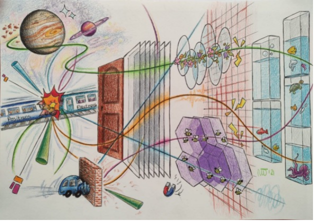


Status and Plans for the DRD3 collaboration
(R&D on Solid-state Detector Technologies)

Xin Shi

on behalf of the collaboration

2025.11.07

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

Semiconductor Sensors

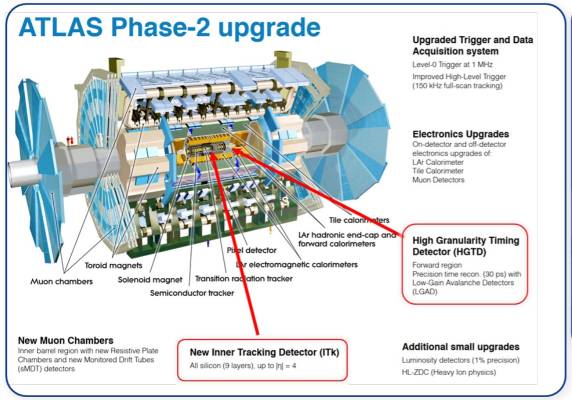
Semiconductor detectors are the cornerstone of all present and future experiments:

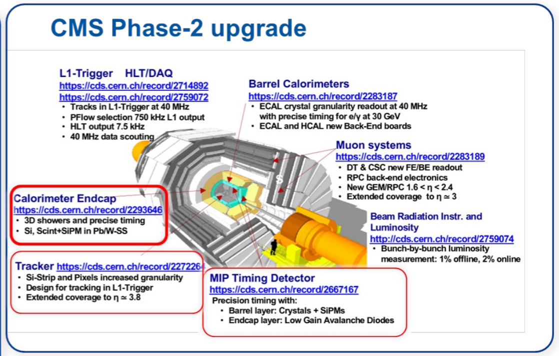
- several R&D collaborations (RD39, RD42, RD48 and RD50) in the past with crucial contribution to the HL-LHC upgrades in all experiments
- Improvements:
  - position resolution (CMS/ATLAS hybrid pixels on p silicon)
  - timing layers (ATLAS-HGTD, CMS-ETL)
  - large scale use in calorimeters (CMS HGCAL, p-type Si)
  - lightweight monolithic pixel detectors (ALICE ITS) with excellent position resolution

New Major Challenges for the future:

- FCC-ee/CEPC/ILC: vertex detectors with low mass, high resolution (Target per layer spatial resolution of ≤ 3-5 μm and $X/X_0 \leq 0.05\%$),
- FCC-hh/SppC: low power and high radiation hardness (up to $8 \cdot 10^{17}$ $n_{eq}cm^{-2}$). Resolving many pp hits in a bunch by ultra-fast timing in O(10-100ps)
- Full integration with electronics, mechanics, services
- Large area sensors at low cost for calorimetry

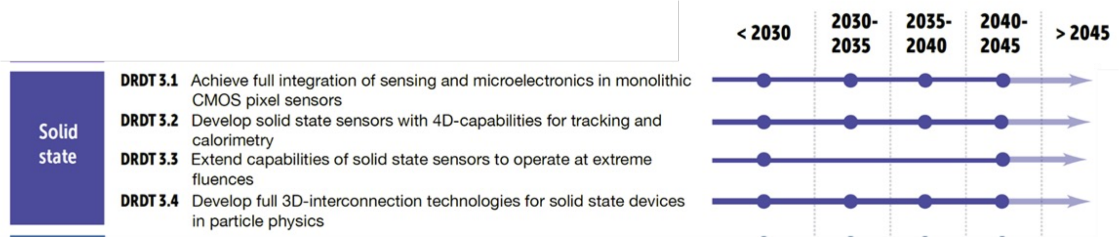
Coming after the accelerator upgrade in 2029





…also very close collaboration with LHCb!

