Science and Technology Facilities Council

Particle Physics:

Towards a UK Technology R&D Roadmap for Accelerators, Detectors, and Software and Computing

A report provided by the Particle Physics Technology Advisory Panel on behalf of the STFC scientific community

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EXECUTIVE SUMMARY

The Particle Physics Technology Advisory Panel (PPTAP) was established in late 2020. Its role was twofold, to (i) **coordinate the UK response to the European Committee on Future Accelerators (ECFA) and European Laboratory Directors Group (ELDG) research and development (R&D) roadmaps** that were initiated following the publication of the European Strategy for Particle Physics Update (ESPPU) in 2020, and to (ii) **provide a report for STFC's Technology and Accelerator Advisory Board (TAAB) on developing a coherent response** to these European activities.

The panel was composed of mid-career researchers from across the different disciplines of accelerator and particle physics detectors covered by the R&D roadmaps, and chaired by Professor Paula Chadwick. In addition to the nine areas established by ECFA for the detector R&D roadmap, and the five covered by the ELDG for the accelerator R&D roadmap, one more field of expertise, **software and computing, was felt to be relevant and included in the panel**. The panel met regularly throughout the first part of 2021 and its members actively sought input through a variety of mechanisms to both encourage and coordinate UK response to the roadmapping exercises.

The panel was able to identify strengths within the community, and issues confronting them. It noted that the traditional approach that understandably focuses on the science drivers, and the projects delivering these, were **missing the opportunities of creating technology synergies that could enhance science delivery, skills development, and career trajectories**. The financial constraints of recent years have further aggravated this by concentrating R&D into construction projects, where there is limited time and capacity, thereby restricting cross fertilisation, and potentially squeezing out early-stage innovation.

The panel recognised the importance of innovative R&D to the long horizon associated with particle physics (PP) in terms of skills development and retention of capability, with consequent beneficial economic impact for the UK. It noted that there were **interdisciplinary opportunities both within and beyond STFC**, and felt that a more strategic approach would help in leveraging these. **Engagement with industry around early technology readiness level R&D should be encouraged**, as whilst industry can of course provide off the shelf solutions, its appetite for early co-development activity is currently underutilised and far simpler to kick-off than often envisaged.

The UK has a vibrant PP community, but its robust and fruitful future should not be taken for granted. There is much technology R&D required globally, and a technology funding line to support this is equally required in order to enable the UK to be part of next-generation particle physics experiments; the status quo does not respond to the ESPPU nor the ECFA and ELDG roadmaps or their implementation. **An adjustment to the UK approach and funding to shape the emerging European structures to both plan and deliver technology R&D is required in order to position the UK to continue its strong engagement, including a renewed focus on software and computing**. Focused funding, potentially through responsive-mode funding calls for shorter, smaller R&D projects, would allow this to evolve in a strategic fashion.

Particle Physics Technology Advisory Panel Recommendations

R1.

The Particle Physics Technology Advisory Panel recommends that the UK must respond to complement the implementation of the European Committee on Future Accelerators and European Laboratory Directors Group R&D Roadmaps by undertaking an STFC-funded programme of long-term Accelerator, Detector, Software and Computing technology R&D, at least within the constraints, but not necessarily within all, of the activity areas identified in the Roadmaps

R2.

The Particle Physics Technology Advisory Panel recommends that a funded Accelerator, Detector, Software and Computing technology R&D framework be implemented by STFC to both direct and respond to community and STFC requirements. This should provide a breadth of funding opportunities with regard to length and monetary value, with a selection of directed responsive mode funding opportunities available for HEIs, National Laboratories, and other PSREs, and encourage low-TRL co-development with industry

R3.

The Particle Physics Technology Advisory Panel recommends that any funding of the implementation of an Accelerator, Detector, Software and Computing technology R&D framework should be in addition to funding allocated to current and future activities within the broader PP programme

R4.

The Particle Physics Technology Advisory Panel recommends that both initial and ongoing peer review mechanisms and agreed assessment criteria must play an important role in evaluating ‘singular’, cross-community or ‘multiple’, and ‘blue skies’ low-TRL, Accelerator, Detector, Software and Computing technology R&D options, and that they promote outcomes towards a resilient and sustainable PP programme

R5.

The Particle Physics Technology Advisory Panel recommends that an STFC technology R&D roadmap, rather than framework, for underpinning technology R&D direction is necessary in order to make strategic future choices

INTRODUCTION

Background and Context

1. STFC funds a diverse, vibrant, and world-leading particle physics (PP) community across its Accelerators, Detectors, and Software and Computing (ADSC) sub-disciplines and, moreover, does so for a hybrid ecosystem of University and National Laboratory components, often working in collaboration. Funding for the PP community is underpinned by STFC Core Programme budgets to provide as much long-term security and flexibility to respond to opportunities, and breadth and balance of activities, as possible, e.g. via Programmes Directorate and National Laboratory budgets. The Core Programme is the funding mechanism within STFC to deliver on the PP strategy, which the PP community is heavily engaged in shaping, primarily via STFC's advisory panel structures and their various roadmapping and programme evaluation contributions.
2. The Programmes Directorate funding directed specifically towards PP is largely through consolidated and accelerator institute grants, which support a wide range of activities from R&D, through construction to exploitation and analysis, and project grants that fund shorter- and longer-term large, complex, and/or novel construction projects. Within the wider STFC Core Programme there is available funding, for example, to award fellowships and to promote industrial engagement, and in tandem there are financially significant funding opportunities outside of the Core Programme via UKRI collective funds, such as the Infrastructure, Strategic Priorities, and International Collaboration Funds. The PP community is active and successful in attracting external investment to support diverse activities, such as via the Royal Society and European schemes.
3. Against this backdrop, STFC funds what is a strong PP community; however, the persistence of flat-cash funding over the last decade has resulted in a real-terms decrease in funding, which has had a detrimental effect on the overall health of STFC's programmes. At its most severe extent, this has manifested itself in 'managed retreats' from UK involvement, funding only *some* of the UK's world-leading science, an erosion of the UK skills base, and non-trivial descopes to proposals during peer review. Furthermore, the removal of funding opportunities such as the Project Research and Development scheme could arguably have narrowed too far the funding choices available to STFC communities, to those of very large and very specific projects and only the necessary technology R&D to deliver them.
4. Whilst evidenced in recent programme evaluations and balance of programme exercises, to put it simply and via colloquial consensus, the UK's world-leading position on the international PP stage is waning and, to a potentially large extent, living on past successes.
5. The reduction to STFC's programmes in breadth and depth represent what past review exercises, such as the 2020 Balance of Programmes, have termed "minimally viable", but have concurrently recognised that the community has not stagnated and is indeed very active with a good breadth of activities, and construction projects are obviously important to the progression of available facilities and experiments. What is evident, however, is that there have been missed opportunities in terms of depth of activities for progressing and developing programmes in line with UK ambitions. STFC supports PP communities in the

ADSC disciplines below, and the technology R&D required to achieve their respective individual and combined goals.

- **Accelerators:** Collider and Beamlines, Light Sources, Intense Hadron Beams, and Advanced and Novel Acceleration Techniques
- **Detectors:** Energy Frontier, Flavour, Neutrino, Dark Sector, and PP Theory
- **Software and Computing:** Hardware through to Software, HTC & HPC, techniques and applications

6. There is a clear pathway between the design and construction of accelerators to produce a beam, detectors and experiments to initiate physics discoveries, and computing to simulate, store, analyse, and interpret data. It is also clear that the technology for each is quite distinct, but interdependent. What can often be lost in the siloed world of funding, are the strong links between PP, the neighbouring disciplines within STFC, and the still broader range of UKRI science. These are particularly evident between PP and elements of the nuclear, particle astro, and astronomy communities, where there are often strong crossovers with technology requirements, the communities and people involved, how these collaborations form and operate, and how they could possibly engage with industry. Running alongside this and equally important is the development and retention of skills and experience by the people active in this field, which can also be inadvertently lost.

7. STFC has taken the deliberate approach in recent years to keep minimally funded communities active within these areas, both to avoid irreparably breaking the chain and in the hope that funding could improve in line with the ambitions of the UK Government to ramp-up R&D spend to 2.4% of GDP, thereby reviving these communities in line with scientific aspirations. The initial outlook, whilst very much in the midst of a post-Covid-19 recovery landscape, appears hopeful from a UKRI and STFC funding perspective in the coming years. In addition, there have been successful joint ventures with other members of the UKRI research council family, such as ExCALIBUR hardware testbed and software activities, and Quantum programmes. Whilst this is an extremely positive and encouraging position, there are challenges arising from the specific nature of the technology needed by the PP community that may limit its ability to pursue these opportunities. With that in mind, it is essential that advantage is taken of the synergies within the PP programme itself.

