training and Development

In PPD, we contribute to the training of students at all stages of their career, from primary school to PhD. We also offer vocation training via the STFC apprenticeship scheme, and participation in university Year in Industry programmes. We also seek to continuously develop the skills of our own staff, and to pass on relevant expertise to the academics, researchers and students with whom we collaborate, via both formal and informal training opportunities.

PPD hosts a number of PhD students, co-supervised with various UK universities, and funded by STFC. Until recently the group trained an average of one student per year, but starting in 2019, we have increased this number to a minimum of five entrants annually, eventually leading to a sizeable cohort of students at RAL. This will allow a sufficient critical mass to ensure that PPD is an attractive and well-adapted environment for student training. Wielers has been appointed as Graduate Coordinator for PPD.

In addition to directly STFC-funded students, we have co-supervised PhD students through schemes including the NExT institute, PD-funded projects, the Data Intensive Science CDTs and EU ITN grants. PPD academic staff, who typically do not have students of their own, often play a significant role in engaging with University students within international collaborations. For instance, PPD staff supervise the efforts of around five students per year within the ATLAS ITk group alone.

Our CERN-based staff also train MPhys students from Southampton University, who send their a group of highly qualified students to CERN for their final year. We are seeking to expand and build on this scheme in coming years, with an emphasis on both physics and engineering students.

We also provide training within other STFC-funded schemes. We regularly provide a Year in Industry placement in the computing group and will train an apprentice in this group next year. We have also participated in the STFC graduate training scheme, hosting a graduate for 3 months in 2017 in the ATLAS High Level Trigger group. Another Year in Industry student working on communications and outreach has recently joined us. In future years we hope to expand our offer to include placements in engineering, project management and business administration.

As part of the the RAL summer student programme, we host around ten summer students (usually 3rd year undergraduates) for a two month period, and ten work experience students (school pupils aged 15-18) for a period of one or two weeks. Our CERN-based staff take part in the CERN summer programmes. For example, the LHCb group supervised 7 CERN summer students in the last five years.

PPD hosts a large number of visiting academics from UK and international institutes. This includes both experimentalists in PP and PA areas, but also theorists and phenomenologists, users of our facilities and laboratories (e.g. MICE collaborators and visiting fellows). Through a Newton Fund award, we have employed an researcher working in conjunction with Santiago (Chile) in order to develop their engagement with Particle Physics and ATLAS in 2015-2018. At present, there is a constant flow of visitors from IHEP Beijing, coming to RAL to learn from us the techniques to build the ATLAS tracking detector for the HL-LHC.

Many PPD staff teach and tutor in UK universities, including Oxford, Durham, London, Southampton and Warwick. Some of us run tutorials for students and post-docs, e.g. on statistics, or simulations of neutrino interactions, not only in the UK but internationally. From 2019, we will be re-introducing an aspect of formal graduate training in experimental and data analysis techniques, designed to be complementary to the graduate courses offered by UK universities, and open to all UK PhD students. RAL PPD staff often teach at the STFC summer schools held for both experimental and theoretical particle physicists.

Finally, we place an emphasis on formal and informal training and development of our own staff. As with any academic group, our staff have access to comprehensive library resources. We run a PPD seminar series, inviting national and international speakers, and also organise the overall RAL seminar series covering general science and technology topics. All staff are enrolled in a formal Annual Performance Review process, which provides an opportunity to examine and meet training needs. Adequate professional development is a criterion for progression within STFC. Courses, often held in conjunction with other laboratory departments, are available on topics ranging from specific technical skills (e.g. FPGA programmming, software skills) to project and financial management. Three PPD staff are currently undertaking a PhD, partially supported by RAL.

12.3 Outreach

Between 2016 and 2019, PPD directly engaged with over 6000 members of the public through the RAL outreach programme, including masterclasses, public talks and site tours.

12.3.1 Particle Physics Masterclass

Every year, PPD hosts a particle physics masterclass for A-level students from schools across the country. More than 700 students visit the lab over four days, coming from as far afield as Folkestone and Huddersfield. The masterclass is organised by Kirk and Olaiya, in coordination with RAL Public Engagement, ISIS and Diamond. Students join a day of talks, take tours of the ISIS and Diamond facilities, and enjoy computer exercises and Q&A sessions. In addition to educating the students, the masterclass provides an opportunity for accompanying teachers to further their own understanding and learn about the latest developments in particle physics.

Teachers state how their one-to-one interaction with PPD physicists improves their insight and teaching, which also benefits the students who cannot attend the masterclass. Our knowledge of the success and benefits of the masterclass is obtained through direct interaction with students and teachers and through feedback forms. We use the feedback to improve the masterclass year after year.

From the 2019 feedback:

- Students and teachers said the event was a "superb opportunity to hear from world experts and see particle accelerators and associated technology close up"
- A quarter of students said they were more likely to go on to study a STEM subject at university.

The impact the masterclass has on the students and teachers makes the masterclass one of the most significant RAL outreach activities of the year.

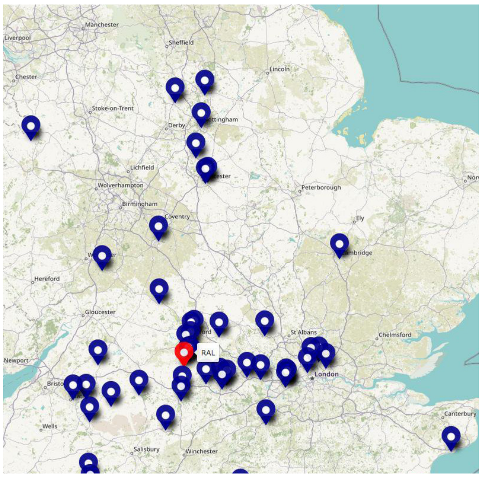


Figure 12.1: (left): Students taking part in the PPD masterclass computer exercise. (right): Map of schools attending the 2019 masterclass.

12.3.2 Laboratory Open Days

For the 2015 Harwell Open Day (with 16 000 visitors), we arranged the indefinite loan of the ZEUS Central Tracking Detector from the Science Museum (now on permanent display at RAL). We maintain an exhibition area with detector components, model detectors and a virtual reality headset for RAL visitors.

