ECFA - DRD3
(solid state detectors)

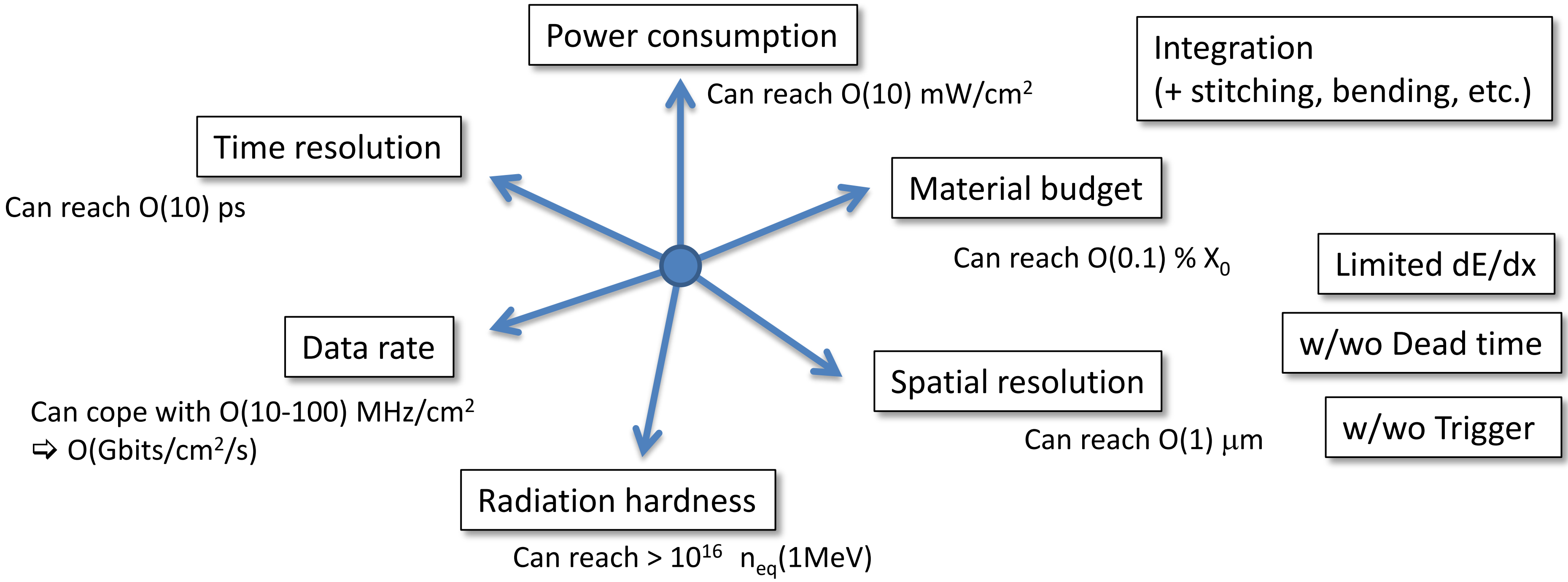
Synthesis about in2p3 involvements

Lab	contacts
APC	Marco Bomben
CPPM	Marlon Barbero, Patrick Pangaud, Pierre Barrillon
IJCLab	Abdenour Lounis, Ana-Sofia Torrento-Coello
IP2I	Didier Contardo
IPHC	Auguste Besson, Jérôme Baudot
LPNHE	Giovanni Calderini
LPSC	Marie-Laure Gallin-Martel
IRFU	Stefano Panebianco, Philippe Schwemling

- DRD3 organization and milestones
- IN2P3 involvements in each labs & each WP
- Synthesis on human resources and funding needs

Special thanks to G. Calderini, D. Contardo, M-L. Gallin-Martel

Solid state (silicon and others) detector figure of merit for HEP



Power consumption

Can reach O(10) mW/cm^2

Integration
(+ stitching, bending, etc.)

Time resolution

Can reach O(10) ps

Material budget

Can reach O(0.1) % X_0

Limited dE/dx

w/wo Dead time

w/wo Trigger

Data rate

Can cope with O(10-100) MHz/cm^2
⇨ O(Gbits/cm^2/s)

Spatial resolution

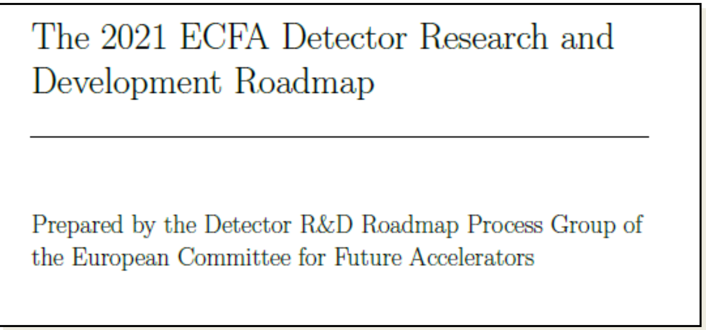
Can reach O(1) μm

Radiation hardness

Can reach > 10^{16} n_{eq}(1MeV)

- Ultimate performances look like the ideal tracking or vertexing detector. However
  - ✓ Very antagonist requirements (e.g. Data rate and Power, time vs spatial resolution, etc.)
- Need a **hierarchy** or **specialized** layers
  - ✓ Governed by physics requirements and experimental conditions
  - ✓ R&D needed to improve the parameter space

The 2021 ECFA Detector R&D roadmap: Solid State detectors

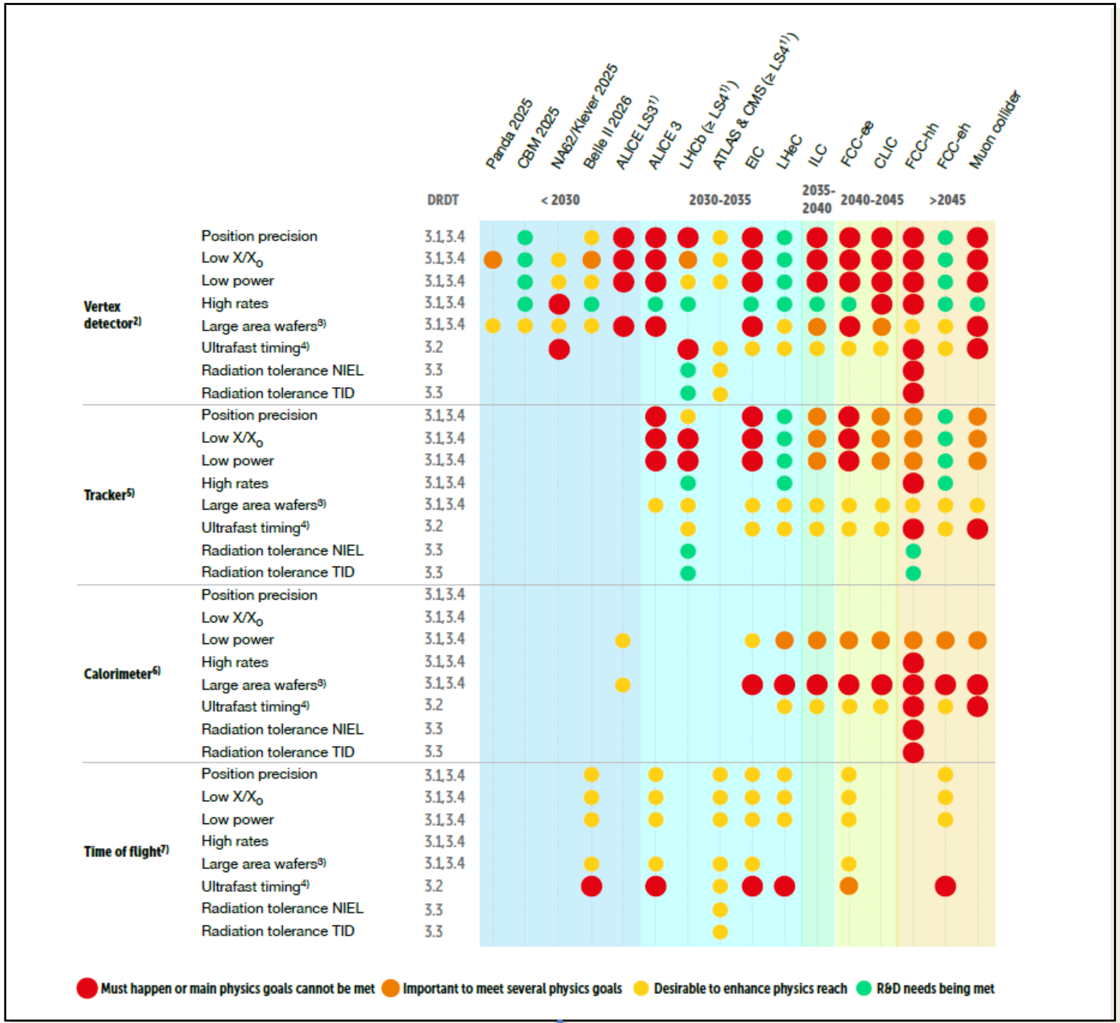


The 2021 ECFA Detector Research and Development Roadmap

Prepared by the Detector R&D Roadmap Process Group of the European Committee for Future Accelerators

THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group



		DRDT	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≥ LS4 1))	ATLAS & CMS (≥ LS4 1))	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030					2030-2035					2035-2040	2040-2045		>2045		
Vertex detector 2)	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_0	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers 3)	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing 4)	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker 5)	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_0	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers 3)	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing 4)	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		
Calorimeter 6)	Position precision	3.1,3.4																
	Low X/X_0	3.1,3.4																
	Low power	3.1,3.4					🟡				🟡	🟠	🟠	🟠	🟠	🟠	🟠	🟠
	High rates	3.1,3.4														🔴		
	Large area wafers 3)	3.1,3.4					🟡				🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	Ultrafast timing 4)	3.2										🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3														🔴		
	Radiation tolerance TID	3.3														🔴		
Time of flight 7)	Position precision	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low X/X_0	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low power	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	High rates	3.1,3.4																
	Large area wafers 3)	3.1,3.4				🟡		🟡		🟡	🟡			🟡				
	Ultrafast timing 4)	3.2				🔴		🔴		🟡	🔴	🔴		🟠			🔴	
	Radiation tolerance NIEL	3.3								🟡								
	Radiation tolerance TID	3.3								🟡								

