Silicon trackers
DRD3/8/X

Jens Dopke, Laura Gonella, Daniel Hynds, Eva Vilella Figueras

International Status DRD8

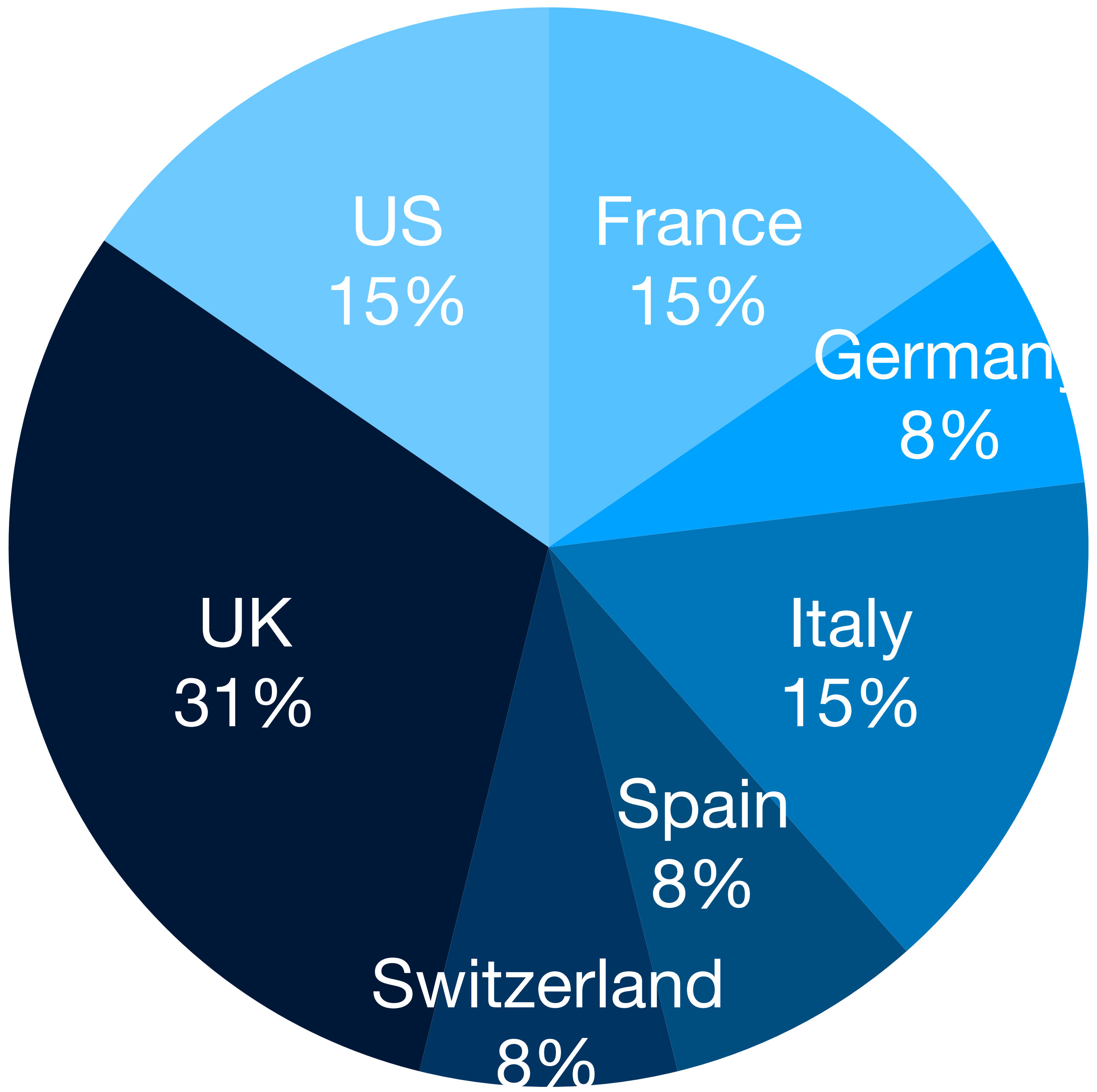
At present the ECFA DRDT8 community have submitted a Letter of Intent (LoI) to DRDC proposing the establishment of

