December 5, 2023

# DRD-UK Consolidated Grant Submission 2025-2029

*On behalf of* University of Birmingham, University of Bristol, Brunel University London, University of Cambridge, University of Edinburgh, University of Glasgow, Imperial College London, King's College London, University of Lancaster, University of Leicester, University of Liverpool, University of Manchester, University of Oxford, Queen Mary University of London, STFC Particle Physics Division, STFC Technology Department, Royal Holloway University of London, University of Sheffield, University of Sussex, University College London, University of Warwick

**Abstract**

An international organisation for strategic R&D activities is being setup to serve the needs of the future experimental programmes in particle, particle astro-physics and related nuclear physics areas. The necessary national infrastructure, training and industrial support will form part of this activity. The UK is fully engaged in this process and is organising its activities, in alignment to the international DRD collaboration and major international partners. This submission describes the DRD collaboration areas, and lists the projects with which the UK institutes have engaged and for which effort is requested in the group submissions. A request for maintenance and operations funds is made.

# Contents

# 1 Introduction to DRD [2 pages]

Particle physics detector R&D is entering a new era with the major projects of ATLAS and CMS Phase II now in their construction phase. R&D for the next decade is focussed on a set of medium and smaller scale projects and will potentially lay the path for a major future collider project on the 20+ year horizon. Consequently, an international programme of strategic R&D in detector systems is being setup. The UK community (particle, particle astro-physics and relevant nuclear physics) is fully engaged in this process, which it has helped shape, and provides several of the international leaders of the DRD process and collaborations.

The costs involved in developing cutting-edge technologies are rising while the field remains – by commercial standards – a low-volume, niche market. Increasingly, costs can be met only through a significant pooling of resources. The new DRD structures will have the necessary critical mass to meet these challenges while ensuring that creativity is maintained. These long-term strategic funding programmes will sustain research and development in order for the technology to mature and to be able to deliver the experimental requirements. This strategic R&D programme will:

- Provide international coordination to identify and target common technological goals that will underpin the next generation of experiments facilitating long-term developments
- Provide and coordinate instrumentation training and skill development for the next generation of experimental particle physicists, engineers and technical staff
- Construct and support specialised facilities (design build and test) supporting international capability in detector development and construction
- Provide methods of establishing meaningful longer-term relationships with industrial partners

The DRD collaboration aims to develop a programme over the next years to meet these goals. In this new international framework the UK is well placed (infrastructure, expertise, leadership) to further build, or in some cases rebuild, strong international leadership if supported through appropriate investment.

## 1.1 Organisation

The DRD Collaborations, see Fig. 1, cover areas of relevant R&D, with UK involvement in all. The formation follows from a three year process following the European Particle Physics Strategy recommendation with a roadmap [1] and implementation document [2] produced. A Detector Research and Development Committee (DRDC) has been put in place. The operational model will be similar to CERN experimental collaborations, thus allowing strategic priorities to be determined and cross-institution and international collaboration to be performed.

These DRD collaborations will address the needs of strategic R&D to underpin future experimental programmes. These will build upon and expand from the success of CERN RD collaborations [3], such as RD50 (which underpinned most of the silicon developments that enabled LHC detctors and beyond, and the UK had the long-term co-spokesperson) and RD53 (where a common ATLAS/CMS Upgrade II pixel chip basis was developed).

The DRD collaborations are expected to ramp-up over the first three-four years cycle. A UK structure has been setup to coordinate the activities. A steering board has been appointed with representatives from each of the 20 UK particle physics groups and UK coordinators appointed for the DRD collaborations (see Appendix A) . UK community meetings have been held and the coordinators are working with the international community to shape the overall projects.

### 1.2 UK goals

In the past years, particle physics detector system construction has been a significant UK strength with major international projects having been delivered and currently in construction. However, the development of new technologies has lagged behind other leading nations in some important areas. The extensive expertise and infrastructure in the UK, established through our involvement in major build and development programmes, can be leveraged to enable a fast and cost-effective rebuilding of technology R&D leadership. The DRD collaborations provide the opportunity for the UK to coordinate and target its R&D programme on the key technologies in which it wishes to play a leading for the next decades, developing appropriate infrastructure and working with UK industry. Establishing this generic R&D was a recommendation of the recent STFC Strategic review of particle physics [4]. Training in instrumentation and industrial engagement can be further strengthened in the UK, and these are both areas that can benefit from this initiative, along with managing the future environmental impact of the field.