PPD staff also volunteered at the 2016 Daresbury and 2016/17 UKATC open days. We support the science activity at the annual WOMAD festival, to which we send our Cloud Chamber and former director Wark, as well as his band! In addition, we have provided a stand for the Science Tent at RAL's own MADfest event. Since 2017, Dark Matter Day has provided an opportunity to engage with schoolchildren, as well as politicians and stakeholders (as shown in Figure 12.2).

Figure 12.2: Dark Matter Day 2017, House Of Commons. (L-R): Dr Laura Manenti (then UCL), Prof. Sean Paling, Dr Pawel Majewski, and Ed Vaizey MP.

12.3.3 Boulby

The Boulby Underground Laboratory welcomes many visitors, mostly stakeholders. In addition, Boulby has its own outreach programme. The team give frequent talks to schools and the general public, they have produced a number of educational and promotional videos and have featured in several TV and radio documentaries [60]. The facility also has a distinctive social media presence (Facebook, Twitter, Youtube). PPD has recently helped create a new exhibition in Whitby Museum showcasing Dark Matter searches and other science studies at Boulby.

12.3.4 CERN

Many visitors go to CERN, including stakeholders, students and members of the public. PPD staff are frequently involved with visitor tours. Staff provide guided tours and explain the research that takes place at CERN. We also liaise with schools planning on visiting; this includes schools attending our masterclass, with PPD staff members able to link information between the two events.

12.3.5 Public Talks

PPD staff regularly give public talks to audiences including primary schools, secondary schools, interest groups (e.g. Newbury Astronomy Group, Reading Geek Night) and churches, as well as to members of the public visiting RAL.

12.3.6 National Public Engagement Competitions

PPD staff have competed in national scientific engagement events. Harder previously won the "I'm a Scientist – Get Me Out of Here" contest. Other group members have participated in subsequent rounds, including "I'm a Scientist Live in Swindon". Martin-Haugh was selected for the 2018 Royal Society Pairing Scheme, spending a week at Department for Business, Energy and Industrial Strategy (BEIS) and bringing the BEIS Future Sectors Team to visit RAL and Harwell Campus [61].

13 Community Support

PPD provides several administrative and financial services on behalf of the UK particle physics community.

13.1 National and International Meetings

The UK HEP Forum [62] is a two day topical meeting at Cosener's House, Abingdon, organised annually by PPD jointly with the Institute for Particle Physics Phenomenology, Durham (IPPP). Topical forums of this kind have been held at Cosener's House since at least 1967. PPD physicists (Ricciardi) and administrators lead the organising committee.

PPD provides travel and subsistence for senior UK academics attending international committees including LHCC, SPC, ICFA, EPS, APPEC, ELDG, and others. We also provide support for the UK subscription to the International Particle Physics Outreach Group. A low level of discretionary travel funding is allocated for 'pump-priming' new projects through travel support, where such projects are likely to form the future basis for formal statements of interest to STFC.

13.2 Financial Administration

13.2.1 SLA Management

PPD administers the Particle Physics Service Level Agreement (SLA) – the mechanism that funds the project-supported component of the UK-PP. This involves very close coordination with Programmes Directorate (PD), who determine funding allocations as a result of peer review, and STFC Finance. Our management accountant (Rankin) oversees the financial status: formally notifying PIs of allocations, supporting inquiries from the projects, including training, monthly reports to STFC Finance, final reports each financial year and reporting to PPD and PD. The bridge between Finance and PD is provided by the PPD Programme Manager (Haywood, with Lowe). PPD also facilitates access to Shared Business Services (SBS) for university colleagues: budget holders and those purchasing equipment. In addition, PPD tackles issues affecting the community as they arise, such as VAT on components for the CERN experiments. As funding becomes increasingly tight, the need for maximum efficiency has required an increasingly 'hands on' approach to ensure balanced budgets and timely reporting.

13.2.2 Travel and Expenses Administration

PPD monitors the short-term travel expenditure for the SLA projects, handling the invoicing of the university departments (Shand, with Lowe & Haywood). PPD also takes responsibility for defining and communicating STFC policy as it affects the UK Community, in particular for travel claims and long-term accommodation at overseas facilities (CERN and worldwide).

13.2.3 Procurement, Contracts and Logistics

PPD acts as the interface between the STFC procurement and finance teams, and the PP community. For large capital purchases, or contracts involving movement of goods across international borders, complex rules often apply, and advice from suitably qualified professionals is needed. This will become a significant part of our activity as the ATLAS, CMS and DUNE projects begin to undertake major capital programmes in the coming years.

13.3 CERN UK Liaison Office

PPD (Diallo, Boutemy Amdal, Heemskerk) operates the CERN UK Liaison Office (UKLO), providing support for UK visitors to CERN, whether short-term or long-term. The UKLO is responsible for:

- Providing support for UK visitors to CERN, whether short-term or long-term.
- Providing accommodation for UK long-term attachments (LTAs), for both staff and students, interacting with rental agencies, utility companies etc.
- Supporting the occupants of accommodation, in particular maintaining the quality of furnishings.
- Operating the UK LTA process (approvals and financial support), not just for travellers to CERN, but world-wide. This is done with crucial web support from Steve Lloyd (QMUL).
- Providing logistical support for UK collaborators moving equipment to / from CERN.
- Handling the interactions between the CERN Team-accounts and SBS. This involves engagement with STFC Finance.

13.4 STFC Committees

PPD hosts and supports the STFC Particle Physics User Advisory Committee (PPUAC) for the UK community to discuss practical issues in support of the scientific programme. This is chaired by a senior community member, and acts as an advisory committee to the Director of PPD.

Our STEM staff play a full role in STFC advisory and peer-review committees. Shepherd-Themistocleous was recently the chair of PPAP, with responsibility for delivery of the UK input to the ongoing European Strategy process.

A PPD Staff

A.1 Current Staff Members

A.1.1 Directorate

Prof. David Newbold – PPD Director, CMS, DUNE, SoLid

Oversees all group research and community support activities. Liaises with other National Laboratory departments and Programmes Division. Expertise in collider physics, and trigger / DAQ systems. CMSUK Upgrade Principal Investigator. Past DUNE DAQ coordinator.