- **DRD8: R&D Collaboration Mechanics and Cooling of Future Vertex and Tracking Systems**

This has been warmly received and the steering committee have begun defining working groups

- C. Gargiulo, A. Jung, A. Mussgiller, P. Petagna, B. Schmidt, G. Viehhauser

DRD8 - UK Involvement



Country/Institute	Contr.WG1	Contr.WG2	Contr.WG3	Contr.WG4	Total
France					
IPHC Strasbourg	1.5				1.5
CPPM Marseille		0.25	0.25		0.5
LPNHE Paris		0.4	0.3		0.7
Germany					
DESY	0.5	1.5	0.5		2.5
GSI Darmstadt		0.25		0.25	0.5
Italy					
INFN Pisa	0.2	0.2			0.4
INFN Perugia		0.25	0.25	0.5	1
Spain					
CNM Barcelona		0.5			0.5
IFIC Valencia	0.2	0.6	0.2		1
Switzerland					
CERN	1	2	1	1	5
Univ. of Geneva	0.25	0.5	0.25		1
United Kingdom	0.65 (12%)	6.80 (43%)	1.55 (21%)	1.00 (26%)	10.00 (31%)
UKRI-STFC RAL		0.25			0.25
University of Bristol		0.5			0.5
Bristol Comp. Inst.		1.5	0.25		1.75
Nat. Comp. Centre	0.25	2		1	3.25
Univ. of Manchester		1	1		2
Univ. of Oxford		0.75			0.75
Univ. of Sheffield			0.1		0.1
Univ. of Liverpool	0.4	0.8	0.2		1.4
USA					
Purdue University	1	2	2	1	6
Fermilab		0.5	0.5		1
LBNL and SLAC		0.5	0.5		1
Grand Total	**5.3**	**16.0**	**7.3**	**3.8**	**32.4**

Total (31%)

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DRD8 Working Groups

WG1 **Global/System Design and Integration**	Mechanics for advanced layouts; service integration; life-cycle design; MDI layout; robotics and remote operations; scalability
WG2 **Low Mass Mechanics and Thermal Management**	Novel materials for structures and cooling; advanced manufacturing; integrated cooling; vacuum-tight composites
WG3 **Detector Cooling**	Evaporative and liquid cooling; gas cooling; connection technologies; instrumentation including flow measurements
WG4 **Design and Qualification Tools:**	Numerical simulations; topology optimisation; virtual reality; 3D design methods; CAD links to GEANT4