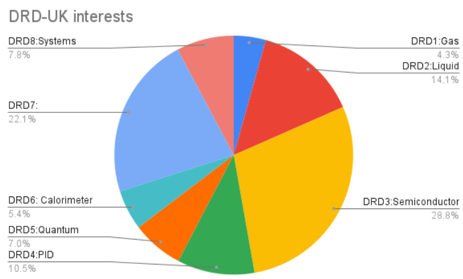


Figure 1: UK DRD activity.

The capability to design, develop, and scientifically exploit advanced detector technologies underlies practically all STFC experimental research. Sustaining such capability requires access to appropriate laboratories and facilities, and a well-trained workforce across all career levels. The DRD programme will give the opportunity for students to develop a skill set for experimental particle physics and of benefit to the UK economy.

Detector technology should be a key impact-generating output of the STFC research programme, and there is proven scope for interdisciplinary and industrial use of both particle physics detectors and the related data-processing systems. The international coordination of activities gives the opportunity for UK industry to reach a wider pool of researchers from which future orders for the experimental programme will emerge.

The UK programme will be led by the demands of future experiments with strong UK interest, and PIs of future UK projects are engaged in the process.

## 2 DRD collaborations overview & workplan [6 pages]

### 2.1 DRD1: Gaseous Detectors [0.5 pages]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.2 DRD2: Liquid Detectors (neutrinos and dark matter) [1 page]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

[To be completed by UK coordinators, deadline by xmas break ]

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.3 DRD3: Semiconductor detectors [1 page]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

[To be completed by UK coordinators, deadline by xmas break ]

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.4 DRD4: Particle identification [0.5 page]

*Contributing institutes: University of Birmingham, University of Bristol, University of Cambridge, University of Edinburgh, Imperial College London, University of Leicester, University of Oxford, STFC particle physics division, University of Warwick*

Particle identification (PID) is critical for many experiments, where separating between different charged-hadron species is key to suppressing otherwise dangerous sources of experimental background. The UK has a strong history of developing and delivering PID systems for particle physics experiments. Notable examples include the LHCb Ring Imaging Cherenkov system and the NA62 KTAG. Measurements relying on PID are a core part of both LHCb and NA62's physics programmes. The UK is also leading efforts to develop PID detectors for the next generation of experiments. These include new Cherenkov detectors for LHCb and HIKE and a proposed system exploiting time-of-flight information for PID in the LHCb TORCH detector. Particle identification will also be necessary to fully exploit the large data sets taken at the $Z$ pole by future $e^+e^-$ experiments and UK institutes are involved in the design efforts for those experiments. With advances in material science it may also be possible to develop entirely new PID systems for future experiments based on novel, meta-material, radiators. Such efforts are at a relatively early stage but could provide interesting alternatives to gas or aerogel radiators in future experiments.

International DRD-4 activities focus on both specific solutions for PID and the more general need to develop new generations of fast-timing photon-detectors that can be tiled to cover large areas, and can withstand the extreme rates expected in future experiments. These technologies have use in PID experiments but also have applications in calorimetry systems and e.g. dark matter detectors (for example in Darkside-20k). Common efforts to develop photon detector technologies are a significant part of the UK and international DRD-4 effort. UK groups involved in DRD-4 are working closely with a variety of industrial partners to develop photon detectors that meet the challenging needs of future experiments. The partners include Photek Ltd, a UK industrial partner who are a leading manufacturer of vacuum photon-detector devices, as well as international industrial partners in Photonis, INCOM, Hammatsu and FBK.

## 2.5 DRD5: Quantum sensors and technology [0.5 page]

*Contributing institutes: King's College London, STFC Rutherford Appleton Laboratory, University of Oxford, University of Birmingham, University of Liverpool, Imperial College London, University of Cambridge, University of Lancaster, University of Sheffield, Royal Holloway, University College London, National Physical Laboratory.*

[To be completed by UK coordinators, deadline by xmas break ]

Initiated through the Quantum Technology for Fundamental Physics (QTFP) Programme, significant ongoing activities are taking place in the UK, involving international collaboration with institutions in the US and elsewhere.

One major focus is the development of Neutral Sr Atoms for large-scale atom interferometry projects like AION and MAGIS, as well as optical atomic clocks. Extended R&D efforts can make the most significant contributions in the network of clocks and long-baseline atom interferometry.

The UK, along with AION and its counterpart MAGIS in the US, holds a prominent position in the development of long-baseline atom interferometry. The primary objective of this program is to search for Ultra-Light Dark Matter and Gravitational Waves in an unexplored frequency range. However, the required R&D for this quantum technology extends beyond fundamental physics goals and offers valuable insights for optical clocks and quantum computing platforms based on neutral atoms.

