DRD3 - Solid State Detectors
- Research Proposal -

D.Bortoletto, D.Contardo, E. Vilella Figuras, H.Pernegger, N.Cartiglia, C.Gemme, A.Macchiolo, M.Mikuž, M.Moll, I. Pintilie, S.Seidel, M.Bomben, G.Kramberger, A.Morozzi, F.Moscatelli, J.Schwandt, S.Spannagel, D.Dannheim, M.Fernandez Garcia, M.Jakšić, I.Vila Alvarez, T.Bergauer, T.Koffas, A.Oh, G.Pellegrini, X.Shi, G.Calderini, D.Dannheim, T.Fritzsch, F.Hügging

June 6, 2023

Contents

1 Scope of the DRD3 collaboration

The DRD3 collaboration has the dual purpose of pursuing the realization of the strategic developments outlined by the Task Force 3 (TF3) in the ECFA road map [1] and promoting blue-sky R&D in the field of solid-state detectors.

Presently, the DRD3 proto-collaboration comprises about 100 groups, 75% from Europe [2].

1.1 The DRD3 working group structure

The DRD3 structure is based on grouping activities broadly focused on common goals. At the moment, the following eight working groups are foreseen [2]:

- WG1 Monolithic CMOS Sensors
- WG2 Sensors for Tracking and Calorimetry
- WG3 Radiation damage and extreme fluences
- WG4 Simulation
- WG5 Characterization techniques, facilities
- WG6 Non-silicon-based sensors
- WG7 Interconnect and device fabrication
- WG8 Dissemination and outreach

WGs carry on both the strategic and blue-sky R&Ds

1.2 Strategic R&D

The four strategic Detector R&D Themes (DRDT), identified in [1], are shown in Table 1:

DRDT 3.1 **CMOS sensors**	**DRDT 3.2** **Sensors for 4D-tracking**
DRDT 3.3 **Sensors for extreme fluences**	**DRDT 3.4** **A demonstrator of 3D-integration**

Table 1: The four strategic DRDTs of DRD3

Five WGs map directly into the DRDTs, while three WGs are transversal and provide material to all DRDTs. The relation between DRDTs and WGs is shown in Fig. 1.

The implementation of the strategic R&Ds, as defined by the road-map, will happen via several joint projects, called work packages (WP), Each focused on a given technology. Presently, the envisioned WPs are listed in Table 2. Additional WPs might be defined following the request of the DRD3 members.

Figure 2 reports the timeline of the near-future experiments. In the following, their needs are used to define the most important strategic R&D for the next few years.

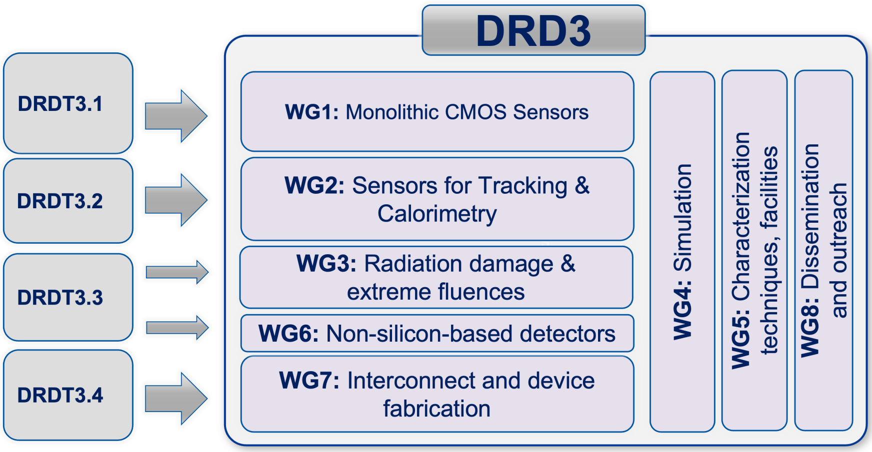

Figure 1: Relationship between DRDTs, Work Packages (WP), and Working Group (WGs)

Figure 2: Timeline of the near-term R&D

1.3 Blue-sky R&D

One of the main goals of the DRD3 collaboration is to foster blue-sky research. The main tool to achieve this goal is to request that each institute pays an annual fee of 2,000 CHF to create a common fund to finance selected common projects (CP). It is foreseen that each proposed CP finds 50% of the financing among the proponents, while DRD3 finances the other 50%. In order to access the DRD3 contribution, each CP has to be presented to the collaboration to be evaluated. Fig. 3 shows the relationships between working groups and strategic or blue-sky R&D graphically.

Work package	Goal
WP 3.1: TPSCo 65 nm	
WP 3.2: TowerJazz 180 nm	
WP 3.3: LFoundry 150 nm	
WP 3.4: TSI 180 nm	
WP 3.5: LFoundry 110 nm	
WP 3.6: IHP 130 nm	
WP 3.7 3D sensors	
WP 3.8 LGAD	
WP 3.9: Wide bandgap (SiC, GaN)	
WP 3.10: Diamond	
WP 3.11: Silicon	

Table 2: DRD3 work packages

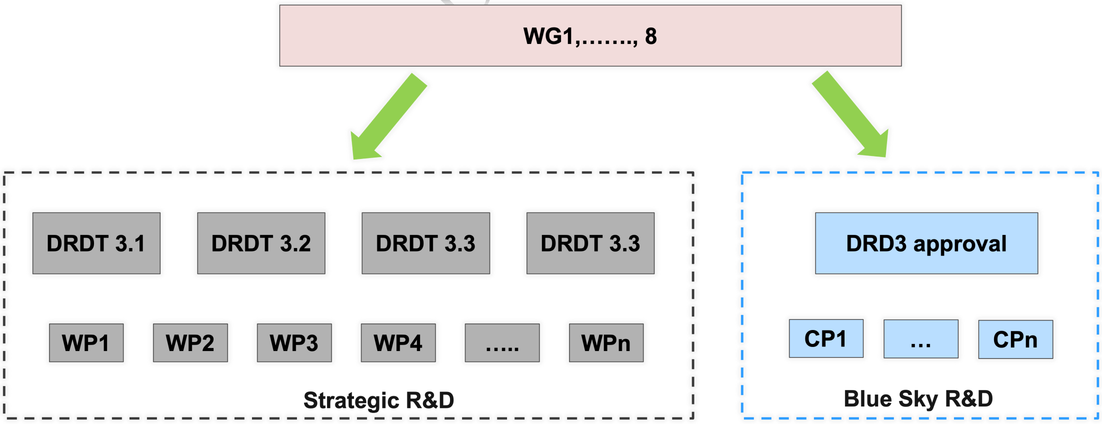

Figure 3: Relationship between working groups and strategic or blue-sky R&D

2 WG1: Depleted CMOS MAPS

WG1 aims to advance the performance of monolithic CMOS sensors for future tracking and calorimetry applications, tackling the challenges of very high spatial resolution, high precision timing, high radiation tolerance, low mass, and reduced power and cost. WG1 will also explore timing layers for 4D tracking. It is, therefore highly aligned with DRDT3.1. It will benefit from close collaboration with DRD7 and DRD3 WG2 for developing timing layers.