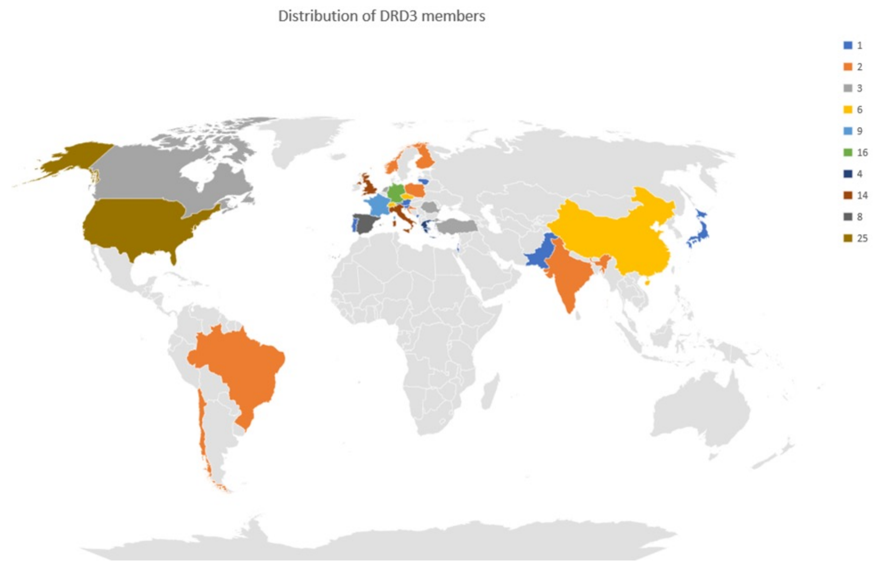
European Commission for Future Accelerators
Road map document on sensors

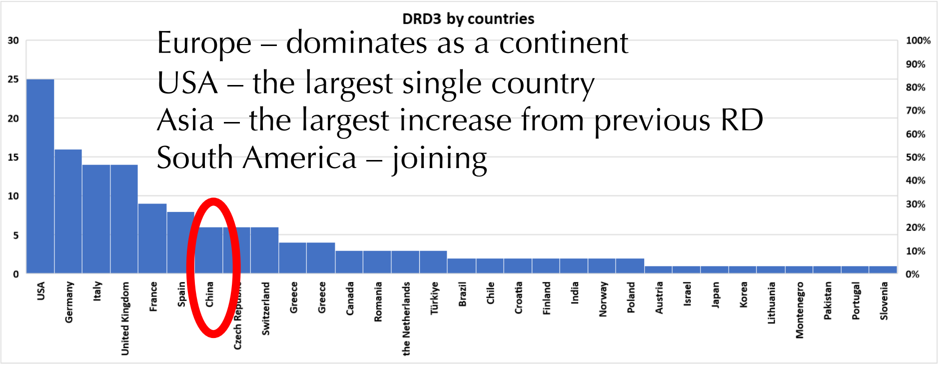


ECFA Detector R&D roadmap [CERN CDS]

The DRD3 collaboration

A large collaboration on semiconductor has been formed at CERN to guide and steer the developments of semiconductor sensor developments in the next decades **-148 Institutes currently involved with 700+ people**





Large interests from the community:

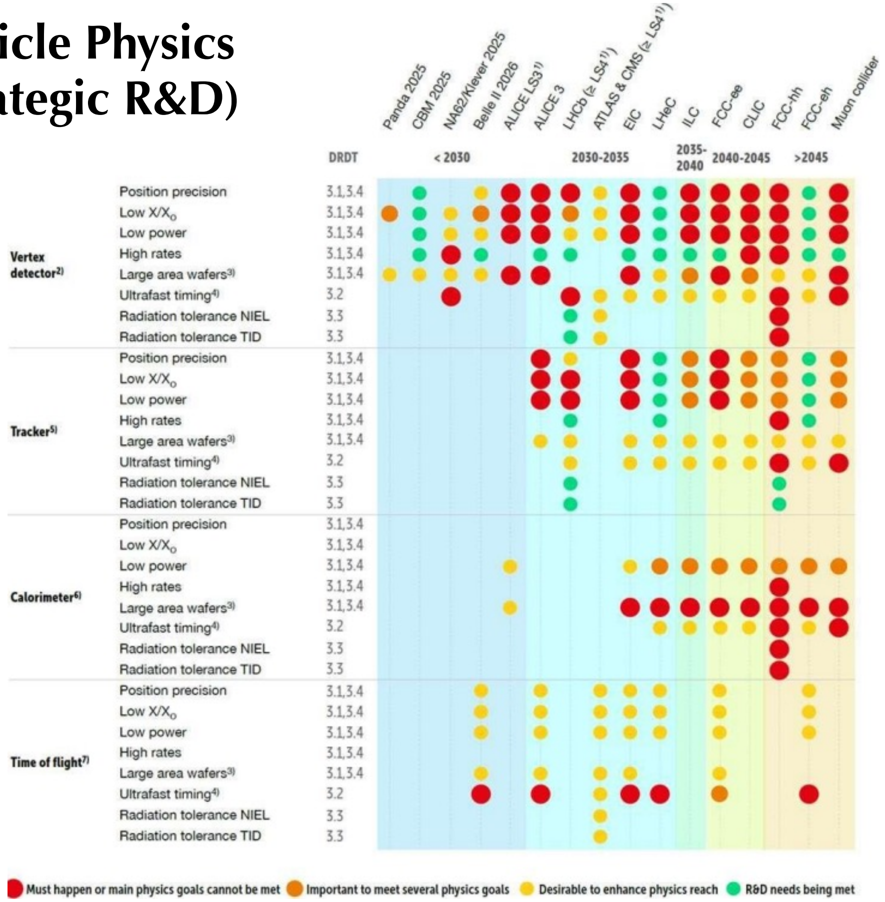
- Integration of most **RD42** and **RD50** groups
- Interest from institutions from outside:
  - not in previous RD collaborations
  - Outside particle physics (nuclear, medicine, astro)
- Collaboration is constantly growing
- Different forms of collaboration
  - members
  - observers
  - industrial partners