International Roadmapping Activities

8. The collective UK PP community is well-established, and equally well-embedded and influential internationally. This is a privileged position, and important when considering that the R&D, construction, and exploitation activities associated with particle physics and similar disciplines usually take in the order of decades to achieve. This is due primarily to the high costs attributed to the cutting-edge technology R&D required and the necessarily very large scale of the resulting infrastructure and facilities. Because of these, there has been a natural evolution of the PP and similar communities to coordinate activities around global international collaborations.

9. Part of this story is the UK's Member State status in CERN and membership of other international facilities to deliver against STFC strategy within that collaborative environment.

In the case of PP, CERN represents the global focus of current near-term activities, and tied to this global stewardship takes on a role of international direction-setting. In June 2020, CERN published its European Strategy for Particle Physics Update (ESPPU). This document set out a number of general considerations and high-priority future initiatives, as well as essential scientific activities to undertake, and drew on the synergies of PP with neighbouring disciplines. In brief, it made clear that the successful completion of the high-luminosity upgrade of the LHC and detectors should remain the focal point of European particle physics. In doing so however, CERN made a number of recommendations for future activities beyond this realisation in a European (and global) context.

10. The vibrancy of the PP community and the extent of possible future accelerators and their associated experiments is manifesting itself in uncertainty regarding the way forward, placing the PP community at a crossroads as it seeks to determine the long-term future of the field and next generation facilities. A common theme across the ESPPU recommendations is the need for R&D across accelerator and detector technologies as well as software and computing infrastructures. It recognises potentially common technologies where these exist, but most importantly, calls for R&D activities in all areas to be ramped-up and intensified internationally.

11. The UK has a broad interest across these ADSC technologies and is well-positioned to play a significant role within their respective R&D. Following the publication of the ESPPU, CERN charged ECFA and ELDG with translating its recommendations into roadmaps for required accelerator and detector technology R&D. These groups established taskforces to explore particular technology R&D routes and to consult global communities. The task forces and panels established by ECFA and ELDG are shown in Table1. Further details of the ECFA and ELDG Roadmapping processes are provided in Annexes 7 and 8, respectively, with UK representation and cross membership with PPTAP provided in Annex 3.

Table 1: ECFA Task Forces and ELDG Panels for detector and accelerator Roadmapping activities

ECFA
TF1: Gaseous Detectors
TF2: Liquid Detectors
TF3: Solid State Detectors
TF4: Photon and Particle Identification Detectors
TF5: Quantum and Emerging Technologies
TF6: Calorimetry
TF7: Electronics and On-detector Processing
TF8: Integration
TF9: Training and Skills

ELDG
Panel: High Field Magnets
Panel: High-Gradient Plasma and Laser Accelerators
Panel: High-Gradient Acceleration RF Structures and Systems
Panel: Bright Muon Beams and Muon Colliders
Panel: Energy Recovery Linacs

12. Computing and software were not identified as part of the process, nonetheless there is on-going activity and roadmapping in which the UK is actively involved. This is principally through the HEP Software Foundation, as well other international efforts (IRIS-HEP, etc.). To date it has been largely driven by the infrastructure projects (the Worldwide LHC Computing

Grid, Data Organization, Management and Access), and international experimental technical design reports (ATLAS, CMS, etc.) which have determined the R&D needs for the next decade. Defining the roadmap beyond that point is more challenging.

UK Particle Physics Technology Advisory Panel

13. The significance of the ESPPU roadmapping exercises was recognised along with the need to participate, consult, contribute and respond. What was evident from the outset was that the UK would neither want, nor be able, to play a significant role across the full remit of potential technology R&D routes under consideration by ECFA and ELDG. The need to prioritise and focus is evident both because of skills and experience within the community and the financial situation, including available headroom in the current PP and other related budgets. In part to address this, but also to develop a coherent, strategic, and holistic approach to responding and planning of ADSC R&D activities within the international context, the Particle Physics Technology Advisory Panel (PPTAP) was established in the UK.
14. PPTAP was a 'task and finish' panel with membership derived from PP university groups and relevant National Laboratory departments, deliberately consisting of earlier-career individuals likely to be professionally impacted by decisions made regarding the future direction of the PP field over the coming decades. PPTAP met regularly throughout 2021, in brief, to produce a coherent UK position and contribute to the development of the ECFA and ELDG R&D Roadmaps related to the ESPPU. Full details of the PPTAP Terms of Reference, membership and its schedule of meetings and activities can be found in Annexes 1, 2 and 4 respectively.
15. Chaired by Paula Chadwick, Durham University, PPTAP consisted of 26 individuals, including Accelerator, Detector, and Computing sub-groups, and seven observers. Each of the 17 members represented UK coverage in each of the 14 ECFA Task Forces (detectors) and ELDG Panels (accelerators). Whilst present in the ESPPU, the ECFA and ELDG roadmapping activities did not explicitly include computing and software. PPTAP membership was extended to specifically include two members of the UK community to cover High-Throughput Computing and software. PPTAP member Iacopo Vivarelli was the UK National Contact for ECFA.
16. PPTAP members were considered experts in their field, and the collective membership was structured such that it could maintain an overview of the ECFA and ELDG road mapping activities, participate in road mapping expert panels, and liaise with other advisory panels as appropriate. Its members worked to establish the need for UK particle physics and associated accelerator R&D activities, in the context of the PP programme, as well as the current level of expertise and relevant activity within the UK. To do so, its members consulted and interacted with the wider community to ensure its views were canvassed and there was an appropriate and effective route for communication with STFC.
17. Consultation by PPTAP with the PP community has been extensive and multi-modal throughout this exercise, and moreover, in tandem with UK community consultation from the multiple ECFA and ELDG Task Forces and Panels. Initially, PPTAP consultation was via an online survey to gather high-level input across a broad and diverse audience, which at reasonably short notice received 60 responses. See Annex 5 for the Community

Consultation Survey template. In addition a more detailed Software & Computing survey was conducted. Following this, members from each PPTAP area coordinated a community workshop around the area they were representing. See Annex 6 for an example of a workshop. These workshops were coordinated to discuss in greater detail the survey responses and technology R&D topics within each PPTAP area. These outcomes fed into the ECFA and ELDG roadmapping activities and this PPTAP report.

SCIENCE DRIVERS

18. The underpinning science drivers are the curiosity-driven questions about understanding the world and universe that we live in. These fascinate and intrigue people from all walks of life and as a consequence enthuse the young, inspiring them to engage with Science, Technology, Engineering, and Mathematics (STEM) throughout their education and beyond. The demands of the field make it a crucible for innovation, with new technologies which find life in cutting-edge experiments and then translate to other fields and industry. Engagement in the field attracts researchers to UK institutes and promotes opportunities.

19. Within the UK the PP community has coalesced around a sub-set of the global PP community's activities, focusing its efforts and funding around the following five themes which address the most significant science questions within PP. These themes, which are driven by the STFC physics questions, readily align with CERN activities, in line with the UK Member State membership status in CERN, as well as it being the primary laboratory for the UK PP community.

    - PP theory
    - Collider physics
    - Neutrino physics
    - Quark flavour and precise muon physics
    - Dark sector physics

20. Over the years, the PP community has identified physics objectives that relate back to the physics questions (See annex 9) and these have shaped the UK's technology strengths and expertise. Some technologies, for example silicon detectors, are specific and refined by the science driver, others such as data acquisition are ubiquitous and evolve and adapt to the environment in which they are used.

21. The size, cost and long-term nature of the field can mean that the technology choice influences the science strategy, particularly with accelerator facilities. This is part of the dilemma facing the international community and often manifests itself by splits in the community favouring one technology over another. Whilst some of the time this can be accommodated, and may even be an advantage as it offers complementary measurements at other scales, ultimately costs mean that it cannot, and a choice has to be made. The international decisions on future technology will set the direction and the UK community will want to both influence this and be an active participant. To maximise the return on future investment STFC will need to focus and prioritise and play to its strengths.

Recent UK Activity

22. STFC seeks to encourage its different communities to regularly review and update their roadmaps and activity led by the different advisory panels. The Particle Physics Advisory Panel published its latest roadmap in 2021 and the Particle Astrophysics Advisory Panel is finalising the update to its 2016 roadmap.

23. These roadmaps set out the interests of the communities they represent and the possible routes that could be taken to address the science questions through different collaborations. There is a wide range of possible avenues to explore and whilst the roadmaps do not pursue them all, they still set out a number of different choices. The roadmaps act as a useful guide to where UK interests lie.