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Time of flight

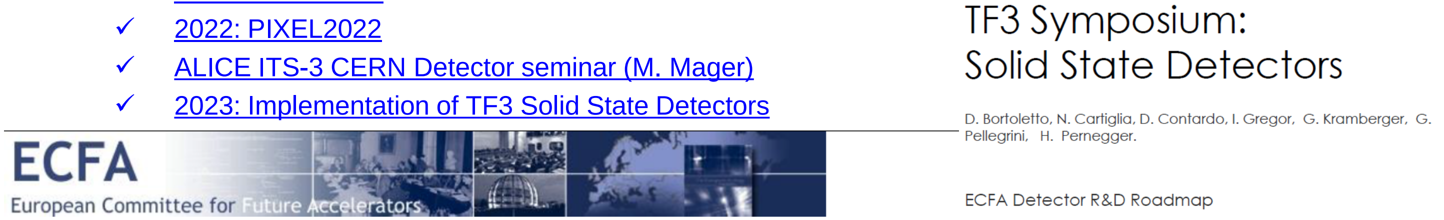
Granularity, low power, low material budget

High rates, radiotolerance, fast timing

Calorimeters

Solid state detectors landscape (focus on tracking)

- A very active area. e.g. see
  - ✓ 2021: ECFA Detector R&D Roadmap Symposium of Task Force 3 Solid State Detectors
  - ✓ 2022: VCI 16th Vienna conference
  - ✓ 2022: 15th Pisa Meeting on Advanced Detectors
  - ✓ 2022: AIDAInnova Kick-off meeting
  - ✓ 2022: Vertex2022
  - ✓ 2022: PIXEL2022
  - ✓ ALICE ITS-3 CERN Detector seminar (M. Mager)
  - ✓ 2023: Implementation of TF3 Solid State Detectors

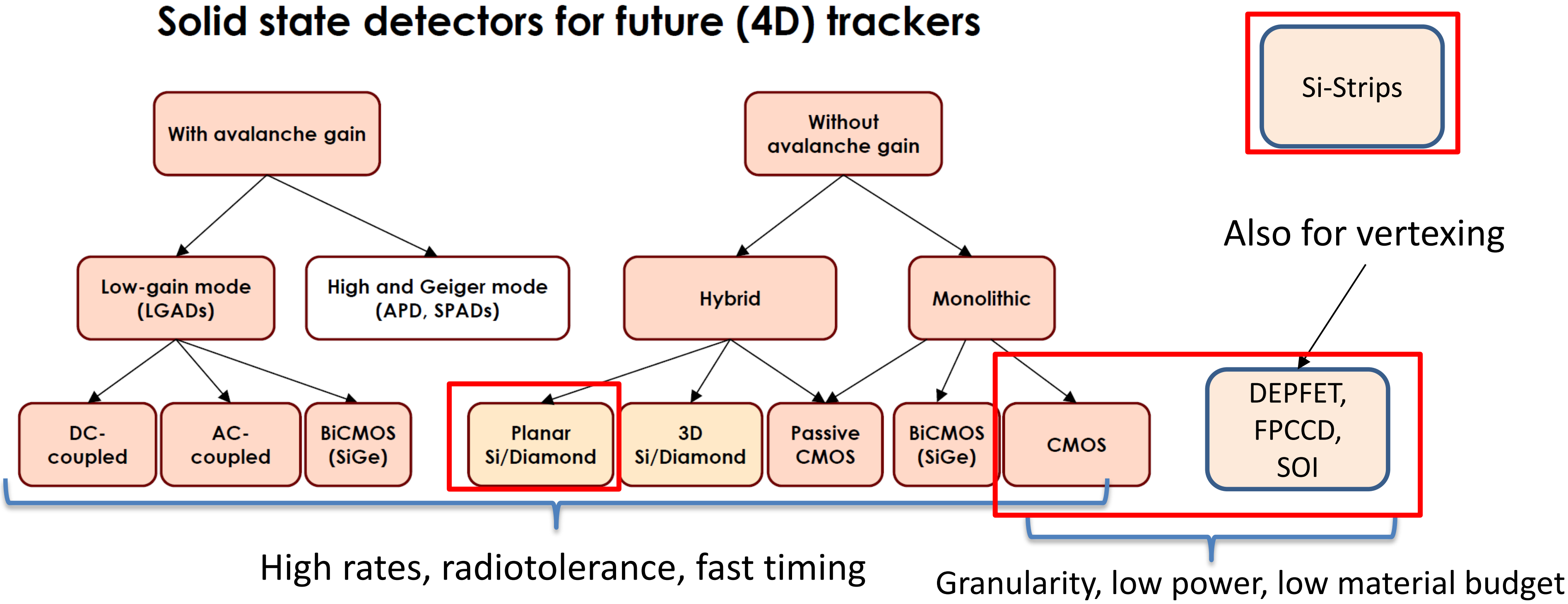


ECFA
European Committee for Future Accelerators

TF3 Symposium:
Solid State Detectors

D. Bortoletto, N. Cartiglia, D. Contardo, I. Gregor, G. Kramberger, G. Pellegrini, H. Pernegger.

ECFA Detector R&D Roadmap



Solid state detectors for future (4D) trackers

DRD3 organisation

(WG2 includes LGADS & hybrids)

Within the ECFA roadmap
4 Detector R&D Themes (DRDTs)
have been identified for the
Solid State Detectors in particle physics.

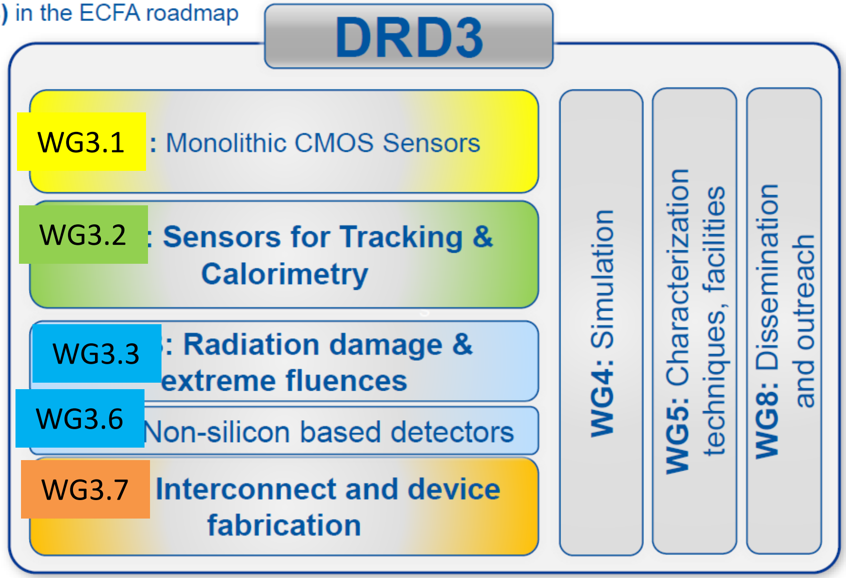
DRDT3.1. Achieve full integration of sensing and microelectronics in **monolithic CMOS** pixel sensors

DRDT3.2. Develop solid state sensors with **4D-capabilities for tracking and calorimetry**

DRDT3.3. Extend capabilities of solid state sensors to operate at **extreme fluences**

DRDT3.4. Develop full **3D-interconnection technologies** for solid state devices in particle physics.

- We are covering all ECFA DRDTs
- Additional WGs were added to cover simulations, facilities and dissemination corresponding to **General Strategic Recommendations (GSRs)** in the ECFA roadmap



DRD3

WG3.1 : Monolithic CMOS Sensors

WG3.2 : **Sensors for Tracking & Calorimetry**

WG3.3 : **Radiation damage & extreme fluences**

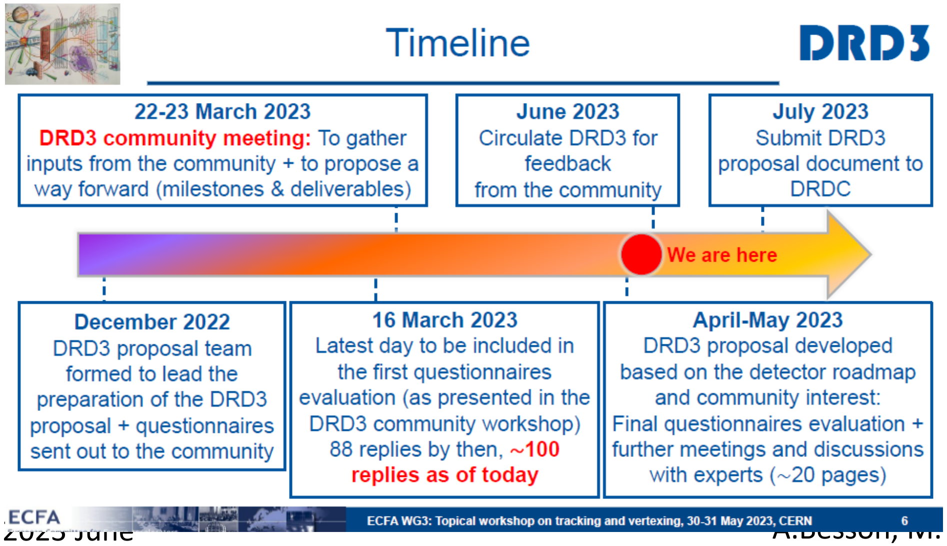
WG3.6 : Non-silicon based detectors

WG3.7 : **Interconnect and device fabrication**

WG4: Simulation

WG5: Characterization techniques, facilities

WG8: Dissemination and outreach



Timeline

DRD3

December 2022
DRD3 proposal team formed to lead the preparation of the DRD3 proposal + questionnaires sent out to the community

16 March 2023
Latest day to be included in the first questionnaires evaluation (as presented in the DRD3 community workshop)
88 replies by then, **~100 replies as of today**

22-23 March 2023
DRD3 community meeting: To gather inputs from the community + to propose a way forward (milestones & deliverables)

April-May 2023
DRD3 proposal developed based on the detector roadmap and community interest:
Final questionnaires evaluation + further meetings and discussions with experts (~20 pages)