Milestones

Four milestones are identified to provide a path to develop monolithic CMOS sensors for use in ALICE-3, LHCb-2, EIC, Belle-3 and HGCAL, and timing layers for the ATLAS and CMS upgrades (until the end of 2028). These developments will be used as stepping stones for future sensor solutions for ILC, CLIC, FCC-ee, MC and FCC-hh in the longer term (until the mid-2030s).

Each milestone has several deliverables in the identified technology processes. This WG will develop as well instrumentation to equip beam telescopes. This proposal covers the time period until 2027 in detail and sketches a possible plan moving beyond.

- **MS 1.1: Spatial resolution** Specification of 3 μm position resolution;

  Deliverables:

  - 2024-2025:
  - 2026-2028:

- **MS 1.2: Timing precision** Specification of 20 ps timing precision;

  Deliverables:

  - 2024-2025:
  - 2026-2028:

- **MS 1.3: Readout architectures** For 100 MHz/cm^2;

  Deliverables:

  - 2024-2025:
  - 2026-2028:

- **MS 1.4: Radiation tolerance** Specification of 10^{16} n_{eq}/cm^2 NIEL and 500 MRad.

  Deliverables:

  - 2024-2025:
  - 2026-2028:

WG1 Milestones, estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 1.1	Spatial resolution: specification of 3 μm position resolution;	0	0
MS 1.2	Timing resolution: specification of 20 ps timing precision		
MS 1.3	Readout architectures for 100 MHz/cm^2	0	0
MS 1.4	Radiation tolerance: specification of 10^{16} n_{eq}/cm^2 NIEL and 500 MRad.	0	0

Table 3: WG1 Milestones for < 2027

2.1 Reviews

Explain the plan for reviews.

2.2 Technology processes

The technology processes considered in this programme, and their main features, are outlined next.

TPSCo 65 nm: Developing the 65 nm technology for large area detectors is a clear goal, as well as improving its timing precision. Progress on power consumption is needed too. This technology uses an epitaxial layer, which is currently fixed at 10 μm and this might be a limitation. Stacking can be considered at an earlier stage than implemented in the table, but this needs more investigation. TPSCo currently offers engineering run submissions only, which are expensive and therefore sharing the wafer between large chips and small R&D chiplets (1.5 mm $\times$ 1.5 mm) is highly encouraged. The submission schedule for this technology process is driven by DRD7, and DRD3 will take advantage of good relationships with them. Two engineering runs are currently planned, the first one in mid-2024 and the second one mid-2025. While the 2024 engineering run is principle fully committed to DRD7 project led designs, there might be scope for DRD3 to include some test structures in this submission already as this is seen as an excellent model for the future. There is interest in defining standard interfaces to streamline the developments for test systems.

TowerJazz 180 nm:

TSI 180 nm:

LFoundry 150 nm: The LFoundry 150 nm process (LF15A) is a mixed digital/high performance analog, high voltage CMOS technology node. It features up to six layers of aluminum interconnection, with the possibility of an additional thick layer of top metal, particularly suited to efficiently route power supplies to large pixel matrices. This process includes as well a deep p-well layer which is useful for embedding digital logic inside the collecting electrode. The foundry offers standard and high resistivity wafers, and has shown to be open to process modifications. There are typically two MPW organized per year. MLM engineering runs are also possible, and can be particularly cost effective for joint submissions handled by several teams. The LF15A technology has been successfully used in the past years for tracking based CMOS demonstrators (e.g. LF-CPIX, LF-MONOPIX chips and RD50-MPW chips) and for non-amplified CMOS timing sensor concepts with performance better than 100 ps (CACTUS chips). Characterization of irradiated samples have shown the technology to be radiation tolerant up to dose levels suitable for the innermost layers of tracking detectors at the HL-LHC. The community is currently negotiating a framework agreement with this foundry to produce a certain number of submissions over a fixed period, taking advantage of special conditions and potentially lower production costs.

LFoundry 110 nm: The LF11is is an automotive-grade CMOS Image Sensor node, offering 1.2V core and 1.8V IO devices, SRAM option (eSilicon memory compiler), MIM capacitors and a 6 Aluminum BEOL stack, allowing for the implementation of complex FD-MAPS and SPAD/SiPM devices. Access to fabrication is possible through regular MPW runs, MLM and Full maskset runs with a pilot lot start with 25 wafers. The foundry allows for the use of custom high-resistivity substrates on FSI and/or BSI process flows, including hence the possibility to use a dedicated maskset for backside lithography. While the maximum reticle size is 26 mm $\times$ 32mm, the LF11is technology comes with a 1D or 2D stitching option. The technology is used by INFN since 2015 for the implementation of FD-MAPS on active fully-depleted thicknesses ranging from 50 to 400 μm, using MPWs for first prototypes and 3 dedicated engineering runs. The flexibility of the foundry process and product engineering teams allow to explore multiple wafer splits (n-epi thickness, n-type or p-type starting substrate, substrate resistivity, implementation of a gain layer creating a monolithic LGAD, FSI or BSI process on different wafer thicknesses) on a dedicated pilot engineering run. In the framework of ARCADIA, INFN and LFoundry agreed on the terms to allow for the participation of third-party design groups to joint production runs. In this case, the 3rd-party design group will be provided with regular access to the CMOS LF11is iPDK for the implementation of proprietary architecture and FDMAPS designs. Other than providing a library of signal samples for the chosen sensor geometry, INFN handles the sensor integration to the third-party design, final DRC of the design database during the preparation for tapeout. This option enables a straightforward, low-risk and very fast ramp-up of the R&D on FDMAPS using LF11is technology for new groups and design teams.