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International Status DRD3

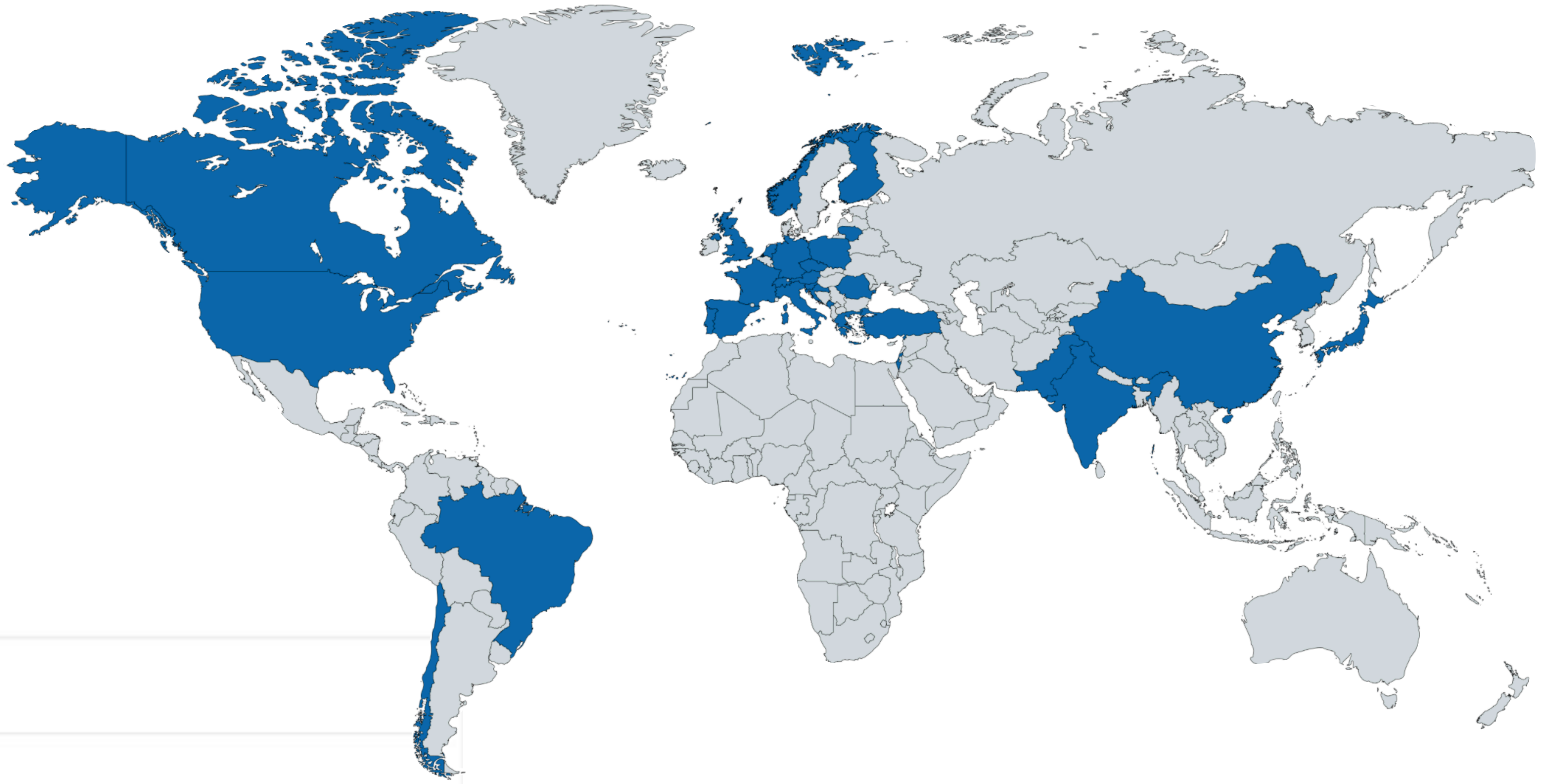
DRD3 have received “preliminary approval” from the DRDC and are in the process of looking for Working Group and Work Package co-ordinators

