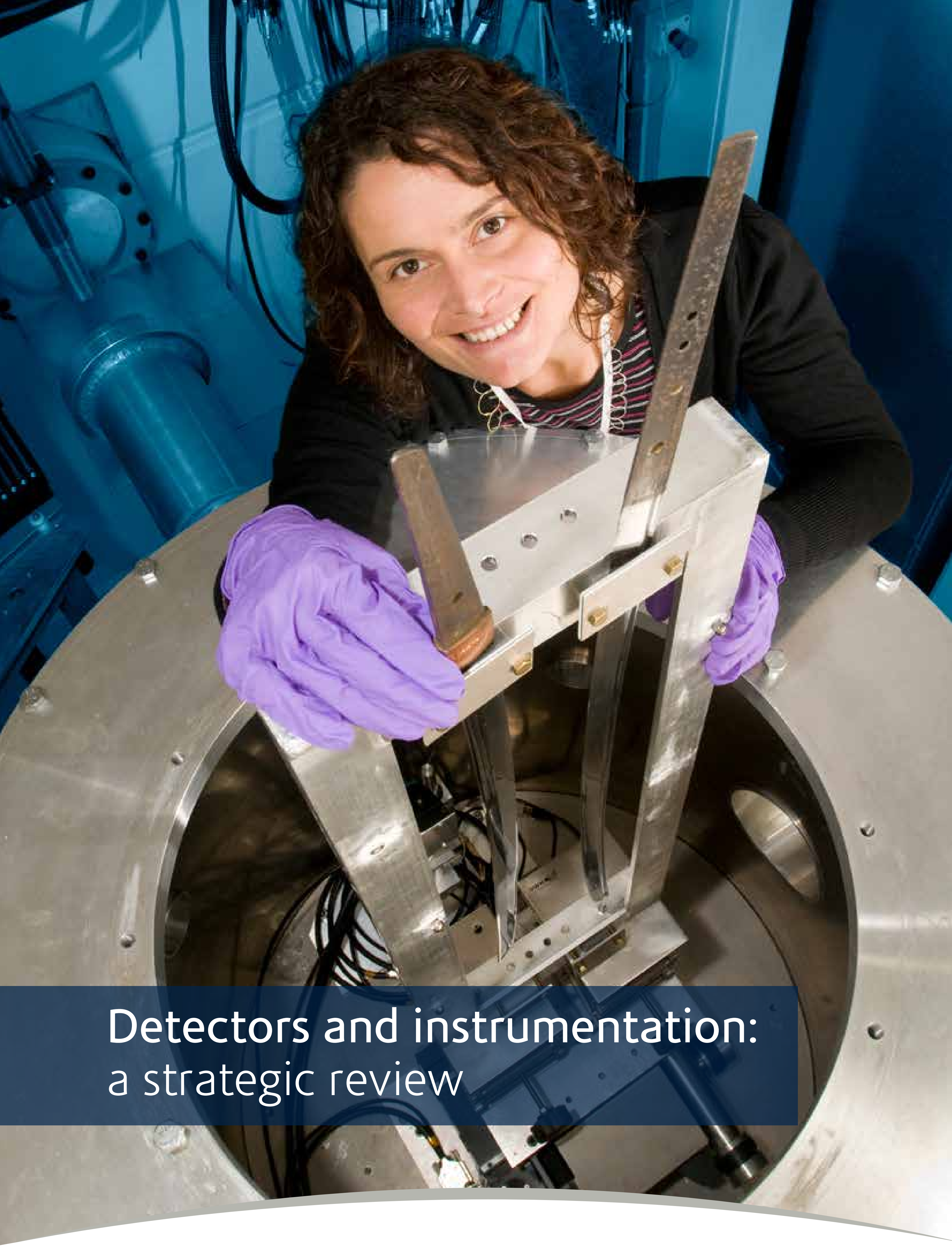

Detectors and instrumentation: a strategic review

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Contents

Foreword

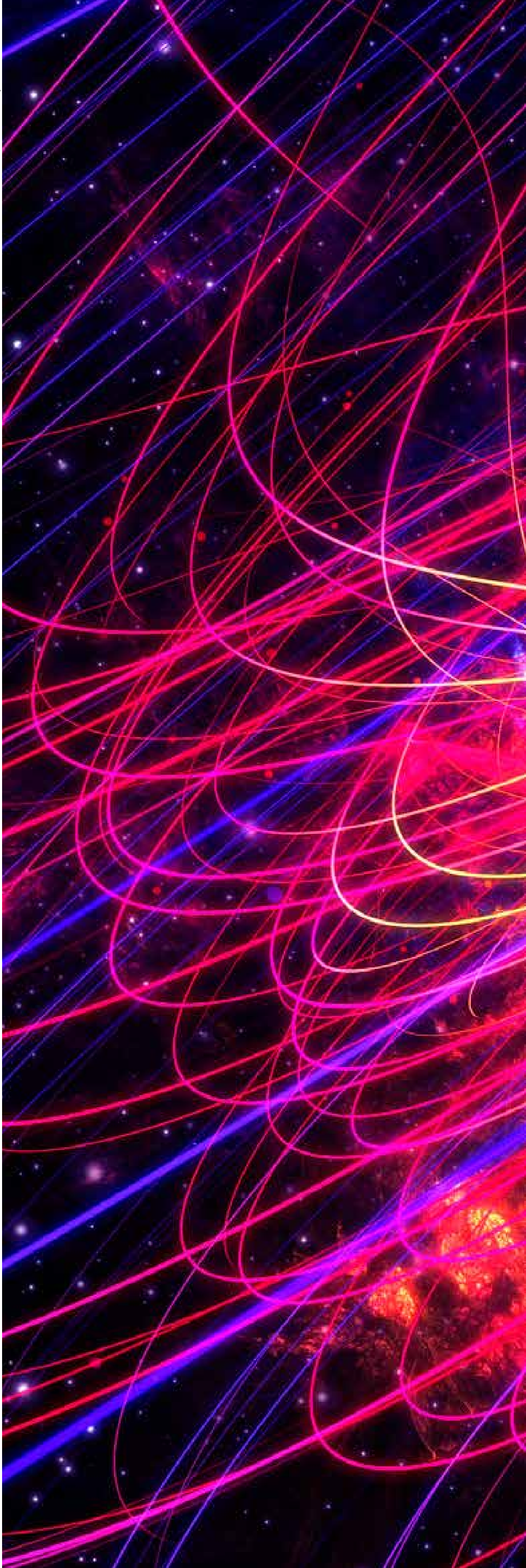
"…make yourself a rotating-needle (electroscope-versorium) of any sort of metal, three of four fingers long, pretty light, and poised on a sharp point after the manner of a magnetic pointer. Bring near to one end of it a piece of amber or a gem, lightly rubbed, polished and shining: at once the instrument revolves."

William Gilbert of Colchester, On the Loadstone and Magnetic Bodies.., (1600). Tr. Paul Fleury Mottelay (1893).

This early description of how to build a simple charge detector likely marks the beginning of the long history of the use of detectors in physics to make the invisible, visible. Today, detectors are key to addressing STFC's science challenges. Not only do fundamental physics measurements require increasingly sophisticated detectors, but detector developments of the future, such as quantum detectors, are based on our understanding of fundamental physics. Thus we have a 'virtuous circle' – physical understanding informs new detector concepts, which in turn enable greater physical understanding. In the process, many of the detectors created initially for fundamental science become vital for other applications such as communications, medical physics and imaging, to name but a few.

The Detectors Review Panel has kept all these aspects in mind: the developments required for forthcoming STFC priority areas, applications of current detector technology and detector development in the more distant future. In doing so, the panel has relied on the wide-ranging expertise of its members from national laboratories, industry and academia, both from the UK and overseas. I would like to thank them all for their hard work, and for putting up with the Panel Chair.

Professor Paula Chadwick, Panel Chair.



Detectors and instrumentation underpin much of UK Research and Innovation's research programme. Within STFC these technologies are central to our science programmes in particle physics, nuclear physics and astronomy. They also underpin the science at our large scale facilities and support the UK economy at our Science and Innovation Campuses.

In recognition of the importance of maintaining the UK's world-class capabilities in detector development, STFC initiated an activity to develop a strategic plan to underpin STFC's future priorities and investment in this area. The first stage of this process was to commission this report, which summarises a Strategic Review undertaken by an independent panel. This report presents the status and future requirements for the detectors and instrumentation used by STFC and the science communities we support.

I am extremely grateful to the panel for their efforts in pulling together this comprehensive Strategic Review report. The panel has had to grapple with the complexity of numerous detector technologies and their applications and this is reflected in the breadth and diversity of the findings and recommendations contained in this report. While it is clear that the panel's recommendations are very pertinent to activities where STFC is the principal funding lead, many are relevant to other councils of UK Research and Innovation (UKRI).

In formulating the STFC future strategy for detectors and instrumentation, we will be guided by the panel's findings. Where appropriate, we will also engage with our partners across UKRI and in industry.

We are aiming to publish the STFC strategy for detectors by the end of summer 2019.

Professor Mark Thomson, STFC Executive Chair.

Executive summary

Detectors and instrumentation are intrinsic elements of all the experimental science and technology programmes that STFC supports. As a result, this strategic review has had to grapple with a complex mix of technologies, applications and science drivers in order to arrive at the recommendations presented in this report.

Much of STFC's detector-related research and development activity is in support of the large UK facilities; Diamond Light Source (DLS), ISIS Neuron and Muon Facility and the Central Laser Facility (CLF), as well as the major international science programmes in fundamental physics and astronomy at locations such as CERN and the ESO observatories. Equally important are the space based detector applications where STFC works with the UKSA, ESA and many other organisations and industries across the world. As a result the UK's detector research, development and application activities are often at the cutting edge of technology and are recognised as world-class in many areas.

The diversity of the detectors and instrumentation activities means that the STFC-supported community is dispersed across the national laboratories, facilities and numerous university groups. In many cases the activity at a location may depend on a small number of scientists, engineers and technologists who have highly developed skill sets. Maintaining and growing these specialist resources is a challenge for the organisations and the loss of key skills represents a significant risk to STFC's science programmes.

Forging a stronger and more connected detectors community will have many benefits; from more cross-fertilisation of ideas and generating synergies between different fields of application, through to enhancing the recognition of the contribution of detectors specialists to important advances in science and technology. This report considers options to achieve this, including establishing networks and topic specific or generic detectors centres of expertise.

A number of specific technology or application needs have been identified, with recommendations to enhance or strengthen capabilities and these can be critical to enabling progress in particular science areas. However, many detector developments can also be important for multidisciplinary science needs and there is a strong history of new detector developments being quickly applied to achieve wider societal benefits including in the medical and security fields.

It is also true that the detector needs of STFC's core science areas can gain from investments being made in related fields. The increasing attention being directed at quantum technologies and how these can be applied in diverse areas is opening up exciting possibilities for using quantum techniques in space, as well as ground based experiments including gravitational wave detection and particle physics experiments.

The review has recognised that priorities for STFC investment should be driven by the needs of the 'top down' science and technology challenges that are being addressed, rather than being set by 'bottom up' opportunities in particular detector and instrumentation development.

A priority assessment has therefore been carried out that considers the science and technology gains that can be posited for the recommendations made by the review. This assessment has identified five priorities that are either essential to enable major science gains or will provide major new capabilities for a wide range of applications. These are:

- to establish an agile detectors development funding mechanism
- develop radiation hard semiconductor devices for high-energy and particle physics and medical imaging
- support the development of alternative non-silicon materials and devices in particular for neutron detectors
- assess how ground-based fundamental physics experiments using quantum detector technology can be taken forward
- assess the benefits of setting up a quantum systems detector centre for space and ground based experiments.

In addition to these, 27 other high priority recommendations are made relevant to the full range of STFC's science and technology topic areas.

The information in the report is grouped into a number of topic areas in order to capture where the findings are generic across technology and application areas and where the findings are more specific in nature. Section 2 of the report provides a high level summary of the strategic review findings and recommendations for the topic areas and section 3 presents a more detailed analysis. Detector technology is rich in acronyms and a glossary of terms is provided. A bibliography giving sources for additional background and reference information is also provided. The glossary and bibliography are contained in the appendices, together with additional technical details for some of the topic areas.

1. Introduction

STFC's Strategic Context and Future Opportunities planning document[1] identifies five technologies that are essential for the delivery of STFC's programme that cannot be procured reliably on the open market. These are:

- accelerators
- e-infrastructure
- detectors and instrumentation
- specialist engineering
- optics.

Meeting the needs for developing the skills and capabilities in the national laboratories and facilities, and in the academic groups supported by STFC, requires a strategic approach that is reviewed and refreshed on a regular basis.

In October 2017 STFC's Executive Board agreed that a cross cutting strategy should be developed to consider the needs of STFC (including Diamond Light Source) and its user communities for detectors and instrumentation. The strategy will inform the approaches to be taken to meet the future science requirements and the associated investments needed.

Detector technologies have made significant advances over the past decade with performance improvements in some areas enabling new discoveries to be made. Detector improvements have also resulted in highly cost effective enhancements to the capabilities of many large facilities. However, detector capabilities are still often the limiting factor in achieving the desired science goals.

This Strategic Review of Detectors and Instrumentation, carried out by an independent advisory panel, is a key input to developing the strategy. The panel has broad knowledge of detectors and instrumentation development and application from across the international, industrial and university sectors. The panel membership is shown in appendix 1.

Detector performance enhancement at the ILL neutron source – An upgrade programme of the ILL reactor based neutron source instrumentation suite, including the detectors, resulted in an average increase in count rate over the whole instrument suite by a factor of 24. Achieving an equivalent increase in source intensity was not technically possible.

Image credit: ILL

1. See Bibliography entry 1 in appendix 5

1.1 Aims and objectives

Detectors and instrumentation is a wide field of activity so the review has aimed to give an overview of the broad technology challenges and medium term development opportunities relevant in the topic areas of interest, but not at the level of specific, individual detectors. The principal timescale for the review's considerations has been the next 10 years including the opportunities for short term (~1-5 years) and medium term (~5-10 years) actions.

The terms of reference for the review were for the panel to consider and make evidence-based recommendations on:

- the future opportunities for detectors and instrumentation development, both in the UK and internationally, including the scale of any financial investment needed. This should include the potential for incremental developments of current systems and also for new materials and systems
- the robustness of STFC (and DLS's) needs assessments and the current capabilities (within STFC, DLS, science community and industry) in detectors and instrumentation, including identifying strengths and weaknesses against the identified needs
- the priorities for future detector and instrumentation development relevant to STFC (and DLS), including where there are synergistic opportunities for developments that can benefit multiple application areas and what actions are needed to realise these
- where STFC (or DLS) should seek to take an international leadership role, or conversely areas where minimal or no involvement would be appropriate
- the underpinning infrastructures required to deliver the high-priority detector and instrumentation needs, identifying any gaps and how these could be addressed
- the skills required to deliver the high-priority detector and instrumentation needs, where there are any gaps and how these could be addressed.

1.2 Review methodology

To ensure that the panel was well informed on the status of the extensive activities relevant to detectors and instrumentation across STFC's science and technology areas of interest, the panel was briefed on:

- STFC and DLS assessments of the current science programme requirements for detector and instrumentation, and the ongoing development activities in the national laboratories and facilities
- the detectors related elements distilled out of the recent roadmaps published by STFC's science area advisory panels and facilities[2].

In addition, STFC initiated a consultation exercise across its science communities. Coordinated responses were received via the Advisory panels and individual responses from a number of institutions. Responding organisations are listed in appendix 2.

1.3 Scope of the review

Detectors, both the sensing components and the associated instrumentation systems, are a systemic requirement across all of STFC's science and technology areas. Table 1 seeks to illustrate the complexity of the range of detector technologies and performance requirements across STFC's science areas and demonstrates the significant breadth of topic areas and activities that the review has covered. Note that this is not intended to be fully comprehensive and draws on the consultation responses and other expert inputs to the review.

2. See Bibliography entries 2-9 in appendix 5

Table 1. Illustration of detector applications and needs across STFC's science areas.

		Detector Technologies and Perfromance Requirements	Science and Technology Application Areas: Particle Physics	Particle Astrophys	Nuclear Physics	Neutron/muon	Lasers	Light Sources (synchrotrons and FELs)	Astrronomy	Space science
Sensors and detectors – types/functions /materials	**Requirements**	THz detectors (inc interface with photonics)					■	■	■	■
		Large area photon detectors	■	■				■		■
		Energy resolving cameras				■	■	■		■
		High speed	■		■	■	■		■	■
		High spatial resolution	■	■			■	■		■
		Low radioactivity		■						
		Ultra low mass and low power	■							
		Imaging (inc: backscatter, correlative & fluorescence lifetime, ToF neutrons)				■	■			
	Technologies	CCDs (inc: large area, centrioding, fully depleted, integrating)					■	■	■	■
		Scintillation detectors and multi-spectral scintillators	■		■	■	■	■		■
		Micro strip gas chambers	■			■				
		Time projection chambers	■	■						
		Cryogenic detectors		■						
		PMTs, SiPMs, MCPs,	■	■	■	■	■		■	■
		CMOS sensors (inc HR/HV)	■		■	■		■	■	
		Si/SiLi	■		■					
		Fast timing (fast Si)	■		■			■		
		Multi element, Ge and high Z	■	■	■		■	■	■	
		Silicon carbide	■							■
		Diamond materials	■			■	■			
	Emerging Technologies	Quantum based systems	■	■			■	■		■
		Superconductiong detectors (KIDS, TES)		■					■	■
		Alternative materials and fabrication techniques (inc He3, Xe etc)		■	■	■	■			■
Data acquisition, processing, electronics and interconnects	**Requirements**	Rad hard design	■			■	■	■		■
		Wavefront sensing					■		■	■
		Modal noise reduction							■	
		Advanced interconnects and compact packaging	■		■			■	■	■
	Technologies	100Gbit Ethernet links	■		■				■	
		kHz processing of Mpixel images					■	■		
		High speed serial link modelling and simulation	■		■			■		
		Readout for X-ray diffraction area and fluorescence detectors						■		
		Data compression and sparsification	■			■				■
		ASICs (multiple needs)	■	■	■	■			■	■
		Signal processing (PSA, DSP, sims, charge transport modelling)			■			■		
		High performance ADCs			■		■	■	■	■
		Time stamping, data synchronisation, thinned MAPS	■		■	■		■		

As well as the specific detector elements, the design, construction and operation of detectors requires capability in many disciplines such as:

- advanced engineering (including mechanical, electrical, electronics, software, systems)
- advanced optics (including adaptive optics, waveguide spectrometers, f-b gratings, improved optics for particle collider detectors, large interferometers for gravitational wave research)
- cryogenic systems (including small size, high reliability coolers, cryostats with low vibration)
- nano-positioning and high stability systems (for samples and optics).

The review has not explicitly addressed all these supporting disciplines, but the skill sets needed have been considered.

The detectors and instrumentation field is a complex mix of technologies and the ways they are developed, adapted and deployed to meet the science investigation needs in many research areas. The panel assessed all the information inputs to the review and carried out a mapping exercise in order to structure and help focus its analysis and develop useful recommendations. This exercise identified a number of topic areas which are listed in Table 2. The topic areas have been categorised as:

- multiple: relevant to all or many technologies and applications
- specific: mainly relevant to specific technologies or specific applications.