The AION project has capitalized on expertise from national particle physics laboratories such as RAL and Daresbury to streamline the design and production of key components for Cold Atom Quantum Laboratories. AION has centralized the design and production of critical components like Ultra-High Vacuum (UHV) and Laser-Stabilization (LS) systems, instead of each lab independently constructing them. This centralized approach has significantly enhanced the construction process, optimizing resource utilization and time. Ongoing R&D efforts are underway to further enhance this design and production process, in close collaboration with UK industry partners like Torr Scientific and Kurt J. Lesker companies.

Furthermore, this centralized design and production strategy can serve as a model for the modular and distributed development and assembly of other cold atom projects, ranging from atomic clock experiments to neutral atom quantum computing systems.

The QTFP programme has catalysed the development, through the QSHS and QTNM projects in the UK, in collaboration with ADMX and Project 8 in the USA, of ultra low noise technologies in the microwave regime. The physics targets of these technologies are studies in the neutrino sector and searches for light dark matter such as QCD axions. The primary technologies under development are phase coherent low noise parametric amplifiers, power sensors, and qubit arrays. Such electronics promise unprecedented sensitivity to new physics.

Practical utilisation of cryogenic electronics for fundamental physics also requires that multiple channels of such electronics be multiplexed, and increasingly that this multiplexing be achieved also at cryogenic temperatures. Furthermore, such electronics should also be controlled, and again the controllers would ideally be cryogenic, to avoid extended loops and time delays in the controller. R&D on cryogenic multiplexing and control electronics comes within the remit of DRD5.

## 2.6 DRD6: Calorimeters [0.5 page]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

[To be completed by UK coordinators, deadline by xmas break ]

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.7 DRD7: Electronics and data handling [1 page]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

[To be completed by UK coordinators, deadline by xmas break ]

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.8 DRD8: Challenges of large scale systems [0.5 page]

*Contributing institutes: Trumpton, Camberwick Green, Ambridge*

[To be completed by UK coordinators, deadline by xmas break ]

Main aims. UK roles. Future experiments that will benefit. Possible links to UK industry.

## 2.9 Industrial engagement, infrastructure and training activities [0.5 page]

*Contributing institutes: All*

[To be completed by UK coordinators, deadline by xmas break ]

# 3 M & O request and effort table [2 pages]

[Chris]

Requests for travel to support networking (that is in addition to what can reasonably be expected to be covered through the usual CG travel allocation) • travel to support international leadership positions associated with the R&D activity • support for engagement with international collaborators workshops • training (that is not already covered through STFC training schemes) • support for engagement with industrial partners

Table of effort requested in CG split by DRD and university (suggest entries for PPD and TD expectations also)

| | **DRD Collaboration** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Institute** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **Other** |
| Birmingham | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Bristol | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Brunel | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Cambridge | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Edinburgh | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Glasgow | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Imperial | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| King's | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Lancaster | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Leicester | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Liverpool | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Manchester | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Oxford | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| QMUL | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| RAL PPD | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| RAL TD | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| RHUL | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Sheffield | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Sussex | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| UCL | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| Warwick | — | — | X.Y | X.Y | — | X.Y | — | X.Y | X.Y |
| **Total** | X.Y | X.Y | X.Y | X.Y | X.Y | X.Y | X.Y | X.Y | X.Y |

Table 1: Effort expressed in FTE years dedicated to work in the DRD collaborations, as requested in the group CG submission or funded by other sources.

# 4 Summary [few lines]

[Chris]

few lines only just to finish document

# Appendices

# A Coordination Roles

## A.1 DRD-UK steering board members

The UK DRD steering board is composed of one member per UK particle physics group. The current members are listed below. The term of all positions is three years. The PI is elected by the members of the steering board. The steering board members are the group leaders of the institutes or a member selected by the group leader.

In addition the University of Leicester space science research centre is contributing and is represented on the steering board by the University of Warwick.

| **Institution** | **Representative** |
|---|---|
| Birmingham | ALLPORT, Philip |
| Bristol | GOLDSTEIN, Joel |
| Brunel | KHAN, Akram |
| Cambridge | WILLIAMS, Sarah |
| Edinburgh | GAO, Yanyan |
| Glasgow | BATES, Richard |
| Imperial | TAPPER, Alex |
| King's | DI LODOVICO, Francesca |
| Lancaster | O'KEEFFE, Helen |
| Liverpool | VOSSEBELD, Joost |
| Manchester | PARKES, Chris (PI) |
| Oxford | BORTOLETTO, Daniela (Chair) |
| QMUL | HOBSON, Peter |
| RAL PPD | WILSON, Fergus |
| RAL TD | FRENCH, Marcus |
| RHUL | BOISVERT, Veronique |
| Sheffield | VICKEY, Trevor |
| Sussex | HARTNELL, Jeffrey |
| UCL | THOMAS, Jenny |
| Warwick | RAMACHERS, Yorck |

Table 2: Members of the DRD UK Steering board.