24. Regarding software and computing, the UK has produced a number of whitepapers to outline its software and computing strategy. This is also examined more generally in the UKRI Science Case for UK Supercomputing and Government Office for Science large scale computing report. Roadmap whitepapers on the Digital Research Infrastructure landscape have been developed by a UKRI expert group covering AAAI Federation, Cloud, Network, Research Data, Software and Skills, and Supercomputing.

UK Challenges, Requirements and Priorities

25. Historically, the focus within the Frontier Science funded programme has, perhaps not surprisingly, been on the science drivers, with less attention being given to the significance and merits of the technology choices associated with this. It could be argued that the underpinning fields of accelerators and software and computing are an exception, and the consolidated grants to the universities have sought to support technology-based skills and expertise to be deployed across more than one experiment. Nonetheless, there are pressures here too which can drive technology to be focussed on individual projects.

26. Whilst there is widespread recognition of the importance of technology and the accompanying skills and expertise, challenges remain. A considerable length of time, sometimes spanning decades, can elapse between the design and build phase through to installation and then delivering on the obligations that exist to maintain the equipment through its working life. As funding constraints have grown there has been an increasing focus on large construction projects; the current career pathway in universities, with its emphasis on publications and independent research, often fails to recognise the skills and expertise such projects require. The consequence of this is that the skills pipeline has become damaged, and the UK is reaching a point where it has fewer experts with sufficient knowledge to engage in planning, building, and running the next generation of detectors and accelerators and associated technology.

27. The level of participation and engagement in the ESPPU R&D roadmaps and equivalent software and computing activities demonstrated that there is a strong aspiration within the community to be actively involved in shaping the future, and indeed the UK is driving many aspects of the roadmaps via its participation. At present there are diverse opportunities, many of which the UK has the skills to exploit. Deciding which way to go has to be steered

by financial realism, and understanding the technology context provides another layer that will promote cohesion. Providing this more contextualised picture should not only benefit the science and leadership through the creation of synergies, but also benefit the development of skills and careers with a corresponding beneficial impact in these areas.

UK TECHNOLOGY R&D OPTIONS

28. The ESPPU is clear in its statements for the ramping-up and intensification of this ADSC technology R&D to meet the physics objectives of the future, and the ECFA and ELDG Roadmaps have identified those areas with the greatest likelihood of providing the tools and means by which to answer the PP community's physics questions. In considering these two roadmaps it is clear that the UK has good foundations upon which to develop its contributions, to a greater or lesser extent, across the full remit of ECFA and ELDG. There are, however, multiple questions arising as to which to pursue, when and why, and whether these should be limited to those of direct relevance to ECFA and ELDG.
29. Software & computing requires a slightly different approach due to the rapid pace of technological change. Rather than focussing on a list of distinct R&D needs, which can become obsolete, future requirements could be better addressed by taking enabling steps and focussing the extensive UK expertise by better linking these experts across the experiments/projects. There are numerous cross-cutting topics of relevance to all experiments, including hardware accelerators (including GPUs), green computing including low power compute units (including FPGAs and ARM), and power efficient software algorithm, cyber-security, machine learning techniques, quantum computing, digital twins, intelligent networks, the role of cloud computing, exascale computing, and future data storage options. Many of these are being explored in more detail by the HEP Software Foundation working groups, in which the UK PP community is engaged and responding to by way of STFC 'construction' project funding for SWIFT-HEP.
30. PP generally uses commercial off-the-shelf computing and networking hardware to ensure cost-effectiveness and the ability to deliver resources at scale. The hardware companies are keen to engage, but the field has little sway over them as it represents a tiny proportion of their income. However, the field should continue to engage with industry to understand the future developments that could enhance our software & computing, to understand how to use the products most effectively and to provide feedback on product development that, if adopted, would be beneficial for the field.
31. A more integrated approach to technology driven by a long-term view should allow greater flexibility and could create an environment that allows rapid transition of technology from one area to another. A clear candidate for this is the greater use of machine learning and AI in many aspects of design and development. It is worth noting that the skills associated with this are highly prized and the field lends itself both to being a training ground for, and for forging links with, industry.
32. Whilst not a primary driver, it is clear that sustainability and Net Zero are increasingly important and will become influential as government-level funding and support are sought internationally. Experience shows that sustainability needs to be built in at the design stage, and so the two R&D roadmaps offer an opportunity to influence future experiments so that

this is factored in. Understanding the environmental impact of a technology choice is likely to be increasingly important and might be relevant when making strategic and investment decisions.

UK Strengths

33. PPTAP sought to understand the strengths within the field through a number of community specific workshops. From these it is clear that the UK has in-depth expertise in a number of areas, some of which are well established and have grown through active engagement and leadership in detectors, accelerators, and software and computing.

34. Within both accelerators and detectors there are diverse subsectors, each of which will have strong groups. If by way of illustration we take just one of these as an example, liquid detectors, there are strong groups in water Cherenkov, liquid scintillator, liquid, and noble gas detectors. A similar exercise could be undertaken for each of the other areas, and it quickly becomes clear that there is diversity and vibrancy within the UK across all of the accelerator and detector and technologies (see Tables 2, 3, and 4 on the following pages). Equally, the UK has strength in cross-cutting areas such as electronics and data acquisition. Likewise within software and computing the UK has significant leadership in a significant number of important areas, including in exploitation of computing accelerators, exploitation of low power compute units, computing operations, enabling software and computing, reconstruction algorithms, software framework development, development of cross-experiment development tools, use of HPC and development of collision simulation/generation programmes.

35. This diversity and vibrancy are both a strength and weakness. Whilst on the one hand they demonstrate agility and flexibility, there is a risk of a loss of focus and missed opportunity through overreach. In seeking to address this, the workshops identified some common themes emphasising the importance of skills and pulling out the need for small-scale R&D funding to enable early engagement with a feeling that competitive peer review could have a strong role to play, particularly in the 'fail fast' early stages that lead to innovation breakthrough and success.

36. The UK approach to PP is coherent and strategic across its university and National Laboratory activities, however, if there is a failure to respond to the ESPPU call for an upturn in ADSC technology R&D, and to play a significant part in delivering it, then the UK will find itself becoming rapidly less influential and potentially unable to meet its on-going commitments as skills are not developed and experience is lost. Sustained and at times significant funding of PP means that UK currently has the knowledge and skills that allow the UK to adapt, to engage in, and to lead, activities across the breadth of the ECFA and ELDG roadmap remits if given the opportunity.

37. Tables 2, 3, and 4 that follow, take a high-level approach to a Strengths, Weaknesses, Opportunities, and Obstacles, analysis of the current and potential technology R&D landscape in the UK, as well as an in-depth look at areas of expertise and applicable projects for UK technology R&D within the ECFA and ELDG panel remits.

Table 2: Strengths, weaknesses, opportunities, and obstacles analysis of the UK accelerator and detector particle physics community regarding current and potential technology R&D

Strengths	Weaknesses
Multiple including, beam dynamics, RF systems, beam instrumentation, feedback and control, plasma, surface science ERL, muons, permanent magnets, thin-film SRF, mm-wave & THz, particle sources	Links with industry under-developed Discontinuity in funding projects
Multiple including DAQ, Silicon, Quantum	Approach to dependencies not joined up (performance requirements) Lack of investment in electronics Quantum – no project/facility to scale up
Well-established expertise Leadership roles Training and hands-on opportunities Well-established track record of R&D in a number of areas Strong input into R&D roadmaps Integration Software and computing expertise	Lack of access to R&D facilities/beamlines Disparate small groups in some areas (novel acceleration, calorimetry, integration, gaseous detectors) Lack of career paths for technical experts Lack of coordinated computing & software training Little early TRL collaboration with industry

Opportunities	Obstacles
Expertise in areas of growing importance (thin film, ERL, permanent magnets, MM-wave, sustainable design) STFC facilities (CLARA, EPAC) leading to international opportunities (EuPRAXIA) Future UK facilities (UK XFEL, ISIS II)	
Expertise in essential, as yet unfilled and needed, areas	
International R&D underway Low-cost test stands and bench-top experiments Long-standing experienced communities (DAQ, integration, beam dynamics) Leadership building from expertise (muon, ERL, beam dynamics) Partnership with industry Greater coordination of computing and software training and expertise	Little UK R&D underway Funding – often just project related, lack of investment for co-creation and early-stage R&D Industry not well plugged in Overall cost of end goal Sustainability of end goal

Accelerators	Detectors	Both

Table 3: UK accelerator particle physics community areas of current and potential technology R&D expertise and applicable projects within the ELDG panel themes