IHP 130 nm: SiGe process

3 WG2: Sensors for tracking and calorimetry

WG2 aims to advance the performance of sensors for 4D tracking, and it is aligned with the goals of DRDT2. The scope of the WG2 is quite broad, as it addresses the R&D of sensors for very different environments: vertex or tracker, low/high radiation, low/high occupancy, low/high power, and low/high material budget. Presently, sensors with 4D capabilities are foreseen in many systems, from Time-of-Flight systems with only 1-2 layers of sensors with the best possible resolution to large 4D trackers with many layers. In this latter case, if the temporal resolution is good enough, recognition algorithms can use four coordinates in the reconstruction, simplifying the pattern recognition. Broadly speaking, at hadron colliders the challenges are mostly linked to radiation levels (mostly in the vertex detector) and very high occupancy, while at lepton colliders the challenges are linked to material budget and low power consumption.

3.1 Spatial and temporal resolutions at extreme radiation levels

For this R&D, the new innermost layers of ATLAS/CMS and the LHCb velo pixel systems are used as stepping stones for the broader developments needed for FCC-hh

- **MS 2.1: Reduction of pixel cell size for 3D sensors.**

  Deliverables:

  - 2024-2025: 3D sensors test structures with pixel size smaller than the current $50 \times 50\ \mu m^2$ or $25 \times 100\ \mu m^2$
  - 2026-2028: Large size 3D sensors with reduced pixel size.

- **MS 2.2: 3D sensors with a temporal resolution of about 50 ps.**

  Deliverables:

  - 2024-2025: Production of small matrix with pitch $42 \times 42\ \mu m^2$ or $55 \times 55\ \mu m^2$ to be connected with existing read-out ASICS
  - 2026-2028: Production of large-size sensors (using the selected geometry from the R&D runs) and interconnection with custom-made read-out ASIC

3.2 Spatial and temporal resolutions at low radiation levels and low material and power budgets

The phase 3 ATLAS/CMS upgrades might seek to introduce 4D layers at moderate radiation levels (a few 1E15 n/cm^2), with a spatial resolution of about 10 - 30 μm. Sensors for lepton colliders require very low material budget and minimal power consumption.

- **MS 2.3: LGAD Sensors with very high fill factor, and an excellent spatial and temporal resolution.**

  Deliverables:

  - 2024-2025: LGAD test structures of different technologies (TI-LGAD, iL-GAD, RSD, DJ-LGAD), matching existing read-out ASICs.
  - 2026-2028: Large size LGAD sensors based on the best performing technology.

- **MS 2.4: LGAD sensors for Time of Flight applications**

  Deliverables:

  - 2024-2026: Production of LGAD (RSD) sensors with large size for Tracking/Time of Flight applications to demonstrate yield and doping homogeneity. Study of spatial and time resolution as a function of the pixel size.
  - 2026-2028: Structures produced with vendors capable of large-area productions to demonstrate the industrialization of the process.

WG2 Milestones, estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 2.1	Reduction of pixel cell size for 3D sensors	240	9
MS 2.2	3D sensors for timing (50×50 um, < 50 ps)	480	18
MS 2.3	LGAD for 4D tracking < 10 um, < 30 ps, wafer 6” and 8”	480	18
MS 2.4	RSD for ToF (Large area, < 30 um, < 30 ps)	120	6

Table 4: WG2 Milestones for < 2027

4 WG3: Radiation damage and extreme fluence operation

This WG aims to provide a fundamental scientific understanding of radiation damage processes in solid-state detectors and detector materials at low, high, and extreme radiation levels of up to 5×10^{18} cm^{-2} and 5000 MGy, as anticipated for the forward calorimeters in the FCC-hh after an integrated luminosity of 30 ab^{-1}. The existing and newly generated knowledge will be used to optimize the radiation tolerance of the various detector types under development within the collaboration through defect and material engineering, device engineering, and optimization of operational conditions. The work is organized in two areas. The first is the study of the radiation damage mechanisms in detector materials including the formation of microscopic defects and their impact on device performance; the second is the study and modeling of radiation damage to devices. In both areas the full range from very low to high fluences and finally up to extreme fluences beyond 2×10^{16} cm^{-2} has to be covered. The latter work covers the Roadmap DRDT 3.3. on extreme fluence operation, while WG3 reaches deeply into all four Roadmap DRDTs for solid-state detectors wherever radiation damage is of concern.

4.1 Radiation damage and hardening studies at material level

The understanding of radiation damage at the microscopic level and of the consequences on materials and device properties is a necessary prerequisite for efficient and successful detector development. Comprehensive investigations of defects generated in irradiated sensors providing accurate evaluations of defect concentrations and trapping parameters can be achieved by employing specific spectroscopic techniques based on capacitance or current measurements (e.g. DLTS, TSC, TSCap). Such methods have been successfully applied on fabricated silicon sensors up to fluences of about 10^{15} $\mathrm{n_{eq}/cm^2}$. They provide both the characteristics of radiation-induced defects that are also fundamental input parameters to sensor performance simulations under various conditions and knowledge for developing material and defect engineering strategies. As the extrapolation of damage parameters to higher fluences has proven to be too pessimistic, and the defect formation process is not a linear function of fluence, further characterization work at higher fluences is essential but exceeds the range of applicability of present experimental characterization methods. Therefore, the understanding of the radiation damage at extreme fluences requires, in addition, comprehensive modeling of defect generation, including the higher order radiation-induced defects, and the employment of other techniques suitable for detecting defects in large concentrations, i.e. above 10^{16} cm^{-3}, such as EPR, FTIR, XRD, Raman and PL. Even more demanding is the understanding of radiation damage in wide band gap (WBG) and other materials where presently, compared with silicon, significantly less knowledge exists. In addition, the changes of the fundamental semiconductor properties (e.g. carrier mobilities, carrier lifetime) at extreme fluences are very poorly known, although they are needed for any detector design work. These challenges will be addressed in the years to come, starting with developing the defect engineered strategies for obtaining detailed and precise electrical characterization of point and cluster defects generated by irradiations up to fluences of 10^{16} $\mathrm{n_{eq}/cm^2}$ by means of DLTS, TSC, and TSCap techniques. Highly irradiated devices (above 10^{17} $\mathrm{n_{eq}/cm^2}$) will start to be investigated by EPR, FTIR, XRD, Raman and PL, with the aim of providing the needed information about the chemical structure of radiation-induced defects and their introduction rates, to be used in developing a realistic radiation model up to extreme radiation fluences. From carrier lifetime and Hall effect measurements the change of the carrier lifetime and mobility will be evaluated.