## A.2 DRD-UK Coordinators

Each DRD collaboration has a set of UK coordinators. The coordinators are selected by the PI after discussion with members of the relevant community.

| **Area** | **Coordinator** |
|---|---|
| DRD-1 [Gas] | BRANDT, Oleg; MAJEWSKI, Pawel; |
| DRD-2 [Liquid] | GUENETTE, Roxanne; MONROE, Jocelyn; SAAKYAN, Ruben; SCOVELL, Paul; |
| DRD-3 [Si] | DOPKE, Jens; GONELLA, Laura; HYNDS, Daniel; VILELLA FIGUERAS, Eva |
| DRD-4 [PID] | BLAKE, Thomas; ROMANO, Angela |
| DRD-5 [Quantum] | BUCHMULLER, Oliver; DAW, Ed |
| DRD-6 [Calo] | SALVATORE, Fabrizio; WATSON, Nigel |
| DRD-7 [Electronics] | FITZPATRICK, Conor; FRENCH, Marcus; POTAMIANOS, Karolos; PRYDDERCH, Mark; ROSE, Andrew |
| DRD-8 [Systems] | GOLDSTEIN Joel; VIEHHAUSER, Georg |
| Training | LAZZERONI, Cristina; BATES, Richard |
| Industry Engagement | FARROW, Richard; CASSE, Gianluigi |

Table 3: Coordinators of the DRD UK activities.

# B DRD activity lists

## B.1 Task List for DRD1: Gaseous Detectors

| No. | Name | Description |
|---|---|---|
| 1.0 | Coordination | Coordination tasks for DRD 1 in the UK and in the international collaboration. |
| 1.1 | Migdal | Observation and measurement of the Migdal effect. R&D: DRD1 WP8-D development of radio pure TPCs for precise track imaging and calorimetry with avalanche-based R/O. Deliverable: stable operation of low-pressure TPC with large dynamic range ranging from low energy electron recoils (few keV) to nuclear recoils. Beneficiaries: direct detection DM searches. |
| 1.2 | Thermal $n$ imaging | Develop a fast neutron gas detector with sub-millimetre spatial resolution, evaluate operation with low GWP gases, identify optimum ASICs. R&D: (a) DRD1-WG3: operation of $\mu$RWELLs with low GWP, high density (higher than $CG_4$) gases and (b) DRD1-WG5 evaluation of ASICs for MPGD detectors. Beneficiaries: thermal and epithermal $n$ detectors. |
| 1.3 | EcoGas4gasDet | Identify novel low-GWP gas mixture for high-field ($E \gtrsim 5$ kV/mm) gaseous detectors. R&D: DRD1-WP1-T5 “Eco-friendly gases”. Deliverable: ideal novel gas mixture following criteria of: (a) low-GWP, (b) non-flammability, (c) ageing stability, (d) detector performance. Beneficiaries: large-scale future detectors at HL-LHC (ANUBIS), FCC, fixed target, $\nu$ detectors. |
| 1.4 | HiResLrgScale | Identify future materials for high-resolution, high rate, large scale RPC detectors. R&D: DRD1-WP1-T1 “New resistive RPC materials and production techniques for resistive layers” and WP5 “Development of high-granularity demonstrators”. Deliverable: materials and processes for next-generation RPCs following criteria of: (a) mechanical rigidity, (b) conductivity, (c) density/weight, (d) cost. Beneficiaries: large-scale future detectors like FCC-ee/hh, fixed target, $\nu$ detectors. |
| 1.5 | WarTPC | Further augment the capabilities of a High-Pressure gaseous TPC (HPgTPC) for measuring $\nu$ interactions. R&D: DRD1-WP4-T “Gas mixture”, DRD1-WP8-T1 ”Enhanced operation of optical readout across gas densities”, DRD1-WP8-T2 ”Enhanced operation of charge readout across gas densities”, DRD1-WP8-T4 “Ultra-low-energy reconstruction of highly ionizing tracks”. Deliverable: identify novel gas mixtures to further augment HPgTPCs, highly granular optical TPC readout, prototype calibration system, enhanced operation of charge readout across gas densities. Beneficiaries: $\nu$ detectors. |
| 1.6 | glass THGEMs | Develop and characterise novel glass THGEMs using optical gas TPC. R&D: DRD1-WP8-T1 ”Enhanced operation of optical readout across gas densities”. Deliverable: development and and characterisation of novel glass THGEMs using optical gas TPC, including radiopure THGEMs. Beneficiaries: DM detectors. |