ELDG PANEL	AREAS OF EXPERTISE	EXAMPLES
MAGNETS	Bulk trapped-field superconductors High Temperature Super Conducting magnets *Permanent magnets*[1] R&D superconducting materials Superconducting undulators Very high-field accelerator magnets	HL-LHC-UK-2 *ZEPTO* DLS-II and UK XFEL
HIGH-GRADIENT ACCELERATION – LASER/PLASMA	Dielectric/terahertz Electron-driven plasma Laser driven plasma Proton-driven-acceleration Hybrid schemes	CLARA facility, CLF, EPAC, EuPRAXIA AWAKE
HIGH-GRADIENT ACCELERATION – RADIO FREQUENCY AND RF SYSTEMS	Cryomodule development Fast Tuners High Efficiency RF Sources High frequency RF Thin Film RF	ALICE, HL-LHC, PIP-II Ferroelectric tuner capable of removing microphonics Prototypes (FCC, CLIC, industry) ISIS-II and UK XFEL Relativistic acceleration with THz, involvement with CERN XBox, UK XFEL involvement with ARIES and IFAST thin films
MUON ACCELERATION	Muon Cooling demonstrator - ~10 T solenoid development for cooling - High gradient normal conducting RF Fixed field accelerators for protons and muons - Magnet development Proton driver Targetry	MICE ISIS II, EMMA ISIS II, nuSTORM, PAMELA ISIS II, Neutrino Factory R&D T2K, DUNE
ENERGY RECOVERY LINACS (ERLS)	ERL technology (SRF, magnets, diagnostics, ultrahigh vacuum, controls, operation) Single and multi-pass design and beam dynamics High current photoinjectors Application of ERL technology for wider applications	Design and operation of ALICE ALICE, PERLE, 4GLS design, UK-XFEL studies ALICE, PERLE, LHeC injector CLS-grid, collaboration with AWE on nuclear security, decommissioning applications, and medical isotope production via Compton gammas

[1] Not included in the ELDG Roadmap

Table 4: UK detector particle and particleastro physics community areas of current and potential technology R&D expertise and applicable projects within the ECFA panel themes

ECFA TASK FORCE	AREAS OF EXPERTISE	EXAMPLES
GASEOUS DETECTORS	-	-
LIQUID DETECTORS	Liquid Argon TPC Liquid Xenon TPC Photosensor operation at low temperature Radio assay Training in R&D, operation, and analysis	Darkside, DUNE LZ LZ, Darkside all
SOLID STATE DETECTORS	Integration of large detector systems R&D - Depleted CMOS sensors - Diamond sensors - High resolution large-area pixel sensors - LGAD for fast timing detectors - Low mass (thinned) sensors - Multipurpose pixel sensors - Radiation hard Si strip sensors - 3d pixel sensors - Sensor characterisation	ALICE ITS3, ATLAS SCT (barrel & endcaps), CERN-RD50, LHCb Velo tracker, Mighty Tracker, Mu3e
PHOTON AND PARTICLE IDENTIFICATION DETECTORS	SiPM MCP-PMT RICH detectors Time of Flight	Large scale dark matter searches using noble gas – Darkside, DUNE, CTA LHCb, TORCH, NA62 LHCb TORCH
QUANTUM AND EMERGING TECHNOLOGIES	Commercialisation and links to industry Quantum Technology for Fundamental Physics (only one in Europe) Facilities	 QSNET Quantum enhanced interferometry QUEST AION Tritium production (Culham), Boulby mine
CALORIMETRY	High-Granularity calorimeters backend Single sensor development Optical crystal calorimetry Dual readout optical fibres – development & software	CMS HGCal EPICAL/FOCAL/DECAL CMS barrel & endcap Dual readout TB, AIDAinnova
ELECTRONICS AND ON-DETECTOR PROCESSING	Board design	ATLAS, CMS, DUNE

	Data acquisition FPGA design Interconnect & Packaging Micro electronic design Optical transceivers Triggering System design	(eFEX, Serenity, COTS)
INTEGRATION	Cooling CFRP mechanics DCS/monitoring Detector integration Integrated system design System testing	ALICE, ATLAS, DUNE, SNO

Synergies with Neighbouring Disciplines

38. The UK PP community has a long history of strong collaboration, which is evident within and between the themes of the STFC PP programme, and with neighbouring disciplines. Closest collaboration exists with the Nuclear and Particleastro communities, wherein technological choice and requirements have a degree of overlap. Indeed, the current funding model in the UK, combined with the global multi-institute collaborations formed and funded around particular projects and experiments, well evidences the successes attributable to this approach.

39. Working examples of technological synergies across these disciplines are possible, and there is recognisable potential for further successes. Better photon detectors are an obvious area with synergies to particle physics in general, and developments in the HV CMOS direction would be beneficial for gamma-rays. Detectors for low-mass dark matter are essentially resonators at low temperatures; such configurations are often used to realise qubits, and the readout is the same low noise devices used in the quantum computing community. The only differences are the high magnetic field and the large volume resonant structure that are needed for axions. Also, interferometric position sensors, such as those used for gravitational wave detectors, can be used for the accurate positioning of components in synchrotrons and accelerators. Additionally, there are less direct potential synergies with the condensed matter and fusion communities in high-field magnet development. A construction project-driven approach to funding is perceived as having curtailed the extent and scale of complementary inter-disciplinary R&D, where alternative approaches from a technology perspective could reinforce beneficial synergies. Moreover, there are other synergies such as quantum technologies, which have multi-disciplinary applicability, that are potentially only just tapped and could offer many more opportunities, alluding to the realisation of benefits from what was once blue-sky R&D.

40. In the software & computing area, there are numerous opportunities for synergies to be exploited with other areas: these include digital twins, integrating HEP functionality into existing scientific computing frameworks (e.g. PyHEP, Scikit-HEP, Boost-Histogram), shared compute resources (sharing expertise and improving cost efficiency, e.g. IRIS, DiRAC, GridPP) and as a conduit for knowledge-transfer in machine learning/data-science.

41. Large accelerator facilities are built relatively infrequently however accelerator technology R&D has benefits beyond the frontier science areas not just in enhancing national facilities and capabilities, but also more broadly, for example via the Accelerators for Security Healthcare and Environment initiative at the Cockcroft Institute and other medical accelerator applications. The accelerator community in the UK has a strong track record of using its core funding to leverage support from elsewhere and working with other disciplines. There may be further opportunities presented by smaller facilities that serve biomedical, industrial and other societal applications that could be exploited to allow the development of novel accelerator technologies.

42. The specificity and cutting-edge nature of the field can make it insular and less active in seeking interdisciplinary engagement, to the detriment of the field. The recent notable exception is Quantum Technology for Fundamental Physics, a programme jointly funded by STFC and EPSRC. This programme, which sits between technology and science, is proving beneficially disruptive and innovative. It has demonstrated how a change in approach

pushing blue-skies R&D to the fore has resulted in a national programme that has put the UK at the vanguard in cold atom quantum sensors with the potential for world leading facilities like Tritium.

UK IMPLEMENTATION AND OUTCOME

43. Having produced the ESPPU R&D roadmaps, CERN and the European communities will now be looking at how to respond. The active role played so far in these processes should place the UK in a good position to do the same, with thought given as to how much to adopt the technology-driven approach established within the roadmaps. This has to be set in a realistic financial context, but should consider that large facilities are not built often enough to deliver technology developments and as a result technology is often driven towards the conservative end. Exploitation of smaller and/or incremental projects that extended to mid-scale (cost) and high-risk activities is a funding approach currently missing from the landscape, and could allow activities that would otherwise be on the critical path of a construction project to fail, re-group, and redirect.

44. In a ‘do nothing’ scenario it is clear that, while UK PP might survive in the short term, it would not flourish. The main loss would be the lack of opportunity for innovative blue skies R&D with engagement coming solely through large projects; there would be access to data and exploitation and limited technology development, but later involvement would mean an erosion of the UK’s skills base, loss of influence and, ultimately, choice.

45. Equally, there are multiple opportunities available to the UK, and recognising the potential benefits realised from exploiting these opportunities is important. The first step may be to take a strategic approach in looking for opportunities to leverage funding in a way that plays to technology strengths. It will nonetheless be important to recognise the maturity of technology options available, and provide a funding ecosystem in which both mature and nascent technology R&D can be explored, e.g. SCRF and laser/plasma acceleration.

46. Given the requirements necessitated by the large and complex datasets that will be a central feature of almost all future PP experiments, it is essential that software & computing R&D is one of the key pillars of the development of all future PP programmes, with sufficient investment to ensure that the initial software and computing demands can be met and maintained over the lifetime of the programme.