4.2 Radiation damage and hardening studies at device and system levels

A wide variety of radiation damage studies will be needed by the detector community in both the near and long terms. Tracking and timing detectors, including for example several configurations of LGAD and 3D sensors, are already aimed at the earliest LHC upgrades. These will continue to need regular irradiations with various particle species up to approximately 5×10^{16} $\mathrm{n_{eq}/cm^2}$. Technology development in new directions will need radiation testing and radiation damage modeling as well; this includes large area and thick silicon devices, applications for the LHCb and ALICE upgrades, the Electron-Ion Collider, and space-based detectors. New efforts in high-granularity calorimetry and quantum-imaging detectors are already seeking characterization within radiation contexts. Devices proposed for later upgrades need radiation damage studies in the near term too, for evaluation of monolithic active pixel sensors (MAPS), monolithic CMOS, and ASICs. Within the community there are already calls for facilities able to provide up to 10^{18} $\mathrm{n_{eq}/cm^2}$, with multiple beam energies and species. TCAD and Geant4 simulations are underway for new structures and require validation with data. Data are urgently needed, from both TCT instruments and testbeams, combined with dedicated data collected by the LHC experiments for leakage current and depletion.

New materials are under exploration which require either new or extended parameterized models of their radiation damage response. These include all materials studied in WG 6, and in particular the wide bandgap semiconductors, which may have the benefit of reduced cooling requirements. Radiation studies are also needed for new vertical and heterogeneous integration techniques that are directly connected to materials improvements. And the foundational research toward understanding how fundamental material properties such as mobility, effective dopant concentrations, and carrier lifetimes, evolve with dose, continues solidly. The semiconductor detector community needs to understand the limit of validity of the current models (e.g. Hamburg Model) and understand where the presently used non-ionizing energy loss (NIEL) hypothesis fails to determine the best directions in defect and device engineering. We do not lose sight of the fact that technology transfer beyond High Energy Physics, for example to medical imaging, dosimetry, nuclear safety, and security, requires rigorous radiation validation as well.

The present community for development of radiation tolerant semiconductor detectors includes many institutes, comprising university groups and national laboratories. Regular trainings are being offered at nearly all of them to expand the community and build a corps of expert junior researchers. Milestones to be achieved in the next three years include (1) improved or new models for new materials and extreme radiation conditions; (2) a transfer of information from models to simulations; and (3) sufficient irradiation facilities and test beam support for this diverse program. A critical milestone on the timescale of six years is the reliable availability of facilities providing integrated fluence on the order of 10^{18} $\mathrm{n_{eq}/cm^2}$, in both charged and neutral species.

Milestones

Estimated cost and FTE <2027			
	Description	**Cost [kCHF]**	**FTE/y**
MS 3.1	Build up data sets on radiation induced defect formation in WBG materials	0	0
MS 3.2	Develop silicon radiation damage models based on measured point and cluster defects	0	0
MS 3.3	Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation	0	0
MS 3.4	Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to $10^{18}\mathrm{n_{eq}cm^{-2}}$	0	0

Table 5: WG3 Milestones for $<$ 2027

5 WG4: Simulation

The simulation work will be dedicated to development of common simulation packages, tools and radiation models. There will be two lines of activities that will be pursued: TCAD tools and so called MC tools. While the former are commonly used in sensor design, process simulation and radiation damage modeling the latter are extensively tested in sensor performance evaluation (with particle and Transient Current Tecnique) benefiting from much faster code and integration of other software packages e.g. GEANT4.

Another important activity in WG4 will be continuation of radiation hardness modeling, bulk and surface, starting from the defect level using mainly TCAD, but also MC tools. Radiation hardness models for WBS will be explored and developed.

The WG4 will be important part of many Work Packages, from simulations of sensors development and performance in WG1, WG2 to exploiting the defect investigation of WG3 to simulations of common tools useage (WG5) and WBS (WG6).

5.1 Activities

The following activities are foreseen in the WG4

- TCAD activities will focus on providing verification of tools (mainly Silvaco and Synopsis, but also looking to other tools emerging) implementation of new physics models (impact ionization, mobility parametrization etc.), exporting tools, communication with software companies (e.g. implementation of WGS) and keeping the implementation of common solutions to device simulations.
- TCAD simulations will be complemented with charge transport simulation tools - Monte Carlo tools - allowing detailed studies of complex sensor performance. Different tools have been developed so far, but currently the most supported and advanced tool is AllPix2, which will form the main/production framework, while other tools will continue to be used as verification and development tools. It is foreseen that improvements in MC simulations will eventually be integrated into AllPix2. The biggest obstacle for Monte-Carlo tools is currently lack of implementing adaptive/time dependent weighting and electric fields in induced current simulations.
- Modeling of the radiation damage in simulations has been evolving over the last two decades, but there is no superior model not tailored to certain device that would from the defect level comprehensively describe all the macroscopic properties of silicon, even more so at extreme fluences (WG3).
- Development of signal processing tools that can be used with MC and TCAD tools and general digitization models for different sensors technologies,

5.2 Milestones and resources

Estimated cost and FTE <2027			
	Description	**Cost [kCHF]**	**FTE/y**
MS 4.1	Flexible CMOS simulation of 65 nm to test design variations	~ 50 shared with MS 4.2,4.3,4.4	~ 2
MS 4.2	Implementation of newly measured semiconductor properties into TCAD and MC simulations tools	~ 50 shared with MS 4.1,4.3,4.4	~ 3
MS 4.3	Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models.	~ 50 shared with MS 4.1,4.2,4.4	~ 2
MS 4.4	Developing of bulk and surface model for $10^{16}\text{cm}^{-2} < \Phi_{eq} < 10^{17}\ \text{cm}^{-2}$	~ 50 shared with MS 4.1,4.2,4.3	~ 2
MS 4.5	Collate solutions from different MC tools and develop algorithm to include adaptive electric and weighting fields	0	~ 5

Table 6: WG4 Milestones for < 2027. The cost is related to obtaining TCAD licences.