We are here

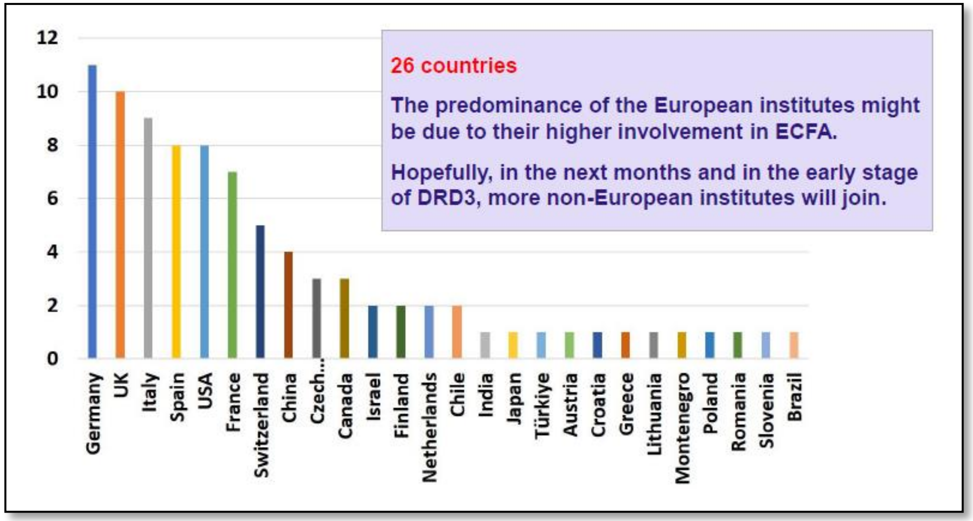
June 2023
Circulate DRD3 for feedback from the community

July 2023
Submit DRD3 proposal document to DRDC

Lab	Main WGs	Secondary WGs
APC	WG3.1; WG3.3	WG3.2, 3.8
CPPM	WG3.1; WG3.3	WG3.3, 3.5, 3.7, 3.8
IJCLab	WG3.2; WG3.3	WG3.5, 3.7, 3.8
IP2I	WG3.1; WG3.2	WG3.7
IPHC	WG3.1	WG3.5, 3.7, 3.8
LPNHE	WG3.2 ; 3.7	WG3.1, 3.3, 3.5, 3.7, 3.8
LPSC	WG3.6	WG3.5
IRFU	WG3.1, WG3.2, WG3.7	

- WG 3.1: Monolithic CMOS sensors
  - ✓ Spatial resolution of 3 µm
  - ✓ Timing precision of 20 ps
  - ✓ Readout architectures for 100 MHz/cm^2
  - ✓ Radiation tolerance of 10^{16} n_{eq}/cm^2NIEL and 500 MRad
- WG 3.2: Sensors for tracking and calorimetry
  - ✓ Spatial and temporal resolutions at extreme radiation levels
  - ✓ Reduction of pixel cell size for 3D sensors
  - ✓ 3D sensors with a temporal resolution of about 50 ps
  - ✓ Spatial and temporal resolutions at low radiation levels and low material and power budgets
  - ✓ LGAD sensors with very high fill factor and an excellent spatial and temporal resolution
  - ✓ LGAD sensors for Time of Flight applications
- WG 3.3: Radiation damage and extreme fluence operation
  - ✓ Build up data sets on radiation induced defect formation in WBG materials
  - ✓ Develop silicon radiation damage models based on measured point and cluster defects
  - ✓ Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation
  - ✓ Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to 10^{18} n_{eq}/cm^2
- **WG 3.4: Simulation**
  - ✓ Flexible CMOS simulation of 65 nm to test design variations
  - ✓ Implementation of newly measured semiconductor properties into TCAD and MC simulation tools
  - ✓ Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models
  - ✓ Developing of bulk and surface model for 10^{16} n_{eq}/cm^2 to 10^{17} n_{eq}/cm^2 NIEL
  - ✓ Collate solutions from different MC tools and develop algorithms to include adaptive electric and weighting fields
- **WG 3.5: Measurement and characterization techniques**
  - ✓ Development of new semiconductor characterization techniques is a priority for future detector developments
  - ✓ These techniques should enable high-resolution imaging and defect spectroscopy of semiconductor materials, as well as advanced characterization of charge transport properties
  - ✓ The Two Photon Absorption –TCT setup, Caribou DAQ system and the Ion Beam testing and irradiation facility at RBI have been identified as good examples and further improvements are being proposed
- WG 3.6: Wide bandgap and innovative sensor materials
  - ✓ 3D diamond detectors, cages/interconnects, base length 25 µm, impact ionisation
  - ✓ Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels
  - ✓ Improve tracking capabilities of WBG materials
  - ✓ Apply graphene and/or other 2D materials in radiation detectors, understand signal formation
- WG 3.7: Sensor interconnection techniques
  - ✓ Yield consolidation for fast interconnections
  - ✓ Demonstration of small pitch (< 30 µm) pixel interconnections
  - ✓ Demonstration of radiation hardness and thermomechanical constraints
  - ✓ Development of maskless post-processing for commonly-used interconnection technologies
  - ✓ Bring part of the commonly-used interconnection technologies to specialised academic groups
  - ✓ Develop device-to-wafer interconnection technologies
  - ✓ Develop wafer-to-wafer in presently advanced interconnection technologies
  - ✓ Develop VIAS in multi-tier sensor/front-end assemblies
  - ✓ Develop connection techniques for post-processed devices
- **WG 3.8: Outreach and dissemination**
  - ✓ Disseminating knowledge on solid-state detectors to people working in high energy physics
  - ✓ Disseminating knowledge on solid-state detectors to high-school students and the general public
  - ✓ Design and set-up of the DRD3 website
  - ✓ Collection of the outreach material
  - ✓ Set-up and organize schools and exchange programs
  - ✓ Set-up of the DRD3 conference committee

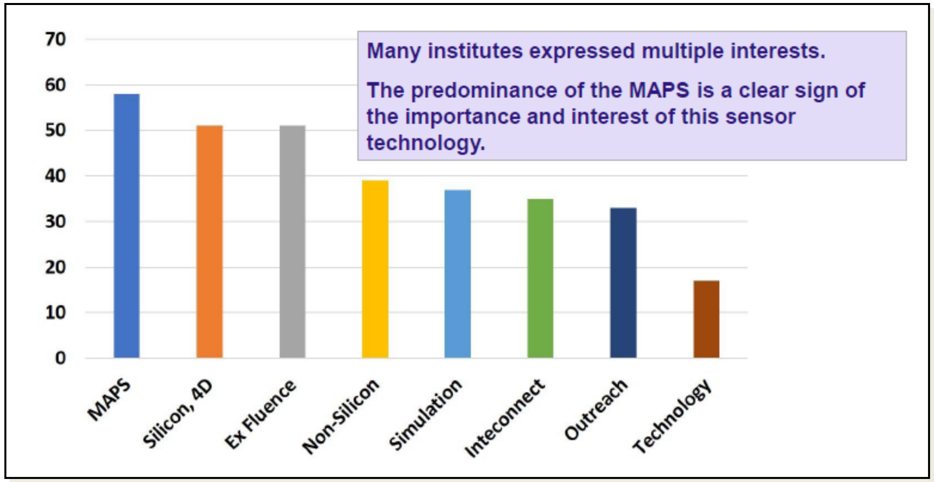
DRD3 questionnaire: 7 IN2P3 labs



26 countries

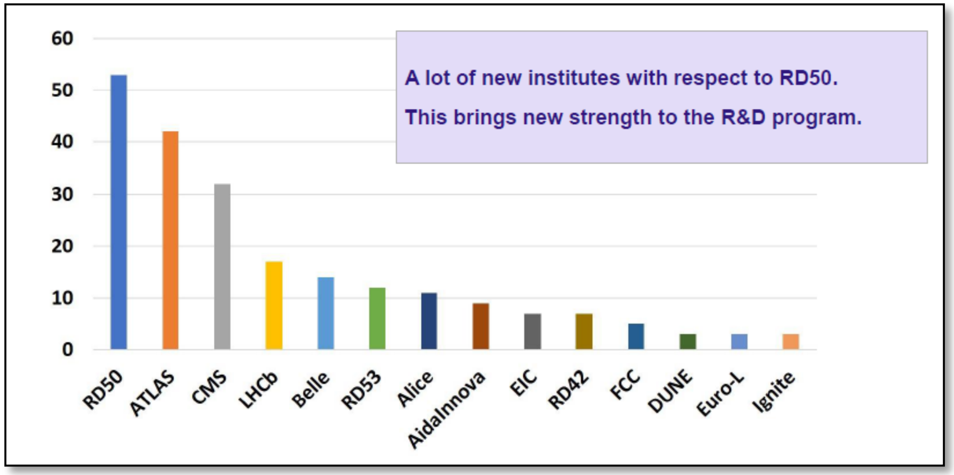
The predominance of the European institutes might be due to their higher involvement in ECFA.

Hopefully, in the next months and in the early stage of DRD3, more non-European institutes will join.



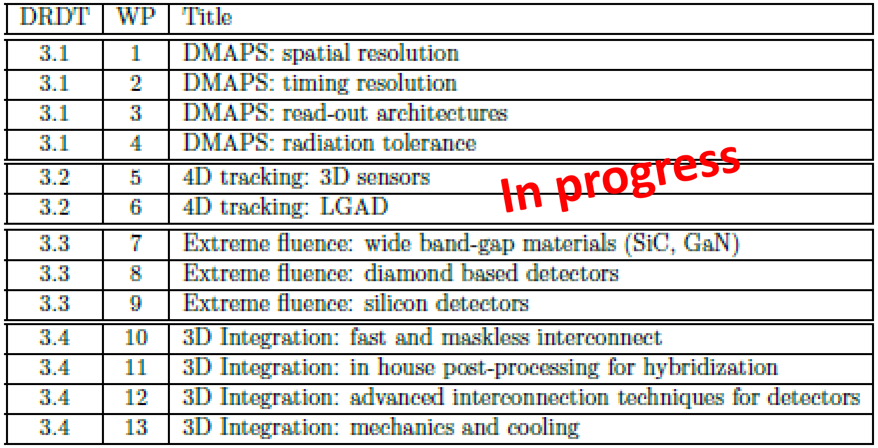
Many institutes expressed multiple interests.

The predominance of the MAPS is a clear sign of the importance and interest of this sensor technology.



A lot of new institutes with respect to RD50.