47. The software & computing area identified a clear need for training and to have sufficient Research Technical Professionals available to supply the necessary and sufficient expertise to address current and for most future R&D developments. This will ensure software is adaptable, future-proof, and portable, so it can easily address changing experimental needs, avoid ‘lock-in’, and take advantage of ever-evolving future computational developments.

48. More widely, there was a recognition that as technologies span several experiments a different, broader approach to detector R&D to complement the construction project funding might be beneficial. It was felt that this might successfully promote technology innovation as well as helping to de-risk new technologies, which could result in longer term savings.

Funding Framework Considerations

49. The long-term nature of PP experiments and their related investments, twinned with a recent history of financially constrained funding opportunities, has given rise to a PP programme in the UK which has had to prioritise the construction and exploitation of long-term investments of high priority to the UK community. This necessary focus on flagship construction projects has directed technology R&D activities toward very specific outcomes, with any synergies and applications outside of their intended purpose often occurring by chance rather than design, or by financial necessity.

50. In light of the ECFA and ELDG R&D Roadmaps, PPTAP reached broad agreement that there were obvious benefits to taking alternative approaches to undertaking ADSC technology R&D in the UK. In brief, these concern, (i) the coordination of distributed R&D activities, (ii) a combination of top-down and bottom-up directed programme approach to R&D, and (iii) the provision of long-term funding opportunities to allow continuity and technology development progression. These are inherently interdependent, and support a broad-based and deep ADSC technology R&D ecosystem from which to birth and develop the direction of projects.

51. The roadmaps recognise the importance of R&D facilities, especially those which provide infrastructure typically only available at a few larger laboratories in Europe and globally. The UK will need to understand how and where it fits into this picture, as the roadmaps also allude to greater international coordination and the possible introduction of a hub-and-spoke concept. This fits well with the broadly applicable ADSC technology R&D areas, such as microelectronics, as its complexity, specialisation, and engineering and prototype requirements, favour the sharing of skills and resources. Differing approaches will be required across ADSC however, with accelerators needing to be far more directed and strategic, and detectors and software and computing able to be far more responsive and dynamic. In balancing these ambitions, a secure future for training and skills development of the next generation within cutting-edge ADSC technology R&D at universities and smaller laboratories is of critical importance. PPTAP sees the benefits to this approach. This may not require a radically different approach as some elements already exist and much could happen through cooperation and evolution, but a more formal implementation of this structure could be undertaken in a UK context, which might require significant coordination and community consultation. As with the broader topic of international coordination, key to UK success will be its ability to respond rapidly with initial, followed by further developed, and ultimately strategic, funding.

52. Greater coordination, particularly international, is likely to attract significant and complementary funding opportunities at the European level. The PP community consultation demonstrated a desire for longer-term stable funding of ADSC technology R&D. There is an opinion within both PPTAP and the PP community that the hub-and-spoke organisational concept could allow for this longer-term ecosystem, where laboratories and universities could appropriately scale their activities. The highly visible, clearly delineated, and readily accessible opportunities garnered via greater international coordination are more important

than the 'model' followed however, and hubs should reflect expertise and leadership as well as size and delivery capability. In essence, HEIs and laboratories should expect to vie for both hub and spoke monikers dependent on the activity in question.

53. Software and computing have key roles to play as the field invests in innovative, blue-skies R&D, to ensure that game-changing developments (e.g. quantum computing, new data formats, ability to run on future computer architectures, intelligent networks) can be quickly identified and prepared for, as well as being used to steer and harness the future. Directed-responsive competitive bids or HEP 'blue-skies' fellowships, including Research Software Engineers, could play an important role in strengthening collaboration. Indeed, all ADSC areas would benefit from technology-focused fellowship offerings.

54. In this context, cross-experimental R&D projects can be beneficial, allowing the sharing of expertise and producing enhanced solutions for the same cost. The return on investment is likely to be enhanced through engagement in cross-experimental research projects. Certain areas of HEP have established valuable expertise in various areas (for instance in applied machine learning), whilst other areas would strongly benefit from the infusion of such expertise. Forums and collaborative projects would allow that expertise to be transferred easily across the field, maximising research output.

55. Finally, and alluded to already, could be a shift from the current funding model of experiment-construction-project driven ADSC technology R&D to that of technology R&D driven programmes. The implication of such a shift is largely conceptual, but in practice has potentially significant impact on funding models for the UK PP community. To avoid the undertaking of disparate and generic R&D, the preferred approach may be through programmatic R&D, and directed responsive-mode funding, which allows progressive development of ideas and technology projects over several cycles.

Skills, Training, and Career Development

56. Early-stage R&D with "hands-on" activities lends itself well to supporting many stages of career progression and development. It provides ample opportunities for PhD projects as well as transfer of knowledge from experienced researchers and technicians to early-career staff through mentoring and team working. It also offers the chance for early-career researchers to bid for and hold grant awards in their own right, in a way that the more long-term and complex construction projects in PP seldom do. These "hands-on" enhancements to the skills pipeline are likely to be attractive to people at all stages of their career and a valuable piece of the academic training ground.

57. Early-stage researchers can find it difficult to establish themselves in experimental PP. Opportunities immediately post-PhD can be limited, depending on when the student graduates in relation to the construction programme. Mobility is often a requirement, even if only to spend some weeks away commissioning equipment, which is difficult for anyone with family responsibilities. Smaller R&D projects can provide more opportunities and thus foster greater diversity in the research-base.

58. It is easy to see how this environment can also promote links with industry, critically around two-way exchange and not one-way transfer, as industry can very capably both provide and

improve R&D as well as delivery. This is demonstrated elsewhere by the well-established Industrial Cooperative Awards in Science & Technology (CASE) awards and success with Centres for Doctoral Training. Taking active steps to linking these to R&D might be advantageous. Industry is actively open to co-development of lower technology readiness levels, which would begin to take full advantage of its capabilities. Intellectual property concerns are less significant at this level due to the collaborative and not contractual engagement. Universities and National Laboratories are very open to industry engagement; however, emphasis should be placed on early agreement of starting points and expectations on each delivery partner. Characterising technology R&D options is equally important, so as to understand what, if anything, industry can do on its own.

59. Software and computing expertise are intrinsically bound to PP and vital for development of future tools and access to data. As a consequence, effective training is essential to enable and improve research programmes. At present, training varies significantly in the UK, being constructed from a patchwork of training offerings lacking coherence, with the result that it is lagging compared to offerings in other countries. A UK-wide coherent and integrated programme focussing on critical areas of expertise, available to PhDs, PDRAs, core staff, and academics, with industry-led workshops to exploit the latest hardware developments (e.g. FPGAs, GPUs, CPUs, intelligent networks), could be made available to address this. One route to achieving this could be realised by building current initiatives into a national scheme, with a menu of options available, including regular Carpentries style workshops, more advanced courses where specific skill-sets are needed, recommendations for standard learning outcomes at undergraduate/postgraduate level, building upon/expanding investment in the CDTs, and collaborating with international initiatives (e.g. HSF, IRIS-HEP, HEP-FIRST).

60. Effective training in ADSC should be coordinated across the UK and across Europe through ECFA to ensure alignment with partners and collaborators. The UK has extensive and highly-regarded training opportunities at present - for example, those delivered individually and collaboratively by the Cockcroft and John Adams accelerator institutes - which could easily be intensified, with specific topics and themes ‘spun out’, or indeed have the format transplanted to different disciplines. This training should provide courses for all career levels, with particular emphasis to “hands-on” opportunities. The synergies between detector training and accelerator diagnostics training should be exploited.

61. People trained in the ADSC area have problem-solving skills that are highly attractive to industry and business, aligning with government priorities and helping to address skills-gaps in the economy. The significant flow of skilled talent to industry, particularly in software & computing roles, is both a benefit and a risk. At a reasonable level it is beneficial, but at too high a level it can lead to issues around the retention of critical expertise and talent that underpins infrastructure, projects in construction, and computing archives, as well as the current experiments. Careful thought should be given to the establishment of, and support for, Research Technical Professional career paths that value and recognise the broad range of key technical roles including those within software and computing, e.g. Research Software Engineers, Data Scientists, and Systems Administrators.

62. The problems associated with not having this are evident in software and computing where the work of RTPs is often not planned strategically and their effort is not always costed transparently. A more coordinated strategy, funding a sufficient number and diversity of RTPs across HEP would be beneficial. This could see them based at different physical and

remote locations with a diversity of projects to work on, and a long-term commitment to those projects. This flexible workforce could enable cost efficiencies due to savings in compute cycles, storage, and equipment costs as a result of their work.