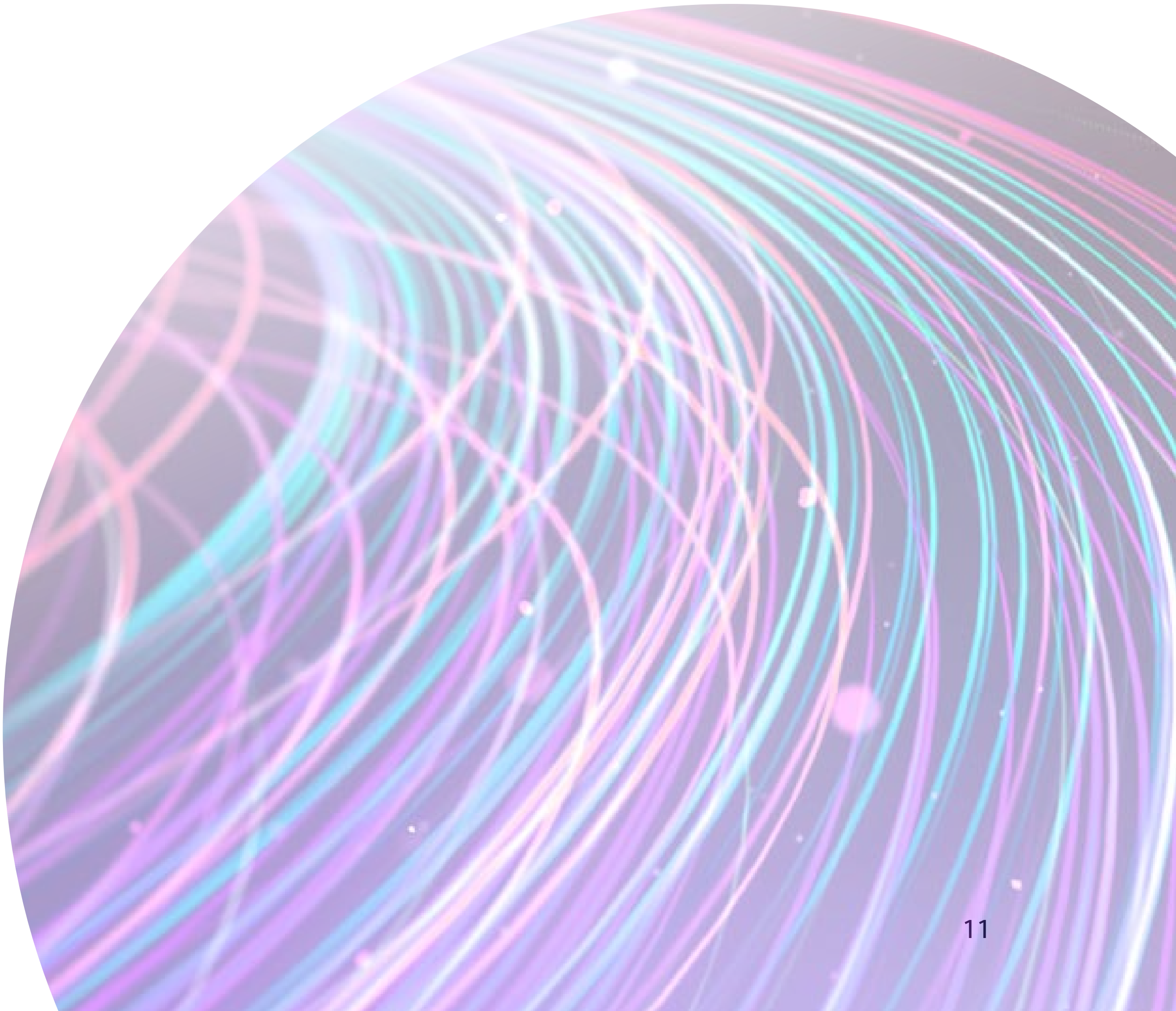


Image credit: Pixabay

Table 2. Review topic areas.

Topic area	Coverage	Multiple/Specific
People	Skills, training, career development, recruitment and retention, community building and responsive funding	Multiple
System engineering	Application of systems engineering approaches to detector and instrumentation projects	Multiple
Data chain	Techniques to manage high volume and high speed data extraction	Multiple
ASICs and FPGAs	Capabilities needed for detector electronic systems and architectures	Multiple
Interconnects	Techniques used to structure detector elements and build up into the required scale	Multiple
Fabrication and testing	Facilities for constructing and testing detectors and components	Multiple
Non-Si materials	Multi-element, germanium and gas technology applications for photons and particles (including neutrons)	Multiple
Silicon photomultipliers	PMTs, MCP PMs, SiPMs technologies	Specific
CMOS technology	Techniques to enhance the application of CMOS technologies	Specific
Ultra-fast detectors	Avalanche technologies for very high speed applications	Specific
Time projection chambers	Large scale noble gas detectors for particle physics and particle astrophysics experiments	Specific
Quantum detectors	Space based system requirements and potential applications in ground based detectors for fundamental physics	Specific
Superconducting detectors	Kinetic Induction detectors and Transition Edge heterodyne systems	Specific
Gravitational wave detectors	Future sensor options	Specific

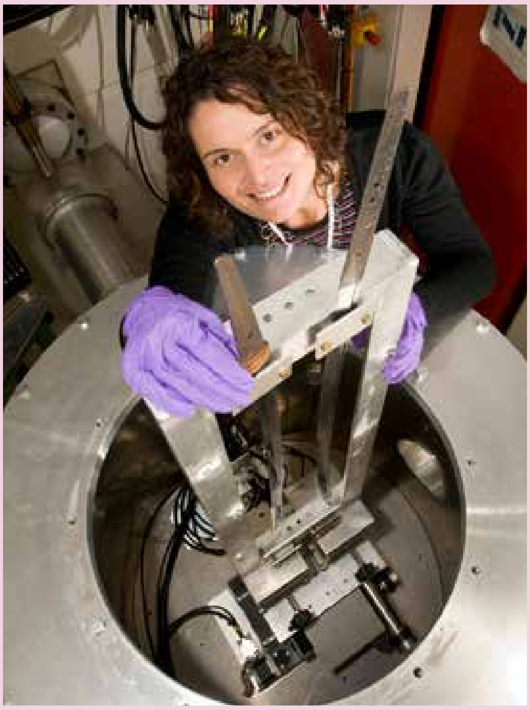
2. Summary of the review recommendations

Details of the review findings and recommendations for all the topic areas are given in section 3. Here the recommendations are summarised for each area and then the panel's analysis against priorities is presented.

2.1 Topic area recommendations – multiple technologies / applications

The panel considered the recommendations in the 'people' topic area as fundamental and underpinning to all the detectors and instrumentation activities in all the science and technology application areas. The issues include career progression, skills development, and retention.

People – skills and recognition
Highly skilled people at all levels are needed to deliver the strategic programmes – frontier research, scientific facilities, and national research and innovation campuses – which all include substantial detector and instrumentation activities.



Actions to consider:

- **establish a Fellowship scheme (or modify an existing scheme) tailored to detector related research activities in engineering and instrumentation, potentially including technician roles**
  » helps to create prestigious post-doctoral research posts that are not subject to short-term project funding constraints, aiding retention
- **establish one or more centres for doctoral training (CDTs) in detector research and development**
  » training that is currently dispersed across the communities can be more effectively delivered
- **target detectors activity for apprenticeship training**
  » builds the pipeline of new blood into the detector specialisms
- **develop a set of performance metrics that can be used to recognise individual contributions and achievements that would complement the established publication metrics**
  » helps underpin career progression opportunities for detectors specialists
- **build greater recognition, across all capability levels and skill areas, of the contributions that detector specialists make to projects, science outcomes and the maintenance of well-founded laboratories**
  » enables engineering and technical staff to be promoted and retain technical roles.

The panel considered that a broader underpinning aspect of the people related issues is the need to build a stronger detectors community. In addition to this the panel considered that there is a strong underpinning need for a flexible funding mechanism that enables rapid investigations into detector problems in all application areas. As well as reducing the risks to science programmes this would also help stimulate advanced skills development.

People - detectors community and funding
Detector expertise is dispersed across the communities and there is no agile funding mechanism to support rapid investigations.

Image credit: Pixabay

Actions to consider:

- establish a detectors network
  » forges a detectors community with enhanced recognition and a stronger voice
- investigate options for Detectors Centres, closely integrated with the Network
  » creates centre(s) of expertise and capability providing greater continuity and enabling and maintaining stronger links with industry
- establish a Detectors Development funding mechanism that can enable rapid investigation of options and trials of potential solutions
  » mitigates technical and scheduling risks across all science areas and can stimulate skills advancement.

The other multiple topic area recommendations are as follows.

Systems engineering
Systems engineering principles and practices are already applied in the major detector and instrumentation projects and there are benefits from broadening this.

Actions to consider:

- large detector and instrument development projects should have funding to recruit systems engineers, and this expertise should be available to advise and assist smaller projects as appropriate
  » strengthens the systems engineering capability across all areas - links to skills activity
- develop threshold criteria for when formal systems engineering approaches must be applied and when informal good practice approaches using systems engineering concepts can be followed
  » spreads good practice - links to the networking activity.

Image credit: Pixabay

Data chain

The ability to transfer data through and out of detectors at high speed and high volume is an increasingly important requirement and could become a bottleneck for the next generation of detectors.

Actions to consider:

- **initiate a coordinated approach by establishing a working group composed of experts from the application areas with the most significant data chain needs**

» identify the needs and potential solutions across the science areas and ensure that an optimal approach is adopted that will meet current and future data demands.

ASICs, FPGAs and interconnects

There is a need to strengthen and retain expertise in the design of the sophisticated electronics systems that are now increasingly integral to detector design, construction and operation. This includes expertise in ASICs (application specific integrated circuits), FPGAs (field-programmable gate arrays) and the underpinning digital electronics design. Similarly new interconnect technologies are being developed and the UK needs to retain its ability to stay at the cutting edge.

Actions to consider:

- **develop central libraries of ASIC and FPGA design knowledge, approaches and expertise and fund research into new design opportunities**

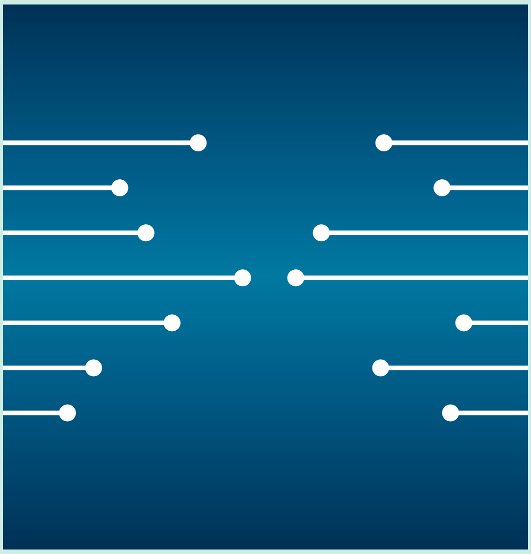
» helps build a stronger pool of UK digital electronics capability - links to the network and agile funding activities

- **invest in the Interconnects activity in the national laboratories and university community**

» maintain the critical mass of interconnect expertise that can develop and implement new techniques

- **build good industrial partnerships**

» ensures that reliable interconnect options at large scale are available when needed - links to the detectors network and centre activity.



Fabrication and test facilities

Fabrication and test facilities exist across the STFC laboratories, university groups and industry. Access to these facilities can be important to enable detector related research and development to proceed.

Actions to consider:

- **improve awareness of existing fabrication facilities relevant to detector development, including access arrangements**

» increases community awareness of capabilities - links to the network activity.

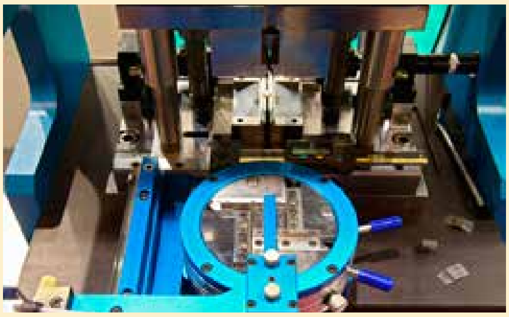


Image credit: Dreamstime.com

Non-silicon detectors

The wide-ranging application of non Si-materials based detectors to support research across large numbers of scientific areas such as high-energy physics, astronomy, nuclear physics, laser physics, condensed matter science and dark matter as well as medical imaging and security applications means there is a strong case for continued support.

Actions to consider:

- **encourage early stage material research and development especially in collaboration with UK industry, with additional resources to support an increase in researchers in these critical areas**

» helps ensure access to the highest quality materials at reasonable cost

- **support the development of alternative materials and devices, in particular to meet the needs of new and upgraded neutron facilities**

» important for areas such as neutron detectors where current materials are inadequate or too high cost

- **develop radiation hard semiconductor devices used in high-energy and particle physics, and medical imaging**

» helps future proof technologies

- **develop faster scintillating materials with higher light yield and improved gamma-neutron separation for condensed matter science and security applications**

» improves performance and extends areas of application

- **encourage greater collaboration between detector development groups and materials science departments**

» can accelerate finding new materials that can have better performance and reduced supply risks - links to the network activity

- **establish a UK stock of ultrapure noble gas for future particle astrophysics if STFC decides to support initiatives in this area**

» will strengthen the opportunity for UK leadership in future international dark matter experiments and enable small scale experiments in the UK.

Image credit: Dreamstime.com

2.2 Topic area recommendations – specific technologies/applications

Silicon photomultiplier technologies
Silicon photomultiplier technologies are used in many applications across STFC's science areas, however developments are largely driven by commercial interests which means that this is a potential risk to the science programme.

Actions to consider:

- **monitor the supply situation for SiPMs and engage with industry to ensure manufacturers are aware of the developing science programme needs**

» helps to foresee any interruptions in supply and may attract new manufacturing capability - links to the detectors network and detectors centres initiatives

- **support research and development to overcome the performance limitations of SiPMs including high dark count rate, insensitivity to xenon scintillation in the VUV (175nm) and limits on detector areas**

» helps achieve performance requirements needed for future dark matter detectors.

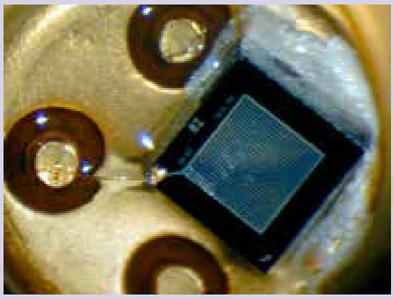


Image credit: G.Levi

CMOS technology

CMOS detectors are increasingly replacing earlier CCD technologies. To fully exploit CMOS technologies there needs to be post-processing development work to optimise devices for specific applications not covered by mainstream foundries, for example to enable improved radiation hardness and customise the spectral response.

Actions to consider:

- support establishing a back thinning capability to enable detection of radiation outside the visible region including UV, NIR, soft X-rays and high energy particles. This will require a facility capable of processing at least 8" CMOS wafers.

» will significantly enhance CMOS detector capabilities. Whilst this is of interest to industry the economics will be very sensitive to the volumes processed

- support research into new entrance window engineering for soft X-ray detection

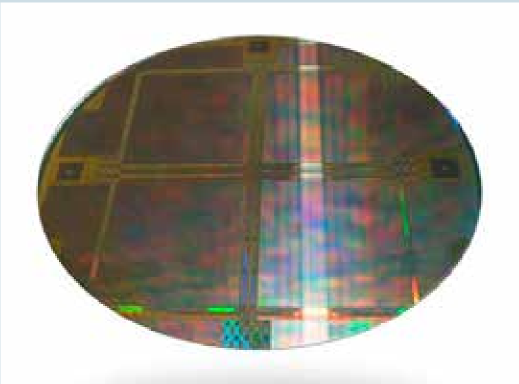
» will extend the range of CMOS application and not currently available from industry

- support the development of DMAPS (depleted monolithic active pixel sensors) for high energy physics applications and increased functionality in the packaging to provide very wide analogue response together with fast frame readout for X-ray detectors

» this links to the interconnects and ASICs areas

- support research to enable customisation of CMOS detectors for differing application requirements

» the detectors for different applications (e.g. soft and hard X-ray, gamma, neutrons) require very specific designs including that for radiation hardness but also different post processing. Space applications will require qualifying a representative device for space up to at least a TRL of 6.



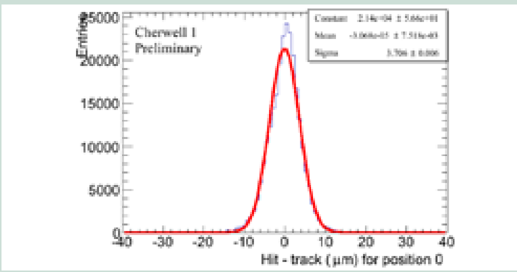
Ultra-fast silicon detectors

Very high speed silicon detectors need to be developed for a range of applications including triggering systems for future particle detectors and also in soft X-ray detection.

Actions to consider:

- support work to improve the radiation hardness of fast detectors

» needed to be able to operate in future particle detectors



Time projection chambers

Time projection chambers are key detectors in particle and astroparticle physics - for the long baseline neutrino programme, for neutrino-less double beta decay searches, and for dark matter searches. Their operation for rare event searches in ultra-low background environments, typically underground, brings specific requirements for these and similar detector systems.

Actions to consider:

- **maintain and develop the operation of the world-class radio-assay capability at Boulby**
  - » this supports the next generation of rare event searches and stimulates engagement with industry
- **develop new capability on radon assay and control and on cleanliness assay and control**
  - » this is critical to enhance the sensitivity of new dark matter and neutrino detection systems. Cleanliness assay and control also has wider application in other areas of science and in industry.

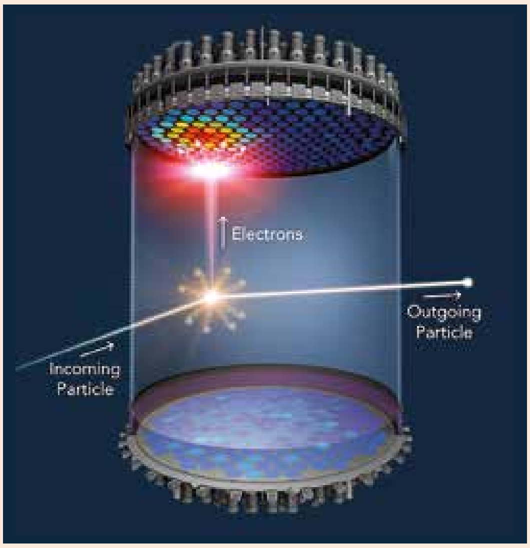


Image credit: Lux Zeplin

Quantum Detectors

Quantum technologies are being considered for space applications but there is a need to prove they can operate in the space environment. Of growing interest is the application of quantum sensor technology in ground-based experiments to enable new investigations in fundamental physics.

Actions to consider:

- **establish close working links with the National Quantum Technologies Programme (funded via EPSRC) and other stakeholders**
  - » to understand the level of investment, current achievements, and synergies with respect to quantum technologies and systems
- **continue to develop a capability focusing on the space engineering of quantum systems**
  - » builds on the current activity at RAL Space
- **assess how ground-based fundamental physics experiments can be taken forward**
  - » identify what specialized capabilities will be needed
- **assess the benefit of setting up a single facility for ground and space based experiments — a Quantum Systems Detector Centre**
  - » has the potential to serve both space and ground-based experiments - links to the Detectors Centre activity.