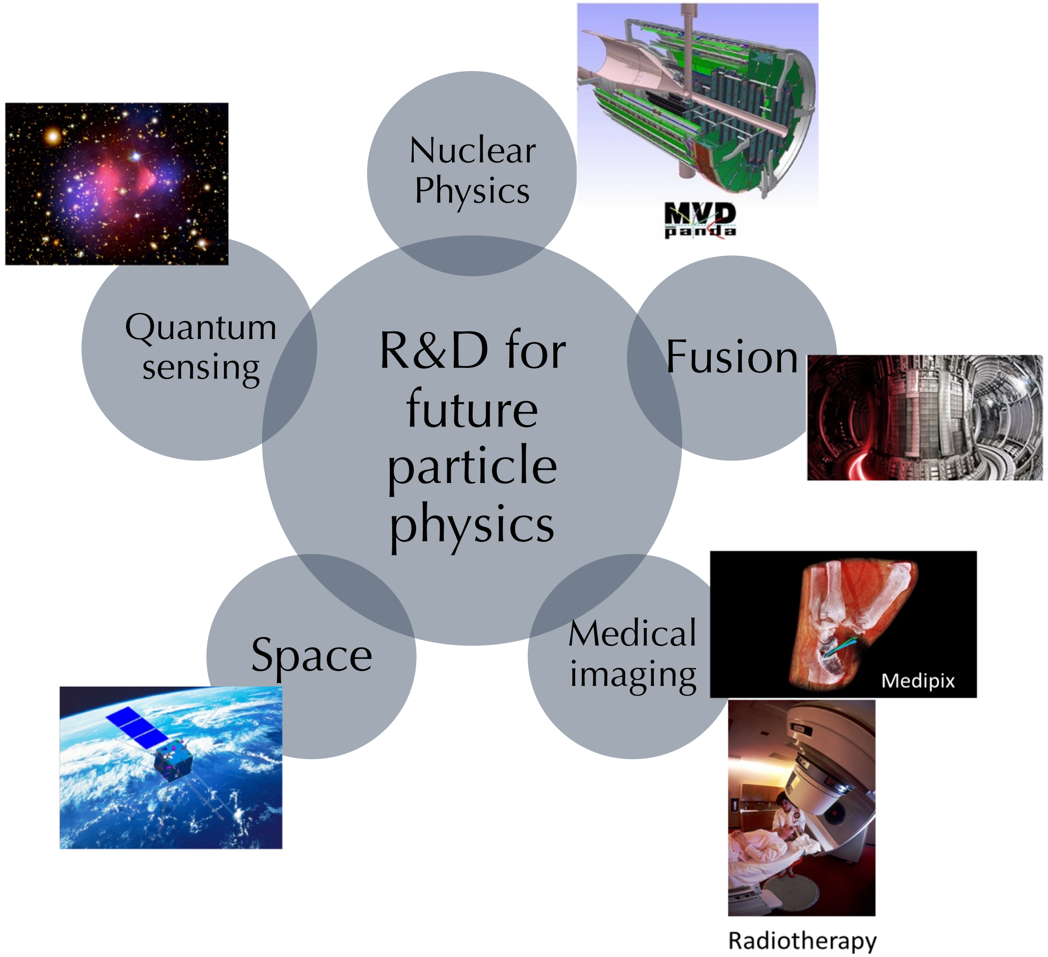
- Collaboration approved in June-2024 for 3 year with prospects of prolongations. It is in the last steps of formalizing the MoU. Collaboration is **already fully functional and operational although many groups still involved in HL-LHC.**