Realising Benefits

63. Whatever approach is taken, progress should be tracked and measured. The Key Performance Indicators should be chosen that are suitable within a technology framework, for example Technology Readiness Levels, and associated with the funding cycle and milestones. Given the nature of R&D phases, a sympathetic approach to failure needs to be built in allowing it to be recognised quickly so that resources can be redirected, and advances made.

64. Successful monitoring will generate a strong evidence trail that can be used to justify and bid for resources effectively, as well as demonstrate to stakeholders the impact on leadership, skills, and physics outcomes of the investment. Existing functions within STFC can be utilised to implement and further develop benefits realisation and monitoring and evaluation frameworks.

FINAL REMARKS

65. The PP community is conducting ADSC technology R&D, and it currently has a broad range of skills and expertise that enable it to engage in a breadth of activities. However, funding constraints have largely confined this to construction projects, increasingly forcing a necessary focus of activities in high-priority construction projects. Basic, widely applicable, and blue-skies R&D that might benefit a wider number of, or create and direct, projects has disappeared, bringing with it a risk of duplication, loss of efficiency, and missed opportunity. The ECFA and ELDG Roadmaps both respond to the ESPPU call for ramped-up and intensified ADSC technology R&D required from the international community to achieve the physics goals of future decades, focusing its direction toward distinct areas where solutions are needed to allow progress.

66. **PPTAP recommends that the UK must respond to complement the implementation of the ECFA and ELDG R&D roadmaps by undertaking an STFC-funded programme of long-term ADSC technology R&D, at least within the constraints, but not necessarily within all, of the activity areas identified in the ECFA and ELDG Roadmaps.** PPTAP also recognises that PP does not operate in a vacuum, and that whilst neighbouring communities and synergies with PP have been noted here, they do of course have similar roadmapping activities within their distinct scientific communities. However, this report's findings are broad enough to make explicit that similar issues exist in the particleastro and nuclear communities, for example, and would respond well to the same or similar solutions for PP.

67. PPTAP believes that a more strategic funding framework for this R&D in the UK would be highly beneficial, not least because the UK cannot afford, nor does it have the depth and breadth of required expertise and leadership, to play a significant role in all areas identified by the ECFA and ELDG Roadmaps. Whilst strengths can be identified in a way that allows some areas to be discounted, prioritisation is harder to achieve. The ESPPU and its related ECFA and ELDG Roadmaps and implementation provide a framework for community discussion to generate advice to STFC to formulate a UK response. **PPTAP recommends that a funded ADSC R&D framework be implemented by STFC to both direct and respond to community and STFC requirements. This should provide a breadth of funding opportunities with regard to length and monetary value, with a selection of directed responsive mode funding opportunities available for HEIs, National Laboratories, and other PSREs, and encourage low-TRL co-development with industry**.

68. Implementation of this will require funding as the status quo does not constitute a response to the ECFA and ELDG roadmaps. PPTAP recognises both the known funding constraints as well as the more recent funding opportunities available across UKRI, and **PPTAP recommends that any funding of the implementation of an ADSC technology R&D framework should be in addition to funding allocated to current and future activities within the broader PP programme**, and that this should be taken into consideration if funding were to become available.

69. Regardless of the funding levels, PPTAP feels that steps towards the implementation of an ADSC technology R&D framework for PP would be beneficial, and pave the way to a cost-effective and more resilient wider PP programme in the longer term. It should also seek to support well-defined and clearly highly beneficial cross-community examples of technology R&D and ideally at different levels of maturity and technology readiness levels. **PPTAP recommends that both initial and ongoing peer review mechanisms and agreed assessment criteria must play an important role in evaluating 'singular', cross-community or 'multiple', and 'blue skies' low-TRL, ADSC technology R&D options, and that they promote outcomes towards a resilient and sustainable PP programme.**

70. Whilst STFC and its communities can operate and deliver within this initial ADSC R&D framework, **PPTAP recommends that an STFC roadmap, rather than framework, for underpinning technology R&D direction is necessary in order to make strategic future choices**. This report is the first step to a PP or other roadmap, making a first survey of the PP landscape and fit to ECFA and ELDG roadmaps. A future iteration of a roadmap or prioritisation exercise, even if contingent on new funding, should consider including more of the evidence base and potentially across a number of PP's neighbouring disciplines:

    - active community size for the different areas of strength listed in tables 3 and 4, to judge critical mass
    - note any leadership in those areas of strengths (e.g. in CERN RD projects, EU grants, etc.) to judge international standing
    - note any strategic partners in areas of strength, for example industrial partners or international partners
    - include a complete list of UK facilities linking to areas of strength, including those with potential to be used if not already being used

- to match better the SWOO analysis with the areas of R&D expertise to understand which are the areas of strength, and whether these areas also have risks and weaknesses – think granularity. This would help interpret tables 3 and 4, and to set the current level of R&D expertise and readiness in context in order to understand which of the many areas are UK strengths
- better comprehend the status of non-project funded R&D – either through consolidated or accelerator institute grants, or funded outside of STFC, as it will illustrate any more general technology R&D areas supported within the communities

ANNEX 1: PPTAP TERMS OF REFERENCE

1 Background

1.1 The purpose of the Particle Physics Technology Advisory Panel (PPTAP) is to provide a link between Executive Board, Council, the Technology and Accelerator Advisory Board (TAAB) and the community to produce a coherent UK position on the development of the R&D Roadmaps related to the European Strategy for Particle Physics Update.

1.2 The European Strategy for Particle Physics Update, which was published in June 2020, identified the immediate need for active R&D programmes for future detectors and accelerators. The establishment of R&D roadmaps was entrusted to European Collaboration for Future Accelerators (ECFA) in the case of detector R&D and the European Laboratory Directors Group (ELDG) for the critical technologies associated with accelerators.

1.3 The work on both roadmaps will start in early autumn 2020 and is expected to be completed and report to CERN Council by summer 2021. Each activity will draw on input from a number of working groups made up of experts from Member States.

1.4 It may not be possible for the UK to be active in all areas of R&D and as a consequence, it may be decided that the UK should not have representation in every aspect of the road mapping exercises.

1.5 It is recognised that the UK will benefit from a coherent and strategic approach to future R&D in this field that plays to the UK's strengths.

1.6 The lifetime of the panel will coincide with that of the European roadmapping process, expected to conclude in summer 2021. It is therefore expected to complete its activities and its final report to TAAB by October 2021.

2 Terms of reference

2.1 The PPTAP is tasked to:

• Develop a coherent, strategic, and holistic approach to planning of particle physics and the associated accelerator R&D activities within the European context

• Consult and interact with the wider community (university groups and NLD departments) to ensure its views are canvassed and there is an appropriate and effective route for communication with STFC

• Work to establish the need for UK particle physics and associated accelerator R&D activities, in the context of the overall PP projects roadmap, as well as the current level of expertise and relevant activity within the UK,

• Maintain an overview of the ECFA and ELDG road mapping activities, and participate in road mapping expert panels

• Liaise with other advisory panels as appropriate.

2.2 The ongoing work of the panel will be reported to Executive Board as required.

2.3 The panel will produce a final report given an overview of the R&D needs of the STFC particle physics roadmap and existing areas of related expertise. This should provide options based on evidence for UK participation in each area explaining their relevance to the European roadmaps, the benefits, and risks of engaging/not engaging from both a science and technology perspective, and UK community strengths. In addition, the panel will provide advice or response to specific questions from TAAB.

3 Membership

3.1 The PPTAP should be chaired by a knowledgeable and independent senior member of STFC's communities

3.2 The membership will comprise UK representatives to ECFA and ELDG working groups, plus a small number of other UK stakeholders as appropriate. The UK representatives will be established experts in the relevant fields, drawn from the National Laboratories and university communities

3.3 UK representatives are expected to commit to:

- Engage actively with the European working groups to provide expert input on their field
- Develop a comprehensive understanding of ongoing work, interests and needs in UK particle physics, including work outside STFC where relevant
- Act objectively and in accordance with the developing overall UK position, and not to engage in advocacy for particular areas of work
- Engage actively with the Advisory Panel to ensure that all members of the Advisory Panel are well informed.

3.4 PPTAP should include observers from the computing (HTC and HPC) communities, in order to ensure a coherent future approach across all technology areas.