Mrs Gill Birch – PA to Divisions A & B

Provides administrative support for division heads and staff of both divisions. Organises community meetings and events, including the HEP Forum. Undertakes purchasing for ATLAS.

Mrs Debbie Loader – PA to PPD Director

Supports the PPD Director. Oversees PPD operational budgets, space management and staff time booking. Manages the PPD and RAL seminar programme.

A.1.2 Programme support

Mr Chris Lowe – member of TD, partially funded by PPD

Expert in financial administration. Provides oversight of finances (PPD & SLA). Also provides valuable advice on VAT, legal matters and contracts. Oversees Risk and Governance.

Mrs Andrea Diallo – Head of UK Liason Office (UKLO) at CERN

Runs the UKLO office. Manages UKLO staff and organizes all of the UKLO work. Manages large portfolio (approx 60 flats) of properties rented by STFC for staff and students. Manages all finance functions including payments for CERN accounts. Looks after UK car pool. Acts as interface to CERN finance.

Mrs Petra Heemskerk – UKLO

Part of the team that manages the UKLO portfolio of flats. General support for all UKLO functions. Assists with finance functions of UKLO.

Mrs Karine Boutemy-Amdal – UKLO

Part of the team that manages the UKLO portfolio of flats. General support for all UKLO functions. Assists with finance functions of UKLO.

Mrs Tricia Shand – Financial Support

Manages short-term travel for UK PP. Helps with procurement and manages university contracts for students and joint appointees. Supports PA Team, for example with Cosener's House HEP Forum.

A.1.3 Division A

Dr Stephen Haywood – Deputy Director of PPD, Division Head, ATLAS Group Leader

Led performance studies for ATLAS Inner Detector and engineering effort for SCT end-cap at RAL. Current focus on PPD operational activities, including finance, HR, safety, governance.

Prof. Costas Andreopoulos – SBND, T2K; JA with Liverpool

Leads SBN/SBND activities. Physics co-Coordinator for SBND, co-Coordinator of the Systematics and Oscillation Sensitivity Working Group for the overall SBN programme; Chair of the SBND Speakers Committee. Led development of the GENIE neutrino interaction physics simulation package.

Dr Tim Adye – ATLAS

Divides his time between software and performance work for the upgraded tracker and his role as ATLAS liaison for RAL Tier-1. Expert on statistics, supporting a widely used unfolding package.

Dr John Baines – ATLAS HLT Group Leader

Member of the ATLAS Trigger Coordination and former member of the Trigger and DAQ Steering Group. UK HLT Project Leader 2008–2016. Led the ATLAS Inner Detector Tracking Trigger Group and subsequently the ATLAS Trigger Signatures Group. Currently HLT-FTK Integration Convenor.

Mr Sergey Balashov – nEDM, LZ

Participated in nEDM experiment at ILL, manufacturing of UCN guide production components, on-site guide characterisation measurements. Member of the LZUK calibration team responsible for the design, manufacture, assembly and tests of the mechanical parts the LZ source deployment system.

Dr Bruce Barnett – ATLAS

Previous TDAQ (international) L1Calo Deputy Project Leader; also previous L1Calo Run Coordinator. Senior L1Calo collaboration member resident at CERN, providing real-time software and L1Calo system expertise and day-to-day L1Calo/ calorimeter coordination.

Mr Billy Boxer – LZ; joint student with Liverpool

Development and testing of LZUK calibration systems.

Dr Jens Dopke – ATLAS

Expert on electronics, DAQ and system aspects of large PP detectors. Leads the national work package on the loading of strip modules to local supports.

Ms Glória de Sá Pereira – joint student with Liverpool

Works on Machine Learning applications for neutrino LArTPC detectors, with particular emphasis on the characterization of of exclusive neutrino reaction channels.

Dr Dmitry Emeliyanov – ATLAS

Tracking expert with considerable experience in fast tracking algorithms and software acceleration e.g. using GPUs. Implemented the fast tracking algorithms and tools used in Run-1 & 2 and is exploiting machine learning techniques to optimise tracking algorithms for Run-3 and Phase II.

Dr Bruce Gallop – ATLAS

Has a background in DAQ for tracking detectors. Leads the SCT DAQ working group and drives the effort on Strip DAQ for the ITk. Engaged in the development of the production database.

Dr Norman Gee – ATLAS

Previous TDAQ (international) Collaboration Board Chair. Also previous TDAQ Upgrade Coordinator. Previous UK ATLAS Project Management Board Trigger Area Manager. Coauthor of UK Phase-II STFC funding bid. Software and system expert; most of his time is devoted to eFEX system testing.

Dr Asher Kaboth – T2K, LZ; JA with RHUL

Expert in calibration of liquid noble dark matter detectors, optical time projection chambers, and statistical analyses in particle physics. Calibration Working Group convenor (2018–present) for the LZ experiment; LZ ombudsperson. Developing optical time projection chambers since 2006 with both the DMTPC project for dark matter searches and with the STFC-supported HPTPC project for neutrino detection. Leads high-profile small-signal searches in neutrino physics.

Mr Andrei Khazov – nEDM, LZ

Provided detector and electronics expertise to nEDM experiment at ILL. Developed sputtering and electroplating technologies for replica guides, on-site UCN guide characterisation measurements. Member of the LZUK calibration team responsible for the design, manufacture, assembly and testing of the electronics for the LZ source deployment system.

Dr Julie Kirk – ATLAS

Coordinates ATLAS Trigger Software Releases and Validation. Previously B-physics Trigger Coordinator. Implemented the B-physics triggers used in Run-1 and 2, provided validation of the Inner Detector Triggers
and implemented FTK triggers.

Dr Lukas Koch – T2K, HyperK

Expert on DAQ systems and statistical methods in neutrino beam experiments. Currently working on the HyperK super nova trigger. Sub-group convener for neutrino cross-section measurements in T2K. Former European representative for T2K-Young, the young scientist organisation within T2K.

Prof. Ken Long – MICE, visitor from ICSTM

Leader of MICE Collaboration, teaching bought out by STFC enabling him to be based at RAL. Leading work on muon cooling aimed at future neutrino factories and possible muon colliders.