Superconducting detectors

The UK has world-leading expertise in superconducting detector technology spanning the areas of Transition Edge Sensors (TES), Kinetic Inductance Detectors (KIDs) and heterodyne device design, fabrication and testing. New advances in this technology are enabling a step change in current instrumentation enabling ground breaking new science.

Actions to consider:

- **support research groups working in this area contributing to international collaborative instrumentation; consider potential opportunities in future facilities that can exploit superconducting detector technology**

» this retains the instrumentation expertise and can give UK astronomers a leading role in the science opportunities from future international collaborations in these areas, and stimulate spin-off applications.

Gravitational wave detectors

Future gravitational wave detectors will need technological developments in many areas including new sensors and control systems, and instrument configuration design and simulations.

Actions to consider:

- **ensure that GW research needs are addressed in future strategic reviews covering advanced optical and engineering systems. The detector requirements of future generation GW detection systems may change and this should be kept under review**

» future quantum systems may have application in GW detectors.

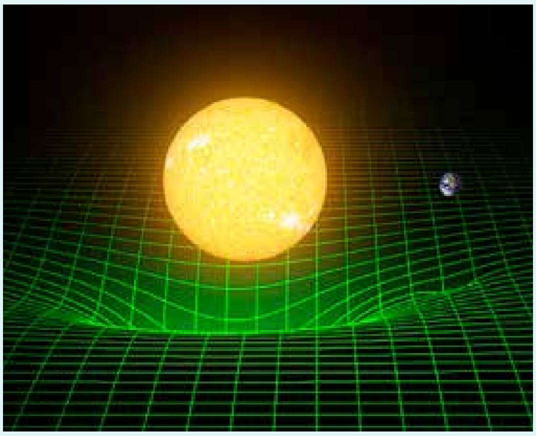


Image credit: T. Pyle/Caltech/MIT/LIGO Laboratory

2.3 Prioritisation of recommendations

The review recommendations have been developed in response to the needs and opportunities identified in the topic areas. In order to maximise the benefit from the review it is desirable to assign some measure of priority to the recommendations. Whilst it would be possible to assign priorities to the recommendations from a purely 'detector development' perspective, the panel recognises that this may not align with the priority science challenges for STFC.

In order to give a useful indication on priorities, the panel has made assessments of each recommendation using the following criteria.

Potential for delivering science gains:

- **essential** to enable major science gain(s) in a high priority area(s)
- potential to support significant science gains across **many high priority areas**
- potential to support significant science gains in **a few high priority areas**
- potential to support **incremental gains** in one or more science areas.

Potential for delivering innovation/technological gains:

- will provide **major new capabilities** for a **wide range of applications** and help give the UK a lead
- will **significantly improve capabilities in a limited area** of application or provide **new capabilities for a wide range** of applications
- will create **significant opportunities for commercialisation/application** in wider societal areas
- will provide **new capabilities** in a limited range of applications or will provide **incremental improvements** in a broad range of existing technologies.

The results of this assessment are given in Table 3 for the recommendations judged to have the highest priorities.

Table 3. Summary of the highest priority recommendations.

Recommendations considered:
- essential to enable major science gain(s) in a high priority area(s) and/or
- will provide major new capabilities for a wide range of applications and help give the UK a lead.

Topic area	Recommendations
People and funding	• establish a detectors development funding mechanism that can enable rapid investigation of options and trials of potential solutions.
Non-Si materials	• develop radiation hard semiconductor devices used in high-energy physics, and medical imaging • support the development of alternative materials and devices in particular for neutron detectors.
Quantum detectors	• assess how ground-based fundamental physics experiments using quantum detector technology can be taken forward • assess the benefit of setting up a quantum systems detector centre for space and ground based experiments.

Recommendations considered to have: • potential to support significant science gains across many high priority areas and • will significantly improve capabilities in a limited area of application or provide new capabilities for a wide range of applications.	
Topic area	Recommendations
People and funding	• establish a fellowship scheme tailored to detector related research activities in engineering and instrumentation, potentially including technician roles • establish one or more centres for doctoral training in detector research and development • target detectors activity for apprenticeship training • establish a detectors network • investigate options for detectors centres.
ASICs	• develop central libraries of ASIC design knowledge, approaches and expertise and fund research into new design opportunities.
Interconnects	• invest in the Interconnects activity in the national laboratories and university groups.
Fabrication and test	• improve awareness of existing facilities related to detector development, including access arrangements.
Non-Si materials	• encourage and resource early stage material research and development especially in collaboration with UK industry • develop faster scintillating materials with higher light yield and improved gamma-neutron separation for condensed matter science and security applications • encourage greater collaboration between detector development groups and materials science departments.
Silicon photomultipliers	• support research and development to overcome the performance limitations of SiPMs.
CMOS technology	• support establishing a CMOS back thinning capability to enable detection of radiation outside the visible region • support the development of DMAPS for high energy physics applications and increased functionality for X-ray detectors • support research to enable customisation of CMOS detectors for differing application requirements.
Ultra-fast detectors	• support work to improve the radiation hardness of fast detectors • support the development of fast amplifiers and time to digital converters.
Quantum detectors	• establish close working links with the National Quantum Technologies Programme • continue to develop a capability focusing on the space engineering of quantum systems.
Superconducting detectors	• support superconducting research capabilities and consider potential opportunities in future facilities that can exploit superconducting detector technology.

Recommendations considered to have: • potential to support significant science gains across many high priority areas, or • will significantly improve capabilities in a limited area of application or provide new capabilities for a wide range of applications.	
Topic area	Recommendations
Systems engineering	• large detector and instrument development projects should have funding to recruit systems engineers, and this expertise should be available to advise and assist smaller projects • develop threshold criteria for when formal systems engineering approaches must be applied.
Interconnects	• build good industrial partnerships for interconnects development.
Silicon photomultipliers	• monitor the supply situation for SiPMs and engage with industry so it is aware of the developing science needs.
TPCs	• maintain and develop the operation of the world-class radio-assay capability at Boulby • develop new capability on radon assay and control and on cleanliness assay and control.
Gravitational wave detectors	• ensure that gravitational wave research needs are addressed in future strategic reviews covering advanced optical and engineering systems.

Image credit: STFC/Simon Wright

3. Topic area details

This section presents the details of the Panel's analysis for each Topic Area. Further technical details for some Topic Areas can be found in appendix 3 and the bibliography giving sources of further information is in appendix 4. A glossary of terms is provided in appendix 5.

3.1 People and skills

Introduction

STFC and UKRI's strategic plans[3] clearly recognise the importance of the highly skilled people that are employed, trained and supported. Without the skills base provided by apprentices, technicians, graduates, doctoral students, postdoctoral researchers, research fellows, university academics, technologists and engineers, it would not be possible to deliver frontier research, scientific facilities, and national research and innovation campuses - all of which include substantial detector and instrumentation activities. This need was identified in the recent Balance of Programmes - Skills Report[4].

Scientists, technologists and engineers working in the field of detector development broadly work in the national laboratories/facilities, universities and industry. While many of the issues are overlapping, there are some which are unique to each context. Whilst it is difficult to precisely identify the scale of the detector specialist pool working primarily in STFC's areas of support, a reasonable estimate is that this is at least 250 people. If those working in other related detector fields in industry and academia are included then the number is significantly increased.

National laboratories and facilities

STFC and DLS employ specialist engineers and technical staff for detector development in many areas, including engineers working in the electrical, electronics, software, mechanical, cryogenics, optical, radio frequency and vacuum fields. Engineering disciplines operate in teams in specific groups and sometimes across several departments. Critical mass is important in many of the engineering disciplines, in order to provide cover, training and development, and succession planning. STFC has a very successful apprentice programme with up to 100 apprentices working in its science and engineering activities including detector development.

Universities

University groups also work on the detector development and construction for a wide range of STFC-funded projects including large detector systems such as ATLAS, CMS, LHCb, ALICE, LIGO, CTA, LUX-ZEPLIN, ELT, JWST-MIRI, ALMA, SKA, ISOL-SRS, AGATAR, NuSTAR, and many others of varying scale. There are many strong, active and highly-skilled research groups devoted to instrumentation.

Industry

Detector development has the potential to drive continued close cooperation between research institutions and industry, especially when technological synergy with commercial applications is identified. Engineers and technicians in industry are often very interested in the science applications of their products, and cooperation with research institutes can be inspiring for them. In addition, such collaboration can help research scientists, engineers, and technicians to consider potential commercial applications. Good links between the industry and research institutions can help to achieve solutions to the technical problems and challenges more efficiently.

Issues

The availability and recruitment of staff with the right skills and/or research interests for the specialised needs of detector development is a challenge across national laboratories and facilities, universities and industry. Once suitable staff have been recruited (and, where necessary, trained), retention is also an issue, perhaps more acutely for the universities and the national laboratories/facilities than industry. A frequent occurrence, particularly for technical staff and engineers in the university sector, is for them to move to industry for higher pay shortly after completing their training. Whilst universities and STFC facilities may rightly be regarded as a training resource for industry, this nonetheless places a significant strain on progressing fundamental research and development.

3. See Bibliography entries 1and 10 in appendix 5

4. See Bibliography entry 11 in appendix 5

In the university sector, the pressures of the Research Excellence Framework (REF) system can make it difficult for early-career researchers working in detector related technology development to secure permanent academic positions. Judgements in relation to recruitment are often made on the basis of published papers, whereas the research output of researchers working in technology development is primarily physical equipment (e.g. for the LHC, ELT etc.) and technical reports rather than refereed papers. Similarly, selection for fellowship schemes (e.g. Ernest Rutherford Fellowship), can favour those with a strong refereed paper publication record. This has a cascade effect on the number of undergraduate projects, the number of PhD students, the number of researchers and, ultimately, academic support for STFC detector and instrumentation projects.

Career progression and promotion is a further difficulty for detector specialists that can adversely impact on retention. Scientists in universities and the national laboratories have 'individual merit' routes available to them to progress to senior positons. These routes are academic in nature and not often suitable for an engineer (who may not have an excellent publication record, PI status or grant income). In addition, engineers and technical staff working on STFC-funded projects that are 'core support' in universities frequently find themselves on rolling fixed-term contracts. In the national laboratories, there is a perception and evidence of highly skilled specialist staff being unable to progress to more senior levels without having to take on a substantive management role resulting in a loss of expertise from projects. The recently launched Technician Commitment[5] is a good example of a response to these issues.

The above factors contribute to there being a relatively low number of PhD's specialising in detectors instrumentation in STFC and its communities. This can be compounded by the requirements of a PhD to produce results within a short space of time which can be particularly difficult in large instrumentation projects that span many years. However, there are examples where post-graduate training has been successfully developed.

A success story for detector post-graduate training at the University of Liverpool

The University of Liverpool Nuclear Physics Group has a long history in blue skies research and instrumentation innovation. The group made a strategic decision roughly 20 years ago to expand its research programme into applied areas, utilising its expertise is advanced radiation detection and associated instrumentation. In particular its work on efficient gamma ray detection is crucial to advances in areas such as medical imaging, border security, nuclear decommissioning and environmental monitoring. In order to progress in this area, students and post-doctoral research associates are essential. The group had to seek funding outside its traditional core support routes for this work and it has been very successful. They established taught Masters programmes in both in nuclear technology and medical physics. These programmes were structured to allow part-time industry based students to attend. This led to a wide range of contacts as well as improving the group's national visibility. Funding has been obtained through grants from the research councils, international research programmes, collaboration with industry, a CDT award, government bodies and university scholarships. Over the last five years the group has had 17 doctoral graduates in detectors and instrumentation. These graduates have found employment in academia, industry (medical physics and imaging, nuclear sector etc.) and the national laboratories.

UNIVERSITY OF LIVERPOOL

5. See Bibliography entry 12 in appendix 5

Recommendations

Developing and maintaining the necessary skills capacity and capability in detector related research, development, design and construction is a critical requirement across all STFC's science areas and facilities. Detector skills include a wide range of topic area expertise including:

- detector and instrumentation materials
- electronics
- software and data manipulation
- precision engineering
- advanced optics
- cryogenics
- fabrication.

As estimated above, STFC needs to maintain a detectors resource pool of at least 250 across these specialisms.

To help secure the required detectors skills base, STFC should work with its academic community, UKRI councils (in particular EPSRC) and industry partners in order to:

- establish a fellowship scheme (or modify an existing scheme) tailored to detector related research activities in engineering and instrumentation in order to help create post-doctoral research posts that are not subject to short-term project funding constraints. The potential for including technicians in the scheme should also be considered
- establish one or more centres for doctoral training (CDTs) in detector research and development so that the training that is currently dispersed across the communities can be more effectively delivered. This will create cohorts of detector post-graduate students that will help build networks and knowledge sharing across projects and institutions, including the national laboratories and facilities. Two CDTs would have the potential to realise up to ten trained specialists per year which could deliver a significant boost to the resource pool
- target detectors activity for apprenticeship training to build the pipeline of new talent into the detectors specialisms. This should include using the apprenticeship mechanisms for mid-career training/re-training and enable apprentices to be included in grant funding
- develop a set of performance metrics that can be used to recognise individual contributions and achievements that would complement the established publication metrics and help underpin career progression opportunities for detectors specialists across the full grade structure. Aspects that should be considered include: facilitating staff to undertake technical training and development throughout their career, encourage the attainment of Chartered Engineer status, encourage STFC/industry secondments
- seek to build greater recognition, across all capability levels and skill areas, of the contributions that detector specialists make to projects, science outcomes and the maintenance of well-founded laboratories. Measures could include the development of consistent and recognised role descriptions and associated pay and reward levels. Enable engineering and technical staff to be promoted on the basis of advanced technical skills and merit rather than requiring them to take on managerial roles to make higher pay grades.

Recommendations for developing the detector community

Detector development expertise and technical capability exists across STFC's science areas and facilities in the national labs, national facilities and core science communities (particle physics, particle astrophysics, nuclear physics and astronomy). The dispersed nature of this expertise coupled with the effects of time-bound project funding, means that a critical mass of capacity, knowledge and capability is hard to maintain across all the specialisms needed. As well as affecting recruitment and retention this also hinders forging and maintaining effective collaborations with industry. Two mechanisms have been identified that are recommended as solutions to these problems: creating a network for the community and creating specific centres of expertise.

Establishing a detectors network will have many benefits including:

- forging a detectors community with enhanced recognition and a stronger voice
- creating better knowledge of and utilisation of technical facilities
- enhancing the coordination of future investments
- linking centres of expertise and identifying synergy opportunities between specialisms
- building stronger links with industry and wider stakeholder groups including the learned societies and international bodies.

The detectors network should build upon existing structures (e.g. the Centre for Instrumentation) and be funded at a level that enables coordination activities to be carried out and maintained effectively. Strong engagement with the national laboratories and facilities would also be beneficial.

A detector systems centre would create a centre of expertise and capability and provide the continuity that the current structures do not easily support. This could also create and maintain stronger links with industry. The Microelectronics Support Centre within STFC's Technology Department is an example of one existing approach. In this case the focus is on training provision for industry and academia. It would be important to avoid any centre established becoming too stand-alone and disconnected from the wider detectors community.

It is recommended that any centre established and the network should be a joined up initiative, operating on the 'hub and spoke' model including the option to establish a number of centres of expertise rather than one specific centre. Consideration needs to be given to whether the centre(s) should have a particular science area or technology focus.

Recommendation for a new funding mechanism

Much of the detector development activity is carried out within the large experimental research and facility development programmes. These funding mechanisms can sometimes restrict the opportunity to carry out rapid investigations into alternative and novel techniques that may help address detector problems. As well as reducing risks to the science programmes, a new and additional funding mechanism would also help stimulate advanced skills development that cannot be funded within the main programme. Access to an agile and flexible funding scheme would be a benefit to all the topic areas considered by the panel and it is recommended that STFC should establish a detectors development funding mechanism (additional to existing mechanisms) that can enable rapid investigation of options and trials of potential solutions, and enable researchers to acquire new skills.

3.2 Systems engineering

Introduction

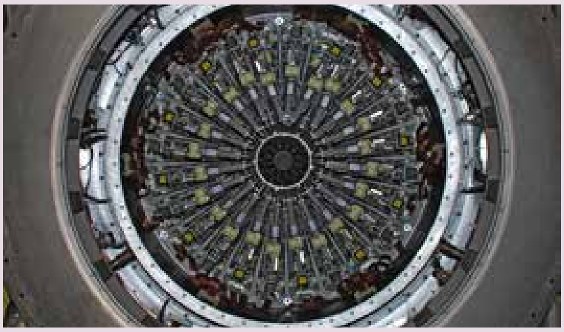
Systems engineering is an interdisciplinary engineering framework that enables the full lifecycle of any given system to be realised. This includes all aspects, from problem conceptualisation, developing the solution, sustainment during operation, expansion or upgrade during the lifetime and ultimately, decommissioning. The term 'system' refers to a collection of technical, natural or social elements which, in combination, operate to fulfil a targeted need. The aim of systems engineering is to comprehensively understand and define all aspects of the targeted need, and assure the realised system (the solution) is comprehensively fit-for-purpose throughout the implemented lifecycle.

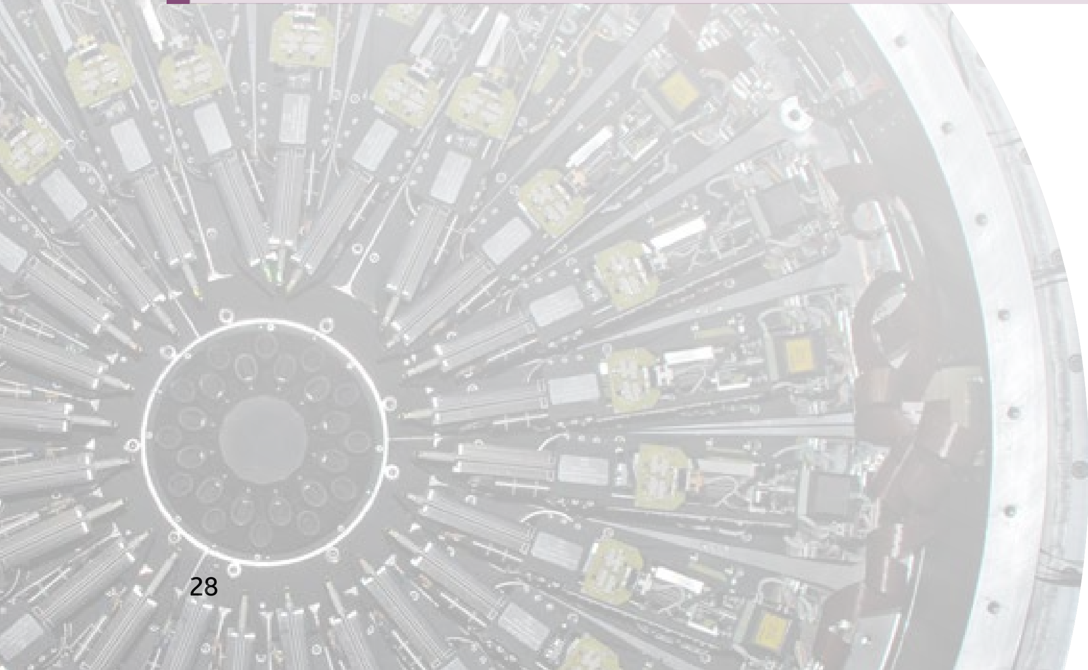
The KMOS instrument project

Built for the Very Large Telescope (VLT), the K Band Multi Object Spectrometer (KMOS) was typical of a modern, large astronomy detector instrument project in that it was developed and delivered by a large multi-national and multi-disciplinary consortium (six institutes across the UK and Germany). The KMOS consortium was led by STFC who were ultimately responsible for the delivery of the instrument to Chile and its commissioning on the telescope at the ESO Paranal Observatory.