## B.2 Task List for DRD2: Liquid Detectors (neutrinos and dark matter)

[To be completed by UK coordinators, deadline Monday December 4th ]

[Less is more! Recommended not to have more than a handful of tasks, as otherwise the limited effort available in CG will be spread very thin.]

| No. | Name | Description |
|---|---|---|
| 2.0 | Coordination | Coordination tasks for DRD 2 in the UK and in the international collaboration. |
| 2.1 | Radiopurity | Develop radiopurity screening and control system applicable across a wide range of rare event search experiments (neutrino, dark matter, etc). Necessitates close collaboration with industry: MIRION, Agilent, XIA, Lead Shield Engineering.<br>• Increase sensitivity of Boulby and RAL based radio-essay systems: 1-10 $\mu$Bq/kg for HPGe, 0.1-1 ppt for ICP-MS, 5 $\mu$Bq for Rn emanation, 0.5-1 mBq/$m^2$ for surface screening;<br>• Develop tools for background evaluation based on radiopurity essays: high-stat simulations of highly shielded detectors, new statistical inference tools;<br>• Development of integrated material data bases, work flows to optimise screening throughput, protocols for clean manufacture and cleanliness control; |

## B.3 Task List for DRD3: Semiconductor detectors

| | | |
|---|---|---|
| 3.0 | Coordination | Coordination tasks for DRD3 in the UK and in the international collaboration. |
| 3.1 | High granularity, rad-hard CMOS sensors | This task will explore the development of fully functional monolithic sensors in commercial CMOS technologies with large volume, low-cost production. UK expertise in CMOS imaging technologies at the 150 and 180 nm node will be used to target high granularity (down to 25x25 $\mu$m$^2$) and high radiation tolerance (towards $10^{16}$ $n_{eq}/cm^2$) in one device, with a modest time resolution (hundreds of ps) [**DRD3 WP 1.1, 1.4**]. This development will benefit vertex and tracking detectors for upcoming and upgraded experiments (ALICE-3, LHCb-2, EIC, Belle-3, ATLAS, CMS), and subsequent further developments towards future e+/e- colliders, muon and hadron colliders. |
| 3.2 | Sensors for 4D-Tracking | This task is concerned with the development of sensor technologies to achieve high time resolution combined with high spatial resolution, fill factor, and radiation hardness. In addition to further the development of 3D sensors and LGAD technology [**DRD3 WP 2.2, 2.3**], it will pursue innovative solutions in the form of monolithic sensors to reach timing resolution in the order of 10s of ps, better than 99% fill-factor, 10s of $\mu$m spatial resolution, and radiation tolerance towards $10^{15}$ $n_{eq}/cm^2$ [**DRD3 WP 1.2**]. Such developments will benefit in the medium-term future (2030-2035) upgrades of LHCb, HIKE, ATLAS and CMS timing detectors, and demonstrate the technologies for use at the proposed future muon and hadron colliders. |
| 3.3 | 3D Stacked CMOS Sensors | Commercially available 3D stacked CMOS sensor technology will be explored to design monolithic sensors with a high level of reconfigurability that could be deployed in both tracking and electromagnetic calorimetry detectors. Exploiting the higher achievable digital logic density and the stitching capability of the process, this development aims at the realisation of a large area, 3D stacked CMOS sensor as a cost-effective solution to equip large detector systems at future collider experiments [**DRD3 WP 1.3, 1.5**]. In addition, 3D stacking technology distinctive advantages in terms of signal and power distribution will be capable of underpinning larger and faster detectors for X-rays and cryo-electron microscopy. This activity has synergies with DRD6 and DRD7. |

**3.4 Sensors for Extreme Fluences**

This task will develop UK expertise and infrastructure for the development of sensor technologies towards the ultra-high fluence environments expected at the FCC-hh. An ambitious programme of measurements will be undertaken to map the evolution of silicon detector properties with progressively higher proton and neutron fluences, towards the ultimate target of testing the operation of detectors at $10^{18}$ $n_{eq}/cm^2$ [**DRD3 WP 3.2, 3.3, 3.4**]. Dedicated test devices will be fabricated at UK companies (e.g. Te2v, Micron). The potential of diamond detectors will be investigated by demonstrating fabrication of 25 µm base length cubic cell 3D diamond devices [**DRD3 WP 6.1**]to be tested up to $10^{16}$ - $10^{18}$ $n_{eq}/cm^2$ [**DRD3 WP 3.1, 3.3, 3.4**]. The UK retains a leading position in the fabrication of diamond sensors through ElementSix Ltd UK, one of two companies worldwide to produce detector grade diamond,
236 and unique worldwide capability to process 3D graphitic wires in diamond.