Dr Pawel Majewski – LZ, AION, Dark Matter Group Leader

Worked on LXe DM detectors for 16 years. ZEPLIN-III Calibrations and Operations Manager.
Worked on the LAr DEAP-3600 experiment, delivering a gamma-ray calibration system. Co-proponent of the LZ experiment; work package manager for the design and fabrication of cryostat. Project Manager for ZEPLIN-III; UK Project Manager for LZ. LZ Calibration Working Group convenor (2017-18).

Dr Stewart Martin-Haugh – ATLAS

In charge of ATLAS Trigger Core-Software for Phase-I and Phase-II. Also working as ATLAS liaison for RAL Tier-1, and involved in common PPD public engagement and communication. Previously implemented fast tracking for Run-2.

Dr John Matheson – ATLAS

Has a background as a detector physicist. Nationally he leads the work package devoted to the loading of pixel modules onto the pixel half-rings.

Prof. Norman McCubbin – ATLAS, emeritus

Former ATLAS Computing Coordinator. Contributes to physics analysis, with special interest in heavy-ion physics.

Prof. Steve McMahon – ATLAS Tracking Group Leader
Silicon detector expert, especially radiation damage. Has been the project leader for the Inner Detector SemiConductor Tracker (SCT) and more recently the ITk. UK PI for the ATLAS Upgrade project. STFC Individual Merit Fellow.

Dr Robin Middleton – ATLAS L1Calo Group Leader

Current TDAQ (international) L1Calo Project Manager, responsible for complete L1Calo system operations and all upgrade activities. Member of TDAQ Steering Group. Also contributing to eFEX online software.

Prof. Bill Murray – ATLAS, JA with Warwick

Led ATLAS physics preparation. Was Higgs Convener in the run-up to Higgs discovery 2012 and then Physics Coordinator. More recently coordinated tracking in dense environments and is currently Higgs and Diboson Searches Convener. Engages with future collider projects.

Dr Federico Nova – HyperK, T2K, SuperK

Member of the Data Acquisition group, Outer Detector group and PhotoDetectors group of HyperK. Expert on MC simulations, multivariate analysis, tracking, data acquisition, parallel computation. Works in particular on delivering trigger algorithms for HyperK. For T2K he provides core support to the Near Detector DAQ activities.

Mr Peter Phillips – ATLAS

Detector systems expert with particular interests in system aspects, detector control systems and chip testing. He leads the national effort on system testing and DAQ.

Mr Weiming Qian – ATLAS, TD funded by PPD

Senior electronic engineer. Led high-speed signal handling during development of the ATLAS eFEX. Now leading eFEX firmware development and system testing. Recognised internationally as an electronic design expert.

Dr David Sankey – ATLAS & CMS

Firmware and networking expert, joint TDAQ (international) Global Processor Level-3 Manager. Focused on Phase-II system design, but also developing eFEX module firmware. Working time is shared with CMS experiment.

Dr Craig Sawyer – ATLAS

International lead on the design, development and fabrication of silicon strip modules. Will work with UK and Chinese colleagues at RAL on the fabrication of these modules.

Dr Ben Smart – ATLAS

Working on the development of DAQ for the pixel detector and the preparation of the RAL facility for pixel module loading and testing.

Dr Weimin Song – ATLAS

Rutherford International Fellow. Working on DAQ for ITk. Interested in QCD and Higgs Physics.

Dr Mark Tucker – nEDM, MICE

Led cryogenic effort of nEDM experiment at ILL. Designed cryogenic components for super-thermal UCN source of PanEDM, provided cryogenics expertise to neutron lifetime experiment of which he is member and co-author to publications. Led the vacuum systems and cryogenic effort on the MICE experiment; main author of the MICE liquid hydrogen paper.

Dr Maurits van der Grinten – LZ, AION, nEDM Group Leader

Led the nEDM effort at ILL, including on-site UCN guide characterisation measurements, data analysis and experimental report publications. Founding member of PanEDM, member and co-author of neutron lifetime experiment. LZUK calibrations work-package manager. In PPD leader of the development, manufacture and tests of the external calibration source deployment systems for LZ.

Mr Giulio Villani – ATLAS

Divides his time between ATLAS and blue sky detector developments. For ATLAS, he developed and qualified the high-voltage multiplexing which is now a standard in the strip detector.

Prof. David Wark – T2K, HK group leader, Visitor from Oxford

Neutrino physics expert. Active in conception, design, construction and exploitation of neutrino and low-background experiments, currently focussing on T2K and HK. Former spokesperson of the nEDM experiment. Former UK co-spokesperson of the SNO experiment. UK PI for T2K. First international co-spokesperson for T2K. Chair of the International Board of Representatives for the Hyper Kamiokande Experiment.

Prof. Alfons Weber – Neutrino Group Leader; JA with Oxford

Expert in neutrino physics. Led T2K near detector (ND) electronics; formerly an overall T2K ND and cross section convenor. UK PI for DUNE/LBNF: in charge of LBNF / DUNE activities in the UK. Past co-convenor of the DUNE beam optimisation task force and the DUNE ND concept study. Leads the DUNE ND design group; member of DUNE executive board and the collaboration finance board.

Dr Monika Wielers – ATLAS Physics Group Leader

Leads physics for PPD Group. Recently involved in CERN Yellow Report on HL-LHC and HE-LHC Physics. Active in studies on long-lived heavy neutrinos. Preparing for bulk production and loading of pixel modules to half rings, including the database. Responsible for PhD Students.

Dr Gary Zhang – ATLAS

Divides his time between qualification of ATLAS HV multiplexer, pixel module mounting and development work for the New Initiatives programme, testing silicon devices.

A.1.4 Division B

Prof. Claire Shepherd-Themistocleous – CMS Group Leader, DUNE Group Leader, Division Head

Expertise is collider physics, trigger and DAQ, ECAL, physics analysis especially with phenomenology connection. Leads all RAL CMS activites and DUNE DAQ group. CMSUK deputy PI for exploitation and upgrades, Deputy Director NExT Institute.