The project office decided from the start to follow a systematic and logical process of dividing the work into packages, each with clear requirements and boundaries, but ensuring that all decisions were based on the performance of the instrument as a whole. In essence, this is the basis of systems engineering.

The management of the KMOS project followed good practice using a well-defined project management system. The difference for this project and other related projects is that the systems engineering approach was integrated into the project right from the start. As a result the instrument was delivered to the telescope in 2012, within its allocated budgets and meeting all of its original science goals, and has been working ever since.





Several aspects of systems engineering are particularly important in large detector development and construction projects funded by STFC. These typically have contributions from multiple stakeholders of varying size and capability: from university groups and small companies and contractors, to national laboratories, research councils and international funding agencies. Systems engineering also helps to manage the technical challenges of large and complex detector systems which can need an optimised approach to the engineering of mechanics, services and cooling to minimise material requirements and achieve the physics performance required. There is clear evidence that when a systems engineering approach is adopted these projects are more likely to be delivered on time, within budget, and to the agreed specification, as illustrated in the KMOS project example opposite.

Issues

Although systems engineering approaches are adopted and followed for all STFC's large instrument development projects, applying them more widely to smaller projects in the national laboratories, facilities and university groups is hampered by the lack of suitably trained staff with knowledge of the principles and how to effectively apply them. There may also be a perception that these approaches can add cost to projects and there is a lack of appreciation of the benefits that can be achieved including cost reduction through greater efficiency and reduced risks.

Recommendations

A systems engineering approach should underlie any project management plan proposed by intermediate and large scale projects. STFC and its university partners should ensure that UK-led large projects have funding to employ someone in that role. STFC should develop threshold criteria for when formal systems engineering approaches must be applied and when informal good practice approaches using systems engineering concepts can be followed. Other recommendations are that:

- STFC should ensure that best practice can propagate across projects, e.g. via Oversight Committee membership or through dedicated meetings or reviews prior to project kick-off, where systems engineers or others with this expertise can advise the new project in a timely fashion. This could form part of the detectors network function
- large projects should consider a pre-construction phase, which is when systems engineering is especially valuable. As part of project conception, experience should be shared from previous projects
- STFC and university groups leading large detector and instrument development projects should strive to hire and retain systems engineers. Where these skills are embedded in large projects, they should nonetheless be available to advise and review the smaller projects as appropriate, so that a culture of engineering quality is maintained. This should be part of the skills development activities already recommended (see section 3.1).

3.3 Data chain

Introduction

We are seeing a rapid increase of both the time-integrated data volume and the instantaneous data flux produced by modern scientific detectors which is expected to continue or even further accelerate in the short to medium term. This increase is being driven by many factors including:

- the growing physical size of detectors and the resulting increase in detection elements
- more automation of experimental systems resulting in longer data collection periods
- developments in the micro-electronics and packaging systems that has enabled a massive increase in data rates.

Issues

In many of STFC's science and facility areas, in particular synchrotrons, high repetition rate lasers, free electron lasers and particle physics experiments, the ability to handle the data flux and data volume is now becoming the limiting factor, and not the front-end sensor. Future developments in optical data transmission and data handling being driven by industry can be used in the scientific fields. However, because of the diversity of options, and the rapid rate of development, there is a risk that individual fields will develop different solutions, which are mutually incompatible. Coordinated approaches to solving these data bottlenecks need to be developed to avoid risks of duplication and expensive investments in non-optimal solutions. This needs to be done across science areas and embrace national and international needs and initiatives.

Recommendations

Solutions to the data chain challenges need to take an integrated approach, analysing the entire data chain for all applications, since the performance is determined by the weakest link in the chain and this can be dependent on the specific field of application. Recognising the breadth of STFC science interests, STFC should initiate a coordinated approach by establishing a working group composed of experts from the application areas with the most significant data chain needs. The working group should:

- make an inventory of the situation (both current and future) regarding data flux and data volume in the different application areas
- make an inventory of the current and potential future solutions in the different application areas
- make an analysis of what the potential advantages and disadvantages of an overarching solution could be, including compatibilities and incompatibilities
- make a recommendation on how to proceed.

3.4 ASICs and FPGAs

Introduction

Application specific integrated circuits (ASICs) are now key components of a detector system. They can implement a wide range of circuitry from a simple charge sensitive preamplifier to a complex system on chip with memory and digital processing. Similarly the availability of field-programmable gate arrays (FPGAs) to connect readout ASICs to data acquisition (DAQ), commodity computing and storage systems has enabled the development of highly configurable systems with high throughput.

Issues

High speed, high channel density, complex functionality, and high data rate are common requirements in high energy and nuclear physics, astrophysics, photon science, and medical imaging. The future European Spallation Source will have similar requirements for its neutron instruments. It is also often a requirement for the frontend to work in very harsh environments withstanding high radiation doses and cryogenic temperatures.

Although large experiments require a significant amount of electronics these numbers are far smaller than those of consumer electronics. The specific nature of such systems makes them unattractive for industry and requires the work of dedicated groups closely connected with the experimental teams.

Currently available CMOS nodes allow for more transistors, lower power and typically higher radiation tolerance than currently deployed chips. However advanced technology nodes and related design tools are expensive and still cannot provide a one-size-fits-all solution. The turnaround time for complex system on a chip design spans over several years and requires system engineering and corresponding planning and coordination. Diverse and dedicated development is forced to fit very aggressive project schedules and little space is left for new ideas to grow into viable solutions.

Recommendations

The unique nature of scientific detectors needs the electronics design to be included as an integral part of the detector design, therefore adequate core competencies in these areas are key to the success of detector research and development. The complexity of the new systems requires the work of larger teams across national laboratories, industry and academia. The UK has world class expertise in ASICs and FPGA design and development, however additional growth is required to address the challenges ahead. Investments in this area will benefit a broad spectrum of detector activities and provide a significant return. It is recommended that:

- an inventory of the available ASIC, FPGA and related digital systems design expertise across the UK is carried out and central libraries are created to take advantage of the expertise distributed across the UK and optimise the future use of resources. This could be carried out within the recommended Detectors Network (see 3.1).

- a funding mechanism should be established to support work on new ideas at an early stage to enable investigations of different approaches and solutions to the increasingly complex problems (this could be part of the general funding mechanism recommended in section 3.1).
- good practice approaches to system calibration should be developed: highly configurable of modern readout electronics comes at a cost, i.e. defining optimal working settings is a demanding task. This is made more difficult by the need to detect smaller and faster signals. Excellent calibration is also needed for a robust implementation of data reduction as close as possible to the front end. This task, often underestimated, requires coordinated and collaborative work involving technical and scientific personnel
- good practice approaches to Information density and power trade-offs should be developed for application at the early research and development phase, including comprehensive cost-performance analysis: e.g. GPUs offer considerable improvements in processing speed compared to CPUs but are more expensive than 'simple' FPGAs, however the cost per speed in an FPGA is very high. One example is the recent study of the LHCb online group and the HTC collaboration where the Intel Xeon with an FPGA computing accelerator has been compared with GPUs and other computer accelerators. These studies should guide system design choices
- in depth engagement with the manufacturers should be established (through the Detectors Network, see section 3.1) to facilitate the production of packaging and assembly solutions customized for specific designs. ASIC, FPGA and GPU related activities are tightly connected to development in industry. Although chip design, firmware and software development are tailored to the needs of specific experiments, they heavily rely on the availability of processes and hardware developed for other applications in the military, nuclear and consumer sectors. The manufacturing volume associated with detector research and development is too small to motivate foundries to discuss modification of processes to meet the science needs. However, hardware developed for general purpose readout and data handling can often be configured and assembled to match the science requirements.

3.5 Interconnects

Introduction

Detectors are made of a number of different components that need to be interconnected in the most efficient way. The choice of the interconnect technology depends on many factors and can impact significantly the performance and scalability of the detector system. The two main types of interconnect technologies are wire bonding and bump bonding. Direct bonding, through vias in silicon or other materials used as interposers, could be seen as an evolution of bump bonding. This evolution is motivated by the need to integrate more functionality in smaller areas, i.e. finer detector pitch with high density sensor-to-readout interconnection. It is also required to implement very fast readouts and often low and optimal power distribution.

Advanced interconnect development

The detector module of the Large Pixel Detector, developed at STFC's Rutherford Appleton Laboratory, comprises a sensor tile connected to readout ASICs by a flip-chip-bonding technique, with bumps and pitch adapter developed at RAL. The detector has been installed at the European XFEL.

Image credit: European XFEL

Issues

Interconnects are critical elements of a detector system and should be part of the detector development planning. A poor interconnect scheme can cause higher noise, generate crosstalk, reduce mechanical robustness, and limit power distribution, just to name a few effects. There are also instruments with very specific operational requirements such as: purity, operation at cryogenic temperatures, and heterogeneous integration of components with different coefficient of thermal expansion. Further research and development effort on interconnects is needed to address these challenges.

Although the most advanced interconnect technologies are already implemented in smartphone cameras and other consumer market products, those are not made available to the scientific detectors community. Vendors providing an interconnect service offer limited options, often far from state-of-the-art, and are not always reliable. To achieve good reliability a continuous process flow has to be maintained, therefore specific requests with limited number of parts are not always well served and suffer low yield.

Recommendations

World-class expertise exists within the UK. However, advanced options currently available in other countries are not available in the UK. These include heterogeneous integration, through silicon vias and direct bonding interconnects. STFC should:

- invest in the interconnects activity in the national laboratories and university community so that the existing capacity and capability can be maintained and grown in order to be able to address the future challenges. Considering the broad impact of novel and reliable interconnects technology on advanced detector systems, it is expected that investments in this area will provide significant return. Historically laboratories that have developed this capability in-house have maintained a significant advantage with respect to their competitors, therefore interconnect labs can be considered an asset.
- build good industrial partnerships to ensure the fabrication of reliable interconnect options in large volumes can be achieved when needed. The recommended detectors network would provide a mechanism to encourage this engagement.

3.6 Fabrication and test facilities

Introduction

Detector development requires the exploration of material properties and fabrication techniques. The UK hosts a large number of fabrication and test facilities ranging in size and capability and which are funded from multiple sources. The access to these facilities for STFC-funded activity depends on the facility type and the nature of the work required.

Many groups funded by STFC maintain their own facilities that may be funded from several sources. Typically, such facilities are on a smaller scale and are tailored to bespoke applications where close process control and/or flexibility in processing techniques are required.

Issues

Detector development in the UK is diverse and requires a combination of large scale general fabrication and test facilities, bespoke specialised facilities and collaboration with industrial partners. However, information regarding potential access arrangements and in-depth descriptions of the capabilities of such facilities is not readily available.

Recommendations

Producing a comprehensive directory of information on processing capabilities, or an efficient way to search for capabilities in the UK, would be extremely beneficial to researchers. Such a system would also provide smaller scale facilities an opportunity to advertise bespoke capabilities to potential collaborators. This type of resource would also be beneficial to the wider UKRI community, and could be linked to other equipment directories (such as the UK HE Facilities and Equipment Sharing Network established by EPSRC).

Generating such a resource could be relatively simple by announcing a request for facilities to complete a web-based template outlining the scope of processes available and relevant contact details to discuss use of these facilities or collaborative effort. Populating a directory of this type would be in the interest of facility managers responsible for attracting users and groups looking to exploit expertise in research collaborations. It is therefore envisaged that such a directory would grow organically.

Where facilities permit, the directory could be used to attract industrial users and collaboration – encouraging the spin out of UK developed technology. Potentially it could also have relevance across international facilities.

It is recommended that, as part of the detectors network initiative recommended earlier (see section 3.1), STFC initiates the development of a suitable detectors fabrication and test facilities directory.

3.7 Non-silicon technologies

Introduction

The important non-si detector technologies for STFC's science areas and facilities are:

- scintillator technologies
- germanium technologies
- multi-element technologies (including HgCdTe, CdTe, CdZnTe, ThBr, SiC)
- gas technologies.

As well as being deployed across a wide range of STFC's science areas, some are increasingly being deployed in applications in other fields including communications, health and security. This wider uptake has often come about from collaborations between industry and research institutes.

University of York and Kromek plc – scintillator commercialisation
The University of York developed a hand-held gamma-ray detector for Kromek using a CsI (Tl) scintillator, building on earlier work funded by STFC. The detector led to a product called D3S sold by Kromek which is intended to be worn by the law enforcement community to monitor for radiation in the field. York is now part of a US DTRA project with Kromek to develop similar systems based on next-generation scintillators like cerium bromide.

Issues

For scintillators there is a continuing need for further research and development to improve sensitivity and spatial resolution and make fabrication improvements. There are also specialist application requirements including for thermal neutrons, a need to develop new scintillating materials that are:

- affordable
- non-hygroscopic
- high neutron sensitivity
- low gamma sensitivity
- fast decay time and high light output
- radiation hard
- have a good lifetime.

Requirements for germanium detector applications include:

- miniaturisation of discrete readout electronics
- ASIC development and associated mounting of the digital processing chain on the detector and online correction of differential non-linearity for energy resolution applications
- digital signal processing.

This needs to be supported with enhanced fabrication, repair and characterisation capabilities and simulation. These are important for example for nuclear physics, synchrotron science, searches for neutrinoless double beta (0NBB) decays and imaging applications.

Multi-element detector improvements needed include larger devices, higher quantum efficiency for IR wavelengths, lower noise and large-area crystal layer growing (for SiC).

The limited access to ^{3}He for neutron detectors continues to be a significant concern for neutron scientists. Some instruments, like the Time of Flight Spectrometers, need thousands of litres of ^{3}He each. The development and use of 10B-films in gas detectors has made good progress during recent years but further work is needed. This technique has now been selected for several instruments at the future European Spallation Source (ESS) and will have application at existing neutron sources (including ISIS Neutron and Muon Source) to upgrade existing instruments.

The development of ^{3}He micro strip gas chamber (MSGC) detectors requiring a small volume of ^{3}He (less than a few tens of litres) is an approach for neutron scattering, in particular for applications requiring high counting rate and good spatial resolution. However this still relies on a sufficient volume of ^{3}He and the production of suitable glass used for the MSGC substrates.

Scaling-up of the LXe-TPC technology for a so-called ‘third generation’ (G3) experiment may require a 5-10 times increase in target mass and will present many new challenges. Research and development towards a G3 successor experiment remains the next priority in dark matter after LUX-ZEPLIN exploitation. The UK possesses virtually no xenon stock, and has no capability for isotopic separation, which is vital for 0NBB searches and may become important for dark matter searches. Contribution to the gas stock of a future experiment is likely to be a requirement for each participating funding agency. Development of new isotopic enrichment strategies, in particular using in-line gas separation techniques during the operation of the experiment, is likely to become a key area of research.

Across all the technologies, access to high quality materials used in producing devices or the devices themselves is a major issue given that a significant number are manufactured or bought from companies outside of the UK.

Developing these detector technologies requires strong materials science input. Whilst there are some good examples of cross-disciplinary collaboration, more engagement with materials science departments would be beneficial.

The successful uptake of any new detector technology requires significant research and commercial development. Research groups can investigate the fundamental material properties and develop low technology readiness level (TRL) devices but continued support is needed until the TRL is high enough to generate new markets and fully engage industry.

Recommendations

The wide-ranging application of non Si-materials based detectors to support research across large numbers of scientific areas such as high-energy physics, astronomy, nuclear physics, laser physics, condensed matter science and dark matter as well as medical imaging and security applications means there is a strong case for continued support. Given STFC's role in supporting science at major facilities, it is important to ensure adequate research and development of detectors is undertaken for future major facilities (e.g. Diamond 2, FEL, future space missions, ESS). The science return from new facilities should not be constrained by the limitations of existing detector technologies. STFC should:

- encourage early stage material research and development especially in collaboration with UK industry to ensure access to the highest quality materials at reasonable cost, with additional resources to support an increase in researchers in these critical areas
- support the development of alternative materials and devices to improve 'at-risk areas'. In particular the development of new detector types (such as 10B-films gas detectors) for neutron applications is critical for the new and upgraded neutron source facilities. Also continue to support the development of small 3He detectors for neutron applications where there is no alternative technique
- develop radiation hard semiconductor devices used in high-energy and particle physics, and medical imaging
- develop faster scintillating materials with higher light yield and improved gamma-neutron separation for condensed matter science, and for security applications
- encourage greater collaboration between detector development groups and materials science departments and carry out audits of materials supply risks (a potential detectors network action)
- establish a UK stock of ultrapure noble gas as soon as participation in a G3 experiment is supported by STFC. This would enable small scale UK experiments and strengthen the opportunity for UK leadership in future G3 dark matter experiments.

3.8 Photomultiplier tubes, microchannel plates and silicon photomultipliers

Introduction

Photomultiplier tubes (PMTs) and their newer alternatives, silicon photomultipliers (SiPMs), are the detectors of choice for a wide range of applications in particle physics, nuclear physics and particle astrophysics, neutron scattering, muon spectroscopy and also for some applications in astronomy. In addition, they are important for medical imaging, where they are often coupled to a scintillator. The key characteristics of both PMTs and SiPMs for these applications are their high sensitivity (particularly to blue light) and rapid response time (~nanoseconds) which makes them particularly useful for transient phenomena. An evolution of PMTs is the microchannel plate photomultiplier (MCP-PMT). In these devices, developed in the 1980s, the dynode chain is replaced by a microchannel plate (MCP).

First developed around 15 years ago, SiPMs may be regarded as the successors to PIN photodiodes and avalanche photodiodes (APDs). They are more robust than PMTs to both physical shocks and excess light exposure, are more compact, insensitive to magnetic fields and operate at low voltages.

Issues

The manufacturing base for PMTs has significantly declined in recent years with now only two major manufacturers. There are indications that the same contraction in suppliers is now happening for the newer technologies of MCP PMs and SiPMs. The Japanese manufacturer Hamamatsu is now the dominant supplier for almost all these detector types. This is creating a significant risk for the future science requirements that depend on these detectors, in particular for the growing reliance on SiPMs. Interruptions in supply (which could be the result of many factors, from natural disasters affecting production, through to competing orders from other larger markets) would have major impacts on the operation of a large number of STFC science projects.

There are also performance requirements that need to be addressed. The main disadvantages of SiPMs are the small areas available at present (typically up to around 50mm^2 although larger areas can be custom built at high cost), temperature dependence and optical cross-talk between cells at high gain. For astroparticle liquid xenon experiments (see section 3.11) SiPMs need to detect VUV (vacuum ultra violet) photons by using an inversed doping profile and removing the encapsulation; at the moment there are very few devices in the market that are VUV-sensitive. Low dark count rates are also needed.

Recommendations

STFC should:

- monitor the supply situation for SiPMs and maintain an awareness of the science programme requirements. This should include engaging with industry to ensure manufacturers are aware of the developing science programme needs. This could be achieved through the detectors network and detectors centre initiatives recommended earlier (see section 3.1)
- support research and development to overcome the performance limitations of SiPMs including dark count rate, sensitivity to xenon scintillation in the VUV (175nm), and to increase detector areas.