Objectives of the collaboration

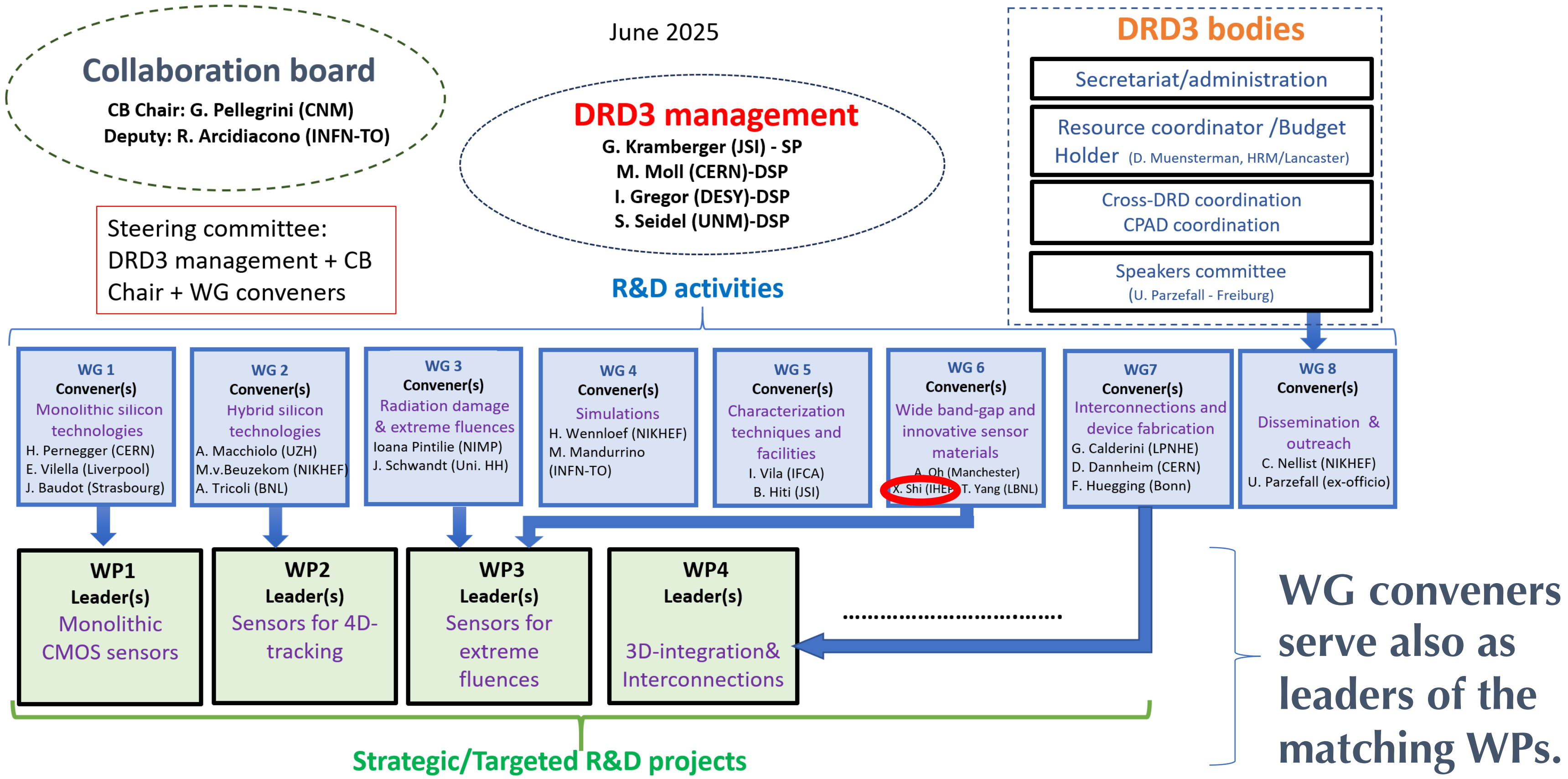
The DRD3 collaboration has the dual purpose of pursuing the realization of the **strategic developments** outlined in the ECFA road map and **promoting blue-sky R&D** in the field of solid-state detectors including the synergies with other fields of science where charged particle detection is a key ingredient.