**3.5 Simulations**

The proposed developments of new technologies within the DRD3 UK activities will be supported by effort on simulations (DRD3 WG4). UK expertise will progress TCAD simulations of CMOS processes to optimise pixel charge collections properties and inform design activities. This work will include the implementation of newly measured semiconductor properties into TCAD and MC simulation tools, and the development of radiation hardness models for extreme fluence [**DRD3 WP 4.2, 4.3, 4.4**]. In addition, this task will work on full detector simulation studies, focussing on design parameters and performance metrics, to evaluate the impact of the developed technologies on the physics programme at future colliders and aid
237 further R&D and finally technology choice .

238 ## B.4 Task List for DRD4: Particle identification

| No. | Name | Description |
|---|---|---|
| 4.0 | Coordination | Coordination tasks for DRD 1 in the UK and in the international collaboration. |
| 4.1 | Design for future experiments | Design of PID systems based on Cherenkov/TOF techniques for future experiments [**international WP 4.3**]. Activities in this package include the design and simulation of new detectors, e.g. of dual RICH detectors for future circular colliders that could provide PID over the momentum range of a few to tens of GeV/c. This package also includes the development of lightweight mechanical supports for detectors, and the development of techniques for measuring the optical properties of optical components for TOF detectors [**international WP 4.4**]. |
| 4.2 | Novel radiators | Development of novel radiators for future PID detectors; including metamaterials with customisable refractive index properties [**international WP4.3**]. Advances in material science have opened the possibility of developing entirely new types of radiator material (such as photonic crystals and materials embedding nanospheres). The properties of these materials are in principle tunable and it is possible that such materials could provide replacements to e.g. fluorocarbon gasses in future experiments.<br>239 This WP has synergy with EPSRC funded research taking place at a number of UK Universities. Activities involve simulation of material properties and testing of sample materials. |
| 4.3 | Vacuum photon detectors | Development and qualification of fast-timing vacuum photon detectors with long-lifetimes and high rate capabilities for Cherenkov/TOF applications [**international WP 4.2**]. Microchannel-plate photomultipliers have demonstrated an ability to reach the tens of picosecond time resolution needed for future experiments. Further work is needed to develop detectors with increased lifetimes that would survive the extreme radiation environments expected in some of those experiments. Development is also needed to produce large area detectors, optimised photocathode materials and readout electronics that would be better suited to particle physics applications.<br>These activities involve industrial partners in the UK, Photek Ltd, and worldwide, who are interested in establishing collaborations to develop technologies to meet the new requirements and fill market gaps. |

| No. | Name | Description |
| --- | --- | --- |
| 4.4 | Solid state photon detectors | Development and qualification of large area detectors using silicon photomultipliers (SiPM) for Cherenkov/TOF applications [**international WPs 4.1, 4.3, 4.4**]. SiPM arrays with mm-scale pixelation and fast timing provide an interesting alternative to vacuum devices in many planned experiments. Development is needed to reach tens of picosecond time resolution and to improve radiation hardness of detectors. Solutions also need to be developed to cool SiPM detectors in high-radiation environments and to read out detectors in high-occupancy environments. |
| 240 4.5 | Accelerated computing for PID | Future Cherenkov detectors will face new challenges in terms of event multiplicities, data rates and background/noise levels, calling for new approaches to detector simulation and reconstruction. The accuracy and precision, necessary for control of statistical and systematic uncertainties, calls for in-depth validation of simulations, and larger volumes of simulated data. Novel reconstruction algorithms for PID will be needed to deal with the large multiplicities and combinatorics in the available processing time. The different experiments would benefit from establishment of general software frameworks and tools, dedicated to PID and other imaging detectors [**international WP 4.3**]. |

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242 ## B.5 Task List for DRD5: Quantum sensors and technology