3.9 CMOS Technology

Introduction

The semiconductor technology is based on the use of silicon and progressive advancements in the technology have given continued performance improvements. Silicon has also optical properties that make it ideal for the manufacture of visible image sensors. As the CMOS technology has advanced over the years this has now taken over for the large majority of image sensors, particularly for consumer products and also increasingly in science applications.

As devices become increasingly complex, the latest trend is the development of 3D stacking to enable the performance of the imaging part of the sensor to be separated from the readout and processing. There is also a significant drive to produce pixels with lower noise with many design groups reporting noise levels below 1e and the possibility of significantly lower noise in the future. For science this is especially interesting for very low signal applications such as astronomy.

Issues

The UK has very limited capability in wafer fabrication of modern CMOS devices. However there is significant expertise in CMOS technologies including design and post processing. Applications of CMOS detectors are growing across the STFC science areas, replacing earlier CCD technologies. To fully exploit CMOS technologies there needs to be post-processing development work to optimise devices for specific applications not covered by mainstream foundries, for example to enable improved radiation hardness and customise the spectral response. In general CMOS devices need to be optimised in a number of different ways:

- for optimised detection of higher energy X-rays, NIR and high energy particles, thicker silicon is needed, which requires working with CMOS foundries to produce devices on thicker more lightly doped material, establishing back thinning processes and new designs to allow thicker silicon to be fully depleted
- for detection of lower energy X-rays and UV back thinning is essential and the most critical requirement is a process with an extremely thin dead layer at the surface
- applications with a very high radiation dose require optimisation of design, the base material being used and the post processing.

Recommendations

STFC should work with the science community and industry to develop CMOS post-processing capabilities for large wafer sizes including back-thinning, entrance window processing, device packaging and space qualification. Industry interests will be influenced by the economics which are very sensitive to the volumes. Specific development recommendations are:

- support the development of a back-thinning capability. CMOS foundries are developing back thinning capability but this is focussed on visible imaging not science applications. A UK science capability should have detection of radiation outside the visible region as the key target including UV, NIR, soft X-rays, neutrons and high energy particles. This will require a UK facility capable of processing at least 8” CMOS wafers in moderate volumes (up to several hundred wafers per month)
- support entrance window processing development. Soft X-ray science applications are growing and will require high QE at energies ~ 200 eV. Developments to date have been driven by the needs of UV detectors; soft X-ray detection will need new entrance window engineering that isn’t currently available from industry
- support the development of device packaging including interconnects. The current detectors used in high energy physics applications are hybrids (sensor bump bonded to an ASIC). Future applications will be dominated by DMAPS (depleted monolithic active pixel sensors) which could require back biasing. For X-ray detectors using CMOS technology for image sensors or active pixels, fully depleted back illuminated monolithic CMOS sensors may not be sufficient. The need is for a very wide analog response together with fast frame readout, this requires that more functionality is available in a very dense package
- Support the development of enhanced radiation hardness. Radiation hardness requires development of both design and silicon processing. The requirements are very different for differing applications with many orders of magnitude difference in dose. In addition the damage effect of most concern is also different, which therefore requires specific solutions for given applications

- support the customization of CMOS detection. The detectors for different applications (soft and hard X-ray, gamma, neutrons etc.) require very specific design including different post processing
- support the space qualification of CMOS technologies. Any facility would require qualification for space up to at least a technology readiness level (TRL) of 6 (model demonstrating the critical functions of the element in a relevant environment). This would entail making and qualifying a representative device.

3.10 Ultra-fast detectors

Introduction

The achievement of time resolutions of the order of 10–30 ps or better brings revolutionary opportunities across STFC's science areas and facilities. In the high-luminosity phase of the Large Hadron Collider (HL-LHC) the experiments will have to discern the events of interest out of an average of ~ 200 in time and out-of-time proton-proton collisions, denoted as pileup. Precision timing layers outside the volume of the tracker detectors will use Low Gain Avalanche Detectors (LGAD), a new type of Ultra-Fast Silicon Detector (UFSD), to improve vertex identification and reduce the impact of pile-up. This will be achieved by measuring the time of individual tracks with a precision of six times better than the spread of the collision time, and distinguishing between collisions occurring very close in space but well-separated in time. High speed detectors are also important tools in high power laser-plasma interaction studies.

UFSDs are useful for applications beyond STFC's core science areas. For example, improved precision in time measurements is essential for proton computed tomography (pCT) cancer treatment to measure residual proton energy to limit radiation exposure to healthy cells. LGADs could also play an important role in X-ray diffraction experiments in the few keV range. In this type of experiment, the charge deposited by the X-ray will be multiplied by the gain of the LGAD leading to an increase in the achievable signal-to-noise ratio.

Issues

A major concern for the use of LGADs at the HL-LHC is their performance in a high radiation environment. LGADs have shown sensitivity to radiation damage since the increase in leakage current due to radiation effects is multiplied by the gain value. Moreover, the junction providing the amplification gain requires p-doping concentrations of order of $10^{16}/cm^3$ and radiation induced acceptor removal reduces the gain.

Recommendations

The LGAD technology promises significant improvements in fast timing for detection and imaging technologies across STFC's science areas. STFC can help facilitate the production and refinement of these devices in the UK. The technology is still in infancy and many areas of development and performance improvements are possible. STFC should:

- support work to improve the radiation hardness of LGADs so that their potential impacts for future physics outcomes of the HL-LHC at very high luminosities can be realised
- support the development of fast amplifiers and TDCs which is essential not only for scientific applications but will also have a wide societal impact, because such technologies are needed in medical imaging. The achievement of fast timing will require novel readout and clock distribution to achieve the required time resolution.

3.11 Time projection chambers

Introduction

Noble liquid (liquid xenon and liquid argon) time projection chambers (TPCs) are used in many projects in particle physics and astroparticle physics and the UK possesses great expertise in these systems. These detectors combine excellent position resolution and tracking capability with good calorimetry properties, made possible by the excellent light and charge yields and transport properties of these dielectric liquids.

The new generation of detectors under development, for projects including the long-baseline neutrino detector DUNE, dark matter detectors LUX-ZEPLIN (LZ) and DarkSide-20k, and neutrino-less double beta (0NBB) decay searches such as nEXO, require target masses of several tonnes and need to operate in conditions with extremely low radioactivity backgrounds, typically deep underground. Gaseous TPCs are also being developed for dark matter and 0NBB decay searches, and as near detectors for the international long baseline neutrino programmes.

Issues

There are several issues affecting these systems which are common to other technologies and are covered elsewhere in this report, including photon sensors, noble element and isotope supply chain and DAQ and data chain needs. Here we consider three topics that are more specific to these detectors.

Radioactivity, radon and cleanliness control

The new challenge for the low-background experiments now under construction is radon control. The presence of a few hundred atoms of radon per tonne of noble liquid, emanating from materials and particulates, creates a significant background.

A next-generation experiment will need to control and/or remove radon during operation to achieve the desired sensitivity to both dark matter and neutrino interactions. This is the main technical risk for a future project and a step-change in technology is needed.

There are new ideas for inline radon removal from noble gases which the UK is well placed to explore, for example utilising novel atomic-trap materials tuned for radon adsorption. Improvements are also needed in radon assay sensitivity and throughput, as well as temperature-dependent emanation data for various materials.

HV delivery

Noble gas and liquid TPCs have been afflicted by electrical breakdown phenomena which have prevented their operation at nominal voltages in practically every instance, but significant progress has been made in recent times as demonstrated by prototyping and research and development efforts. Further developments may be needed to control these effects more reliably, through the treatment of surfaces and more elaborate electrostatic designs. Time is required to understand if the implemented designs (e.g. in LZ and in DUNE) have been successful. In the meantime, exchange of expertise in this area between experiments should be encouraged.

Cold electronics

For the next generation of TPCs, it is highly desirable to bring the readout electronics into the cold detector area, where amplification, digitisation and multiplexing can be performed without introducing extraneous signal count significantly. Complex electronics operating cryogenically are already being developed by the DUNE collaboration. The challenge is to extend this effort to ultra-low background solutions. Research and development is required in this area and the UK HEP community has substantial electronics expertise to play a major role. Cold electronics, including low-background developments, should be explicitly addressed by the proposed coordinating efforts on ASICs and CMOS technologies.

Recommendations

The UK can expand its leadership in radioactivity assay and control but this requires more consistent investment. Capital funding has helped seed these developments, but sustained and coordinated support is needed for people and operations. These assets already underpin the international contributions of the dark matter and 0NBB communities. Furthermore, the radon problem is intimately related to the control of dust to exquisite levels: cleanliness assay and controls are therefore central to all low-background science areas, and also needed in gravitational wave research, space instrumentation and in industry. This includes dust assay and verification, deposition models, development of advanced cleaning techniques and the availability of clean assembly facilities. Expertise has been gained in these areas but these facilities are not generally available in the UK.

We recommend funding sustainably the operation of the world-class radio-assay capability that the UK has been developing at Boulby, RAL and elsewhere, and expanding this in a coherent way to include new capability on radon assay and control and on cleanliness assay and control. This would support the next generation of rare event searches and other STFC science areas, and stimulate engagement with industry.

3.12 Quantum technologies for detectors

Introduction

Advances in experimental techniques and equipment over the past few decades have enabled the manipulation of quantum systems so that the more advanced and subtle aspects of quantum mechanics, superposition and entanglement, can be harnessed.

In 2014 the UK government announced the creation of a National Quantum Technologies (QT) Programme[6] with the aim to turn these well-known but little used effects into commercial products and to help create the associated supply chain, and help propel the UK to a leading position in this field. Similarly other nations are prioritising research and development. This has generated a very competitive international environment requiring continuous effort and ingenuity to retain a competitive advantage.

From the outset, the opportunities for space based QT applications have been highlighted by the community for example: satellite-based quantum key distribution (QKD) for intercontinental secure communication, Earth and planetary global gravity mapping, and tests of the equivalence principle. Moreover, space offers the unique, gravitationally quiet environment that is ideal for ultra-high precision measurements – essential to test the ultimate performance of quantum detectors. Finally, the space industry is an early adopter of innovation and the stakes are raised by the exacting requirements for space hardware. Quantum technologies presently being considered for space applications can be divided into two classes of quantum phenomena: matter-wave interferometry and photon entanglement.

As in all communication related technologies, QKD requires both transmitter and detector units. The detector system must be capable of single photon detection, while the transmitter is usually an entangled photon source. In terms of the actual detector technologies needed for the above applications, these can again be divided into two categories: matter-wave interferometry, encompassing both cold atom interferometers and clocks; and photon entanglement, whose current focus is QKD.

Of growing interest is the application of quantum sensor technology in ground-based experiments which may enable the investigation of several open questions in fundamental physics, with discovery options ranging from observation of new astrophysical sources to searches for cosmological sources of stochastic gravitational radiation in addition to the searches for ultra-low mass dark matter as well as tests of quantum mechanics and general relativity.

Issues

The present challenge is to bring complex experiments demonstrated in the laboratory out in the field. Although the stated aim is generally to focus on terrestrial applications, there is also a strong drive to bring quantum technologies to space. In spite of the fact that the space environment represents a further challenge to the development of QT products i.e. the need to operate in space for several years or even decades without maintenance, in a harsh thermal, vacuum and radiation environment, the benefits of better sensor performance, better measurement accuracy and faster computation are thought to be significant.

For ground-based fundamental physics experiments, although the quantum technology in these proposals is proven to work conceptually, scaling it to the size required for physics exploration is a challenge. For example, in case of atom interferometer (AI) sensors, one major thrust of work is to prove that the technique works at 100m and eventually at the km-scale, and for networked detectors located even further apart. This will be accomplished by scaling AI sensors from 1m to 10m and from 10m to 100m, and eventually from 100m to the km-scale.

6. See Bibliography entry 13 in appendix 5

Recommendations

As a relatively new technology exploitation area, one of the overarching priorities for quantum-based detectors and systems utilisation is to increase the TRL. The UK has invested substantially in the commercialisation of quantum technologies through the National Quantum Technologies Programme. This programme has, among other things, helped increase TRL, in particular with respect to terrestrial applications. Increasingly, space applications are also being considered as critical in support of terrestrial security and financial infrastructure.

STFC should investigate how the recent achievements in quantum sensors and quantum computing could be exploited for the advancement of ground-breaking science and research, both for space based and ground based physics applications. To achieve this STFC should:

- establish close working links with the National Quantum Technologies Programme (funded via EPSRC) and other stakeholders in order to understand the level of investment, current achievements, and synergies with respect to quantum technologies and systems
- continue to develop a capability focusing on the space engineering of quantum systems, being led by RAL Space
- assess how ground-based physics experiments can be taken forward including the need for specialised capabilities
- recognise the likely overlap of engineering expertise and capabilities needed for both space payloads and ground-based experiments. Consideration should be given to the benefit of setting up a single quantum systems detector centre that would serve both space and ground-based experiments.

3.13 Superconducting detectors

Introduction

The UK has amassed world-leading expertise in superconducting detector technology spanning the areas of transition edge sensors (TES), kinetic inductance detectors (KIDs) and heterodyne device design, fabrication and testing. The sensitivity of such devices cannot be rivalled by non-superconducting technologies and they have a wide range of applications in astronomy, and more widely in electromagnetic radiation and quantum sensing.

Device development and underpinning technologies also have applications in Earth observation and climate change, medical imaging, quantum computing and security.

SCUBA-2 - the next generation Submillimetre Common-User Bolometer Array at the James Clerk Maxwell Telescope
Using TES superconducting technology with 10,000 pixels, it is now undertaking its scientific programme of legacy surveys for the community. It was built by an international consortium led by UKATC, and including the University of Edinburgh, Cardiff University, the Joint Astronomy Centre in Hawaii, the US National Institute of Standards and Technology, and a consortium of Canadian universities.

Issues

Superconducting detectors are the only suitable technology for a range of far infrared and sub-millimetre astronomy instrumentation applications aligned with the science goals highlighted in the STFC's science challenges[7] including cosmic microwave background anisotropies, star formation, and galaxy formation and evolution. Significant future opportunities also exist for visible wavelength instruments, where the simultaneous energy-resolving and single photon-counting capabilities of KIDs offer great potential in realising the next generation spectroscopic instruments on new facilities such as the Extremely Large Telescope (ELT). Despite the unique ability of this technology to enable new science, superconducting detectors are not available commercially and require research facilities to develop bespoke devices. Future millimetre and sub-millimetre wavelength astronomical instrumentation calls for detector counts between one and two orders of magnitude larger than the current systems can achieve, as well as incorporating signal processing such as on-chip filtering and polarimetry. Similar increases in detector array sizes are required for energy resolving single photon counting devices where increased energy resolution towards the theoretical limit is an additional key science driver.

Europe in general has limited groups developing and supplying superconducting quantum interference devices (SQUIDs). Such devices have a wide range of applications including astronomy, medical imaging and quantum computing. The UK is also missing a dedicated programme to study the potential opportunities new superconducting materials can offer. Bi-layer and superconducting alloys have the potential to enable enhanced optical coupling to KID architectures and parametric amplification of optical signals reducing the noise in heterodyne receivers to close to or meeting the quantum limit. UK groups continue to make an impact in this important research area through modest funding distributed across several institutes. However, since STFC's withdrawal from the James Clark-Maxwell Telescope (JCMT), the UK community has had limited opportunities to deploy this cutting-edge technology and capitalise on investments made in this area. This is in stark contrast with similar groups across Europe and the United States where heavy investment over the past decade has seen a number of new instruments delivering new and cutting-edge science.

Recommendations

Maintaining research groups active in this key technology area is crucial for the UK to retain the expertise and capabilities that have been built up over the past two decades. It is recommended that a technology development programme is considered that can provide funding in addition to consolidated grant funding to align the expertise amassed by individual UK groups to address the challenges presented by future science opportunities in this area.

It is also recommended that serious consideration is given to medium-scale investment (of the order of £3-5 million) in future facilities that can exploit superconducting detector technology by way of focused instrument development led by UK researchers. Such investment would benefit instrument scientists and astronomers alike, giving the UK a leading role in the science opportunities to be gained from future international collaborations in these areas, as well as stimulating spin-off applications in other fields.

3.14 Gravitational wave detectors

Introduction

The UK has a strong track record in developing enabling technologies for gravitational wave (GW) detection, especially in the areas of test mass isolation and the central optical systems. In GW detectors operating as modified Michelson interferometers on the ground, complex mirror suspensions hold the test masses in a quiet reference frame, minimising seismic noise and the thermal noise arising from thermodynamic fluctuations. The thermal noise associated with the highly-reflective mirror coatings sets one of the critical limits to the sensitivity of current and future instruments; this will ultimately motivate the use of cryogenic optics.

7. See Bibliography entry 14 in appendix 5

The UK community is focusing on two longer term prospects which require demanding hardware developments. The Einstein Telescope is a third generation GW ground-based observatory which will cover the portion of the frequency spectrum from a few Hz to several kHz using 10km long arms and cold optics for the low frequency region. The sensitivity in the high-frequency region is ultimately set by shot noise and will require much higher beam power. The space-based LISA mission aims to cover the frequency range 0.0001—0.1Hz with a constellation of three spacecraft in a triangular configuration with 2.5 million km arm length, flying along an Earth-like heliocentric orbit. In 2017 LISA was selected by ESA as the L3 mission (launch date 2034) and has entered phase-a.

Issues

There is a wide range of promising technological developments, including new materials for mirror substrates, mirror coatings and mirror suspensions, including those for operation at cryogenic temperatures, new sensors and control systems, and instrument configuration design and simulations. These are areas where the UK is internationally regarded and expertise should be maintained.

The low-frequency part of LIGO's spectrum is dominated by technical noise that masks distant and heavy sources, and decreases data quality. New technologies are required to address this problem, including inertial and displacement sensors with optical readout and an exploration of new interferometer configurations going beyond the standard Michelson interferometer, including those measuring the speed of the mirrors or employing active media inside the interferometer. These technologies have applications and impact beyond STFC's fields of science: optical coatings and optical bonding technologies have applications in various fields of photonics and metrology, gravity sensors and inertial sensors are employed in environmental monitoring and geophysics and quantum noise reduction techniques such as squeezed light can be applied to bio-medical imaging.

Recommendations

The sensor elements of current GW research instruments can be met with existing technologies and the challenges relate more specifically to the precision optics and mechanical components that form the complete detection system. STFC should ensure that GW research needs are addressed in future strategic reviews covering advanced optical and engineering systems. The detector requirements of future generation GW detection systems may change and this should be kept under review.

4 Conclusions

In addition to the specific suggestions for action by STFC and its partners, the panel has reached the following overarching conclusions.

The track record of detector and instrumentation development within and stimulated by STFC's science and technology programmes is impressive and in many cases has resulted in the UK having a world-leading capability in some areas. However, detector technologies and the needs of the science priorities are constantly evolving. Maintaining and developing the right capabilities to meet the future needs will need strategic and tactical action involving STFC, UKRI, academia and industry.

The UK detectors community is dispersed across the national laboratories, university departments and industry teams. Strengthening this community by forging stronger links will help build and maintain the critical mass that can deliver the future capabilities needed. Integral to this is attracting, growing and retaining the specialist skills in a broad range of technology areas. Whilst skills challenges are not unique to the detectors community, there are felt to be particular issues related to career opportunities and recognition that risk eroding the detectors skills base.