	Description	**Cost [kCHF]**	**FTE/y**
LT-MS 4.1	General model for extreme fluences accounting for the saturation effects and inclusion of comprehensive models of other WBS.	-	-
LT-MS 4.2	Comprehensive manual to guide the user in TCAD radiation damage effects simulation.	-	-
LT-MS 4.3	Build computational efficient algorithm to approximate dynamic space charge effects for various sensor technologies	-	-

Table 7: WG4 Milestones for > 2027

6 WG5: Measurement and characterisation techniques

Ivan: To be done by end of next week

7 WG6: Wide bandgap and innovative sensor materials

Wide band-gap (WBG) semiconductors have some attractive properties and also some associated problems. Whilst a wide band-gap reduces the leakage current, maintaining low noise levels even at high temperatures, it also increases the electron-hole generation energy. This increase implies that the number of electron-hole pairs generated for the same deposited energy is lower in WBG materials. However, the substantial reduction of the noise level ensures that the overall signal-to-noise ratio (SNR) for WBG-based detectors is high enough, even after irradiation. In addition, the high breakdown field allows operation at high internal electric fields, minimizing the carrier transit time and the trapping probability.
Other innovative semiconductors, such as 2D materials, require investigation. However, their current level of development for use in experiments is still relatively low. As a result, a Blue-sky funding scheme should be applied to support further research in these areas.
WG6 is well aligned with the DRDT3.2 and DRDT3.3 since WBG semiconductors can be used for timing applications due to the high carrier saturation velocity and their radiation hardness make them suitables materials to be used at extreme fluences with the added advantage that they can be operated without cooling.

7.1 Diamond

The high energy physics community has extensively studied diamond as a wide band-gap semiconductor material for sensors, experiments and accelerators have used diamond based beam conditions monitors successfully for decades. Polycrystalline synthetic diamond (pCVDD) with a wafer charge-collection-distance (CCD) of 400 microns is available today, and the aim is to increase the quality to 500 microns and improve wafer uniformity. Diamond detectors have been tested for radiation hardness and can withstand protons, neutrons, and pions at various energies. However, at a fluence of 10^{17} cm^{-2} 24 GeV protons, the Schubweg or average distance a carrier traverses before being captured is approximately 16 microns, resulting in a significant reduction in signal efficiency. 3D diamond detectors with a femtosecond laser process to convert diamond into graphite electrodes can address this problem. The first 3D diamond detector device is planned for use in the ATLAS Phase-II upgrade as small beam condition monitors, and it represents a stepping stone towards larger area applications needed for future projects like the FCC-hh. Further studies and innovative geometries are needed to assess the radiation tolerance of 3D diamond detectors comprehensively. This includes studies of charge multiplication via impact ionisation through adapted electrode geometries to improve not only the radiation tolerance but also the timing performance.

7.2 Wide-band semiconductor

SiC In recent times, the use of SiC in power devices has become widespread, and the quality of this material has reached levels comparable to that of silicon. Additionally, 150mm SiC wafers have become standard in the semiconductor industry, and soon 200mm wafers will be introduced to the market. The high-quality material required for SiC sensors is typically epitaxially grown using Chemical Vapour Deposition (CVD), which allows for precise control of thickness, doping, and homogeneity of crystal films. Recently, SiC epitaxial layers up to a thickness of 200 μm have been obtained. However, the material's resistivity must be increased to deplete these layers with reasonable bias voltages. Alternatively, mip detection in thin layers with reasonable SNR would need signal amplification in the material.

In the mid-term, SiC could be used as beam loss and intensity monitors, as well as in medical applications like (micro-)dosimetry and for neutron/plasma detection in high-temperature environments.

In the coming years, the main technological challenges for SiC detectors will involve studying the radiation hardness of high-quality materials and understanding the defect traps. This will aid in fabricating more radiation-hard materials and developing reliable simulation tools necessary for designing new detectors and predicting their performance in extreme fluence environments. Recent studies have shown that SiC detectors have better timing performance than silicon detectors, necessitating further research to explore the possibility of including a gain layer into the bulk as done for the standard LGAD. A multiplication mechanism in SiC diodes has been observed after neutron irradiation, but it is not yet understood.

GaN is the most rapidly growing semiconductor material used in industrial applications such as telecommunications, power management, high-temperature operation, opto-electronics and aerospace. However, defects in the GaN crystal, such as dislocations and unintentional doping, still present a challenge in terms of improving device-level performance. In the past decade and due to the rapid improvement of material quality of epitaxially grown films, the promise of GaN as a detector material has been demonstrated by several groups. Nevertheless, the widespread use of GaN devices in higher radiation environments (HL-LHC and beyond) will require development to improve their radiation hardness, which in turn requires a thorough understanding of the displacement damage and resulting material defects in GaN, and designing devices using predictive models calibrated to irradiated GaN on native substrates and on SiC. This aligns well with developments in industry where material quality is perceived as the key towards the development of fast RF devices with sub-ns resolution (5G and beyond) and monolithic designs of GaN embeded in Si or SiC substrates for fast power switching and nuclear technology applications.

Estimated cost and FTE <2027			
	Description	**Cost [kCHF/y]**	**FTE/y**
MS 6.1	3D diamond detectors, cages / interconnects, base length 25 μm ,impact ionisation	250	10
MS 6.2	Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels.	350	16
MS 6.3	Improve tracking capabilities of WBG materials	100	1
MS 6.4	Apply graphene and/or other 2D materials in radiation detectors, understand signal formation.	100	1

Table 8: WG6 Milestones for $<$ 2027

8 WG7: Sensor interconnection techniques

Interconnections is one of the critical aspects of future detector and electronics evolution. They have a fundamental role in the development of sensors and readout front-end, under the point of view of integration of the sensor and readout ASICS, but also in the process of construction of multi-tier electronics. Interconnection technologies enter at different levels of technology: from the fast hybridization necessary for the qualification of prototypes, to the stable and reliable flip-chip of modules which enter into a detector and must provide reliable operation for years under stringent radiation, thermal and mechanical specifications, up to the implementation of advanced technologies necessary for the resolution of specific problems. The goal of the DRD3 interconnection task is to organise the different technological and readiness levels of interconnection solutions and the effort towards future advances in the field, to match the requirements of future detectors in a coherent and coordinated way.

To be organised with the uniform structure of the document: Subsection?

8.1 Maskless interconnections: anysotropic conductive films or pastes (ACF, ACP)

Small-pitch hybrid pixel detectors produced with solder bump-bonding techniques are widely used in current and future HEP experiments. The cost of the complex metallization and interconnect processing, performed in highly specialized foundries, dominates the production cost per unit area, and the need to process whole readout wafers dominates the prototyping costs. In addition, this introduces a long turnaround time during the prototyping phase, where several submissions are done and for which usually a limited number of devices are used for test. One of the axes of the DRD3 interconnection working package is thus to study technological alternatives to the standard flip-chip techniques, in order to develop fast, possibly in-house, connection processes able to be used for fast testing of new productions, et possibly at device level. The advantage of avoiding passing by specialised hybridization vendors will translate in a significant savings of time and money.