| No. | Name | Description |
|---|---|---|
| DRD-5.0 | Coordination | Coordination tasks for DRD 5 in the UK and in the international collaboration. |
| DRD-5.1 | Widget | R&D for high-flux atom interferometry is being conducted to support the needs of the AION and MAGIS experiments. This work also directly impacts the development of optical atomic clocks and quantum computing platforms that utilize neutral atoms. Additionally, ongoing R&D efforts are leveraging expertise from National Particle Physics Labs, such as RAL and Daresbury, to streamline the design and production process for key components of Cold Atom Quantum Laboratories. Notably, AION has centralized the design and production of essential components like Ultra-High Vacuum (UHV) and Laser-Stabilization (LS) systems. This collaboration closely involves the UK industry. |
| DRD-5.2 | ULN-Coherent | R&D for ultra-low-noise phase coherent microwave amplifiers in the frequency band 1-100 GHz. Such devices drive the sensitivity of searches for axions and other hidden sector dark matter, of measurements of the neutrino mass in tritium end point experiments employing cyclotron radiation, and in neighbouring field applications in quantum measurement and quantum computing. |
| DRD-5.3 | ULN-Incoherent | R&D for sensor classes that directly measure temperature or energy and thereby avoid the standard quantum limit. 243 Sensor classes include bolometers and a broad class of other energy detectors. Applications include searches for hidden sector dark matter including axions and any other application requiring wideband low noise electronics at ultra low temperatures. |
| DRD-5.4 | Qubit sensors | R&D for the application of various classes of qubit devices to ultra sensitive readout. Applications include cryogenic thermometry, readout of resonant cavity structures used for axion and other dark matter searches, readout of detectors for reactor neutrinos and microwave readout of tritium endpoint experiments. |
| DRD-5.5 | CryoMulti | Development of all-cryogenic electronics for multi-channel multiplexing. Segmented detectors require the multiplexing of many channels that might be better carried out at cryogenic (ie millikelvin) temperatures. Superconducting multiplexing circuits capable of ultra low temperature multiplexing would be developed in this work package. |
| DRD-5.6 | CryoFPGA | Field programmable gate arrays have seen extensive use in physics experiments requiring fast real time deterministic electronics for many purposes. Cryogenic field programmable electronics is being developed for quantum computing applications. In this package we aim to exploit commercially available cryogenic field programmable electronics for physics purposes such as feedback control to stabilise a quantum system in its ground state without recourse to a room temperature electronics chain. |

## 244 B.6 Task List for DRD6: Calorimeters

| No. | Name | Description |
|---|---|---|
| DRD-6.0 | Coordination | Coordination tasks for DRD 6 in the UK and in the international collaborations. |
| DRD-6.1 | Sensor Requirements | Establish requirements for a CMOS MAPS-based sensor optimised specifically for calorimetry, working with (UK) DRD 3.4. These will vary with target application, key criteria for DECAL include need for multiple thresholds per pixel, means of reducing power consumption at source ($\sim$ 10mW/cm$^2$ today) by at least an order of magnitude, sensor size and stitching technologies to instrument $\sim$ 2000 m$^2$ for a calorimeter. Characterisation of SiPMs and their coupling with optical fibres: attenuation lenght and response in frequency of fibres; measurement of time resolution and time precision of state-of-the-art SiPMs; measure of bias voltage, quantum efficency, gain, etc of SiPMs coupled to FERS readout. |
| DRD-6.2 | Power mitigation | Develop set of alternative strategies that can be deployed instead of/in parallel with any sensor, including evaluation of passive cooling using tungsten absorber layers, impact of power cycling on performance (duty cycle depends on target application). |

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| No. | Name | Description |
|---|---|---|
| DRD-6.3 | Interaction modelling | Extend calorimetry data-taking campaign using the EPICAL-2 prototype (and any other sensors available before 2029). Use improved beamline instrumentation to complement existing data from DESY and the SPS, we will benchmark GEANT4 physics models using uniquely granular detector and tune microscopic parameters in AllPix2. Modelling of a dual-readout calorimeter in Geant4 using SiPMs+FERS and comparison with results from current test beam campaigns. Modelling of a possible Large Angle Veto calorimeter (a la Na68) for future high-intensity kaon experiments. (@fab - NA62 or NA68?) |
| DRD-6.4 | Future application and performance | Evaluation of application-specific adaptations necessary for DECAL to be deployed at future projects including high-energy $e^+e^-$, and also as a 'tracking' preshower detector for detectors e.g. FASER2. Develop optimal clustering and pattern recognition using existing tools to enhance linearity and resolution. Evaluation of possible application of SiPM-based calorimeter prototypes for dual-readout calorimetry and/or veto calorimeter for future high-intensity kaon facility at CERN. |

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## B.7 Task List for DRD7: Electronics and data handling

[To be completed by UK coordinators, deadline Monday December 4th ]

[Less is more! Recommended not to have more than a handful of tasks, as otherwise the limited effort available in CG will be spread very thin.]