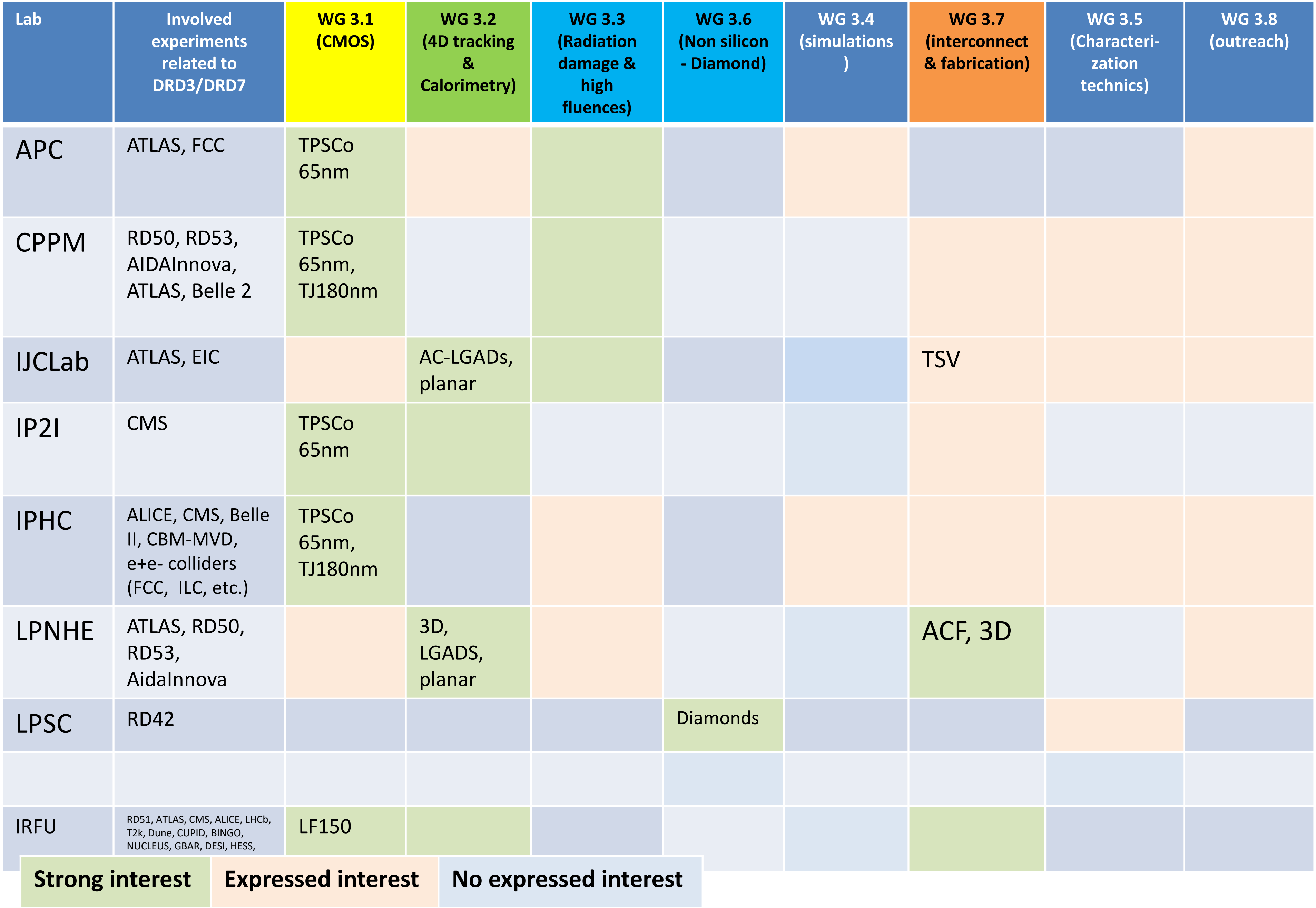
This brings new strength to the R&D program.



DRDT	WP	Title
3.1	1	DMAPS: spatial resolution
3.1	2	DMAPS: timing resolution
3.1	3	DMAPS: read-out architectures
3.1	4	DMAPS: radiation tolerance
3.2	5	4D tracking: 3D sensors
3.2	6	4D tracking: LGAD
3.3	7	Extreme fluence: wide band-gap materials (SiC, GaN)
3.3	8	Extreme fluence: diamond based detectors
3.3	9	Extreme fluence: silicon detectors
3.4	10	3D Integration: fast and maskless interconnect
3.4	11	3D Integration: in house post-processing for hybridization
3.4	12	3D Integration: advanced interconnection techniques for detectors
3.4	13	3D Integration: mechanics and cooling

In progress

Table 2: DRD3 work packages. Additional WPs can be added.

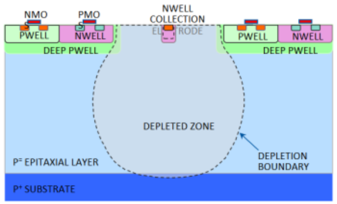


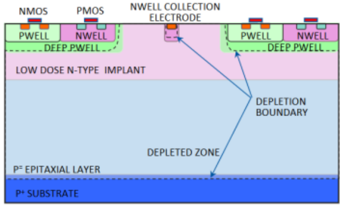
Lab	Involved experiments related to DRD3/DRD7	WG 3.1 (CMOS)	WG 3.2 (4D tracking & Calorimetry)	WG 3.3 (Radiation damage & high fluences)	WG 3.6 (Non silicon - Diamond)	WG 3.4 (simulations)	WG 3.7 (interconnect & fabrication)	WG 3.5 (Characteri-zation technics)	WG 3.8 (outreach)
APC	ATLAS, FCC	🟩 TPSCo 65nm	🟧	🟩	🟦	🟧	🟦	🟦	🟧
CPPM	RD50, RD53, AIDAInnova, ATLAS, Belle 2	🟩 TPSCo 65nm, TJ180nm	🟦	🟩	🟦	🟦	🟧	🟧	🟧
IJCLab	ATLAS, EIC	🟧	🟩 AC-LGADs, planar	🟩	🟦	🟦	🟧 TSV	🟧	🟧
IP2I	CMS	🟩 TPSCo 65nm	🟩	🟦	🟦	🟦	🟧	🟦	🟦
IPHC	ALICE, CMS, Belle II, CBM-MVD, e+e- colliders (FCC, ILC, etc.)	🟩 TPSCo 65nm, TJ180nm	🟦	🟧	🟦	🟧	🟧	🟧	🟧
LPNHE	ATLAS, RD50, RD53, AidaInnova	🟧	🟩 3D, LGADS, planar	🟧	🟦	🟦	🟩 ACF, 3D	🟦	🟧
LPSC	RD42	🟦	🟦	🟦	🟩 Diamonds	🟦	🟦	🟧	🟦
IRFU	RD51, ATLAS, CMS, ALICE, LHCb, T2k, Dune, CUPID, BINGO, NUCLEUS, GBAR, DESI, HESS,	🟩 LF150	🟩	🟦	🟦	🟦	🟩	🟦	🟦

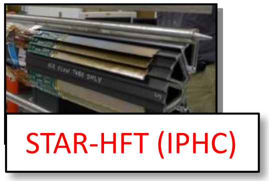
🟩 **Strong interest** 🟧 **Expressed interest** 🟦 **No expressed interest**

WG 3.1: CMOS

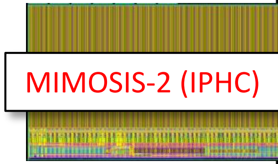
- MAPS:
  - ✓ Monolithic ⇨ low material
  - ✓ Industrial process: feature size: 180 nm, 65nm, etc.
- IN2P3: MP GRAM & DEPHY (since end 2022)
  - ✓ DEPHY: high fluences, high flux for CMOS & hybrid pixels
  - ✓ GRAM: granularity, material budget, low power
- IPHC (C4PI, PICSEL, Belle-2, ALICE)
  - ✓ 20 years: STAR HFT, EUDET telescopes, ALICE ITS-2, AidaInnova, etc.)
  - ✓ 3 teams in HEP are pursuing a CMOS R&D activity:
    - PICSEL: MIMOSIS for CBM-MVD ⇨e^+e^- colliders (TJ180 nm & TPSco 65nm)
    - Belle-2 upgrades (TJ180 nm and beyond)
    - ALICE ITS3 (TPSco 65nm)
  - ✓ DRD3: focus on TPSco 65nm
  - ✓ IPHC Scientific council June 27th
- CPPM
  - ✓ > 10 years: (ITK ATLAS, Belle-2, RD50, RD53, AidaInnova)
    - Depleted CMOS
    - LF150nm, TSI180nm, TJ 180 nm, TPSco 65nm, etc.
    - high fluences, high flux
- IP2I
  - ✓ Interest for fast timing (< 100 ps)
  - ✓ Growing activity in digital micro-electronics with C4PI (TJ 180 nm)
    - Contribution to DRD3.1 (TPSCo TJ 65 nm)
    - Digital on Top methodology for read-out (with DRD7)
    - Low power architecture with ToF measurement
    - interconnection 3D (wafer stacking) (with DRD7)
- APC
  - ✓ Tests for the TPSco 65nm prototypes
  - ✓ Possible contributions to design : ADC (TPSco 65nm)
  - ✓ Expertise in simulations (TCAD, Allpix2) and radiation damages



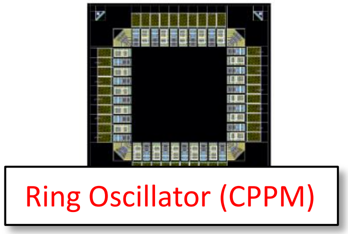


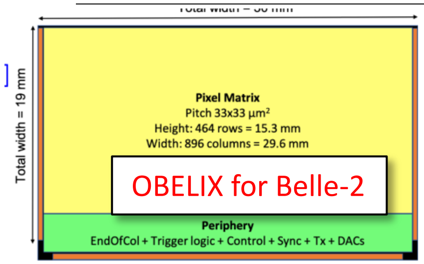

STAR-HFT (IPHC)


EUDET telescope


MIMOSIS-2 (IPHC)

ER1 for ALICE ITS-3

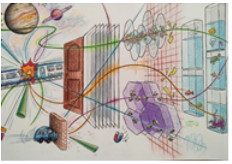

Ring Oscillator (CPPM)



OBELIX for Belle-2

	Description
RG 1.1	Spatial resolution: $\leq 3\ \mu$m position resolution
RG 1.2	Timing resolution: towards 20 ps timing precision
RG 1.3	Readout architectures: towards 100 MHz/cm^2, and 1 GHz/cm^2 with 3D stacked monolithic sensors
RG 1.4	Radiation tolerance: towards 10^{16} n$_{eq}$/cm^2 NIEL and 500 MRad