4 Support

4.1 Programmes Directorate will manage PPTAP and provide support for meetings.

ANNEX 2: PPTAP MEMBERSHIP AND AREA COVERED

Chair

Area Covered	Name	Institute
Particle-astro Physics	Paula Chadwick	Durham University

Accelerators

Energy Recovery Linacs	Deepa Angal-Kalinin	ASTeC STFC
Training/Skills	Robert Appleby	CI/Uni. of Manchester
High Gradient - Advanced RF	Graeme Burt	CI/Lancaster University
Muon	Chris Rogers	ISIS, STFC
Magnets	Ben Shepherd	ASTeC, STFC
High Gradient - Plasma	Matthew Wing	University College London

Detectors

Training/Skills	Adrian Bevan	QMUL
Quantum	Kai Bongs	University of Birmingham
TDAQ	Rob Halsall	TD, STFC
Gas/Liquid	Kimberly Palladino	University of Oxford
Photodetector	Angela Romano	University of Birmingham
Integration	Craig Sawyer	PPD, STFC
Solid State	Eva Vilella	University of Liverpool
Calorimetry	Iacopo Vivarelli	University of Sussex

Computing

Software	Neil Chue Hong	University of Edinburgh
HTC	Tim Scanlon	University College London

Observers

Role	Name	Institute
Director	Phil Burrows	John Adams Institute
National Lab Director	Jim Clarke	ASTeC, STFC
Associate Director	Charlotte Jamieson	Programmes, STFC
RECFA Member	Max Klein	University of Liverpool
National Lab Director	Dave Newbold	PPD, STFC
National Lab Director	Anna Orlowska	TD, STFC
Director	Peter Ratoff	Cockcroft Institute

ANNEX 3: CROSS PPTAP MEMBERSHIP WITH UK AND EUROPEAN ROADMAPPING PANELS

PPTAP Member	ECFA Role	ELDG Role
Deepa Angal-Kalinin	-	ERL R&D Panel Membership
Graeme Burt	-	RF R&D Panel Membership
Max Klein	UK Member of Restricted ECFA	ERL R&D Panel Chair
Dave Newbold	TF7 Panel Chair: Electronics and On-detector Processing	STFC PPD Director
Chris Rogers	-	Muons R&D Panel Membership
Ben Shepherd		Magnets R&D Panel Membership
Matthew Wing		Plasma Panel R&D Membership
Iacopo Vivarelli	National Contact UK	

ANNEX 4: PPTAP MEETINGS AND ACTIVITIES

There were eight meetings of the panel on the dates below via Zoom videoconference. These varied in attendance (availability), but remained quorate, and in duration dependent upon activities; multiple hours (progress updates), half-day (planning and discussion), full-day (report drafting).

Friday	18	December	2020
Friday	15	January	2021
Thursday	11	February	2021
Tuesday	16	March	2021
Friday	07	May	2021
Thursday	10	June	2021
Wednesday	21	July	2021
Monday	20	September	2021

The PPTAP Roadmap/Report was recognised as being timely in Autumn 2021, in line with equivalent developments within the ECFA and ELDG processes. Drafting commenced in June 2021, and TAAB and Science Board meeting dates were determined at this time to receive the draft/final report for information and comment. In addition, TAAB received progress updates at its scheduled meetings from the PPTAP Chair (an existing TAAB Member), and Programmes Directorate and Particle Physics Department representatives. The dates of these meetings, nature of communication, and status of the report are shown below.

Wednesday	23	June	2021	Progress Update	TAAB
Tuesday	28	September	2021	Progress Update	TAAB
Wednesday	17	November	2021	Progress Update	TAAB
Tuesday	22	February	2022	Draft Roadmap	TAAB
email		February	2022	Draft Roadmap	Science Board

ANNEX 5: PPTAP COMMUNITY CONSULTATION

No.	Question	Format	Comments
See preamble above. Once you have clicked to start the survey:			
1	*Name	Text	
Click 'Next' – New survey page with all questions visible (up to the "Tell us about yourself")			
Text at the top of this page reads: When answering the questions, responses should not be constrained by known funding pressures, but should reflect affordable propositions.			
2	Focussing on the field in which you work, but also considering the broader accelerator, detector, and computing ecosystem, what do you see as the UK's main strengths and weaknesses in technology R&D? (200 words)	Text	Max 250 words
3	Focussing on the field in which you work, and thinking about technology and R&D needs, what do you view as the major technical challenges in your field at the moment? (200 words)	Text	Max 250 words
4	What do you see as the biggest barrier to achieving the aims of your field in the next 10-20 years? (200 words)	Text	Max 250 words
5	What problems do you foresee in achieving the aims of your field from 2040? (200 words)	Text	Max 250 words

6	What will be the impact of not addressing these problems outlined in question 5? (200 words)	Text	Max 250 words
7	From which approach are the necessary technology developments in your field likely to come? Evolution of current technologies, (200 words) New and novel technologies, (200 words) A combination of evolution from current and new novel technologies (200 words)	Select as many as appropriate. Each has a text box asking to "please provide a very brief overview of technology R&D options"	Max 250 words Max 250 words Max 250 words
8	What R&D is needed *now, and in the future,* to tackle the problems you identified? (200 words)	Text	Max 250 words
9	What training, skills development, and career support mechanisms, are required to maximise UK impact in R&D? (200 words)	Text	Max 250 words
10	What are the most effective ways for the detector, accelerator, and computing communities to interact with each other, and with other disciplines? How can this be achieved? (200 words)	Text	Max 250 words
11	Do you foresee the solution to your technical or scientific challenge(s) having the potential for broader application beyond your field, or to be of particular national interest? (200 words)	Text	Max 250 words
12	Are there other points/ comments you would like to make, or any information you wish PPTAP to consider in its discussions? (200 words)	Text	Max 250 words

Click ‘Next’ – New survey page with all questions visible: “Tell us about yourself”			
13	Which of the following best describes where you work? University Industry STFC National Laboratory Other research organisation Other	Select one option	‘Other’ Needs text box to specify
14	In which field(s) do you work? Astrophysics Nuclear physics Particle astrophysics Particle physics Other STFC science area Other science area Support or administration of science Industry	Select up to three options	‘Other’ options Need text box to specify
15	How would you describe your professional background? Science Engineering IT professional Technical support Science administration/management Other	Select as many as appropriate	‘Other’ Needs text box to specify
16	How would you describe the stage of your current career? Training Early career Mid-career Late career	Select one option	
17	In bullet form, please highlight your top-three areas of expertise	Text	Follow on question from

			13
18	Name of your employer	Text	
19	Are you happy for us to contact you about your responses? Yes No	Select one option	
20	Would you be prepared to take part in a workshop? Yes No	Select one option	
21	*Please provide your email address	Text	

ANNEX 6: EXAMPLE PPTAP COMMUNITY WORKSHOP

Link to Indico site/agenda for the "PPTAP Detectors Workshop" that took place remotely 02-04 June 2021, with 124 registrations to take part: https://indico.stfc.ac.uk/event/316/

Aims of The Workshop:

1. Gather input from the community to draft the UK roadmap to detector R&D following ECFA symposia consultation phase

2. Highlight common interests between groups and with industry

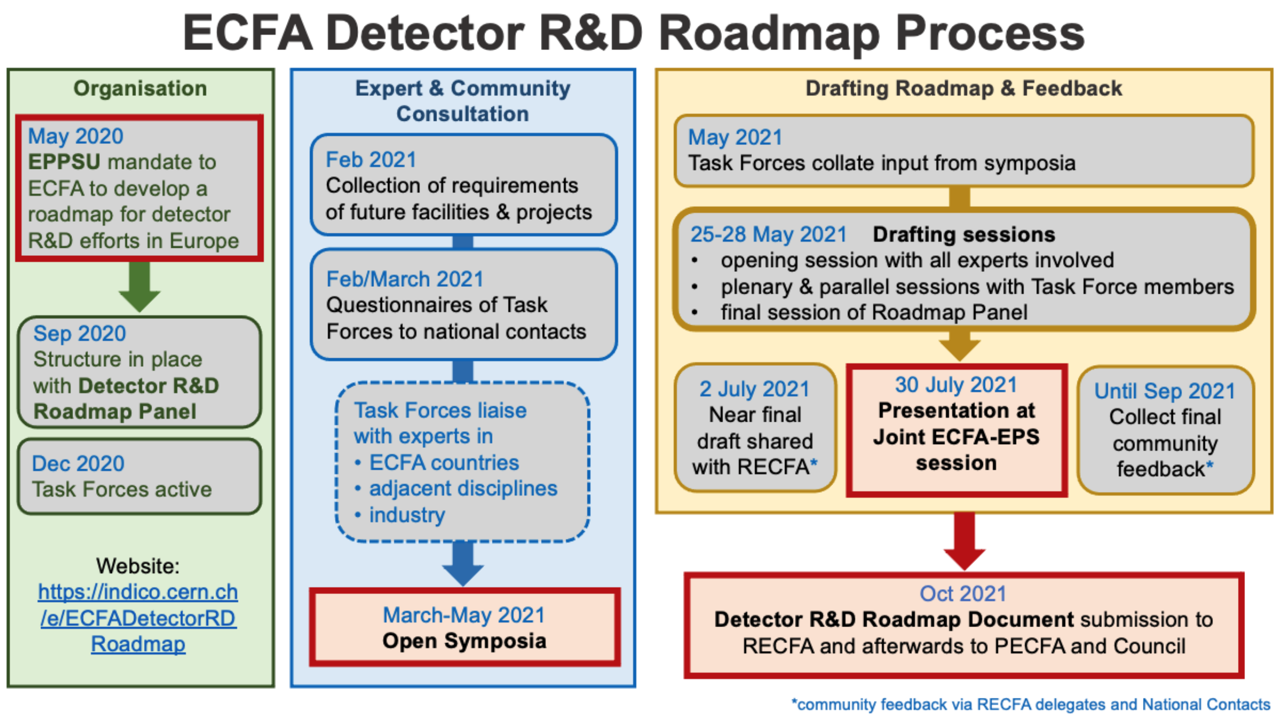
3. Gather visions for R&D structure in the next years