| No. | Name | Description |
|---|---|---|
| X.0 | Coordination | Coordination tasks for DRD 7 in the UK and in the international collaboration. |
| 7.1 | Radiation Tolerant RISC-V System-On-Chip [DRD 7.2.b] | Develop both a technology and design platform to meet the challenges and opportunities of future Front-End Systems, introducing greater flexibility for ASICs to reduce the number of variants and enabling more rapid development based around the SoC approach.<br>• Radiation Tolerance methodology – Investigate strategies such as Watchdog circuits for SEU tolerant processors and SoC blocks (DMA, memory, etc)<br>• SoC generation – Evaluate the SoC methodology promoted by CERN and provide feedback. Investigate integrating SoC with timing and synchronisation systems<br>• SoC specifications – Verify RISC-V operation from an user perspective and feedback into SoC specifications. |
| 7.2 | Virtual Electronic System Prototyping [DRD 7.2.c] | Develop a scalable, flexible toolchain to enable simulation of detector readout systems from particle interaction in the detector to digital<br>254 data output, thereby aiding in the design, optimization, and analysis of future detector systems in high-energy physics experiments.<br>• Virtual Framework User – Evaluate the framework from the user perspective and provide feedback, with the option of greater participation later. |
| 7.3 | COTs Architectures *DAQOverflow* [DRD 7.5a] | Identify experiment-agnostic common TDAQ activities, define generic benchmarks to allow easy comparison of cost/energy efficiency for various compute architectures for the purposes of back-end/trigger processing. Make generic algorithms/tools available for various architectures as a repository of 'best practice'.<br>• Determine relevant figures of merit (Cost/Energy per unit of work)<br>• Collect and review reference implementations and examples<br>• Benchmark these on existing CPU/GPU/FPGA resources<br>• Host these through a documented repository of firmware and software |

| No. | Name | Description |
|---|---|---|
| 7.4 | No Backend [DRD 7.5.b] | Investigate and develop 100Gb Ethernet based links for data readout from more complex front end ASICs to DAQ, benefiting HEP experiments requiring high/concentrated data readout bandwidth.<br>• Front-End ASICs – Design and develop the building blocks necessary for implementing Ethernet up to 100Gb on Front-End ASICs<br>• No Backend Approach – Demonstrate of a full 100GbE system with current and emulated Front-End ASICs, COTS and smart switches, commercial NICs and custom Back-End boards, and custom Software<br>• Smart-Switch for Future Data Readout – Design a COTS-based high-density switch bridging the detector environment to the COTS/DAQ world |

## B.8 Task List for DRD8: Challenges of large scale systems

[To be completed by UK coordinators, deadline Monday December 4th - I know the DRD8 meeting is later that week, hence initial ideas will likely need updating]

[Less is more! Recommended not to have more than a handful of tasks, as otherwise the limited effort available in CG will be spread very thin.]

| No. | Name | Description |
|---|---|---|
| X.0 | Coordination | Coordination tasks for DRD 1 in the UK and in the international collaboration. |
| X.1 | Widget | A short description not longer than approx. five lines expressing the main areas of activity for performing R&D to improve a widget. Give possible beneficiaries e.g. future experiments or areas. Mention possible UK industry link if relevant. |

## B.9 Task List for Industrial engagement, infrastructure and training activities

[To be completed by UK coordinators, deadline Monday December 4th - I know the DRD meeting is later that week, hence initial ideas will likely need updating]

[Less is more! Recommended not to have more than a handful of tasks, as otherwise the limited effort available in CG will be spread very thin.]

| No. | Name | Description |
|---|---|---|
| 9.0 | Coordination | Coordination tasks for industrial engagement, infrastructure and training activities related to DRD 1–8 in the UK and in the international collaboration. |
| 9.1 | Training | Establish and run an instrumentation Centre of Doctorate Training linked to the DRD projects. We will establish and run a graduate programme, consisting of: a mix of online and face-to-face lectures on a variety of courses tailored to PhD students doing instrumentation work; residential laboratories focused on hardware as part of summer school camps; networking events; and industry placements. The topics of individual PhD work will be provided by individual research lines in the DRD-UK programme, creating a synergy and a positive feedback effect between research and training. |

# References


[1] ECFA Detector R&D Roadmap Process Group, *The 2021 ECFA detector research and development roadmap* , Geneva, 2020. doi: 10.17181/CERN.XDPL.W2EX.

[2] ECFA Detector R&D Roadmap Process Group, *The 2022 ECFA detector research and development roadmap implementation plan* , Geneva, 2022. https://indico.cern.ch/event/1197445/contributions/5034860/attachments/2517863/4329123/spc-e-1190-c-e-3679-Implementation_Detector_Roadmap.pdf.

[3] *CERN RD Collaborations*, https://scientific-info.cern/archives/history_CERN/Exp-Programme-04#RD.

[4] STFC Review panel, *Strategic Review of Particle Physics* , 2022. https://www.ukri.org/wp-content/uploads/2023/01/STFC-03012023-SRPP-Final-Report_Dec-22.pdf.

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