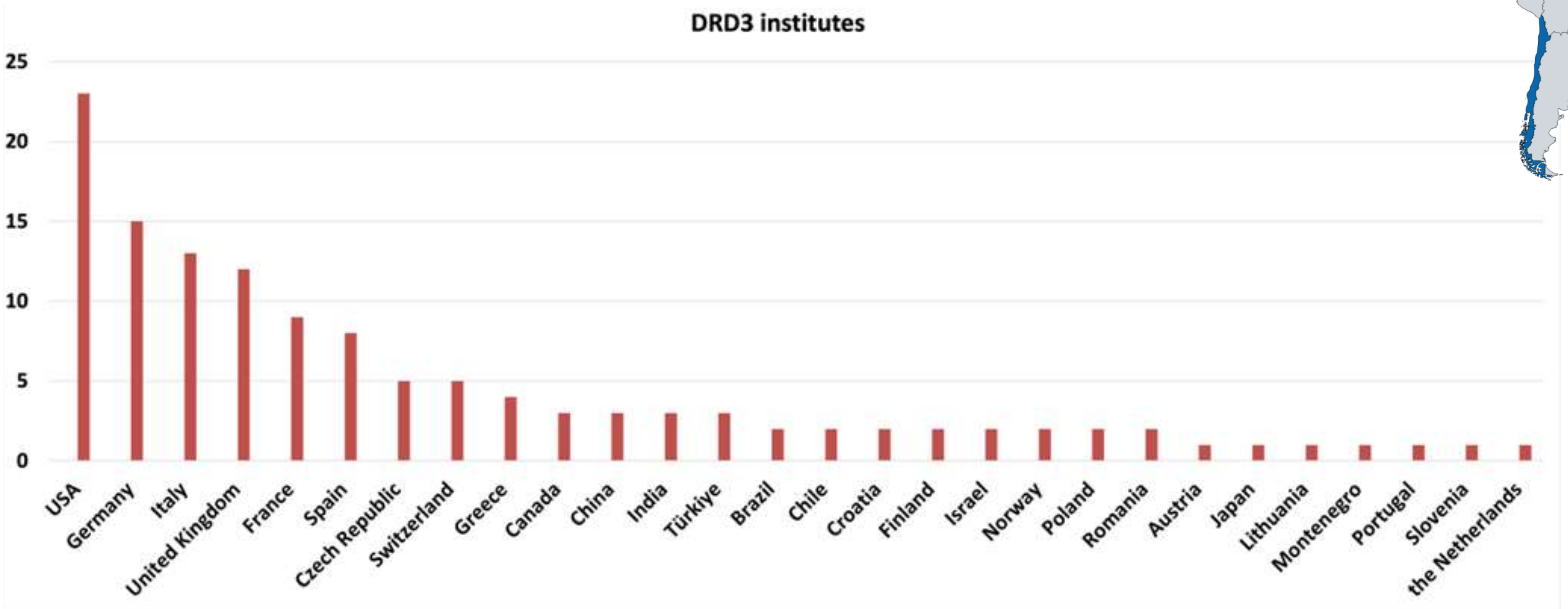
- Institute board chair elected - G. Pellegrini
- Spokesperson elected in the last ~month - G. Kramberger
- Deputies for both chosen, subject to approval by the institute board
- In-person meeting planned for June 17 - 21