STFC's detector capabilities have grown in response to the needs of its science challenges and the major facilities. In recent years there has been a successful broadening of focus to support the needs of the wider science communities and other application areas including medical diagnostics and security systems. Detector and instrumentation technologies are particularly relevant to support the growing areas of multi-disciplinary research and development. This is an area where the capabilities that STFC has created should be a major asset to the new initiatives under the Industrial Strategy.

There are exciting new detector development opportunities, such as the application of quantum technologies, that are nearing the point where they can be deployed in functional detectors in space and high energy physics experiments. This an example of how STFC can gain from investments being driven by other science and technology needs and emphasises the importance of creating a more joined up detector community.

Despite the UK's strong track record in detector development, and the successful spin-offs from STFC and the research community, the supply chains for important materials and devices are now dominated by overseas manufacturers. This is a growing potential risk to STFC's science programmes that is perhaps not fully recognised as it is spread across many programme areas.

Given the important role that detectors play in almost all of STFC's science areas, a significant amount of funding is directed at detectors related activity (although the consolidated grant arrangements means that it proved difficult to precisely quantify the detectors related funding). However it needs to be recognised that the vast majority of this investment is locked into long-term, mission-driven mission driven needs of the science programmes and major facilities. The lack of an agile and responsive funding mechanism risks hampering problem solving needs in the major programmes and stifling innovation. A modest investment here could leverage significant benefits. It is also important to recognise that new detector capabilities can only be fully exploited if the necessary operational funding is also in place.

The panel hopes that the recommendations and conclusions of the strategic review are a helpful input to the future direction of STFC's science and technology programmes.

The contributions to the review from across the national laboratories, facilities and the wider science communities in academia were critical to helping the panel respond to the aims of the review. The panel wishes to thank everyone who contributed to the consultation process.

Appendices

1. Detectors advisory panel membership
2. Consultation inputs
3. Additional information on some topic areas
4. Bibliography
5. Glossary of detector terms

Appendix 1: detectors advisory panel membership

Professor Paula Chadwick (panel chairperson)	Durham University
Professor Henrique Araujo	Imperial College London
Professor Daniela Bortoletto	University of Oxford
Dr João Cabral	Science Board (until Oct 2018)
Dr Gabriella Carini	Brookhaven National Laboratory, New York
Dr Simon Doyle	Cardiff University
Dr Heinz Graafsma	Deutsches Elektronen-Synchrotron (DESY), Hamburg
Dr Bruno Guerard	Institut Laue-Langevin (ILL), Grenoble
Dr Paul Jerram	Teledyne e2v
Professor John Lees	University of Leicester
Dr Bruno Leone	ESA ECSAT, Harwell
Dr Seppo Nenonen	Oxford Instruments
Professor John Simpson	Daresbury Laboratory and University of Liverpool

Appendix 2: consultation inputs

STFC's advisory panels were asked to provide collated responses to the following questions:

- are there any new detector needs for specific research requirements since the last roadmaps?
- if there are competing technologies developing, are there any views on pros and cons for these?
- are there any suggestions for synergy opportunities that could achieve benefits across topic areas?
- where are the most critical developments needed to enhance performance?
- are there any new technologies/techniques that should be considered?

In addition, individual inputs were invited from across the communities.

Responses were received from the following groups and individuals.

Particle astrophysics advisory panel
Input submitted by C Ghag, G. Barker, R. Gregory, S. Hild, and J. Osborne.

Particle physics advisory panel
Input submitted by Philip P Allport, Particle Physics Group, School of Physics and Astronomy, University of Birmingham (on behalf of Universities of Birmingham, Bristol, Brunel, Glasgow, Lancaster, Liverpool, Manchester, Oxford, Sheffield, Queen Mary University of London, The Open University, STFC Particle Physics Department and STFC Technology Department).

Nuclear physics advisory panel
Input submitted by Andy Boston, Department of Physics, University of Liverpool.

Physical sciences advisory panel
Input submitted by Howard Stone, Mark Brouard, Andrew Beale, Kate Lancaster and Colin Danson

Life sciences and soft matter advisory panel
Input submitted by Martin D. King, Department of Earth Sciences, Royal Holloway University of London.

Skills and engagement advisory board
Input provided by Gert Aarts, Andrew Randewich, Ineke De Moortel, Colin Pulham, Sarah Matthews, Mark Cropper, Dave Walton, Jason Gow, Daisuke Kawata, Ian Hepburn, Geraint Jones, MSSL-UCL.

Imperial College London
M.O. Wascko and Antonin Vacheret.

Northumbria University (Newcastle upon Tyne)
Eamon Scullion.

School of Mathematics and Physics - Astrophysics Research Centre QUB
Mihalis Mathioudakis.

Department of Physics and Astronomy, University of Leicester
Paul O'Brien.

Appendix 3: Additional information on some topic areas

Data chain

Data chain is a very generic term. What is meant here is the entire path between the 'detector front-end', producing digital data (bits), and the memory or disks of the DAQ computers. More often than not, the detector front-end includes an FPGA, which besides controlling the front-end is involved in or responsible for data handling and transmission. Therefore, this is to be considered part of the data chain. On the contrary, any analog-to-digital conversion is not. On the other end of the data chain, any science-based operation on the data or data analysis is not any longer part of the data chain. Nevertheless, the data chain can include hardware and or structures that allow for science based data manipulations.

There is an exponential increase of both the time-integrated data volume and the instantaneous data flux produced by modern scientific detectors. This trend is expected to continue or even further accelerate for the time being. There are a number of clear reasons for this.

1. Detectors are continually are getting larger, not only in physical size but more so in number of detection elements (e.g. pixels) working in parallel.
2. Experiments are getting increasingly automated, resulting in more uptime, which increases the time integrated data volume.
3. Thanks to the developments in the micro-electronics and packaging industries, front-end modules show a massive increase in data rates.

In various fields, for example synchrotron, free electron laser and particle physics, the data flux, and to a certain extent the data volumes, are now becoming the limiting factors, and no longer the detector front-ends. At the same time, there are rapid developments, in optical data transmission (for instance multiple terabits/second over a single fibre) and data handling (FPGA, GPU, etc.) in industry that can, should and will be used in the scientific fields. Due to the diversity of options, and the rapid pace of developments, there is a non-negligible risk that individual fields will develop individual solutions, which are mutually incompatible. Whereas the detector front-end as well as the data analysis are very science specific, data transmission and data reception are, to a very large degree, generic. Since these technologies and developments are increasingly costly and manpower hungry, there should be an overarching (STFC, UK and beyond) approach to address these upcoming bottlenecks in data flux and data volumes.

As noted above, there are technical solutions, both for the data flux and data volume increase. Specific areas to address include:

- hardware for high-speed optical data transmission, either commercially available (telecommunication mainly), or under development at research laboratories (optoelectronics and laser labs)
- intermediate layers with intelligence (FPGA, GPU, CPU, etc.) for data reduction
- data reception hardware (switch yards and computers)
- data transfer and storage protocols.

It should be noted that:

- the UK has a strong history in DAQ and data handling for scientific applications
- other countries are establishing structures to encourage a more unified approach in the data handling field (e.g. the Helmholtz Association recently created a new programme for Data Management and Analysis, DMA).

Application specific integrated circuits (ASICs)

Modern detectors are capable of very sophisticated signal processing. This is possible thanks to the high level of integration at the front end and the high-performance back end. Since IC foundries and design tools have become accessible to the scientific community, microelectronics has played an increasingly prominent role in detector development. Application specific integrated circuits (ASICs) are now key components of a detector system. They can implement a wide range of circuitry from a simple charge sensitive preamplifier to complex system on chip with memory and digital processing. Similarly the availability of field-programmable gate arrays (FPGAs) to connect readout ASICs to data acquisition (DAQ), commodity computing and storage systems has enabled the development of highly configurable systems with high throughput.

It is difficult to think of a single detector without an ASIC and/or an FPGA. Noble gas or liquid time projection chambers, strip and pixel detectors, superconducting bolometers, all require complex electronics. Similarly the high granularity and speed required by current and future experiments (will) result in very high data rates, pushing the limits of data transport and processing, and demanding further data reduction as close as possible to the frontend.

The unique nature of scientific detectors needs the electronics design as integral part of the detector design; therefore adequate core competencies in these areas are key to the success of detector research and development.

ASIC, FPGA and GPU related activities are tightly connected to development in industry. Although chip design, firmware and software development are tailored to the needs of specific experiments, they heavily rely on the availability of processes and hardware developed for consumer applications. There are very few IC foundries in Europe and none in UK. The manufacturing volume associated with detector research and development is too small to motivate foundries to discuss modification of processes to meet our needs. On the other hand hardware developed for general purpose readout and data handling can be configured and assembled to match our requirements. More in depth engagement with the manufactures could provide, in some cases, packaging and assembly solutions customized for specific designs.

Non-silicon materials

<u>Scintillators</u>
Scintillators play a key role in a number of scientific areas that come under the remit of STFC including:

- high energy astronomy
- nuclear physics
- laser physics
- condensed matter science
- dark matter.

The importance to medical imaging cannot be emphasised enough as they are used in most nuclear medicine imaging systems and seen as absolutely necessary to improve the dosimetry in radiotherapy systems and in the development of new imaging systems capable of operating in theatres or at the patient bedside.

Scintillators come in many different forms and a wide range of materials that can be matched to the application where they are best suited. Table A1 lists a selection of scintillators that are in use or under development (this is not exhaustive but indicative of the wide variety available).

Scintillator	Peak Emission Wavelength (nm)	Light Yield (ph/keV)	Effective Z	Destiny (g/cm^3)	Suppliers
CsI(TI)	550	66	54	4.51	Hamamatsu
CsI(Na)	420	41	54	4.51	Epic/Hilger/Saint-Gobain
LYSO(Ce)	420	29	65	7.1	Saint-Gobain/Hilger
YAG(Ce)	550	8	32.6	4.55	Epic/Hilger/Saint-Gobain
GLuGAG(Ce)	545	50	38.7	6.8	Hilger
BGO	505	8	75.2	7.13	Epic/Hilger/Saint-Gobain
Gadox(Tb) (Dense Screen)	545	60	61.1	6.53	Scintacor/Mitsubishi
Gadox(Pr,Ce,F)	513	35	61.1	6.53	Scitacor
GOS(Pr)	511	50	61.1	7.34	Toshiba
Hafnium Dioxide (Ce, Y)	600	31	67.3	9.86	Not manufactured
GSO	440	8	59.4	6.7	Molecular Technology
LuAG(Ce)	520	14	62.9	6.7	X-zlab
LSO(Tb)	535	52	66	7.4	ESRF

Uses

Medical imaging[1]:

- SPECT
- PET
- small field of view hybrid gamma cameras.

Gamma-ray astronomy[2]

- liquid and NaI(Tl) scintillators - Lanthanum tri-Bromide ($LaBr^3$(Ce)) and Cerium tri-Bromide ($CeBr^3$).

Dark matter:

- large volumes of liquid xenon at cryogenic temperature (10 tonnes in the case of the LZ experiment)
- gadolinium-loaded liquid scintillator for anti-coincidence veto.

Nuclear Physics and Security applications - large volume gamma and neutron scintillators:

- $LaBr^3$/$CeBr^3$ arrays (fast timing for applications such as DESPEC @ FAIR)
- fast neutron scintillators such as NE213, EJ309.

Condensed matter science - need for large surface of thermal neutron sensitive scintillator, a list of them (non-exhaustive) is shown in table A2:

- ZnS:Ag/LiF is used in many neutron instruments at ISIS. Its main limitations are: low counting rate due to strong afterglow, and non transparency of the scintillator material, which limits the maximum thickness of the screen to a few hundreds of micrometers (resulting in low detection efficiency for short wavelength neutrons)
- LiF glass (GS20) has a fast decay time but is expensive, and its gamma sensitivity is a problem in some configurations.

1. See Bibliography entry 15 in appendix 4

2. See Bibliography entry 16 in appendix 4

Scintillator	Decay time (μs)	PL peak (nm)	PL range (nm)	Hygroscopic	Effective Fiber coupling	Gamma sensitivity
GS20	~0.06	410	360-495	No	Kuraray UV-Blue (1)	~ 2 X 10^{-4}
ZnS:Ag/LiF	~0.2, 100s	450	400-500	No	BCF92 BCF91a Kuraray Y-11	$3*10^{-7}$
ZnO:Zn/LiF	~1.7	500	440-590	No	Transparent Kuraray Green-Orange	$<10^{-5}$
TRUST LiCAF	~1.5	375	360-460	No	Kuraray UV-Blue (1)	~ 2 X 10^{-3}
TRUST LiCAF (2)	~1.9	378	350-460	No	Kuraray UV-Blue (1)	$\sim3.5*10^{-3}$
LiCAF:Eu	~2.2	370	350-460	No	Kuraray UV-Blue (1)	$\sim10^{-2}$
LiI:Eu	1.4*[2]	461	435-500	Yes	BCF91a Kuraray Y-11	$\sim2*10^{-5}$
CLYC:Ce	6.3,1.4 and 0.45*[3]	374	355-440	Yes	Kuraray UV-Blue (1/2)	$\sim2*10^{-5}$

Industrial suppliers

- Pycko – Plastic scintillators, liquid scintillators, ZnS:Ag scintillator
- Eljen Technology (Southern Scientific) - Plastic scintillators, liquid scintillators, ZnS:Ag scintillator
- Advatech - CsI(Tl), YAG(Ce)
- Mi-Net - wide range of scintillators
- Lablogic - Cerenkov Scintillation Cells.

UK manufacturers: Scintacor, Cambridge – CsI, ^{6}Li glass, Gadox / GOS, BaFCl:Eu

Multi-element detectors – SiC, Ge, HgCdTe, CdTe, CdZnTe, ThBr….

Non silicon semiconductor detectors are being developed for a wide range of application areas (e.g. medical, nuclear, astronomy) but there a number of obstacles that are preventing their uptake including cost, fabrication techniques and access to high quality materials. Research and development is taking place within STFC-funded groups but also in non-STFC funded researchers (for example, SiC at University of Newcastle and Warwick, GaAs, AlGaAs at University of Sheffield and The Future Compound Semiconductor Manufacturing Hub, Cardiff).

Uses

- germanium detectors, CZT detectors, room temperature operated high Z semiconductors (Nuclear physics, neutrino physics and medical, environmental, decommissioning and security imaging)
- NIR/IR camera technologies – the use of HgCdTe devices (ground and space based astronomy) – further development needed including larger devices, higher quantum efficiency for IR wavelengths (i.e. 1.7μm, 2.5μm, 5μm, or 10μm and lower noise

- SiC is a potential candidate for high performance hybrid pixel detectors if a further progress in a large-area SiC crystal layer growing can be made.

Germanium detectors are the best for high resolution gamma spectroscopy. Ge detectors are necessary for the UK nuclear physics programme, for example AGATA, are key instruments for light source experiments (e.g. DIAMOND/ESRF) and for the neutrino-less double beta decay projects Majorana, GERDA and LEGEND. There are no UK suppliers of Ge processed material. However, the UK is a world leader in the characterisation and design of detector systems. The UK has expertise in front end detector design and cryostat integration. Key technologies and capabilities required to enable the future science programme include:

- germanium detector fabrication, repair, characterisation and long term support
- miniaturisation of discrete readout electronics (JFET based PAs) for germanium detectors. CMOS readout. Germanium ASIC and associated mounting of the digital processing chain on the detector
- online correction of differential non-linearity for energy resolution applications
- key engineering support is required to support these developments at STFC laboratories and HEI's where appropriate.

Photomultipliers (PMTs) and SiPMs

Photomultipliers have been in existence since the 1930s. They are based on the photoelectric effect, whereby the initial photoemission of electrons from a photocathode is multiplied by a series of dynodes which produce secondary emission to provide a measurable electric pulse. The electrons are accelerated and focused by the electric potential across the dynodes; the gain of the PMT is controlled by the number of dynodes and is typically a factor of ~ 10^6. The cathode usually consists of a deposited photo emissive semiconductor, the spectral sensitivity depending on the material employed: bi-alkali (e.g. SbKCs) for the visible region, multi-alkali (e.g. SbNa2KCs) for visible plus IR, alkali-halide (e.g. CsI) for UV sensitivity and compound semiconductors (e.g. GaAs) for broadband applications. The whole is enclosed within an evacuated glass tube, with a transmissive window of glass or fused silica. Multi-anode PMTs (MAPMTs), which provide for finer pixellation in a single detector, are also now available. PMTs are easily damaged (by physical damage to the vacuum tube or exposure to a bright light), require a high tension power supply and are sensitive to magnetic fields. Despite these disadvantages, they are stable, low-noise detectors and remain the preferred option for high-speed, large-area light detection.

An evolution of PMTs is the microchannel plate photomultiplier (MCP-PMT). In these devices, developed in the 1980s, the dynode chain is replaced by a microchannel plate (MCP). The MCP consists of a large number of glass capillaries, each between 6 and 20μm in diameter, bundled together to the rear of a photocathode. The capillaries are coated with a photo-electron emitting material and an electric field is applied across the ends of the capillaries. When a photon impinges on the photocathode, the resulting electrons are multiplied and accelerated through the MCP, providing similar gain to a conventional PMT. The small size of the individual capillaries means that the spread in arrival times of the electrons is very small, resulting in pulse widths of a few 10s of picoseconds. This makes MCP-PMTs particularly suitable for applications where extremely rapid single-photon-counting is required. The structure of the MCP enables spatial information to be retained and simultaneous events can be read out. MCP-PMTs are also much more robust than PMTs in high magnetic field environments. The main disadvantages are the high voltages required for operation (a few kV) and aging of the MCPs due to ionisation, though this has been greatly improved recently by new coating techniques.

First developed around 15 years ago, SiPMs may be regarded as the successors to PIN photodiodes and avalanche photodiodes (APDs). They are solid-state detectors based on avalanche photodiodes operated in Geiger mode (G-APDs), with a bias voltage between 10 and 25% higher than the breakdown voltage. These provide high gain

(~10^5-10^7) and, as the active layers of silicon are thin (2-4μm); the breakdown process is rapid, resulting in excellent timing properties. Individual G-APDs are small, between 10 and 50μm, so they must be tiled together to produce a detector of reasonable size, sometimes known as MPPCs (multi-pixel photon counters). SiPMs have particularly good single-photon counting characteristics, with a well-resolved photoelectron spectrum that is not possible with a PMT. They are also more robust than PMTs (including resisting damage due to light exposure), are insensitive to magnetic fields and require only a few 10s of Volts for operation. The main disadvantages are the small areas available at present (the maximum being around 50mm^2), temperature dependence and optical cross-talk between cells at high gain.

Uses of PMTs (including MAPMTs)

Medical imaging:

- flow cytometers
- PET scanners
- gamma cameras.

Other Commercial Applications:

- sewerage (Nuron)
- muon tomography
- security (e.g. portal monitors).

Gamma-ray astronomy:

- Imaging Atmospheric Cherenkov Telescopes (CTA).

Dark matter:

- liquid xenon detectors (LUX-Zeplin)
- liquid argon detectors (DEAP-3600).

Particle physics:

- lalorimeters (LHCb, CMS)
- neutrino detectors (T2K, Super-K, Hyper-K, MicroBooNE, MiniBooNE)
- muon detectors (MICE).

Nuclear physics:

- time-of-flight measurement (LYCCA)
- Cherenkov counters (JLab)
- neutron detection
- fast gamma measurements (FATIMA).

Uses of MCP-PMTs

Medical imaging:

- MRI scanners
- PET.