Anysotropic Conductive Films (ACF) and Anysotropic Conductive Pastes (ACP) are interconnection technologies based on microscopic conductive particles suspended in an adhesive medium, a film or a paste. Thermocompression of the ACF/ACP between two conductors results in a permanent attachment and a reliable electrical connection only in the direction of the compression. ACF is today the dominating interconnect technology for displays (LCD and OLED), and is widely used also in e.g. camera modules and RFID manufacturing. For the application in HEP pixel detectors, critical parameters such as bonding force, adhesive film thickness, particle material and diameter and density of particles need to be developed for the specific layout and topology of the respective sensors and readout ASICs. One of the main advantages of these technologies is that they may not require lithographic mask for deposition and represent processes affordable in-house for a large number of laboratories. Processing can happen both at die-to-die and die-to-wafer level.

Relevant milestones in this development could be: in the short term consolidate the connection yield reaching a bench-mark well above the 99% necessary for tracking detectors applications; demonstrate a process optimisation which could satisfy pixel pitch of the order of $30\mu m$ or below; in the mid-term, demonstrate the radiation hardness of the process to fluences and doses typical of future experiments at colliders and demonstrate the reliability of the technology under the thermal and mechanical specifications determined by the above applications.

8.2 Improvement and diffusion of standard interconnection technologies

Present interconnection techniques provided to High Energy Experiments by commercial vendors and RTOs are nowadays reaching the necessary standards in terms of yields and typical technical specifications but remain expensive and time consuming processes. The construction of the LHC upgraded trackers for High Luminosity coming in parallel for several detectors on the same timescale did also show that the production capacity of most of these vendors can be easily saturated. For this reason a step forward should be done for this class of interconnections following two main axes. The first is to make the most common interconnection techniques affordable for internal processing in those of the home laboratories which present some level of existing infrastructure. This can be done for instance with the introduction of maskless processes, some of which is even existing already, but should be further developed to make them useful in realistic conditions. The second is to organise and sponsor the development of advanced processes and the cooperation of commercial vendors and academic groups to address specific complex issues: for example the need for smaller pixel pitches, the resolution of process temperature constraints, the electrical properties of interconnections in terms of maximum current or capacitance, or the structure of the interconnection industrial aspects (die-to-die or die-to-wafer). Milestones would be: in the short term, the development of maskless post-processing for some of the most standard technologies; in the mid-term, to make the most standard technologies available in full or in part inside specialised academic laboratories; to develop a device-to-wafer approach which would be necessary for R&D applications in order to support the multi-projects, where only a small part of each production wafer is used by a collaboration.

3D and vertical integration for High Energy Physics silicon detectors 3D and vertical integration are technologies already largely used in electronics. They are essentially available via industry and in this way they profit of the commercial drive coming from consumers' electronics. The use in High Energy Physics experiments has been already probed to some extent, with the goal of merging - for instance - tiers coming in different technologies: a typical example is a digital layer built in a given technology optimised for some of the specifications, connected to an analog tier built in a completely different process. Vertical integration might also have a fundamental role in the integration of different devices which need to be interconnected and that in today's detectors are exchanging data via external solutions such as flexible circuits. The vertical stacking can also allow to contact / power / read a lower tier through an intermediate one with the use, for instance, of specific vias. The interconnection Work Package of DRD3 should coordinate the access to specific industrial processes for laboratories involved in High Energy Physics detectors. While single groups might be able to deal with secondary industrial actors in the field of vertical integration, the mediation of DRD3 might have a larger chance of success for the involvement of big industrial players, granting continuity and resources. Milestones for the short-term are: the demonstration of wafer-to-wafer process in front-end to sensor connection; the demonstration of the use of TSV to pass power or data through sensors or front-end layers. For the medium/long term: to demonstrate the interconnection capability for post-processed devices.

Estimated cost and FTE $<$2027			
	Description	**Cost [kCHF/y]**	**FTE/y**
MS 7.1	Yield consolidation for fast interconnections		
MS 7.2	Demonstration of in-house process for single dies and a range of pitch (down to $< 30\mu m$) pixel interconnections		
MS 7.3	Radiation hardness testing and verification of thermomechanical constraints		
MS 7.4	Development of maskless post-processing for commonly-used interconnection technologies		
MS 7.5	Bring part of the commonly-used interconnection technologies to specialised academic groups		
MS 7.6	Develop device-to-wafer interconnection technologies		
MS 7.7	Develop wafer-to-wafer in presently advanced interconnection technologies		
MS 7.8	Develop VIAS in multi-tier sensor/front-end assemblies		
MS 7.9	Develop connection techniques for post-processed devices		

Table 9: WG7 Milestones for < 2027

9 WG8: Outreach and dissemination

WG8 aims at promoting outreach and disseminating the activities of the DRD3 collaboration in coordination with other similar ECFA activities.

The WG8 activities can be broadly divided into:

- Disseminating knowledge on solid-state detectors to people working in high-energy physics (training, lectures, mobility)
- Disseminating knowledge on solid-state detectors to high-school students and the general public.

9.1 Disseminating knowledge on solid-state detectors to people working in high-energy physics

These activities aim to provide training and disseminate the experimental techniques needed in DRD3 activities.

- Organize schools for Ph.D. students and young post-docs on TCAD, FOGA programming, GEANT, AllPix2, SIMDET.
- Organize stages for undergraduate students and promote exchange programs between labs. Financial support might be offered
- Participation to instrumentation schools, offering lectures on DRD3 topics (for example, the CERN or FNAL schools)
- Share knowledge of measurement techniques such as device characterizations using IV, CV characteristics, transient studies using TCT, beta telescopes, handling and measurements of irradiated sensors
- Present DRD3 work at conferences, providing opportunities for young researchers to be speakers at important international conferences.
- Publish papers and proceedings so that the DRD3 activities are documented in printed papers.

One exciting aspect is to create partnerships between established and new laboratories so that the upcoming groups can profit from the accumulated knowledge of the more senior groups.

The DRD3 website will be the point of entry to advertise all DRD3 activities. It will contain links to the DRDs meetings; it will list opportunities for conferences, stages, and so on. It will also collect documentation on how to perform the various experimental techniques.

9.2 Disseminating knowledge on solid-state detectors to high-school students and the general public

Many of the DRD3 members are engaged in outreach activities at various levels, such as high-school seminars, hands-on experiments for young students, and community meetings. WG8 aims to collect materials and suggestions for these activities so that it will be easier for new members to carry on the same activities in new places.