Dr Chris Brew – Computing Group, CMS, DUNE

Particle Physicist and Grid Computing Expert, works on distributed computing on CMS and DUNE, lead architect on the PPD Scientific Computing Systems and leads the PPD Computing Support teams.

Prof. Bob Brown – CMS, emeritus

Expert in calorimetry and collider physics. Co-chair of the CMS publications committee board on exotica and beyond the 2nd generation physics.

Dr Dave Cockerill – CMS Calorimetry Group Leader

Project scientist for the design, construction and installation of the CMS ECAL Endcaps (EE). Responsible for 24h coverage for the Vacuum Photo-Triode High Voltage system.
A leading expert for EE operation and performance, and for predictions for the long term evolution of the system to LHC LS3. STFC Individual Merit Fellow.

Dr Linda Cornwall – Computing Group

After spending over a decade working on satellite ground segments Linda Cornwall has spent the last 18 years working on distributed computing. The focus of her work has mainly been on security, from requirements and policy to software vulnerability handling to ensure the secure sharing of distributed computing resources. Leads the EGI Software Vulnerability Group.

Mr Henry Day-Hall – CMS, joint student with Southampton

Machine learning for b-jet tagging and BSM Higgs searches.

Dr Abdeslem Djaoui – Computing Group

More than 30 years' experience in High Performance Computing; been leading and enabling the adoption of new heterogeneous computing technologies for the benefit of experiments. Focuses on bridging the current gap between hardware provisioners and domain experts programmers, by building tools and providing expertise to users.

Mr Kevin Dunford – Computing Group

Manages the day to day business computing operations and infrastructure for PPD staff and visitors. Works with other STFC helpdesks and Digital Infrastructure in implementing STFC wider IT strategy.

Mr Tim Durkin – CMS, DUNE DUNE

DAQ consortium technical liaison. Responsible for delivering the underground datacentre and optical transport for data. DAQ consortium technical coordination. Electronics hardware and optical signal mapping systems for CMS (L1Calo and ECAL). Delivered SoLid experiment infrastructure. General support for the department in hardware and safety systems.

Dr Sajan Easo – LHCb

Responsible for calibration of the RICH subdetectors, data quality monitoring, and developing the RICH pattern recognition and reconstruction software for both data-taking and simulation.

Prof. Rob Edgecock – Accelerator Science

PI of the RF Distribution System UK in-kind contribution to the ESS and an expert in the environmental and medical applications of particle accelerators.

Dr Katy Ellis – CMS

Since obtaining her PhD in Experimental Particle Physics in 2012, Katy has worked outside of the field in various software roles in industry and research. She has now returned to Particle Physics and is currently the RAL Tier-1 Liaison for CMS.

Mr Billy Ford – CMS, joint student with Southampton

Machine learning for jet reconstruction and BSM Higgs searches.

Dr Kristian Harder – CMS, DUNE

Electronics infrastructure expert, developing firmware and software for system integration and testing. Work package co-manager of the CMS-UK Phase-2 upgrade common technology platform, and member of the CMS-UK upgrade project office.

Dr Sam Harper – CMS

Electron and physics analysis expert. Currently in charge of all electron/photon activities in CMS. In September becomes CMS trigger co-coordinator, in charge of all trigger-related activity in CMS.

Dr David Kelsey – Computing Group Leader

Budget holder for all GridPP at RAL. Having created many international security groups he leads activities in Trust, Security and Identity Management for GridPP, WLCG, EGI and EOSC-hub. He is a member of the HEPiX Board and chairs its working group on the migration to IPv6. Kelsey is a member of the ISGC/Taipei Programme Committee and an advisor to Trusted CI.

Dr Jacob Linacre – CMS

Marie Curie Individual Fellow. Software and computing expert. Former CMS top quark properties subgroup convenor and CMS Tier-1 processing coordinator. Leads CMS top quark spin measurements and part of the F.A.S.T. group pioneering modern analysis software approaches in CMS.

Mr Ian Loader – Computing Group

Handles the day-to-day management and support of the GridPP Tier-2 and PPD's Linux community, maintaining systems and infrastructure as well as the deployment of longer term strategic tasks.

Dr Konstantinos Manolopoulos – CMS, DUNE

Firmware engineer. Currently working on the CMS Phase-2 upgrade electronics, on the CMS Level-1 Track Finding and on the DUNE DAQ system.

Dr Raja Nandakumar – LHCb

LHCb UK GridPP Tier-1 Liaison. He is responsible for the smooth running of both the UK Tier-1 and Tier-2 centres for LHCb.

Dr Emmanuel Olaiya – CMS

Expert in computing, software and physics analysis. Manages CMS data at RAL Tier-2. Using Machine Learning techniques for analyses and HL-LHC trigger upgrade.

Dr David Petyt – CMS

Formerly CMS ECAL Project Manager and ECAL Detector Performance Group convenor. Currently leading CMS UK contribution to ECAL Phase-2 upgrade project. ECAL Endcaps High Voltage on-call expert based at CERN. ECAL Resource Manager and Deputy ECAL Trigger Coordinator. RAL PPD external funding opportunities liaison.

Dr Thomas Reis – CMS

ECAL and L1 trigger expert. Working on HL-LHC ECAL upgrade. Off-detector processing in FPGAs, algorithm development for anomalous APD signal tagging. Previously L1 trigger DQM coordinator and responsible for trigger offline software integration.

Dr Antonis Papanestis – LHCb, DUNE

LHCb RICH I and II Project Leader for five years (and deputy for five years before that). He now divides his time between LHCb and DUNE; on LHCb he continues to support the RICH management and operations, and on the upgrade he liaises with the STFC engineers and CERN. Project manager for DUNE UK.

Mr Will Pilcher – Computing Group

Joined STFC as an IT Apprentice with Technology Department and moved to PPD in 2014. Works mainly on system deployment, configuration management and user support.

Dr Stefania Ricciardi – LHCb

Actively involved in physics analysis, manages PPD's contribution to the RICH upgrade, and oversees the LHCb UK upgrade budget.

Dr Thomas Schuh – CMS

FPGA and firmware expert. Designed and implemented Track Finding algorithms for the novel CMS Track Trigger that is part of the CMS HL-LHC upgrade.