Sample of questions for discussion:

- What are the key technical challenges for the UK in each R&D area?
- What are the organisational / logistical barriers for us?
- How much is all this going to cost? Is it justified?
    - -- What is the likely UK participation in future projects?
    - -- What is the length, breadth and scale of R&D activities leading to them?
    - -- Are there commonalities we can exploit?
    - -- What demonstrator / exemplar projects should we target, and when?
- How do we ensure and maintain efficiency?
    - -- Commonalities between projects
    - -- Reduction of internal design competition
- What happens if we do nothing?
- What is the relationship with industry and other research areas?
- How do we convince people to act on this?
- How do we sustain a community?

ANNEX 7: ECFA PROCESS, TIMELINE, AND UK COMMUNITY CONSULTATION

Taken from the European Community for Future Accelerators R&D Detector Roadmap [website.](#)



Task Force membership:

- TF1 Gaseous Detectors
  - Convenors: Anna Colaleo (INFN Bari), Leszek Ropelewski (CERN)
  - Expert members: Klaus Dehmelt (Stonybrook), Barbara Liberti (INFN Roma), Maxim Titov (CEA Saclay), Joao Veloso (Aveiro)
- TF2 Liquid Detectors
  - Convenors: Roxanne Guenette (Harvard), Jocelyn Monroe (RHUL)
  - Expert members: Auke-Pieter Colijn (NIKHEF), Antonio Ereditato (Yale/Berne), Ines Gil Botella (CIEMAT), Manfred Lindner (MPI Heidelberg)
- TF3 Solid State Detectors
  - Convenors: Nicolo Cartiglia (INFN Turino), Giulio Pellegrini (IMB-CNM-CSIC)
  - Expert members: Daniela Bortoletto (Oxford), Didier Contardo (IN2P3-IP2I), Ingrid Gregor (DESY and Bonn), Gregor Kramberger (Jozef Stefan Insitute), Heinz Pernegger (CERN)
- TF4 Photon Detectors and Particle Identification Detectors
  - Convenors: Neville Harnew (Oxford), Peter Krizan (Jozef Stefan Institute)
  - Expert members: Ichiro Adachi (KEK), Christian Joram (CERN), Eugenio Nappi (INFN Bari), Christian Schultz-Coulon (Heidelberg)
- TF5 Quantum and Emerging Technologies
  - Convenors: Marcel Demarteau (ORNL), Michael Doser (CERN)

    - Expert members: Caterina Braggio (Padova), Andy Geraci (NWU), Peter Graham (Stanford), Anna Grasselino (Fermilab), John March Russell (Oxford), Stafford Withington (Cambridge)
- TF6 Calorimetry
    - Convenors: Roberto Ferrari (INFN Pavia), Roman Poeschl (IN2P3-IJCLab)
    - Expert members: Martin Aleksa (CERN), Dave Barney (CERN), Frank Simon (MPP Munich), Tommaso Tabarelli de Fatis (INFN Milano-Bicocca)
- TF7 Electronics and On-detector Processing
    - Convenors: Dave Newbold (RAL), Francois Vasey (CERN)
    - Expert members: Niko Neufeld (CERN), Valerio Re (INFN Pavia), Christophe de la Taille (IN2P3-OMEGA), Marc Weber (KIT)
- TF8 Integration
    - Convenors: Frank Hartmann (KIT), Werner Riegler (CERN)
    - Expert members: Corrado Gargiulo (CERN), Filippo Resnati (CERN), Herman Ten Kate (Twente), Bart Verlaat (CERN), Marcel Vos (IFIC Valencia)
- TF9 Training
    - Convenors: Johann Collot (IN2P3-LPSC), Erika Garutti (DESY and Hamburg)
    - Expert members: Richard Brenner (Uppsala), Niels van Bakel (Nikhef), Claire Gwenlan (Oxford), Jeff Wiener (CERN)

ANNEX 8: ELDG PROCESS, TIMELINE, AND UK COMMUNITY CONSULTATION

Task Force Chairs and UK Membership:

ELDG

Panel		Chairs	UK Member(s)
High Field Magnets (Low field and HTS)		Pierre Vedrine, IRFU Luis Garcia-Tabares Rodriguez, CIEMAT	**Ben Shepherd, ASTeC (PPTAP)**
High Gradient Acceleration			
	Plasma and Laser	Ralph Assman, DESY Edda Geschwendtner, CERN	Simon Hooker, Oxford **Matthew Wing, UCL (PPTAP)** Laura Corner, Lancaster
	RF (NC and SC)	Sebastien Bousson, IJC LAB Hans Weise, DESY	**Graeme Burt, Lancaster**
Muon Collider		Daniel Schulte, CERN Nadia Pastrone, INFN	Ken Long, Imperial **Chris Rogers, ISIS (PPTAP)**
Energy Recovery Linacs		**Max Klein, Liverpool (PPTAP)**	**Deepa Angal-Kalinin, ASTeC (PPTAP)**

ANNEX 9: MAPPING EXPERIMENTS TO SCIENCE CHALLENGES

The following is the full list of STFC science challenges, of which all funded activity must attempt to address. Those addressed by the STFC particle physics community (taken from the 2021 Particle physics Roadmap update) are shown in bold.

A:1. What are the laws of physics operating in the early Universe?

A:2. How did the initial structure in the universe form?

A:3. How is the universe evolving and what roles do dark matter and dark energy play?

A:4. When and how were the first stars, black holes and galaxies born?

A:5. How do stars and galaxies evolve?

A:6. How Do Nuclear Reactions Power Astrophysical Processes and Create the Chemical Elements?

A:7. What is the True Nature of Gravity?

A:8. What can gravitational waves and high-energy particles from space tell us about the universe?

B:1. How does the Sun and other stars work and what drives their variability?

B:2. What effects do the Sun and other stars have on their local environment?

B:3. What processes govern how planetary systems form and evolve?

B:4. What are the conditions for life and how widespread are they?

B:5. How diverse are exoplanets and is our earth typical?

B:6. What are the processes that drive space weather?

C:1. What are the fundamental particles and fields?

C:2. What are the fundamental laws and symmetries of physics?

C:3. What is the nature of space-time?

C:4. What is the nature of dark matter and dark energy?

C:5. How do quarks and gluons form hadrons?

C:6. What is the nature of nuclear matter?

C:7. Are there new phases of strongly interacting matter?

C:8. Why is there more matter than antimatter?

C:9. What will precision measurements of the Higgs boson reveal about the Universe?

The table below is taken from the 2021 update of the Particle Physics Advisory Panel's Community Roadmap. It shows how current experiments/activities and potential future colliders map onto the science challenges at the core of STFC.

	A1	A3	A7	A8	C1	C2	C3	C4	C5	C6	C7	C8	C9
HL-LHC (GPDs)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HL-LHC (LHCb)	✓	✓		✓	✓	✓	✓	✓	✓			✓	
Future e^+e^-	✓		✓		✓	✓	✓		✓			✓	✓
Future hh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Future eh	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-collider flavour	✓	✓			✓	✓		✓	✓			✓	
ν osc.	✓	✓		✓	✓	✓	✓	✓			✓	✓	
$0\nu\beta\beta/\nu$ mass	✓	✓			✓	✓	✓					✓	✓
e^-/n dipole moments						✓						✓	
Direct dark sector	✓	✓		✓	✓	✓	✓	✓				✓	