WG8 Milestones and Estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 8.1	Design and set-up of the DRD3 web site		
MS 8.2	Collection of the outreach material		
MS 8.3	Set-up and organize schools and exchange programs		
MS 8.4	Set-up of the DRD3 conference committee		

Table 10: WG8 Milestones for < 2027

10 Summary of the DRD3 Milestones

Table 11 to Table 17 report all DRD3 milestones.
Table 18 to Table 20 show the link between the milestones and the DRDTs.

WG1 Milestones, estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 1.1	Spatial resolution: specification of 3 μm position resolution;	0	0
MS 1.2	Timing resolution: specification of 20 ps timing precision		
MS 1.3	Readout architectures for 100 MHz/cm^2	0	0
MS 1.4	Radiation tolerance: specification of 10^{16} n_{eq}/cm^2 NIEL and 500 MRad.	0	0

Table 11: WG1 Milestones for < 2027

WG2 Milestones and estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 2.1	Reduction of pixel cell size for 3D sensors	240	9
MS 2.2	3D sensors for timing (50 $\times$ 50 um, < 50 ps)	480	18
MS 2.3	LGAD for 4D tracking < 10 um, < 30 ps, wafer 6” and 8”	480	18
MS 2.4	RSD for ToF (Large area, < 30 um, < 30 ps)	120	6

Table 12: WG2 Milestones for < 2027

WG3 Estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 3.1	Build up data sets on radiation induced defect formation in WBG materials	0	0
MS 3.2	Develop silicon radiation damage models based on measured point and cluster defects	0	0
MS 3.3	Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation	0	0
MS 3.4	Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to $10^{18} \mathrm{n_{eq}cm^{-2}}$	0	0

Table 13: WG3 Milestones for $<$ 2027

Estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 4.1	Flexible CMOS simulation of 65 nm to test design variations	$\sim$ 50 shared with MS 4.2,4.3,4.4	~ 2
MS 4.2	Implementation of newly measured semiconductor properties into TCAD and MC simulations tools	$\sim$ 50 shared with MS 4.1,4.3,4.4	~ 3
MS 4.3	Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models.	$\sim$ 50 shared with MS 4.1,4.2,4.4	~ 2
MS 4.4	Developing of bulk and surface model for $10^{16}\mathrm{cm}^{-2} < \Phi_{eq} < 10^{17}\ \mathrm{cm}^{-2}$	$\sim$ 50 shared with MS 4.1,4.2,4.3	~ 2
MS 4.5	Collate solutions from different MC tools and develop algorithm to include adaptive electric and weighting fields	0	~ 5

Table 14: WG4 Milestones for $<$ 2027. The cost is related to obtaining TCAD licences.

WG6 Milestones and estimated cost and FTE <2027			
	Description	**Cost [kCHF/y]**	**FTE/y**
MS 6.1	3D diamond detectors, cages / interconnects, base length 25 μm ,impact ionisation	250	10
MS 6.2	Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels.	350	16
MS 6.3	Improve tracking capabilities of WBG materials	100	1
MS 6.4	Apply graphene and/or other 2D materials in radiation detectors, understand signal formation.	100	1

Table 15: WG6 Milestones for < 2027

WG7 Estimated cost and FTE <2027			
	Description	**Cost [kCHF/y]**	**FTE/y**
MS 7.1	Yield consolidation for fast interconnections		
MS 7.2	Demonstration of small pitch ($< 30\mu m$) pixel interconnections		
MS 7.3	Demonstration of Radiation hardness and thermo mechanical constraints		
MS 7.4	Development of maskless post-processing for commonly-used interconnection technologies		
MS 7.5	Bring part of the commonly-used interconnection technologies to specialised academic groups		
MS 7.6	Develop device-to-wafer interconnection technologies		
MS 7.7	Develop wafer-to-wafer in presently advanced interconnection technologies		
MS 7.8	Develop VIAS in multi-tier sensor/front-end assemblies		
MS 7.9	Develop connection techniques for post-processed devices		

Table 16: WG7 Milestones for < 2027

WG8 Milestones and Estimated cost and FTE <2027			
	Description	**Cost [kCHF]/y**	**FTE/y**
MS 8.1	Design and set-up of the DRD3 web site		
MS 8.2	Collection of the outreach material		
MS 8.3	Set-up and organize schools and exchange programs		
MS 8.4	Set-up of the DRD3 conference committee		

Table 17: WG8 Milestones for < 2027

DRDT:	3.1 DMAPS						3.2 4D Tracking		3.3 Extreme Fluence			3.4 Intercon.	
Workpackage:	TPSCo 65 nm	TowerJazz 180 nm	LFoundry 150 nm	TSI 180 nm	LFoundry 110 nm	IHP 130 nm	3D	LGAD	Silicon	Diamond	Wide Bandgap		3D-integration
MS Description													
1.1 Spatial resolution: specification of 3 μm position resolution													
1.2 Timing resolution: specification of 20 ps timing precision													
1.3 Readout architectures for 100 MHz/cm^2													
1.4 Radiation tolerance: specification of 10^{16} $\mathrm{n_{eq}/cm^2}$ NIEL and 500 MRad.													
2.1: Reduction of pixel cell size for 3D sensors							X						
2.2 3D sensors for timing (50 $\times$ 50 um, $<$ 50 ps)							X						
2.3 LGAD for 4D tracking $<$ 10 um, $<$ 30 ps, wafer 6” and 8”								X					
2.4 RSD for ToF (Large area, $<$ 30 um, $<$ 30 ps								X					
3.1 Build up data sets on radiation-induced defect formation in WBG materials										x	x		
3.2 Develop silicon radiation damage models based on measured point and cluster defects									x				
3.3 Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation							x	x	x	x	x		
3.4 Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to $10^{18}\mathrm{n_{eq}cm^{-2}}$										x	x		

Table 18: Mapping of DRDTs, WPs, and Milestones

DRDT:	3.1 DMAPS						3.2 4D Tracking		3.3 Extreme Fluence			3.4 Intercon.	
Workpackage:	TPSCo 65 nm	TowerJazz 180 nm	LFoundry 150 nm	TSI 180 nm	LFoundry 110 nm	IHP 130 nm	3D	LGAD	Silicon	Diamond	Wide Bandgap		3D-integration
MS Description													
4.1 Flexible CMOS simulation of 65 nm to test design variations													
4.2 Implementation of newly measured semiconductor properties into TCAD and MC simulations													
4.3 Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models.													
4.4 Developing of bulk and surface model for $10^{16}\text{cm}^{-2} < \Phi_{eq} < 10^{17}\ \text{cm}^{-2}$													
4.5 Collate solutions from different MC tools and develop algorithms to include adaptive electric and weighting fields													
5.1 XXXXX													
5.2 XXXX													
5.3 XXX													
5.4 XXX													