Mr Joe Taylor – CMS, joint student with Bristol

Search for low mass NMSSM Higgses in cascade decays and L1 trigger jet energy calibration.

Dr Alessandro Thea – CMS, DUNE

Electronic systems expert. Online software, FPGA control and infrastructure expert. Delivery of L1Calo and Run Technical Coordinator for L1 trigger. Appointed Technical Lead for the DUNE DAQ consortium.

Mr Alexander Titterton – CMS, joint student with Bristol and Southampton

Exploring Sensitivity to NMSSM Signatures with Low Missing Transverse Energy at the LHC. Experiment and phenomenology.

Dr Ian Tomalin – CMS

Expertise in tracking. Developing track finding algorithms for FPGA-based electronics of CMS HL-LHC silicon tracker upgrade. UK Workpackage leader for CMS HL-LHC Track Finder. Convenor for CMS upgrade tracking algorithms group.

Mr Obinna Utobo – Computing Group

Year in Industry Student studying for a B.Sc. in Computer Systems at Nottingham Trent University, working on User Support and developing asset tracking and information display systems.

Dr Harri Waltari – CMS

Rutherford International Fellow. Phenomenologist, working on nonminimal supersymmetric models. Currently investigating signatures that could emerge from sneutrinos and their connection to neutrino mass generation mechanisms.

Dr Tom Williams – CMS

Online software and trigger expert. Coordinates software and firmware development for CMS UK Phase-2 upgrade common technology platform, Core IPbus developer. Designing algorithms for phase-2 upgrade of CMS level-1 trigger. Led development of C++ online software framework for phase-1 upgrade of CMS level-1 trigger.

Dr Fergus Wilson – LHCb Group Leader, NDI Group Leader

Before joining LHC, commissioned detectors for the ZEUS (DESY), NOMAD (CERN) and BaBar (SLAC) experiments. He was the BaBar UK spokesperson and LHCb Editorial Board chair. STFC Individual Merit Fellow.

A.1.5 Boulby

Prof. Sean Paling – Facility Director and Senior Scientist

Facility Governance, Science Programme Development and Support, Stakeholder Liaison.

Mr Ed Banks – Science Support Technician

DRIFT/CYGNUS joint site lead, miscellaneous science project support, facility technical support.

Mr Jimmy Beadle – Deputy Facility Manager – Infrastructure

Development and maintenance of facility surface and underground buildings and services.

Ms Emma Meehan – Senior Science Support Technician

BUGS facility ops management, miscellaneous . science project support, facility outreach coordinator.

Mr Christopher Toth – Facility Scientist

AIT-WATCHMAN project support, miscellaneous science project support, facility IT coordinator.

Ms Louise Yeoman – Deputy Facility Manager – Administration and Operations

Facility administration, finances, record keeping, training, mine liaison support.