DRD3 - UK Involvement

UK groups constitute ~15% of European institutes in DRD3

- In total 132 institutes signed up, with more than 500 individuals subscribed to the CERN e-group





DRD3 - UK Involvement

University of Glasgow

The University of Edinburgh

The University Of Sheffield.

Lancaster University

University of Birmingham

Manchester 1824
The University of Manchester

University of Liverpool

Warwick
The University of Warwick

University of Bristol

University of Oxford

University of Cambridge

Queen Mary
University of London

Brunel University London

UKRI Science and Technology Facilities Council
Particle Physics

DRD3 technology goals

Large UK involvement in preparation of the ECFA roadmap

- Short term goals based on HL-LHC upgrades
- Medium goals low-mass based on e^+e^-
- Long term goals around upgrade to hh machine or muon collider

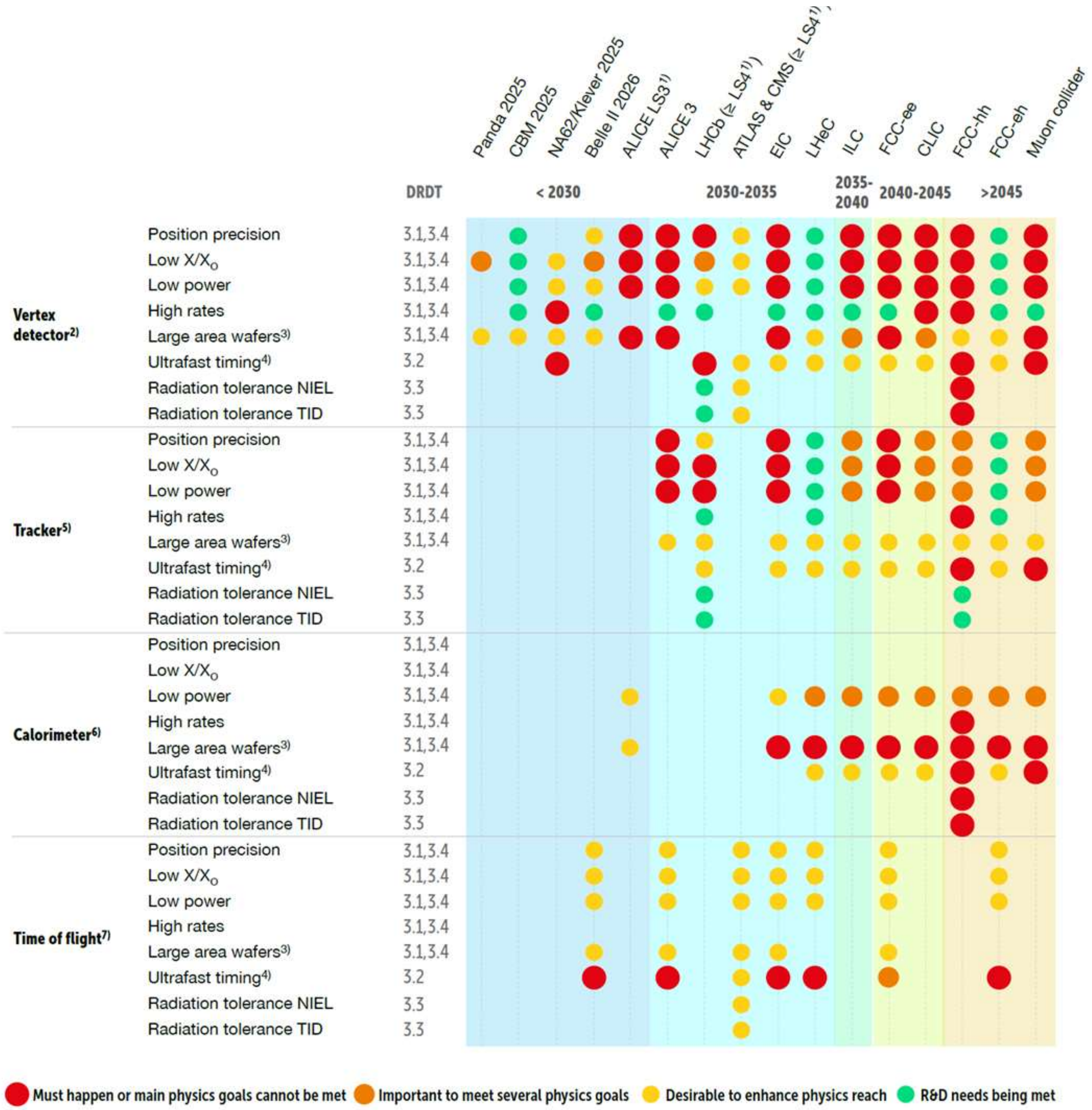
Solid state

DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors

DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry

DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences

DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics



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DRD3 Organisation

Spokesperson
Gregor Kramberger

Deputy 1
Michael Moll

Deputy 2
X

Deputy 3
Y

Institute Board Chair
Giulio Pellegrini

Deputy
R. Arcidiacono

WG1 Monolithic Silicon

WG2 Hybrid Silicon

WG3 Radiation Damage

WG4 Simulation

WG5 Charact. Tech.

WG6 Non-silicon

WG7 Intercon. Tech.

WG8 Outreach

Secretariat

Speakers committee

Resource co-ordination

Cross-DRD co-ordination

WP1 Monolithic CMOS

WP2 4D Tracking

WP3 Extreme Fluence

WP4 3D Integration

International Status DRD3 - operating principles

Working groups

- Discussion forums
- Proposals for blue-sky R&D

Work packages

- Defined projects with resources required, co-ordinate effort
- WPs extendable, can join later

Working Groups

Working Packages	Work Package Projects	WG1- Monolithic silicon technologies	WG2- Hybrid silicon technologies	WG3- Radiation hardening	WG4- Simulation	WG5- Characterization techniques, facilities	WG6- Wide bandgap and innovative sensor materials	WG7- Interconnection technologies	WG8-Outreach and dissemination
WP1 - CMOS sensors	1.1 Spatial resolution	■			■	■			■
	1.2 Timing resolution	■			■	■			■
	1.3 Read-out architectures	■							■
	1.4 Radiation tolerance	■		■	■	■			■
	1.5 Low-cost large-area CMOS sensors	■	■	■	■	■		■	■
WP2- Sensors for 4D-tracking	2.1 3D sensors		■	■	■	■	■	■	■
	2.2 LGAD		■	■	■	■	■	■	■
WP3- Sensors for extreme fluences	3.1 wide band-gap materials (SiC, GaN)		■	■	■	■	■	■	■
	3.2 diamond-based detectors		■	■	■	■	■		■
	3.3 Extreme fluence: silicon detectors		■	■	■	■			■
WP4- 3D-integration and Interconnection	4.1 Integration: fast and maskless interconnect	■	■					■	■
	4.2 3D In house post-processing for hybridization	■	■					■	■
	4.3 Advanced interconnection techniques for detectors	■	■				■	■	■
	4.4 Mechanics and cooling	■	■					■	■