In progress



Ball park performance targets MCMOS

Three main time scales/phases to define program up to: 2027-28, 2029-2035, >2035

Ball park generic performance targets*
mandatory/desireable

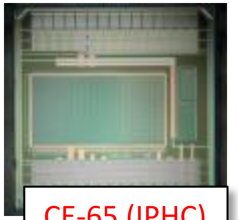
	Tracking VD/CT	Timing Layer + Calorimeter
Heavy Ion	ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) µs	O(20) ps (TL)
Flavour collider	ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) ns	O(20) ps in (TL)
Lepton collider	e-e : ultralight low power tracker pitch down to ≲10 µm, @ O(100) MHz/cm^2 timing driven by power timing driven by power dissipation µ-µ : O(20) ps rates and irradiation tbc	O(10) ps in TL O(< 50) ps in calorimeter driven by power power dissipation
pp collider	HL-LHC: 25-50 µm @ O(5) GHz/cm^2 5x10^{15} to 5x10^{16} neq/cm^2, 250 - 500 MRad timing O(<50) ps timing O(<50) ps	HL-LHC: pitch O(<1) mm O(20) ps in TL, NIEL 5x10^{15}
	FCC-hh: < 10 - 20 µm @ 30 GHz/cm^2 4D tracking 4D tracking O(<10)ps up to O(10^{18}) to O(10^{18}) neq/cm^2, up to O(50) GRad	FCC-hh: 5D calorimeter O(<10)ps up to O(10^{18}) neq/cm^2, up to O(50) GRad O(50) GRad

* ranges representative, ex. for VD and CT with more stringent constraints to be achieved in VD

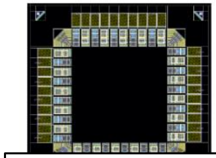
WG3.1: CMOS TPSCo-65 nm submissions and connexion with DRD3/DRD7

IPHC, CPPM, APC, IP2I

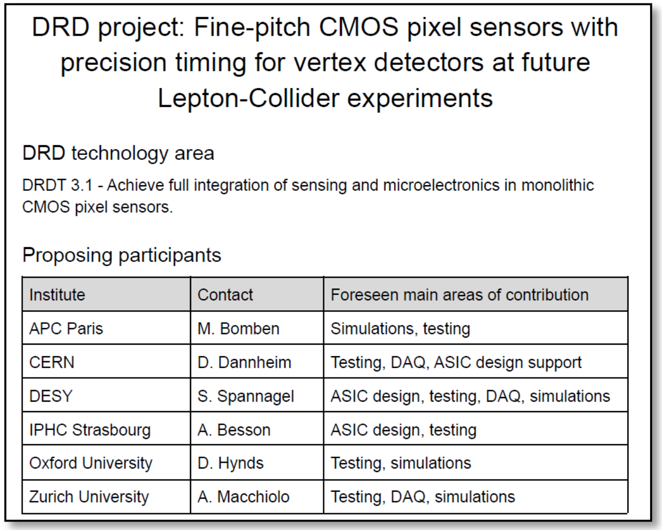
- CMOS TPSCo 65nm (ALICE ITS-3 + EP R&D WP1.2)
  - ✓ Offers attractive perspectives w.r.t. TJ180nm
    - Stitching (12 inches wafers)
    - Potentially smaller pitch, faster, less power consumption, etc.
  - ✓ Main CMOS technology supported by CERN in the coming years
  - ✓ IPHC & CPPM already in the consortium participating to the technology validation
  - ✓ TJ 180nm probably less (or not) supported in the future
- 2 lines of submissions in CMOS TPSCo 65nm
  - ✓ Submissions dedicated to ALICE ITS-3 (ER2 & ER3) ⇨ stitching, bent sensors
  - ✓ Submissions for generic R&D, supported by CERN EP R&D WP1.2 (« MLR2 » and beyond)
- Generic R&D possible contributions
  - ✓ One expression of interest submitted with M1/M5 main driver (future e+e- colliders vertex detectors)
    - Goal: gather groups to reach a critical size
    - Targets 3 μm spatial resolution, improved time resolution (5-500 ns), controlled Power (< 50 mW/cm^2), data flow (10-100 MHz/cm^2) and low material budget (50 μm thickness)
    - Demonstrator to equip new generation beam telescope
    - Proposing Institutes: CERN, DESY, IPHC, APC, etc.
    - Open to other participations
  - ✓ Other projects in discussion (tracking, timing, calorimeters, link to MP DEPHY ?)
    - e.g. Fast timing (<100 ps); low power architecture, etc.



CE-65 (IPHC)



Ring Oscillator (CPPM)



DRD project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments

DRD technology area

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

Proposing participants

Institute	Contact	Foreseen main areas of contribution
APC Paris	M. Bomben	Simulations, testing
CERN	D. Dannheim	Testing, DAQ, ASIC design support
DESY	S. Spannagel	ASIC design, testing, DAQ, simulations
IPHC Strasbourg	A. Besson	ASIC design, testing
Oxford University	D. Hynds	Testing, simulations
Zurich University	A. Macchiolo	Testing, DAQ, simulations

WG 3.2 (& WG3.3): Sensors for tracking & vertexing
High resistivity and timing

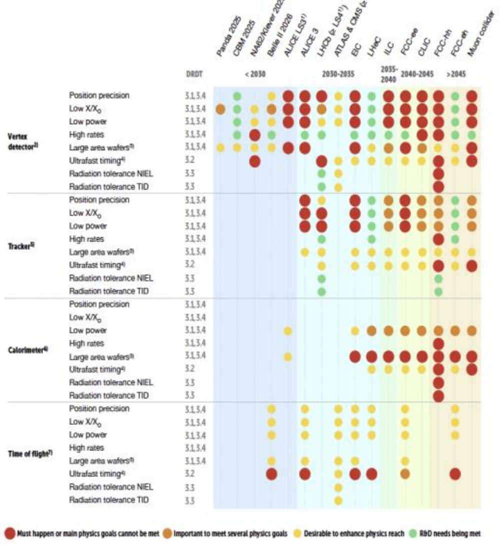
LPNHE, IJClab

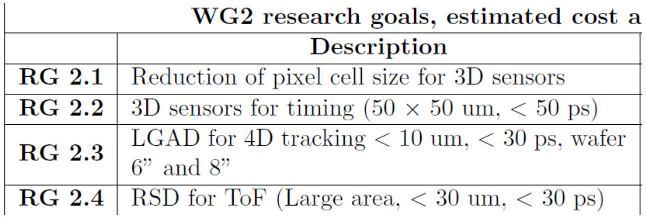
- High resistivity
  - ✓ presently the only solution for very high fluences
    - (FCC-hh, μμ colliders)
- Timing O(10 ps)
  - ✓ milestone of the next 20 years in several applications
- Radiation hardness + 4D capability
  - ✓ necessary typically for high multiplicity environments

  & high rate experiments (both for tracking and for calorimetry)

⇨ Interplay with material budget, power, rates, occupancy, area and radiation hardness, interplay with electronics (capacitance, signal shape, etc)

- Thin sensors for increased radiation hardness in large surfaces
  - ✓ (standard planar sensors but also thin LGADs cf. RD50)
  - ✓ LGAD for timing capabilities (also for calorimetry)
  - ✓ 3D sensors for 4D at extreme fluences

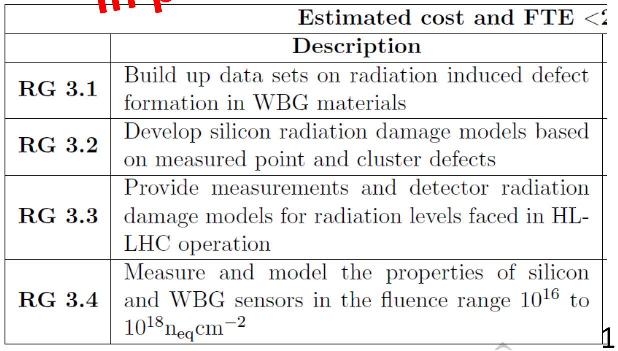




WG2 research goals, estimated cost a

	Description
RG 2.1	Reduction of pixel cell size for 3D sensors
RG 2.2	3D sensors for timing (50 × 50 um, < 50 ps)
RG 2.3	LGAD for 4D tracking < 10 um, < 30 ps, wafer 6” and 8”
RG 2.4	RSD for ToF (Large area, < 30 um, < 30 ps)

In progress



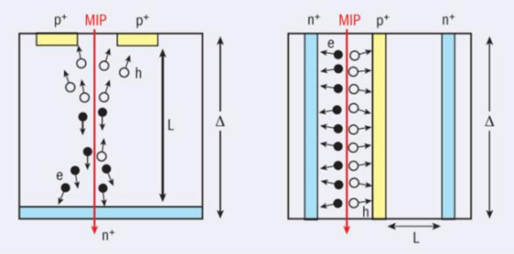
Estimated cost and FTE <2

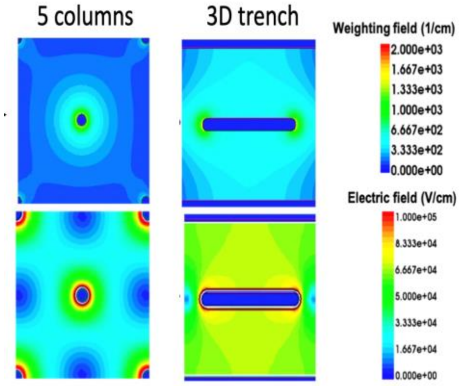
	Description
RG 3.1	Build up data sets on radiation induced defect formation in WBG materials
RG 3.2	Develop silicon radiation damage models based on measured point and cluster defects
RG 3.3	Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation
RG 3.4	Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to $10^{18} n_{eq} cm^{-2}$

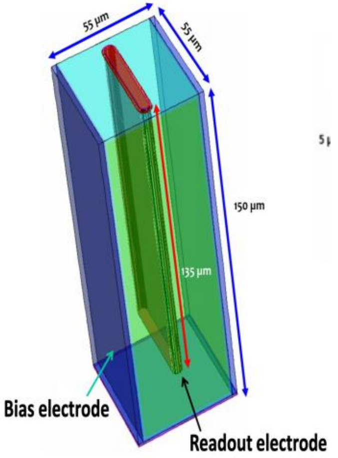
WG 3.2: 3D sensors for 4D tracking applications