A.2 Organisation Chart

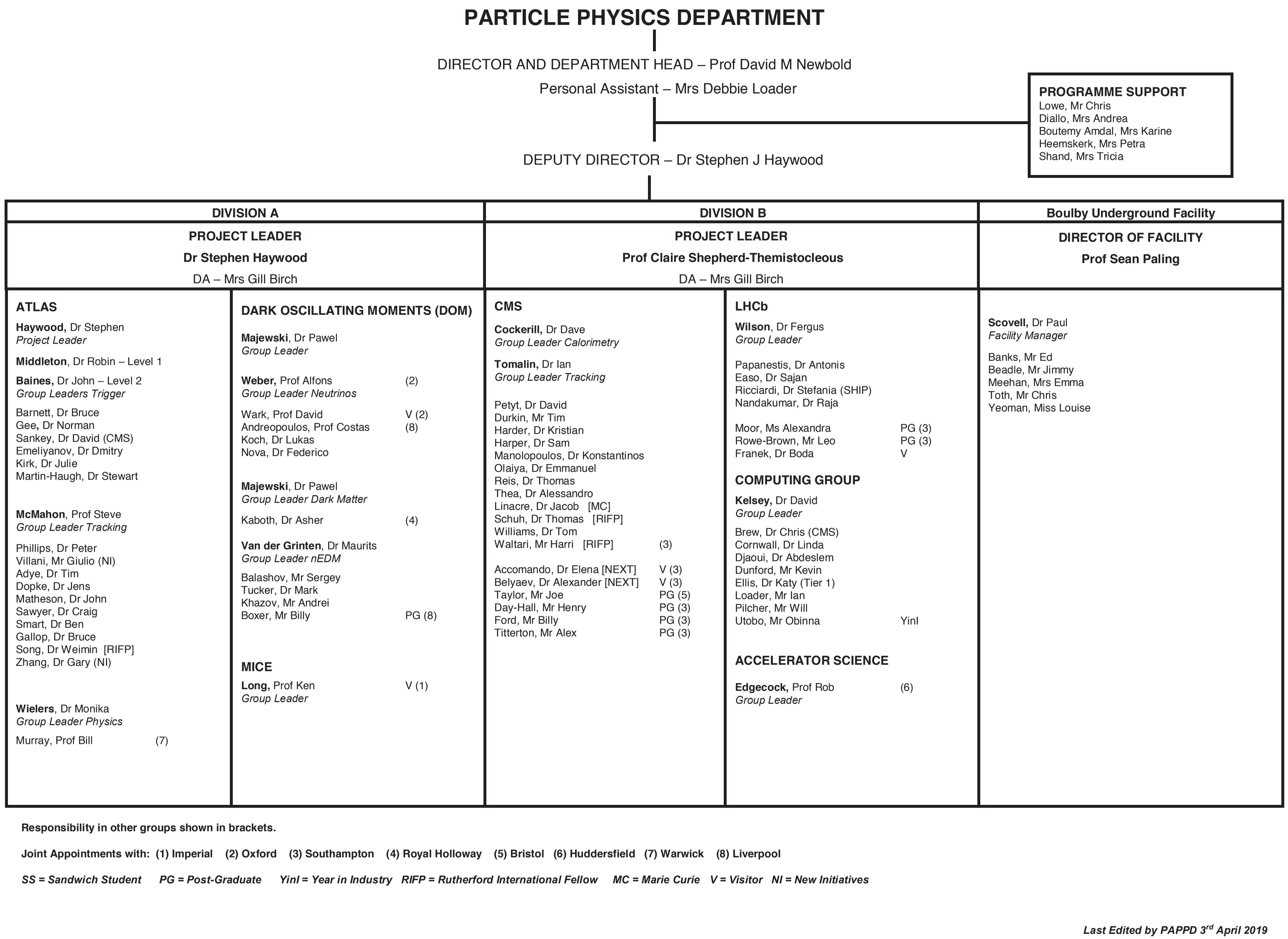


Figure A.1: RAL PPD org chart at April 2019

A.3 Staff Profile

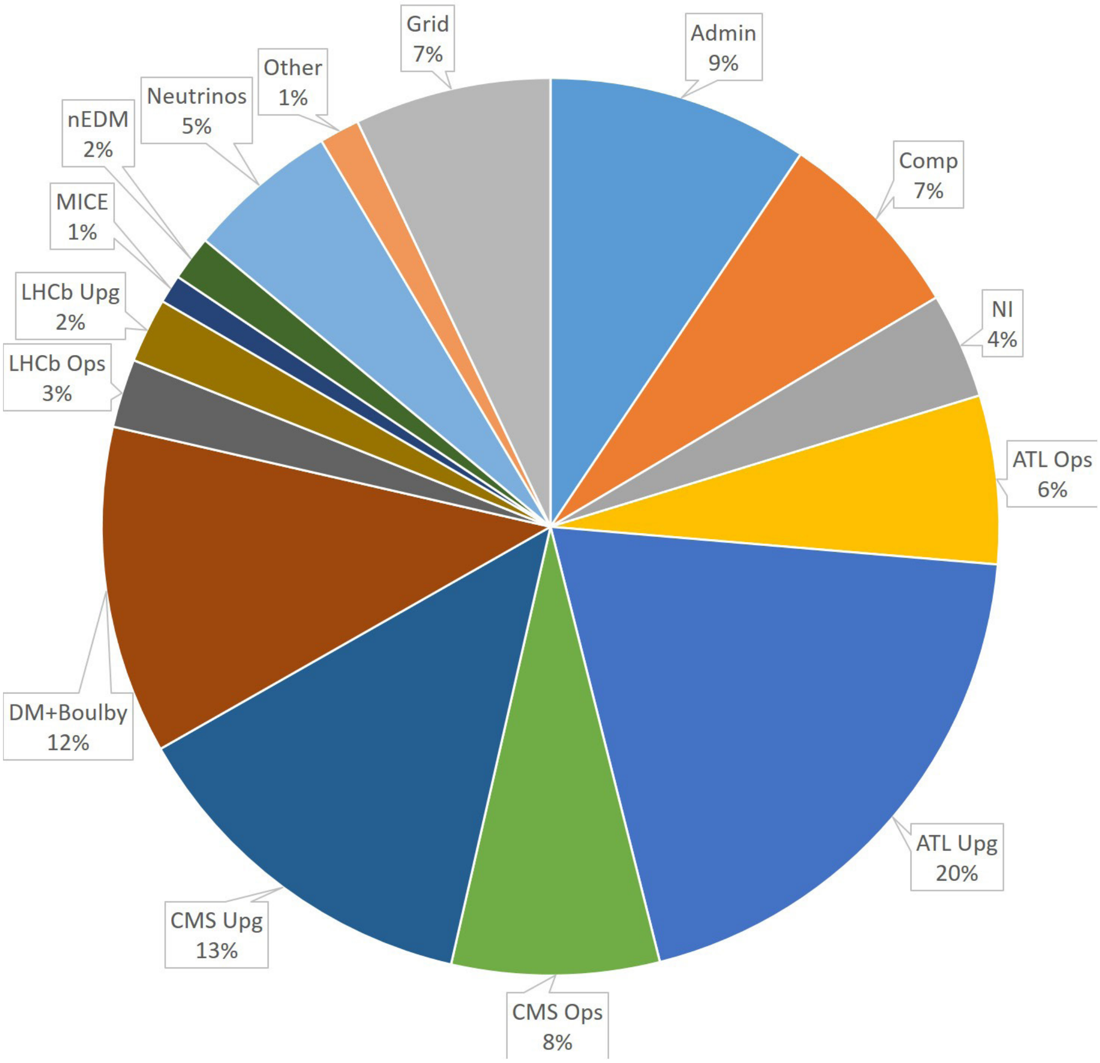


Figure A.2: FTE breakdown by project, FY 2018/19

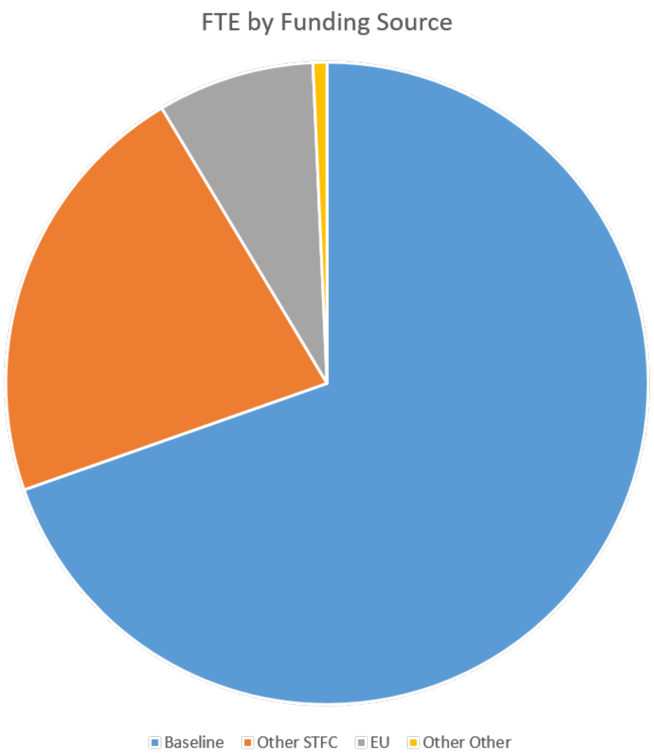