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International Status DRD3 - WG layout

Transverse topics that cross different technology areas

WG1
Monolithic Sensor Technologies

WG2
Hybrid Silicon Technologies

WG3
Radiation Damage Characterisation

WG6
Wide Bandgap and Innovative Sensor Materials

WG4
Simulation

WG5
Characterisation Techniques; Facilities

WG7
Interconnection Technologies

WG8
Dissemination and Outreach

International Status DRD3 - WP layout

WP1 **Monolithic CMOS Sensors**	Extreme spatial resolution; timing resolution; radiation tolerance; low-cost large-area
WP2 **Sensors for 4D Tracking**	Reduced dead area; 3D sensors; LGADs; RSDs
WP3 **Sensors for Extreme Fluencies**	Defects in WBGs; radiation damage models; fluence mapping; material properties at high fluence
WP4 **3D-Integration and Interconnection**	Yields; in-house processes for single die; maskless post-processing; wafer-to-wafer bonding; VIAs

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UK DRD3 Community Discussions

UK community has met several times since the announcement of the DRD programme

- Most recently Liverpool meeting in June last year: https://indico.stfc.ac.uk/event/781

Attempt to come together and ~cost a coherent UK programme

- Crossed (at least) DRD3, DRD7, DRD8
- Attempted to prioritise which projects would be most beneficial with limited resources

UK DRD3 Community Discussions

Potential projects split into 8 areas:

- Active sensors (CMOS)
- Radiation hardness
- Mechanics
- DAQ and Services
- Simulations
- Demonstrator
- Facilities
- Training

1	WP1 Active sensor technologies (3D integration, MAPS, monolithic/hybrid LGADs)						
2							
3	DRD milestone	Project suggestion	Description	Comments	Info gatherer	Total resources (PhD years)	Total resources (
4							
5		1 3D stacked demonstrator	This project proposes to develop a 3D imaging sensor, i.e. a layer with sensor and analogue front-end and a layer with digital processing, connected via 3D vertical stacking technology. TJ is the foundry chosen for this design. 3D stacking is becoming more and more popular for imagers development and as a process is much more mature and reliable. The demand is so high that one of TJ four yearly MPWs is for 3D imagers and this figure is likely to increase requiring the HEP community to develop expertise with this process. From the technical point of view, the idea is to arrive at a stitched design through 2 - 3 MPW runs and one engineering run. The MPW runs will develop circuit blocks and technology expertise, and the engineering run would prove the stitched design (where RAL already has expertise). With respect to a stitched MAPS sensor techncology, the availability of more metal layers would be a significant advantage to route power and signals over large area (up to wafer scale) sensors (cf. challenges of ITS3 wafer scale design). 3D stacked sensors would also allow more digital logic density and higher granularity. There is also the option to use a smaller technology node for the digital layer, further increasing the logic densitiy and decreasing the power	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. In particular large sensors for 100keV electron microscopy will benefit from proven and reliable 3D integration. The close proximity between pixel and progressing/storing electronics is also ideal for large and ultra-fast burst mode imagers, a niche but growing market.	Laura G., Nicola G.	12 (2 PhD students per year for six years)	17 (1 PDRA and 0 for six years, 10 F in total for 6 years