LPNHE

- 3D sensors
  - ✓ Decouples active thickness to collection distance
  - ✓ Demonstration of fine pitch cell size
  - ✓ Demonstration of innovative more performant processes (flat trenches)
- Applications
  - ✓ ATLAS/CMS Phase-3 (Run5 ~2035)
    - use of 28 nm CMOS technology for the ASICs could allow for finer pixel sizes to improve hard scattering track reconstruction and pile-up rejection
  - ✓ VELO vertex detector at LHCb (Upgrade-II).
  - ✓ All future experiment with timing capability required in extreme fluence
- Deliverables
  - ✓ Short-term: development of small matrices optimized for timing properties and reduced pixel size at high and extreme fluences (10^{17} n_{eq}/cm^2)
  - ✓ longer-term: development of full-scale larger sensors matched to future timing performant front-end chips (28nm)







WG 3.2: LGADs

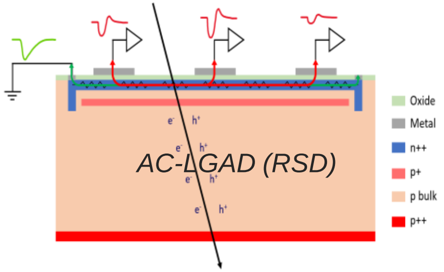
LPNHE, IJClab

$$\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{elec}}$$

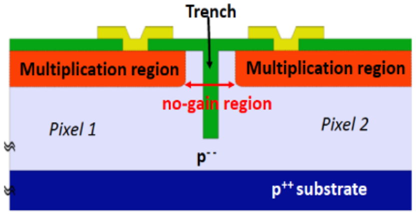
$$\sigma^2_{elec} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

Jitter Timewalk

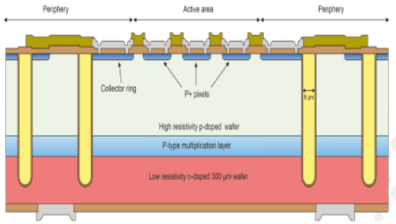
- LGADs
  - ✓ Low Gain Avalanche
    - ▪ Gain O(10), excellent S/N, Possibly thin (50 μm) (reduced landau fluctuation) ⇨ time resolution
  - ✓ Demonstration of the feasibility of producing pixelated LGAD sensors to achieve a position resolution better than 10 μm, with a timing resolution of the order of 30 ps before irradiation.
- Possible applications
  - ✓ replacement of outer pixel layers or disks in the CMS/ATLAS pixel systems in Phase-3. The requested radiation tolerance is in the order of at least 3-5x10^{15} neq/cm^2.
  - ✓ Large areas (cheap)
  - ✓ Fast timing layers in Higgs factories
- Deliverables
  - ✓ Short-term: characterization of the different technological solutions through small matrices connected with timing-performant matching chips (28nm)
    - ▪ Improvement of fill-factor
    - ▪ Optimization of spatial and time resolution
    - ▪ Development of radiation-hardening technologies (implantations and design)
  - ✓ Long term: development of full-scale sensors and connection to matching electronics
    - ▪ Optimization of system parameters (e.g. power dissipation)



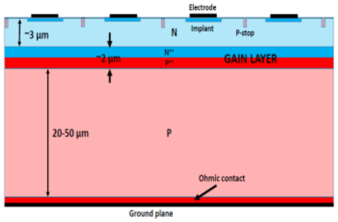
Trench Isolated LGAD



Inverse-LGAD (I-LGAD)



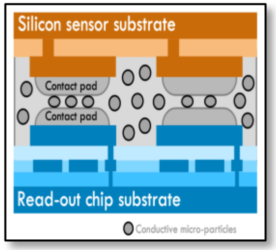
Deep junction LGAD

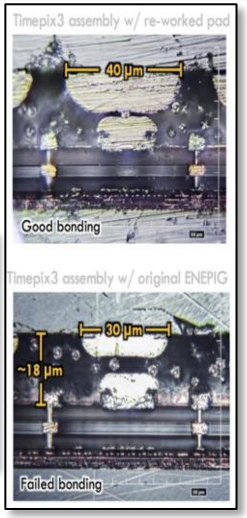


WG 3.7: Interconnection techniques

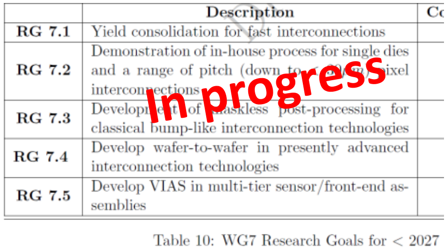
LPNHE, CPPM, IJCLab, IP2I, IPHC

- Different technological levels for different scopes
  - ✓ Cheap and fast interconnection for prototyping applications
  - ✓ Improvements of “standard” interconnection technologies
  - ✓ Development of “advanced” technologies in collaboration with industrial vendors
- In-house fast connections (*Anisotropic Conductive Film/Paste* (ACF/ACP)
  - ✓ Ideal for testing and fast prototyping
  - ✓ Also useful for permanent interconnections
  - ✓ Avoid turnaround time with interconnection vendors
  - ✓ Short-term deliverables: consolidation of connection yield and small pitch
  - ✓ Mid-term deliverable: demonstration of radiation hardness





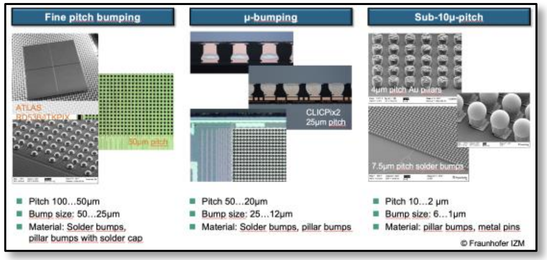
- Bringing “standard” technologies to lab capability
  - ✓ Issues: costs and availability
    - Move part of process to laboratories
  - ✓ Studies
    - small pitch
    - process-temperature constraint
    - electrical properties (current, C)
    - connection flow
  - ✓ Short-term: develop maskless post-processing
  - ✓ Mid-term: process possible in selected labs



	Description	Cc
RG 7.1	Yield consolidation for fast interconnections	
RG 7.2	Demonstration of in-house process for single dies and a range of pitch (down to < 20µm) pixel interconnections	
RG 7.3	Development of maskless post-processing for classical bump-like interconnection technologies	
RG 7.4	Develop wafer-to-wafer in presently advanced interconnection technologies	
RG 7.5	Develop VIAS in multi-tier sensor/front-end assemblies	

Table 10: WG7 Research Goals for < 2027

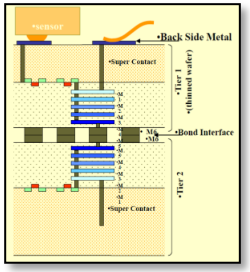
In progress

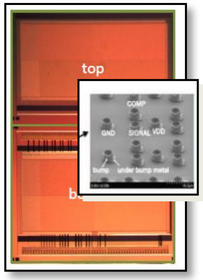


Fine pitch bumping	µ-bumping	Sub-10µ-pitch
Pitch 100…50µm	Pitch 50…20µm	Pitch 10…2 µm
Bump size: 50…25µm	Bump size: 25…12µm	Bump size: 6…1µm
Material: Solder bumps, pillar bumps with solder cap	Material: Solder bumps, pillar bumps	Material: pillar bumps, metal pins

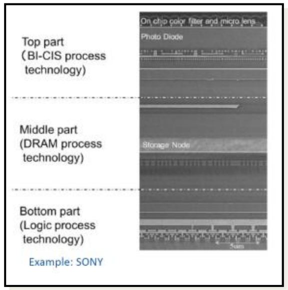
© Fraunhofer IZM

- Advanced 3D and vertical integration
  - ✓ Commercially driven
  - ✓ Allows Multi-tier, mixed-technology (e.g. stack digital/analog)
  - ✓ Allows power/reading transmission
  - ✓ Short term: TSV
  - ✓ Mid-long term: connection made possible for post-processed devices



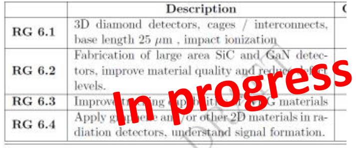


Double tier
(CMOS TJ 180nm, IPHC)



Industrial wafer stacking in CMOS

WG 3.5 & 3.6 : New characterization techniques & Wide bandgap and innovative sensor materials



	Description
RG 6.1	3D diamond detectors, cages / interconnects, base length 25 μm , impact ionization
RG 6.2	Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels.
RG 6.3	Improve tracking capabilities of WBG materials
RG 6.4	Apply graphene and/or other 2D materials in radiation detectors, understand signal formation.

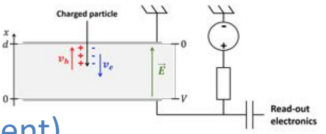
In progress

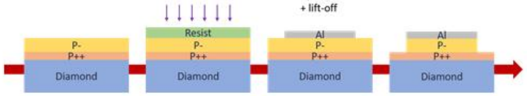
Table 9: WG6 research goals for < 2027

LPSC

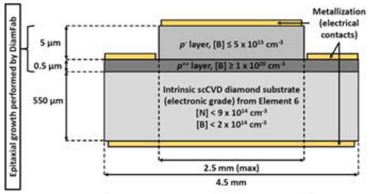
- Diamond monolithic telescope for short range particle detection
  - ✓ Fabrication in collaboration with DIAMFAB (start-up Institut Néel)
  - ✓ Epitaxial growth of the p- and p++ layers, etching, contacts (NANOFAB - Institut Néel)
  - ✓ Diamond instrumentation on PCB (LPSC)
  - ✓ Characterization in laboratory: eBIC (electron Beam Induced Current), ToF – eBIC & alpha spectroscopy

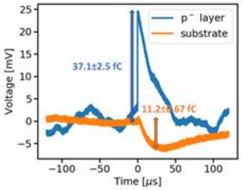
Solid state ionization chamber





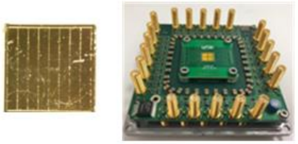
Diamond ΔE-E telescope

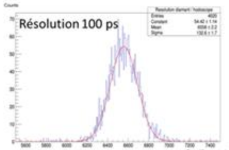




- Beam monitors
  - ✓ Diamond technology sCVD and pCVD metallized with thin (100 nm) Al layer by laser lithography mounted on a PCB with various arrangements (single, 4x4 mosaic or 9x1)
  - ✓ FE electronic developments: e.g fast preamps, DFC, QDC
  - ✓ BE electronic developments e.g TDC (40 on a single Cyclone 10 FPGA - STD 25 ps / CMOS 130 nm STD 12 ps)