Other commercial uses:

- nuclear Industry
- LIDAR systems.

Particle physics:

- Ring imaging Cherenkov detectors (LHCb).

Uses of SiPMs

This lists the current, or immediately intended, applications of SiPMs. It is likely that many, if not most, of the applications listed for PMTs above will eventually employ SiPMs.

Medical imaging:

- PET scanners
- dose monitoring.

Other commercial appplications:

- radiation safety monitors (Kromek)
- muon tomography
- oil exploration (Halliburton).

Gamma-ray astronomy:

- imaging atmospheric Cherenkov telescopes (CTA).

Particle physics:

- neutrino detectors (T2K, DUNE)
- calorimeters (CMS upgrade, ILC)
- trackers (LHCb upgrade).

Commercial producers and developers

PMTs: Japan: Hamamatsu; **US/UK:** ET Enterprises

MCP-PMTs: France/Netherlands/USA: Photonis; Japan: Hamamatsu; UK: Photek

SiPMs: Canada: Zecotek; China: NDL; Germany: KETEK, First Sensor; Republic of Ireland: SensL; Italy: AdvanSiD, FBK; Japan: Hamamatsu; Netherlands: Philips; Russia: MEPhI (development); South Korea: National Nanofab Center (development); USA: Excelitas, RMD/Dynasil (development).

The market leaders are probably Hamamatsu (CTA, LHCb upgrade and under consideration for several experiments), FBK (CTA) and SensL (under consideration for several experiments). There are no manufacturers or developers in the UK, but the UK is world-leading in the coupling of SiPMs to scintillators (Kromek, University of York).

Supply threat

In the 1980s, there were several manufacturers of PMTs, including EMI, RCA/Burle, Philips and Hamamatsu. Despite an amalgamation in the early 2000s which created Photonis (RCA/Burle/Philips), only Hamamatsu and ET Enterprises (EMI/ADIT, owned by US firm Ludlum Measurements) survive as manufacturers of PMTs. The latter manufactures in the UK as well as the USA. It is probably fair to say that Hamamatsu is the dominant manufacturer. There are also rather few manufacturers of MCP-PMTs: Photonis, Hamamatsu and Photek.

The situation for the newer SiPM technology is somewhat better, but nonetheless some companies appear to have folded (CPTA in Russia and Photonique from Switzerland) and others have ceased manufacturing SiPMs (STMicroelectronics, Italy). There is a possibility that this market ends up similar to the PMT market, resulting in one or two dominant manufacturers.

CMOS detectors

The CMOS technology is now by far the most significant process for silicon detectors, having overtaken CCDs between 10 and 20 years ago. However, most CMOS foundries are driven by high volume commercial applications and cannot easily be influenced by scientific requirements. The challenge is to take advantage of the developments that foundries make. This requires establishing a working relationship with them to make the changes that are useful for science, for example:

- use of thicker active material suitable for X-rays or NIR applications
- optimisation of back-thinning technology for UV detection
- development of pixel detector technologies for high radiation environments such as the LHC or future hadron colliders
- development of high spatial resolution sensors needed for future e^+-e^- colliders.

In general, the development of semiconductor technology is driven by the need for ever higher speeds on more complex devices with lower costs. This has led to the density of transistors on silicon double every two years for more than 40 years, a rule known as Moore's Law. For visible detectors this has seen pixel sizes shrink to around 1μm and enabled the manufacture of high resolution high performance image sensors of extremely small size especially for smartphone cameras. However, in general image sensors have not used the latest 22 or even 14nm nodes technologies developed for microprocessors. Detectors for scientific applications are manufactured with slightly older processes with node sizes ranging from 65 to 180nm.

For scientific detector applications the larger node sizes have significant advantages and are likely to be used for the foreseeable future:

- generally small pixels are not required
- a higher voltage enables a better charge storage capacity
- the Non-Recurring Engineering (NRE) cost of the very latest processes with the smallest node sizes, which is tens of millions of pounds, would be the dominant cost for small volume manufacture
- smaller foundries running the larger node sizes tend to be more flexible and allow for modifications to non-standard processes
- they are also more amenable to work on projects where only a small number of batches are required.

There are several imaging foundries around the world that offer sufficient flexibility that they can be used for the processing of scientific detectors including Tower-Jazz Panasonic, L-Foundry, X-Fab and ams AG.

As devices become increasingly complex the latest trend is the development of 3D stacking to enable the performance of the imaging part of the sensor to be separated from the readout and processing. Sony are the leaders in this technology[3] and although this technology is developed for obtaining the highest performance from very small pixels (1.2μm) it provides a route to manufacture extremely high speed sensors with parallel processing of the pixel data. The standard process developed by Sony is not accessible for science applications. However efforts to use this and similar technologies for X-ray and IR detectors are ongoing in Japan and USA. Teledyne-DALSA is also developing this technology. There is also a significant drive to produce pixels with lower noise with many design groups reporting noise levels below 1e and the possibility of significantly lower noise in the future. For science this is especially interesting for very low signal applications such as astronomy.

Silicon as a detector material

By far the most common use of silicon as a detector material is for visible sensors but it can also be used for a wide range of wavelengths/energies.

Visible light detection: the bandgap of silicon is around 1060nm and so for pure visible detectors the NIR is filtered out to give a photo-optic response matching the human eye. Detectors of this type would generally not be used directly for scientific instruments although they can be used in combination with phosphors.

NIR detection: for detection of NIR wavelengths for applications such as astronomy thicker silicon is required as the absorption depth of radiation in silicon increases rapidly as the wavelength approaches 1060nm. Astronomy detectors will therefore use silicon that is 40μm thick or even more compared to typically less than 5μm for visible detectors. This technology is well established for CCDs but is more difficult for CMOS as it is much more difficult to apply a high enough voltage to fully deplete the silicon especially for a pinned photodiode structure.

UV detection: the layers on the front surface of the sensor become increasing opaque at shorter UV wavelengths and hence the detection efficiency rapidly decreases. For effective UV detection below around 300 nm a process called back-thinning must be used whereby the substrate from the active wafer is almost completely removed so that radiation can reach directly the active silicon. This process is well established for CCDs and has been demonstrated by Teledyne-e2v in the UK for CMOS detectors although more work is needed to fully industrialise this. Currently wafers must be reduced in size from 8” to 6” before back-thinning and so the process is very wasteful. However a good UV detection efficiency can be achieved using this process. This is an important capability for applications such as solar physics and space weather.

X-ray detection: at shorter wavelengths (or higher energies) silicon becomes increasingly transparent meaning that in general it cannot achieve high detection efficiency at X-ray energies above around 20keV. At the other end of the spectrum, efficient detection of soft X-rays, below about 1keV, requires processes similar to those used for UV detection. The detection of typical X-ray energies, 4-12keV, requires the use of thicker silicon than standard to achieve a good detection efficiency. Although this technology does not exist today for standard CMOS devices, efforts in the direction of high resistivity, fully depleted, back illuminated CMOS are ongoing.

Minimum ionizing particle detection for particle and nuclear physics: silicon sensors are widely used in particle physics and nuclear physics experiments. They achieve excellent detection efficiency for charged particle detection and exquisite position resolution. Up to now, devices which couple readout chips fabricated in CMOS technologies to sensors (hybrid silicon pixels) have been used in most high-energy physics experiments. There is a lot of interest in CMOS-based detectors, where the sensing medium and front-end electronics are part of the same silicon wafer. While devices using standard CMOS technologies have been already deployed in low radiation environments, significant research and

3. See Bibliography entry 17 in appendix 4

development is needed to develop so called Depleted CMOS detectors (DMAPS). DMAPS use high-resistivity and/or high-voltage CMOS processes to increase the charge collection volume of the devices, which enables a larger charge to be collected, and therefore produces a larger signal, which compensates, to some extent, the effects of irradiation. Several sensors are currently under development for particle and nuclear physics applications with Tower-Jazz, L-Foundry and ams AG.

Examples of future developments required in CMOS technology for different applications

<u>Astronomy and X-ray astronomy</u>

The increased NIR sensitivity for astronomy sensors requires three significant developments:

- increased availability of thicker silicon (either epitaxial or bulk), which is currently only possible through some foundries
- a structure that can fully deplete the silicon whilst operating the front surface as a pinned photodiode to minimise dark signal and allow long integration times
- the development of very large area 2D stitched CMOS imagers with small pixels and low noise.

In addition for some applications higher cadence is required than is achievable with CCDs.

For proposed future projects such as GravityCam a combination of exceptionally low noise (~0.2e) and high frames rates is required. This will require further improvements in low noise technology.

<u>Space science</u>

The requirements for space science are as given above with the addition of the need for radiation hardness. Modern CMOS technology is sufficiently resistant to ionising radiation (evaluated in terms of Total Ionising Dose or TID) and proton radiation for most space applications but measures must be taken in the design to make devices resistant to latch-up from heavy ions.

In addition, many sensors in the UV to NIR range are used in space for earth science applications such as:

- pollution monitoring (eg Sentinel5P, Sentinel 5 and Sentinel 4)
- CO2 monitoring
- weather monitoring and forecasting (eg MetImage, MeteoSat and Aeolus)
- monitoring the health of the oceans (eg Sentinel 3, Sentinel 2)
- agriculture (eg FLEX).

The large majority of these missions that are either recently launched or in late stages of development use CCD technology. However, a new range of satellites is being planned by ESA as an extension to the Copernicus programme and these will require a new range of CMOS sensors. Typically, these applications require large pixels and high dynamic range. The improvement in dynamic range is the main development that is required in CMOS technology for earth science applications. Many of these instruments are spectrometers and often the back-thinning process used optimises the coating at each wavelength. This capability does not currently exist for CMOS devices, at least not on 8" wafers.

For solar physics and space weather applications UV detection efficient is critical and the establishment of a full production scale CMOS back thinning process capable of being optimised for different applications is important.

<u>Particle physics</u>

Detectors for particle physics experiments are very different from those that have been developed as an extension of visible imaging technology and are often designed in house. The UK has a leading position in the development of these sensors through STFC technology department and particle physics department at many universities including Liverpool, Oxford, Glasgow, Birmingham, UCL, Sheffield, Queen Mary, Brunel, Manchester, the Open University, Lancaster and Bristol.

'Hybrid pixels', which include a sensor (electronically passive) and a separate readout chip, are the state-of-the-art technology for large scale pixel detectors in most particle physics experiments. The fabrication of sensors by employing CMOS foundries has been successfully demonstrated for strip and pixel sensors. This is interesting since the large production lines can decrease the cost of the devices and allow cheaper integration using bumps already provided by the CMOS vendor (e.g. so-called C4 bumps). Furthermore, one or two metal layers can be used for AC coupling and rerouting.

The UK played an important role in the initial efforts to integrate detector and microelectronics into monolithic sensor solutions (MAPS) and the development of novel sensor architectures, including the deep n-well concept which improves charge collection through introduction of a drift field. More recently, further developments initiated outside the UK have led to MAPS solutions being exploited at heavy ion colliders (RHIC, ALICE upgrade at LHC) and to architectures which use the deep n-well architecture to give devices with greatly improved radiation hardness. Future particle physics detectors are likely to be depleted monolithic active pixels (DMAPS) with extended depletion regions such that charge is collected by drift beneath the full pixel area. The development of such detectors relies on advancements in CMOS technologies and vendors offering process add-ons or modifications to achieve 50 to 100μm depletion depth and fast charge collection via drift while maintaining full CMOS functionality.

The following CMOS features are important for DMAPS:

- high voltage technology add-ons from automotive and power management applications that increase the voltage handling capability and create a depletion layer
- medium to high (> 100 Ω.cm) resistivity silicon substrate wafers, accepted and qualified by the foundry to develop a depletion layer at moderate bias voltages
- multiple nested wells that can be used to isolate transistors and shield deep well potentials in order to optimize charge collection
- backside processing add-ons allowing backside biasing contact acting as an additional field shaping potential of the device.

Medium sized CMOS foundries (Tower-Jazz, L-Foundry, ams) are sufficiently flexible that they are often willing to adopt their processes to provide these features and manufacture these devices. Further developments in this technology will rely on collaboration with the foundries and in house design capabilities. The required developments for future applications are:

- lower cost for very large area detectors
- improved radiation hardness for the HL-LHC and future hadron collider applications
- improved spatial resolution. The smallest pixel size is determined by the amount of CMOS electronics needed to amplify, discriminate, and process the hit information in the area occupied by the pixel cell. To achieve the improved spatial resolution needed for e^+e^- colliders, smaller node technologies should be evaluated. Alternatively, a smaller pixel size could be achieved by encoding and decoding the pixel sensor cell using a CMOS electronics layer the pixel sensor
- improved time resolution.

The UK does not have any interconnection capabilities to assemble hybrid detectors. There is no DMAPS manufacturing capability the UK.

<u>X-ray detectors</u>
Silicon can be used in direct detection for synchrotron and XFELs at lower energies and in combination with phosphors at higher energies. There is a very significant drive especially for XFELs for very high frames rates to match, or at least be closer to, the pulse rates of the new generation of XFELs. This requires detectors with very high levels of parallel processing.

Typical requirements for these applications are:

- increased speeds, especially for XFELs with high pulse rates
- increased dynamic range
- increased resolution
- increased size of detectors (such as the sensor being developed for the Percival project)
- thicker silicon for improved X-ray response.

Hybrid detectors have been used for X-ray applications and will continue to be required especially for the very highest frame rates. 3D stacking technology will be critical in the future to achieve increased performance. There is no 3D stacking technology capability in the UK.

Ultra-fast silicon detectors

Silicon detectors are used ubiquitously to sense and measure precisely particles and photons in many experiments including the study of particle interaction in colliders, cosmic rays in space science, photons in astrophysics, photon science and medical imaging, ionized molecules in mass spectrometers, and charged particles in medical treatment. Presently silicon sensors can measure the arrival time of a particle with a precision of about 200ps. The achievement of time resolutions of the order of 10–30ps or better will change the way we design experiments, bring revolutionary opportunities in many fields, and lead to true 4D tracking.

The high-luminosity phase of the Large Hadron Collider (HL-LHC), foreseen to start in 2026, will lead to the full exploitation of the LHC by providing larger datasets allowing precision measurements of the Higgs couplings, studies of vector boson scattering, and more powerful searches for new particles. At the HL-LHC, the instantaneous luminosity will rise from its current value of about $2 \times 10^{34}/cm^2/s$ to $7.5 \times 10^{34}/cm^2/s$ to deliver an integrated luminosity of 4000 /fb in about 10 years. The increase in luminosity will bring an average of about 200 in time and out-of-time proton-proton collisions (pileup) per 25ns bunch crossing, which presents a challenge.

Currently the LHC experiments are collecting data at an average pileup of about 40. In this regime, the reduction of pile up effects on physics can be achieved by using tracking devices to identify the vertex of interest and reject pileup jets. At the HL-LHC the interaction region will spread over about 50mm (RMS) along the beam axis. Therefore, with an average pileup of 200 there will be about 1.8 collisions/mm. Since the spatial resolution provided by the tracking systems along the beam line (z0) is of the order of a few millimetres, charge particle reconstruction and correct assignment of tracks to primary interaction vertices is no longer effective. In the HL-LHC regime, precision timing can improve track and vertex reconstruction, and provide a substantial reduction of the pileup jet rate.

Reconstruction algorithms in high pileup conditions could be considerably simplified if timing information could be associated to each point of the track and therefore by using only time-compatible hits in the pattern recognition phase. However, in this case the readout electronics is very demanding, as it needs to be able to accurately measure the time of hits on every pixel in the tracker detector. This option is not currently feasible and therefore both ATLAS and CMS have selected a solution with timing layers outside the volume of the tracker achieving a time resolution of about 30ps. This time resolution reduces the pileup to a level comparable to the LHC, thereby recovering the quality of event reconstruction that is currently achieved. Simulations studies have shown that this solution considerably enhances the physics performance by improving the track-to-vertex association. Nonetheless, it is also clear that future applications will benefit from the availability of true 4D information for each point along the trajectory of the track.

Both ATLAS and CMS are planning precision timing layers at the HL-LHC. The ATLAS High Granularity Timing Detector (HGTD) consists of two layers of ultra-fast silicon detectors with an additional layer at low radius, achieved by increasing the overlap of the modules at a radius R < 320mm. The detectors have a pixel dimension of $1.3 \times 1.3mm^2$ and an active thickness of 50μm to ensure occupancies below 10% at the highest expected levels of pileup, small dead areas between pixels, and low sensor capacitance which is important for the time resolution. CMS will also use the same technology in the forward region. Sensor modules will be mounted on two sides of two double-sided disks in order to provide hermetic coverage.

The LGAD technology was first developed by the Centro Nacional de Microelectrónica (CNM, Spain). LGADs are now produced also at the Fondazione Bruno Kessler (FBK, Italy), and Hamamatsu (Japan). Early development stage activity is ongoing at Brookhaven National Laboratory (USA). The industrialisation by a large company like Hamamatsu is a clear statement of the importance of this technology beyond applications for particle physics.

The internal gain improvements are useful for applications to other particle physics detectors and medical imaging. For example, improved precision in time measurements is essential for proton computed tomography (pCT) cancer treatment to measure residual proton energy to limit radiation exposure to healthy cells. LGADs could also play an important role in photon science experiment at low energy (few keV). In this type of experiment, the charge deposited by the X-ray will be multiplied by the gain of the LGAD leading to an increase in the achievable signal-to-noise ratio. Time-resolved (bunch) spectroscopy and diffraction experiments would benefit from these devices that provide the capability to distinguish between single bunches. With this technology high-repetition pump-probe experiments with unprecedented precision will be feasible at synchrotrons like the Diamond Light Source, where ps-bunches at ns separation gaps are produced. The high repetition bunch rate of storage rings provides the statistics required to detect the small excited signal and a detector capable of finalising the signal processing within the single bunch period is necessary. This goes together with bunch resolving diagnostics.

Currently there isn't a vendor in the UK producing LGADs but some groups are working with Micron Semiconductors to fabricate these sensors in the UK.

Time projection chambers

Several projects in particle physics and astroparticle physics rely on noble liquid time projection chambers (TPCs), and several UK groups are developing these technologies further. These detectors combine excellent position resolution and tracking capability with good calorimetry properties, which are made possible by the excellent light and charge yields and transport properties of these dielectric liquids. Target masses of several tonnes of liquid xenon (LXe) and liquid argon (LAr) are being deployed for dark matter searches in the near future (e.g. LZ, DarkSide). LXe-TPCs are also a leading technology for neutrinoless double beta decay (0NBB) searches (e.g. nEXO). These applications highlight another key feature of these detectors, the possibility to realise extremely low radioactivity backgrounds due to the intrinsic purity of the target materials, exploitation of self-shielding, extensive material radioassay programmes, and operation deep underground. The giant LAr-TPCs being developed for DUNE, with masses of tens of kilotonnes, highlight the importance this technology has gained in STFC science. Gaseous TPCs are also actively researched in the UK; initially for dark matter searches (e.g. DRIFT, DM-TPC), but more recently there has been an interest in high-pressure gas TPCs (HPG-TPC) for deployment as near detectors in DUNE and/or Hyper-Kamiokande.

Some of the key challenges common to these applications and in which the UK has major expertise include: pressure vessel design and manufacture, TPC electrode design and manufacture, high voltage delivery and electrical resilience, low-background cryogenic optical sensors, readout electronics, cryogenic systems, gas handling and purification.