Table 19: Mapping of DRDTs, WPs, and Milestones

DRDT:	3.1 DMAPS						3.2 4D Tracking		3.3 Extreme Fluence			3.4 Intercon.	
Workpackage:	TPSCo 65 nm	TowerJazz 180 nm	LFoundry 150 nm	TSI 180 nm	LFoundry 110 nm	IHP 130 nm	3D	LGAD	Silicon	Diamond	Wide Bandgap		3D-integration
MS Description													
6.1 3D diamond detectors, cages / interconnects, base length 25 μm ,impact ionisation													
6.2 Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels.													
6.3 Improve tracking capabilities of WBG materials													
6.4 Apply graphene and/or other 2D materials in radiation detectors, understand signal formation.													
MS 7.1 Yield consolidation for fast interconnections													
MS 7.2 Demonstration of small pitch ($< 30\mu m$) pixel interconnections													
MS 7.3 Demonstration of Radiation hardness and thermo mechanical constraints													
MS 7.4 Development of maskless post-processing for commonly-used interconnection technologies													
MS 7.5 Bring part of the commonly-used interconnection technologies to specialised academic groups													
MS 7.6 Develop device-to-wafer interconnection technologies													
MS 7.7 Develop wafer-to-wafer in presently advanced interconnection technologies													
MS 7.8 Develop VIAS in multi-tier sensor/front-end assemblies													
MS 7.9 Develop connection techniques for post-processed devices													

Table 20: Mapping of DRDTs, WPs, and Milestones

11 Path to the DRD3 collaboration

The institutes participating in the proposal must designate a contact person who will serve as a member of the provisional institution board at the time of the submission of the proposal. Additionally, these participating institutions are expected to provide a comprehensive list of individuals involved in the project.

Following the submission of the proposal and before its final approval by the DRDC, the DRD3 proposal team will act as a search committee for the collaboration board chair. The election of the collaboration board chair, utilizing the CERN e-voting system, will occur immediately after the proposal's approval and prior to the inaugural meeting of the collaboration, expected to occur in the first quarter of 2024. This process is essential to establish a functional structure for the collaboration right after its inaugural meeting. The DRD3 proposal team will collaboratively prepare the agenda and program for the inaugural meeting in collaboration with the collaboration board chair. This marks the conclusion of the DRD3 proposal team's mandate.

The collaboration board chair will then assemble a search committee responsible for selecting a candidate pool for the role of spokesperson. These candidates will present their vision for the DRD3 collaboration at the kickoff meeting, including proposals for working group conveners. The spokespersons' elections will take place during the kickoff meeting of the collaboration, thereby establishing the operational functionality of the collaboration. The spokespersons and the collaboration board chair will formulate a Memorandum of Understanding (MoU) for the collaboration and guide its formation by overseeing the establishment of all collaboration bodies. During the interim period before the preparation and endorsement of the DRD3 MoU, the DRD3 proposal team advises adhering to the rules outlined in the RD50 MoU.

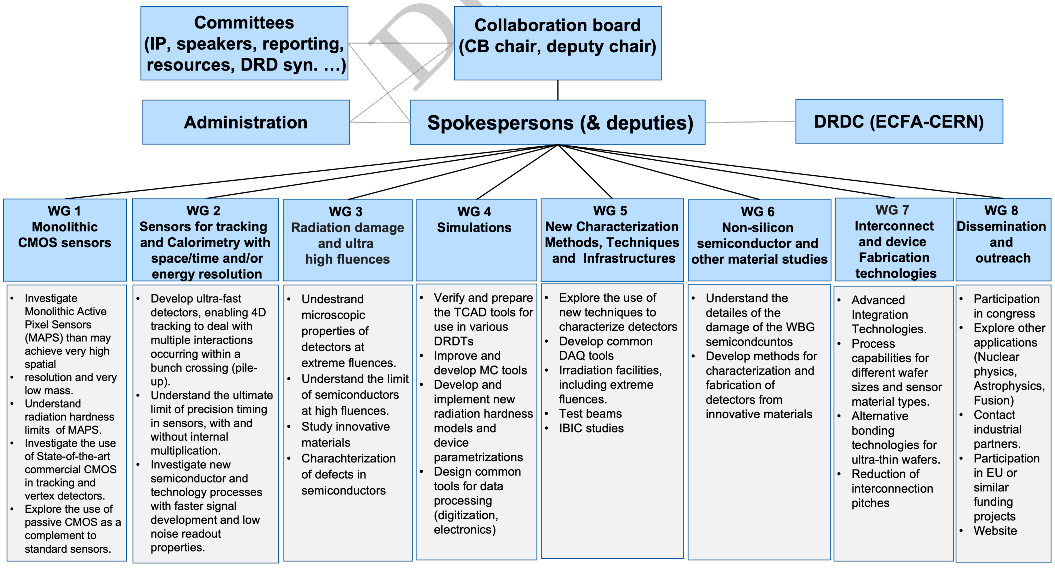

Figure 4: DRD3 organizational chart

11.1 Funding for DRD3 strategic R&D

Funds for the strategic R&D should come from national funding agencies and will be assigned to their respective institutes. The strategic R&D will be the focus of the DRDC reviews.

11.2 Funding for DRD3 blue-sky R&D

Each institute will contribute to the DRD3 Blue-sky common fund. The amount of this levy is set to 2,000 CHF per year. The rules for the funding scheme will be defined by the new DRD3 management.

11.3 Funding for DRD3 operation

Each institute will contribute to the cost of the DRD3 collaboration. The amount of this levy will be defined by the new DRD3 management.

11.4 Funding presently available in the RD50 collaboration

At the end of 2023, the RD50 collaboration will cease to exist. The funding still present in the RD50 common fund will be transferred to the DRD3 collaboration. This fund will be managed by and available to former RD50 members.

References

[1] E. D. R. R. P. Group, *The 2021 ECFA detector research and development roadmap*, , Geneva, 2020. https://cds.cern.ch/record/2784893.

[2] D. group, *Implementation of TF3 Solid State Detectors*, , 2023. https://indico.cern.ch/event/1214410/timetable/#all.