Figure A.3: FTE breakdown by funding source, FY 2018/19

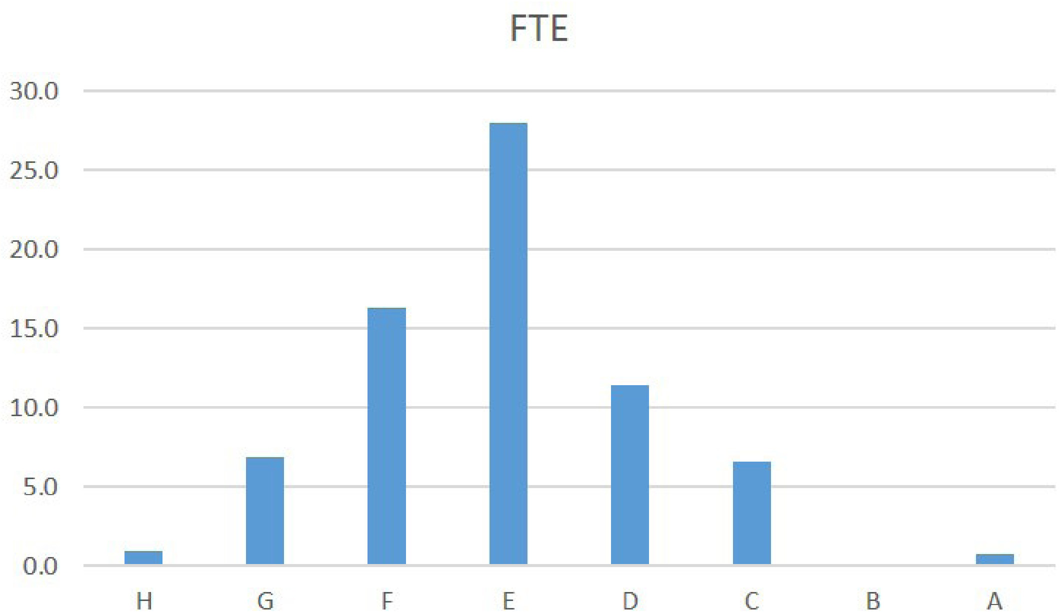


Figure A.4: FTE breakdown by pay band, FY 2018/19

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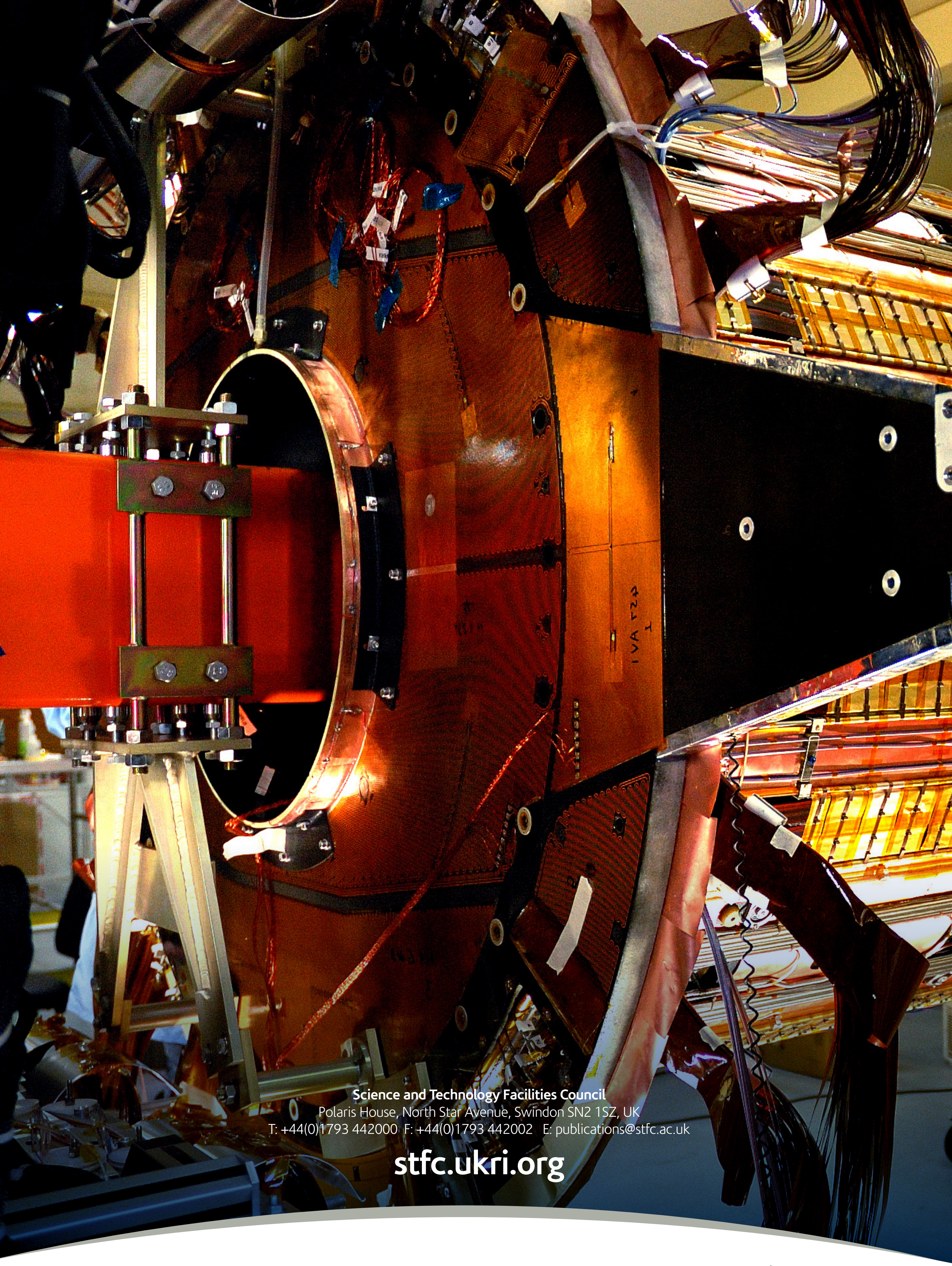

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