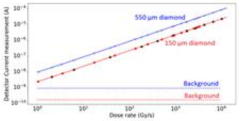
CLARYS –UFT: Ion beam hodoscope 4x4 sCVD mosaic





X&Y orthogonal strips on diamond + 40 fast preamplifiers

IDSYNCHRO: Xrays microbeam monitor ESRF ID17

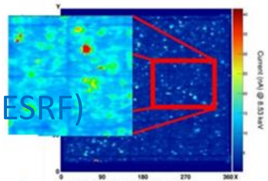


150 channels 9x1 sCVD mosaic

µstrips diamonds + integrated FE electronics (QDC) CMOS 130 nm

- New characterization techniques
  - ✓ ToF eBIC (« pulsed » SEM - Institut Néel) & XBIC (BM05 - ESRF) IBIC (Ion Beam Induced Current – AIFIRA)

p-CVD (E6)

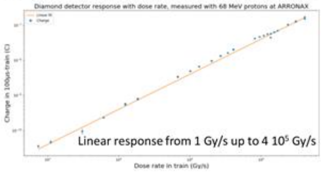


2D current maps

- Application
  - ✓ All future experiments with timing capability or particle counting required in extreme fluence

DIAMMONI: High Dynamic Range 68 MeV proton Pulsed Beam Monitor

Full metallized diamond + FE &BE electronics



Linear response from 1 Gy/s up to 4 10⁵ Gy/s

- Deliverables
  - ✓ Short-term: single crystal and polycristalline CVD diamond beam monitors
  - ✓ Long-term: development of full scale sensors with integrated electronics

Summary

Not all solid state R&D @ in2p3 are in the DRD3 !

- IN2P3 Themes summary
  - ✓ WG3.1 (CMOS)
    - Strong historical R&D and emerging activities
    - Focus on TPSCo 65nm in the DRD3 context
  - ✓ WG3.2 (calo/tracker/timing) & WG3.3 (rad.hardness/high flux)
    - Past and present development of thin sensors for tracking
    - Interest in LGAD sensors for calorimetry and fast timing
    - Interest in 4D tracking and timing applications: after construction of LHC Phase-II upgrades, coherent
    - re-organization of the community is expected to give a unitary contribution to future projects
  - ✓ WG3.6 (non silicon)
    - LPSC in Diamonds (sCVD and pCVD)
  - ✓ WG3.4/5/7/8 Transversal themes are also strategic e.g. interconnection, simulations
    - Past and present involvement of French groups, mainly via independent projects (AIDA, AIDA-2020, AIDAInnova)
    - Cornerstone of ECFA tasks
    - Different technological levels aiming to different applications
    - Strategic positioning of the community in a multidisciplinary field
- DRD3 organization
  - ✓ Milestones for different applications
  - ✓ Inherited from RD50
  - ✓ DRD3-DRD7 strong relation in particular in the CMOS area
    - DRD7 expertise needed for global architectures/design
    - Small prototypes⇨DRD3 / Large prototypes⇨DRD7
    - This connection needs to be preserved for large scale prototypes
- Integration & mat. budget
  - ✓ Mat. Budget not explicitly in the DRD3 themes (e.g. bent sensors, stitching)
  - ✓ Integration R&D (wireless, additive manufacturing, etc.)

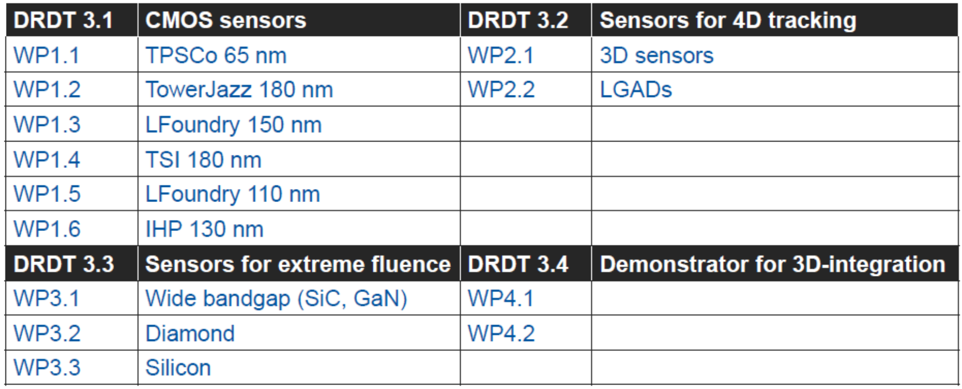
- The IN2P3 strategy inside DRD3 should allow to
  - Guarantee the in2p3 visibility through a national effort for submissions
  - Take advantage of the DRD3 framework (synergies, reviews, milestones, common tools, etc.)
  - Consolidate the position of historical in2p3 activities in DRD3
  - Allow new activities to emerge

Back-up

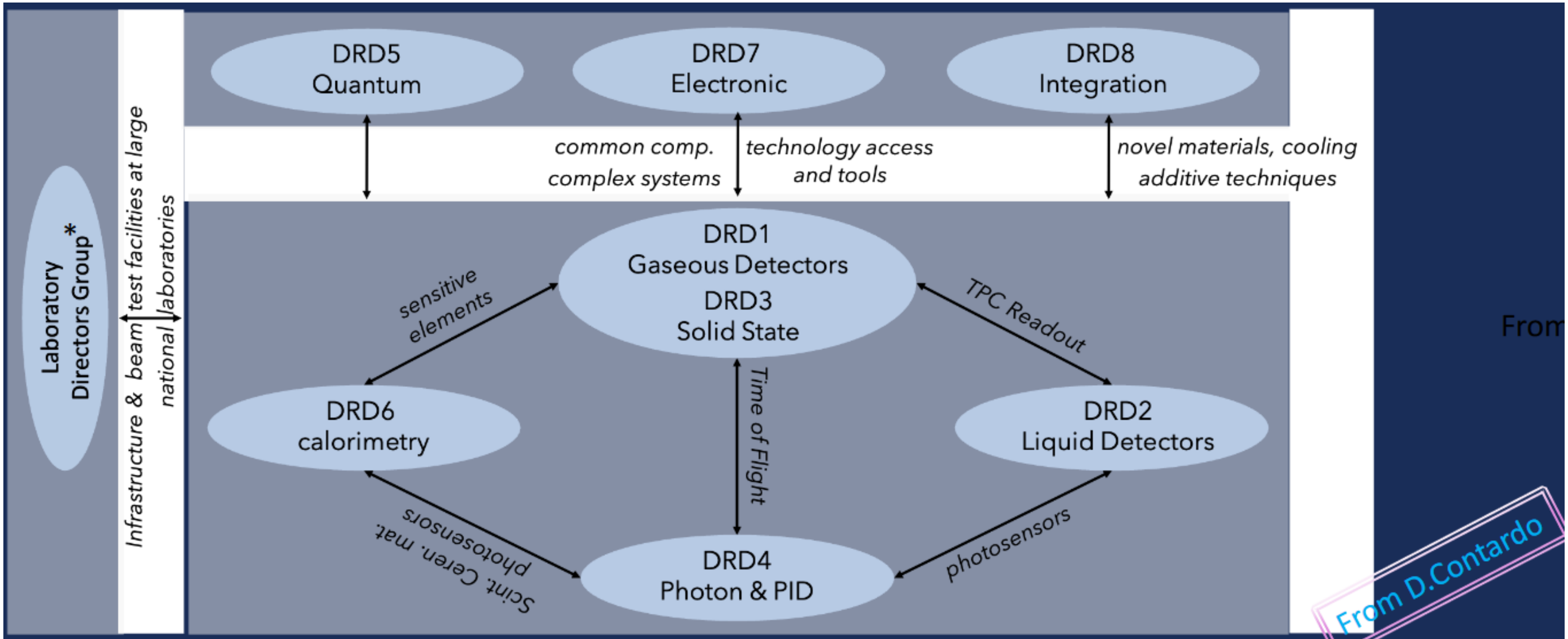
Technologies / Detector types in DRD3/DRD7

Lab	CMOS TJ 180nm (WP 3.1)	CMOS TPSco 65nm (WP 3.1)	DepCMOS LF150 nm (WP 3.1)	Hybrid 65 nm	Hybrid TSMC 28 nm	LGAD	Trenched 3D	Diamonds (WP 3.3)
APC	🟦	🟩	🟦	🟦	🟦	🟦	🟦	🟦
CPPM	🟧	🟩	🟧	🟧	🟩	🟦	🟦	🟦
IJCLab	🟦	🟦	🟦	🟧	🟧	🟩	🟦	🟦
IP2I	🟧	🟩	🟦	🟦	🟦	🟦	🟦	🟦
IPHC	🟧	🟩	🟦	🟦	🟦	🟦	🟦	🟦
LPNHE	🟦	🟧	🟦	🟧	🟧	🟩	🟩	🟩
LPSC	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟩
IRFU	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟩 **Main Interest in DRD3 framework**	🟧 **Interest not necessarily in DRD3**	🟦 **No expressed interest**



DRDT 3.1	**CMOS sensors**	**DRDT 3.2**	**Sensors for 4D tracking**
WP1.1	TPSCo 65 nm	WP2.1	3D sensors
WP1.2	TowerJazz 180 nm	WP2.2	LGADs
WP1.3	LFoundry 150 nm		
WP1.4	TSI 180 nm		
WP1.5	LFoundry 110 nm		
WP1.6	IHP 130 nm		
DRDT 3.3	**Sensors for extreme fluence**	**DRDT 3.4**	**Demonstrator for 3D-integration**
WP3.1	Wide bandgap (SiC, GaN)	WP4.1	
WP3.2	Diamond	WP4.2	
WP3.3	Silicon		



Laboratory Directors Group*

Infrastructure & beam test facilities at large national laboratories

DRD5
Quantum

DRD7
Electronic

DRD8
Integration

common comp. complex systems

technology access and tools

novel materials, cooling additive techniques

DRD1
Gaseous Detectors

DRD3
Solid State

sensitive elements

TPC Readout

Time of Flight

DRD6
calorimetry

DRD2
Liquid Detectors

Scint. Ceren. mat. photosensors

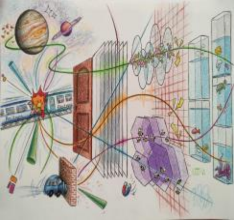
photosensors

DRD4
Photon & PID

From

From D.Contardo

direct the community contributions to Work Packages and resources in proper DRD(s)