Radon control. In the LXe-based dark matter experiments now under construction, the presence of a few hundred atoms of radon per tonne of noble liquid, emanating from materials and particulates, represents a significant background. The decay of some radon daughters dispersed in the liquid defeats the self-shielding afforded for external radiation, and the plate-out of others on surfaces can lead to neutron backgrounds. Radon emanates from detector materials and from dust. The current experiments are investing heavily to render radon backgrounds sub-dominant; for example, the radon assay and cleanliness programmes in LZ represent an investment of several M£. A next-generation experiment will need to control and/or remove radon during operation to achieve the desired sensitivity to both dark matter and neutrino interactions. This is the main technical risk for a future project and a step-change in technology is needed: a technical solution has not yet been demonstrated to this end. 0NBB experiments also have tight radon requirements and a particular concern is the detachment of radon daughters plated out onto surfaces to give a spatially- and temporally-varying background. Albeit to a lower degree, the giant neutrino experiments also need to mitigate radon for their astrophysical programmes to be competitive.

<u>HV delivery</u>
Noble liquid TPCs have been afflicted by electrical breakdown phenomena which have prevented their operation at nominal voltages in practically every instance. These effects are related to spurious

electron emission from cathodic electrodes and by charge accumulation in dielectrics in contact with the liquid. Similar effects are observed in gas TPCs and other wire chambers. This phenomenology and its mitigation are finally becoming understood (owning in great measure to work conducted in the UK) but further developments are needed to control these effects more reliably, through the treatment of surfaces and more elaborate electrostatic designs. HV delivery remains a top risk for noble liquid TPCs for dark matter and 0NBB searches, and the risk impact is a major one for DUNE, partly mitigated through its prototypes.

Cold electronics

In low-background TPCs the readout electronics for its optical or charge sensors are located several metres away outside of the detector: at room temperature and where radioactivity is not a concern. With ever larger detectors being planned, an increase in channel count cannot come at the expense of increased radioactivity. Cables and feedthroughs pose particular challenges for radon emanation which the current experiments are finding challenging to control. The replacement of traditional PMTs by SiPMs, which could lead to even better track imaging capability, may exacerbate these connectivity problems as these are smaller devices which often operate at lower gain. Therefore, it is highly desirable to bring the readout electronics into the cold detector, where amplification and some form of multiplexing can be performed to reduce cable count significantly. It will represent a major challenge to develop complex electronics that can operate cryogenically, not poison the liquid, and are made from ultra-low background materials (in particular for radon emanation); acceptable power dissipation in the liquid is another key requirement.

Quantum detectors

Quantum technologies for space

Quantum technologies presently being considered for space applications can be divided into two classes of quantum phenomena: matter-wave interferometry and photon entanglement.

Matter waves have been known to exist since the formulation of the de Broglie hypothesis ($\lambda = h/p$) and the subsequent experimental confirmation of electron diffraction. Matter waves of neutral matter (atoms and molecules) are now routinely produced in laboratories thanks to the development of laser techniques developed over the last three decades, which can be used to cool, trap, and produce coherent beams of neutral matter. At the same time, laser techniques, collectively known as atom optics, have also been developed to manipulate cold coherent beams of neutral matter. Consequently, it is possible to cool and trap atoms and molecules to create matter-wave beams that can subsequently be split and recombined by suitable light fields. Atom optics setups can be designed to produce a matter-wave interferometer, usually in a Mach-Zehnder configuration. Matter-wave interferometry is likened to its optical interferometry counterpart, in which the roles of matter and light are reversed.

Matter-wave interferometers are extremely sensitive to the differential gravity and inertial effects experienced by atoms or molecules in the two arms of the interferometer, which are recorded as interference fringe shifts. When suitably designed, matter-wave interferometers are the most sensitive gravity and inertial sensors known to date. Furthermore, it has been shown[4] that microwave and optical atomic clocks are also genuine matter-wave interferometers. Hence, matter-wave interferometry encompasses both ultra-high precision inertial and gravity sensing and ultra-high precision frequency and time referencing.

Presently, only microwave clocks are flying on European missions, while matter-wave interferometers based on optical atomic transitions have no space heritage. In spite of several European mission concept proposals to fly matter-wave interferometers in space over the last two decades none have been selected due to the low technology readiness level (TRL) of some of the key subsystems.

Meanwhile, China has successfully launched and has been operating a ^{87}Rb cold atom microwave clock in space on the Chinese space laboratory Tiangong-2. This is a significant step towards the realisation of cold atom interferometer for space because a number of required technologies—such as ^{87}Rb Magneto-Optical Trap (MOT) technologies—have

4. See Bibliography entry 18 in appendix 4

thus been space qualified. Similar European and US developments on board the International Space Station (ISS) have been in the planning but, so far, only NASA's Cold Atom Laboratory has recently been deployed.

Interest in entangled photons from space is twofold: these can be used to 1) share a quantum key between two parties on the ground over large distances, and 2) perform fundamental tests of quantum de-coherence due to gravity[5].

QKD is already possible on ground via optical fibre links. However, due to the combination of fibre losses and a lack of quantum repeaters, the distance over which quantum keys can be distributed is limited to a few hundred kilometres. Hence, satellite QKD has become crucial for the implementation of future global QKD networks. Fundamental test using entangled photons from and to space are also needed in order to shed light on an important interface between quantum mechanics and general relativity: the effect of gravity (gradients) on entanglement.

In terms of the actual detector technologies needed for the above applications, these can again be de divided into two categories: matter-wave interferometry, encompassing both cold atom interferometers and clocks; and photon entanglement, whose current focus is QKD.

Matter-wave interferometer systems can be regarded as detectors or sensors in their own right. However, as opposed to detectors of electromagnetic radiation, such as imagers and radiofrequency receivers, they are characterised by a higher level of complexity as they incorporate several disparate technologies, including but not limited to: laser, vacuum, atom sources, electric and magnetic fields generation and control/shielding, all of which often have to be designed and specifically for a given sensor. Hence, an understanding of the relevant quantum experiments, a command of all technologies involves as well as their system engineering aspects, including assembly integration and testing aspect, are all necessary ingredients for success.

As in all communication related technologies, QKD requires both transmitter and detector units. The detector system must be capable of single photon detection, while the transmitter is usually an entangled photon source.

The European Space Agency has been at the forefront of quantum technologies for at least two decades. Interest in these technologies has been driven both by recommendations from the European Science community and ESA member states' priorities. Initially, the agency's activities in this area focused almost exclusively on fundamental physics tests on-board some of the mission concepts mentioned above, i.e. Hyper and STE-QUEST.

ESA's scope of interest in QT grew to include remote sensing applications, as is the case of Earth satellite gravity gradiometry, a technique that allowed the ESA mission GOCE to deliver a wealth of critical data for a number of disciplines ranging from geodesy to climate change. Future challenges will see quantum technologies as the solution to a problem rather than a technique looking for an application: laser-cooled atom interferometry was identified as the preferred technology for the next generation Earth gravity gradiometry mission.

Gravity gradiometry quantum techniques and hardware developed for Earth observation are inherently transferable to planetary science—and much needed, too. Gravity data from planets in our solar system is very limited and mainly confined to line-of-sight Doppler measurements in cases where planets have orbiting satellites transmitting data back to Earth. However, it is recognised that even further technology development will be needed to adapt the quantum gradiometer design to the much more stringent mass, size and power requirements of planetary missions.

ESA's Human Spaceflight programme has been utilising the ISS not only to study the effect of microgravity on human physiology but also to carry out physics microgravity experiments. The ISS platform is particularly useful for experiments that may require human intervention at some stage of the experiment, such as may be the case for highly complex quantum payloads. In fact, some of the mission concepts mentioned earlier, i.e. ACES and Space QUEST, are to be deployed on the ISS.

5. See Bibliography entry 19 in appendix 4

ESA pioneered space based optical communications technology in 1977 and free space QKD in 2007—transmitting entangled photons between Tenerife and La Palma. These two milestones have made satellite quantum key distribution (QKD) possible today. Satellite QKD is recognised to be critical in establishing quantum-secure communication on a global scale. Developing satellite quantum-secure communication has been signalled as a priority by some of ESA's member states and ESA is currently developing satellite QKD missions for commercial and security applications. The European consortium QUARTZ[6] is a project developed under the umbrella of ESA's programme of Advanced Research in Telecommunication Systems (ARTES) that is dedicated, amongst others, to quantum technologies: the SeCure and laser communication technology programme (ScyLight), which fosters the development, deployment and wider market adoption of innovative optical technologies for satellite communications. Furthermore, a recently formed UK company, ArQit is getting traction on funding mechanisms, including ESA, for driving the realisation of a commercial satellite-based QKD service forward.

Satellite microwave atomic clocks are at the heart of global navigation satellite systems (GNSS). Ongoing improvements in atomic clock technology i.e. using optical rather than microwave atomic transitions, may lead to the redefinition of the second and revolutionise global positioning systems. Optical atomic clocks are so sensitive that they will best operate as master clocks in space, far from gravity fluctuations present on the ground. GNSS satellites using optical clocks will provide unprecedented positioning accuracy and will no longer require ground clock corrections.

Quantum sensors for fundamental physics

The application of quantum sensor technology in ground-based experiments will enable the physics exploitation of several open questions in fundamental physics, with discovery options ranging from observation of new astrophysical sources to searches for cosmological sources of stochastic gravitational radiation in addition to the searches for dark matter as well as tests of quantum mechanics and general relativity.

Examples of quantum sensors that are already directly linked with proposals for ground-based physics exploitations are atom interferometry (AI) and resonant feedback circuits (RFC), which are also among of the best-explored application of quantum sensors so far.

Interference via atoms provides a theoretical 10^{11} increase in sensitivity of gyroscopes[7], as well as achieving the world's most precise measurements of local gravity. AI sensors enable measurement of Newton's constant and α^{em}, searches for Lorentz non-invariance, tests of dark sector physics, and precision space-time sensors. A version of an AI detector at the scale of about 10m would already enable the exploration of new phenomena in the dark-sector as well as tests of quantum mechanics at large distances. It would also serve as a prototype for gravitational wave (GW) detectors. In order to start being sensitive to some first GW signals in the mid-frequency range, an AI detector of the size of about 100m would be required. This would also enable enhanced exploration of dark sector physics, especially extending the mass range for ultra-light DM candidates. To reach the sensitivity required for a comprehensive exploitation of the GW spectrum, an AI detector at the km-scale length would be required. At this scale high-precision test of quantum phenomena and improved sensitivity to dark-sector physics would also be possible.

UK physicist Daw proposed a novel RFC technique to accelerate axion/hidden sector searches. In a 'classic' axion search experiment, a high-Q metal cavity is threaded with a high magnetic field. Daw's technique utilises feedback to form a parametrically controlled high-Q resonator. This resonator can be excited by the axions or hidden sector particles converting into electromagnetic radiation in the resonant circuit. This scheme potentially replaces combined axion conversion / resonant detectors using high-Q metal wall resonators. The speed-up occurs because many, perhaps hundreds or thousands, of resonances may

6. See Bibliography entry 20 in appendix 4

7. See Bibliography entry 21 in appendix 4

be generated in parallel. Searches for hidden sector particles, including but not exclusively axions, that employ a resonant detector, can search at a rate enhanced by a factor of the number of parallel resonances realistically resulting in the coverage of the same axion mass ranged proposed by ADMX for a 5 year run time in 38 days.

The ADMX collaboration will install a two litre prototype for testing this idea during October/November 2018; resonant feedback electronics to drive this test insert will follow next year once the experiment is cold again. However, persuading the ADMX community and other resonant hidden sector searches to adopt this idea for their main magnet volume in place of a cavity will require a full scale system test, substantial further theoretical and simulation work, and design/testing of a resonant feedback insert to fill the 220 litre magnet bore of the ADMX experiment.

Particle physics has a developed quantum interference capability and some of the world leading experts in atom interferometry (Stanford, Berkeley) have approached FNAL for the next phase in developing large scale atom interferometers which will be uniquely sensitive to low energy fields (dark matter, energy), and gravitational waves in the mid-band between LIGO and LISA. The MAGIS-100 proposal has been submitted to the DOE and includes the UK as a partner.

In 2018 large parts of the UK fundamental science community were coalescing around two concrete science proposals that are based on QT. One proposal proposes to establish a UK consortium for the use of QT (including atom interferometry, RFC, ion traps, SC loops, SC nanowires, and opto-mechanical sensors) in fundamental science, while the other proposal envisages to establish a UK Atom Interferometer Observatory and Network for the exploitation of Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves where one arm of the network is MAGIS and the other will be at a UK site or possibly elsewhere in Europe such as CERN.

Although the quantum technology used in these proposals is proven to work conceptually, scaling it to the size required for physics exploration is a challenge. For example, in case of AI sensors, one major thrust of work is to prove that the technique works at 100m and eventually at the km-scale. This will be accomplished by scaling AI sensors from 1m to 10m and from 10m to 100m, and eventually from 100m to the km-scale.

To accomplish this goal will require the development of new enabling technologies such as:

- a new generation of high power, tuneable lasers from UK industry
- CCDs operating at the Fano limit (~0.1eV) but with enhanced readout capability
- large scale (1km length) UHV vacuum systems
- ultra-precise timing over 10,000km baselines
- a next generation of robust control systems for quantum optics; high volume magnetic shielding.

Superconducting detectors – KIDs and TES

The UK has demonstrated world class leadership in the development and deployment of superconducting detector technology. One of the casing examples of this is the deployment of a 10,000 element transition edge sensor (TES) array developed by NIST and integrated into the SCUBA-2 instrument by the UK Astronomy Technology Centre. To date, SCUBA-2 is the largest sub-mm detector array developed and is still in operation on the James Clark Maxwell Telescope in Hawaii. The UK also has the ability to design and fabricate its own large format TES arrays. The Cambridge University Quantum Sensors Group has developed high sensitivity TES devices for the next generation of space-based observatories as well as novel devices with phononic thermal isolation[8].

The UK has also taken a leading role in the development of kinetic inductance detectors (KIDs) with active research ongoing at Cardiff, Cambridge, Durham and Oxford. Casing points here are the Cardiff invented Lumped Element Kinetic Inductance Detector (LEKID) that has been developed by multiple groups around the world and deployed in several instruments. Work at Cambridge has produced pioneering new device modelling of superconducting micro-resonator structures providing valuable new tools for material and device characterisation. The UK is now leading its first full instrument build based on KID technology with the MUSCAT instrument[9] being scheduled for deployment on the Large Millimetre Telescope (LMT) in early 2019. Work ongoing at Durham and Oxford has seen the UK begin development of energy resolving single photon counting detectors as well as beginning collaborations with pioneering groups in the United States working in this field.

Overall the UK has a comprehensive set of expertise in superconducting detector technology including:

- device fabrication
- device design
- material development
- modelling of superconductor electrodynamics
- cryogenics instrument design and fabrication
- high frequency signal manipulation and readout systems
- detector testing in low and high background environments
- full instrument development.

However, the UK is arguably lacking development in some key areas. For example, the UK's TES development relies upon European or American readout schemes and to date the UK is not investing in the potential of the frequency domain multiplexing readout schemes made possible by superconducting resonators and parametric devices. Europe in general has limited groups developing and supplying superconducting quantum interference devices (SQUIDs). Such devices have a wide range of applications including astronomy, medical imaging and quantum computing. The UK is also missing a dedicated programme to study the potential opportunities new superconducting materials can offer. Bi-layer and superconducting alloys have the potential to enable enhanced optical coupling to LEKID architectures and parametric amplification of optical signals reducing the noise in heterodyne receivers to close to or meeting the quantum limit.

Many of these technologies are being invested in the USA and Europe are driven by new large-scale projects such as:

- BLAST-TNG - the first balloon borne KIDs instrument
- Toltec – a multi-colour mm-wave polarimeter that will surpass SCUBA-2 in terms of detector counts and sensitivity
- ARCONs – the word's first Energy Resolving Single Photon Counting imaging array
- Deshima and Superspec – New on-chip mm/sub-mm spectrometers
- NIKA-2 - the first science grade imaging instrument based on LEKID technology.

The UK superconducting community has contributed to all of these projects.

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Appendix 5: Glossary of detectors and instrumentation terminology

ADC	Analog-to-Digital Converter
AGATA	Advanced GAmma Tracking Array
AIDA	Advanced Implantation Detector Array
APD	Avalanche PhotoDiode
ASIC	Application Specific Integrated Circuit
BaF	Barium Fluoride – scintillator material
BGO	Bismuth Germanium Oxide – scintillator material
CCD	Charge Coupled Device
CeBr	Cerium Bromide - x-ray detector material
CfI	Centre for Instrumentation (STFC programme)
CMOS	Complementary Metal–Oxide–Semiconductor
CsI	Caesium Iodide – X-ray detector material
CZT	Cadmium zinc telluride – high energy (gamma and X-ray) detector material
DAQ	Data AcQuisition
DINS	Deep Inelastic Neutron Scattering
DMAPS	Depleted Monolithic Active Pixel Sensors
(D)ECAL	(Digital) Electromagnetic CALorimeter
EMCCD	Electron Multiplying CCD
FATIMA	FERA Amplitude and TIme Multi-parameter Analyser
FPGA	Field-Programmable Gate Array
GS Glass	Glass scintillators
HgCdTe	Mercury Cadmium Telluride - infrared detector material
HPD	Hybrid PhotoDetector
HPGe	High-Purity Germanium detectors
HR CMOS	High Resolution CMOS
HV CMOS	High Voltage CMOS
InGaAs	Indium Gallium Arsenide - infrared detector material
ITAR	International Traffic in Arms Regulations (US regulations)
KIDS	Kinetic Inductance Detector
LaBr	Lanthanum Bromide - scintillator materials
LGAD	Low Gain Avalanche Diode
LWI	Long Wavelength Infra-Red (~8–15μm)
LYCCA	Lund-York-Cologne CAlorimeter

MAPS	Monolithic Active Pixel Sensors
MCP	Micro-Channel Plate
MaPMT	Multi-anode PhotoMultiplier Tube
MEMS	MicroElectronic and Microelectromechanical Systems
Micromegas	Micro-mesh gaseous structure
MIDAS	Maximum Integrated Data Acquisition System
MKIDS	Microwave Kinetic Inductance Detectors
MSGC	Micro Strip Gas Chamber
PERCIVAL	Pixelated Energy Resolving CMOS Imager, Versatile And Large
PImMS	Pixel imaging Mass Spectrometry
PIN	Diode with an undoped intrinsic region between p-type and n-type regions
PMT	Photo-Multiplier Tube
PPCA	Probabilistic Principal Component Analysis
RICH	Ring Imaging CHerenkov detectors
RPC	Resistive Plate Chamber
SDD	Silicon Drift Detectors
Si via	Vertical electrical connection (via) that passes completely through a wafer
SiPM	Silicon Photo-Multiplier
SIS	Superconductor–Insulator–Superconductor
SLS	Static Light Scattering
SOI	Silicon On Insulator (CMOS)
SPAD	Single-Photon Avalanche Diode
SQUID	Superconducting Quantum Interference Device
SWIR	Short-Wavelength Infra-Red (~1.4–3μm)
TES	Transition-Edge Sensor
TPC	Time Projection Chamber
UFSD	Ultra-Fast Silicon Detector
VELO	VErtex LOcating detector
WLS	WaveLength Shifting fibres
YAP	Yttrium Aluminium Perovskite – scintillator material

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