1	WP7 UK facilities						
2							
3	DRD milestone	Project suggestion	Description	Comments	Info gatherer	Total resources (PhD years)	Total resou
4							
5	3.3	1	**Proton Irradiation Facility:** The University of Birmingham host a Scanditronix MC40 cyclotron, a facility unique among UK universities. The accelerator can provide proton and ion beams over a range of energies (up to 40 MeV) and deliver beam currents of up to 2 μA. The facility includes a dedicated beamline for high-intensity proton irradiations of semiconductor devices.The facility has been extensively commissioned over several years and plays a critical role in the quality assurance (QA) programme of the ATLAS ITk Strip sensor production project and serves as a transnational access facility as part of the EUROLABS consortium. Despite these important contributions to large international projects, the full capabilities of the irradiation facility remain unexploited. In particular, irradiation runs are typically conducted with beam currents of between 0.1 − 0.4 μA, limited by the scanning speed and thermal management capabilities of the existing sample enclosure. However, the MC40 routinely operates with beam currents an order of magnitude higher, up to 2 μA, in its other role as a medical radioisotope production facility. Such currents could deliver fluences of 1e17 neq. cm−2 and ionising does in the 10 Grad range in one day. This capability will be established by first developing an upgraded sample enclosure with improved thermal management and beam scanning capabilities to facilitate operations with 2 μA beam currents. Routine continuous operation of the MC40 cyclotron is not possible due to technical and operation limitations. Probing the extreme fluences required by WP2 (up to 1e18 n_eq. cm−2) will require irradiations to span multiple runs (typically a working day). In order to maximise beamtime efficiency and avoid fluence shortfalls, an active beam monitoring system, based on the combination of a Secondary Electron Monitor and Faraday Cup, will be developed to guarantee accurate and efficient fluence delivery.	**Resources**: Equipment and technician time for upg	Andy C.	0	1

Linking UK activities to the DRDs

Two options:

- Sign up to international DRD projects that overlap with UK group interests
- Prepare a UK-wide plan and map this on to the DRD projects

Community feeling was very much on the latter: a UK cross-DRD plan, to feed UK-developed technologies into upcoming projects and be well placed for delivering complete sub-detectors

- Ambition to develop the full detector chain from end to end - ASICs, sensors, mechanics, cooling, DAQ, simulations…
- Much-discussed idea of using a demonstrator to bring efforts together and encourage unified approach

DRD3/8 CG Effort

Over the 4-year CG period looking at 55 FTE years for DRD3 and 15 FTE years for DRD8 activities

- Corresponds to an average of 0.9/0.6 FTE for DRD3/8 at each participating institute

In many cases institutes have requested fractions of several people, given the uncertainty around the DRD programme in the UK

- A lot of effort rebranded from GDD
- Likely represents a small increase on historic (low) levels of non-project instrumentation R&D

	DRD Collaboration								
Institute	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Other**
Birmingham	0.4	—	10.7	1.0	—	0.3	3.9	—	0.1
Bristol	—	—	1.6	0.4	—	—	1.2	6.8	—
Brunel	—	—	0.6	—	—	—	0.3	—	—
Cambridge	1.7	—	1.6	0.4	3.5	—	—	—	—
Edinburgh	—	0.8	4.0	2.8	—	—	–	—	4.4
Glasgow	—	—	5.6	—	—	—	1.6	—	0.3
Imperial	1.4	0.2	—	0.4	3.6	0.4	1.0	—	—
King's	—	1.0	—	—	—	—	—	—	—
Lancaster	—	—	1.6	—	1.4	—	—	—	—
Leicester	—	—	—	0.4	—	—	—	—	—
Liverpool	0.9	3.1	5.9	—	2.3	—	—	0.8	0.2
Manchester	0.4	2.0	3.0	—	—	—	2.0	2.3	0.4
Oxford	—	3.1	6.8	3.3	2.6	—	2.8	4.2	4.2
QMUL	—	—	1.6	—	0.6	—	2.0	—	—
RAL PPD	1.4	1.6	6.3	5.6	0.6	0.4	1.8	0.8	—
RAL TD	—	—	3.0	—	—	—	3.0	—	—
RAL ISIS	1.2	—	—	—	—	—	—	—	—
RHUL	0.8	—	—	—	1.2	—	1.2	—	—
Sheffield	—	0.4	2.6	—	2.5	—	—	0.4	—
Sussex	—	3.0	—	—	0.8	1.0	—	—	—
UCL	—	2.1	—	—	0.6	—	2.2	—	—
Warwick	0.8	—	0.2	1.0	—	—	0.3	—	
York	0.2	—	—	—	—	—	—	—	—
Total	9.2	17.3	55.1	15.3	19.7	2.1	23.3	15.3	9.6