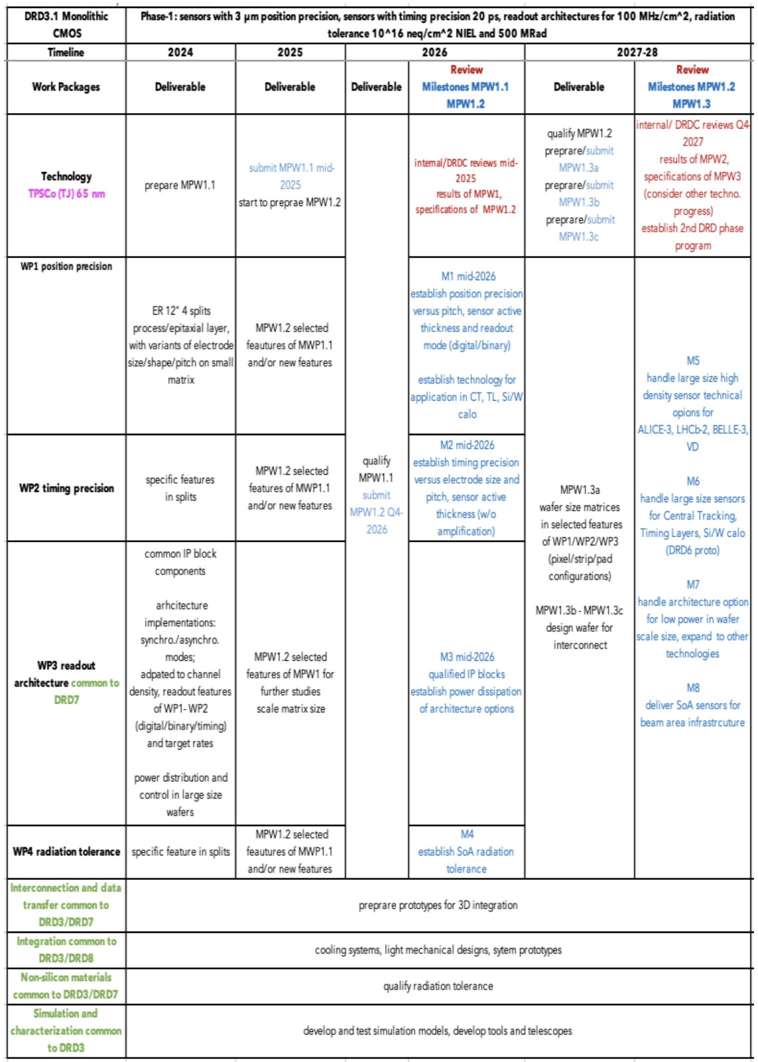


MCMOS 1st R&D phase up to 2027-2028

DRD3

Deliverables: MPW submissions/reviews/milestones (ex. MCMOS TPSC 65 nm)

Work Packages

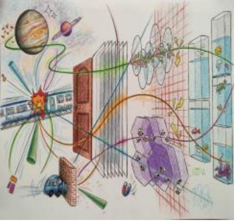


DRD3.1 Monolithic CMOS	Phase-1: sensors with 3 μm position precision, sensors with timing precision 20 ps, readout architectures for 100 MHz/cm^2, radiation tolerance 10^16 neq/cm^2 NIEL and 500 MRad					
Timeline	**2024**	**2025**	**2026**		**2027-28**	
Work Packages	**Deliverable**	**Deliverable**	**Deliverable**	**Review** **Milestones MPW1.1 MPW1.2**	**Deliverable**	**Review** **Milestones MPW1.2 MPW1.3**
Technology TPSCo (TJ) 65 nm	prepare MPW1.1	submit MPW1.1 mid-2025 start to preprae MPW1.2	qualify MPW1.1 submit MPW1.2 Q4-2026	internal/DRDC reviews mid-2025 results of MPW1, specifications of MPW1.2	qualify MPW1.2 preprare/submit MPW1.3a preprare/submit MPW1.3b preprare/submit MPW1.3c	internal/ DRDC reviews Q4-2027 results of MPW2, specifications of MPW3 (consider other techno. progress) establish 2nd DRD phase program
WP1 position precision	ER 12" 4 splits process/epitaxial layer, with variants of electrode size/shape/pitch on small matrix	MPW1.2 selected feautures of MWP1.1 and/or new features		M1 mid-2026 establish position precision versus pitch, sensor active thickness and readout mode (digital/binary) establish technology for application in CT, TL, Si/W calo	MPW1.3a wafer size matrices in selected features of WP1/WP2/WP3 (pixel/strip/pad configurations) MPW1.3b - MPW1.3c design wafer for interconnect	M5 handle large size high density sensor technical opions for ALICE-3, LHCb-2, BELLE-3, VD M6 handle large size sensors for Central Tracking, Timing Layers, Si/W calo (DRD6 proto) M7 handle architecture option for low power in wafer scale size, expand to other technologies M8 deliver SoA sensors for beam area infrastrcuture
WP2 timing precision	specific features in splits	MPW1.2 selected features of MWP1.1 and/or new features		M2 mid-2026 establish timing precision versus electrode size and pitch, sensor active thickness (w/o amplification)		
WP3 readout architecture common to DRD7	common IP block components arhcitecture implementations: synchro./asynchro. modes; adpated to channel density, readout features of WP1- WP2 (digital/binary/timing) and target rates power distribution and control in large size wafers	MPW1.2 selected features of MPW1 for further studies scale matrix size		M3 mid-2026 qualified IP blocks establish power dissipation of architecture options		
WP4 radiation tolerance	specific feature in splits	MPW1.2 selected feautures of MWP1.1 and/or new features		M4 establish SoA radiation tolerance		
Interconnection and data transfer common to DRD3/DRD7	preprare prototypes for 3D integration					
Integration common to DRD3/DRD8	cooling systems, light mechanical designs, sytem prototypes					
Non-silicon materials common to DRD3/DRD7	qualify radiation tolerance					
Simulation and characterization common to DRD3	develop and test simulation models, develop tools and telescopes					

Ball park goals

- explore all performance aspects in several technologies against design/process parameters
- develop few architectures with low power consumption for different work packages
- prepare (start?) 3D integration
- Review achievements, narrow down technology options
- Handle :
  - technical solutions for initial strategic programs: ALICE-3, LHCB-2, Belle-3, ATLAS/CMS…
  - sensors for DRD6 High Granularity Calorimetry prototypes
  - telescope for beam-test infrastructure

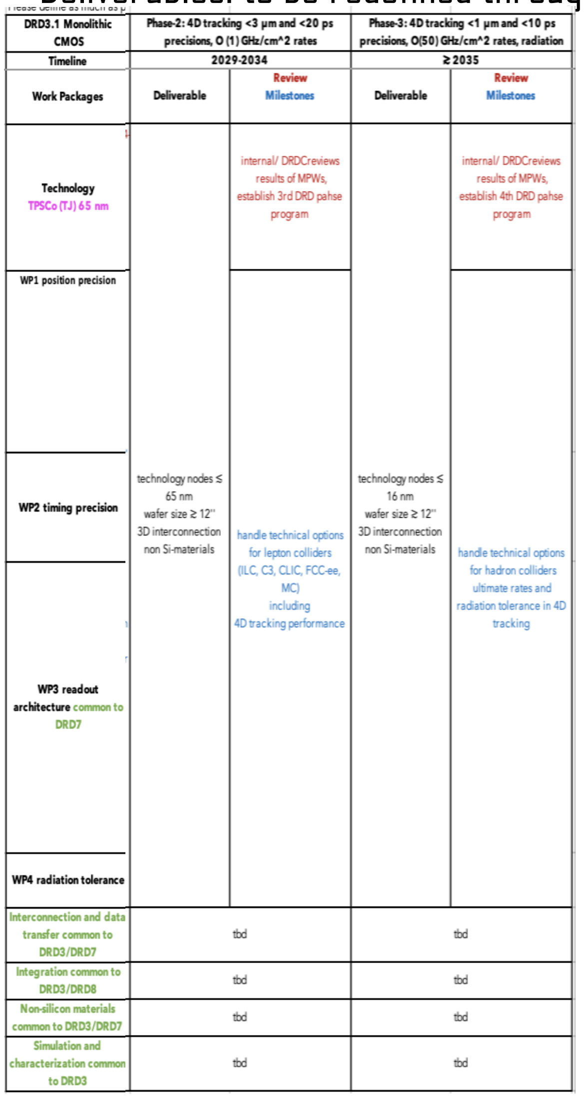
common areas within DRD3 and with DRD7



MCMOS 2nd and 3rd R&D phases

Deliverables: to be redefined through reviewing of Phase 1 progress and achievements

Work Packages



DRD3.1 Monolithic CMOS	Phase-2: 4D tracking <3 μm and <20 ps precisions, O (1) GHz/cm^2 rates		Phase-3: 4D tracking <1 μm and <10 ps precisions, O(50) GHz/cm^2 rates, radiation	
Timeline	2029-2034		≥ 2035	
Work Packages	Deliverable	Review Milestones	Deliverable	Review Milestones
Technology TPSCo (TJ) 65 nm	technology nodes ≤ 65 nm wafer size ≥ 12'' 3D interconnection non Si-materials	internal/ DRDCreviews results of MPWs, establish 3rd DRD pahse program	technology nodes ≤ 16 nm wafer size ≥ 12'' 3D interconnection non Si-materials	internal/ DRDCreviews results of MPWs, establish 4th DRD pahse program
WP1 position precision		handle technical options for lepton colliders (ILC, C3, CLIC, FCC-ee, MC) including 4D tracking performance		handle technical options for hadron colliders ultimate rates and radiation tolerance in 4D tracking
WP2 timing precision				
WP3 readout architecture common to DRD7				
WP4 radiation tolerance				
Interconnection and data transfer common to DRD3/DRD7	tbd		tbd	
Integration common to DRD3/DRD8	tbd		tbd	
Non-silicon materials common to DRD3/DRD7	tbd		tbd	
Simulation and characterization common to DRD3	tbd		tbd	

Ball park goals

- Integrate WP features in same sensors at low power consumption
- Evolve to further technologies/lower nodes toward full 4D tracking
- Implement 3D integration
- Reach ultimate timing precision, rates and rad. tol. for in 3rd phase

common areas within DRD3 and with DRD7