DRD3 CG Projects

C.3 Task List for DRD-UK 3: Semiconductor detectors

No.	Name	Description
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 will be used to target high granularity (down to 25x25 μm^2) and high radiation tolerance (towards 10^{16} n_{eq}/cm^2) in one device, with a modest time resolution (hundreds of ps) [I-DRD3 WP 1.1, 1.4]. Beneficiaries: Vertex and tracking detectors for upgraded and upcoming experiments (ALICE-3, LHCb-2, EIC, CEPC, Belle-3, ATLAS, CMS); developments towards future e+/e- colliders, muon and hadron colliders.
3.2	Detectors for 4D-Tracking	This task is concerned with the development of detector 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 [I-DRD3 WP 2.2, 2.3] and their associated readout electronics, 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 μm spatial resolution, and radiation tolerance towards 10^{15} n_{eq}/cm^2 [I-DRD3 WP 1.2], within an optimised power budget. Beneficiaries: Upgrades of LHCb, HIKE, ATLAS and CMS timing detectors, EIC, CEPC; demonstration of technology for use at the proposed future muon and hadron colliders.
3.3	3D Stacked, Reconfigurable CMOS Sensors	Commercially available 3D stacked CMOS sensor technology will be explored to develop 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 [I-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. Beneficiaries: Tracking and calorimeter detectors at future e+/e-, muon and hadron colliders; X-rays spectroscopy, electron microscopy.
3.4	Sensors and electronics for Extreme Fluences	This task will develop UK expertise and infrastructure for the development of sensor and ASIC 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 sensor 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 [I-DRD3 WP 3.2, 3.3, 3.4]. Dedicated test structures will be fabricated at UK companies (e.g. Te2v, Micron). ASICs performance will be studied up to a few Grad dose. The potential of diamond detectors will be investigated by demonstrating fabrication of 25 µm base length cubic cell 3D diamond devices [I-DRD3 WP 6.1] to be tested up to 10^{16} - 10^{18} n_{eq}/cm^2 [I-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, and unique worldwide capability to process 3D graphitic wires in diamond. The proton irradiation facility at the MC40 cyclotron of the University of Birmingham will be further developed to provide fluence and TID in the range required for this task. In addition, a neutron irradiation line will be developed at the new Accelerator Driven Neutron Facility (ADNF) in Birmingham. Radiation hardness is key to many DRD3 and DRD7 activities. Beneficiaries: Detectors, Front-end ASICs and DAQ at future hadron colliders.
3.5	Simulations	The proposed developments of new technologies within the DRD3 UK activities will be supported by effort on simulations. 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 [I-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 further R&D and technology selection. Beneficiaries: solid state detector developments for future experiments.

DRD8 CG Projects

C.8 Task List for DRD-UK 8: Challenges of large scale systems

No.	Name	Description
8.0	Coordination	Coordination tasks for DRD 8 in the UK and in the international collaboration.
8.1	Low-mass mechanics	Local support structures, materials and geometries. Targeted at silicon vertexing and tracking detectors for future colliders. Tie in to UK materials, composites and manufacturing industry. Non-linear structures, curved silicon, tilted modules, stiffness by shape; Additive manufacturing (metals, plastics, ceramics, fibres), material shape optimisation for mechanical and thermal performance, printing of small-feature components, printing of matrices optimised for mechanical and thermal load transfer; Novel structural materials (composites, ceramics etc.).
8.2	Cooling	Evaporative cooling for high-power applications, gas cooling for low power. Evaporative cooling: integration of new coolants into local support designs; Integrated cooling channels, microchannels (in silicon, ceramics), thin-wall co-cured pipes, melting or vaporising pre-forms; Additive manufacturing: Components for cooling systems; Connection technologies: Leakless connections for fluid pipes, welding/brazing for metals, gluing for non-metals; Gas cooling: Flow design and simulation, vibration loads, local flow measurements; MEMS. Lightweight trackers and vertex detectors for future colliders.
8.3	Service integration	Co-curing of electrical and optical services into support structures, optical fibre stress/strain and environmental monitoring.
8.4	Robotics	Assembly, disassembly, integration, testing, maintenance, handling of activated components. Future collider detectors. Synergy with activities in Nuclear industry.
8.5	Software tools	New improved software for future detector design and optimisation across HEP. Connection of CAD tools to GEANT; Design and simulation of composites, fluid flow; Machine learning for optimisation and design.

Summary

What we don’t lack: **ambition** and **ideas**!

What we do lack: people!