Particle Physics (strategic R&D)





Organizational structure



12-2023 - provisional approval
01-2024 - formation of CB
03-2024 - election of SP
05-2024 - formation of WG-WPs
06-2024 - **approval (scientific proposal)**
06-2024 - first DRD3 week
07-2024 - start of scientific meetings and preparation of WP projects
10-2024 - **approval of the DRD3 rules**
12-2024 - second DRD3 week
01-2025 - finalization of WP projects (adjustment to funding reality)
02-2025 - first DRDC review
06-2025 - third DRD3 week
approval of the first WP projects
11-2025 - fourth DRD3 week
- finalization of MoU

- Working Group (WG) = long term R&D activity (strategic or generic) linked to certain technology/purpose/application/method aiming to fulfil the research goals in scientific proposal
- Work Package (WP) = strategic R&D activity and is linked to DRD Tasks. It should pursue the goals listed there.
- Each work package consist of several WP projects - not yet fully resource loaded at the moment.

DRD3 organization of the work

Strategic R&D
(follow ECFA detector roadmap)
organized in four Work Packages

Supported by DRD3 Common Collaboration Fund

Common activities

- Test-beams, Irradiations…
- Schools
- Meetings
- Awards
- Mobility projects

DRD Common Collaboration Fund (CCF) projects

- small Blue-Sky projects
- common hardware, software
- consumables

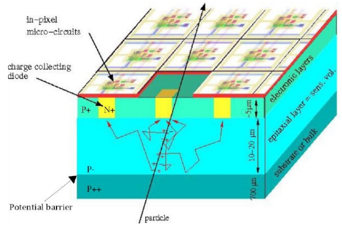
Supported by RD50 Common Collaboration Fund

RD50 Common Collaboration Fund (CCF) projects
28 running projects with resources already allocated

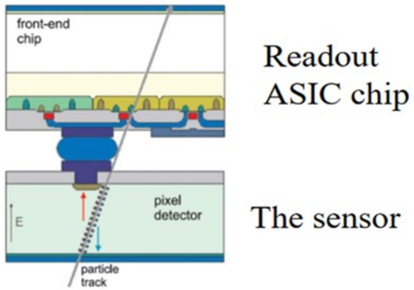
The scheme was demonstrated to be very successful and was agreed by collaboration to be implemented also for DRD3.

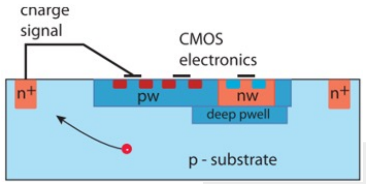
Paths of present silicon sensor R&D

Monolithic devices
(**WG1/WP1-CMOS**)
55-180 nm processes



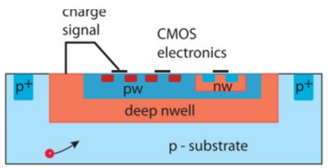
Hybrid devices
(WG2/WP2-4D tracking)



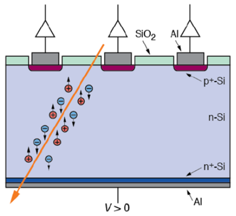


Small electrode device

MAPS

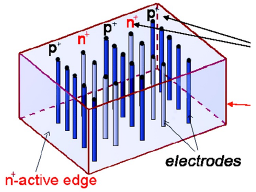


Large electrode device



Planar

3D devices



with gain

Depleted MAPS wo Gain

Depleted MAPS wo Gain

with gain

Large area passive devices (strips)

With Gain (LGADs)

Trench 3D

Column 3D

With Gain

Optimized for rates/power/position resolution

Optimized for radiation hardness /timing

proof of concept ongoing
recent research (working prototype)
proven/demonstrated

WG1/WP1 Monolithic silicon sensors

Aim advance monolithic CMOS performance, combining sensing and readout elements, for future tracking applications, tackling the challenges of:

- very high spatial resolution (≤3 μm)
- high data rate (~100 MHz/cm²)
- high radiation tolerance (10^{16} n_{eq}/cm^2 NIEL and 500 Mrad)
- low mass (~0.05% X_0)
- Good timing (->20 ps/hit)
- covering large areas
- reducing power (few tens mW/cm²)
- keeping an affordable cost

Program shared between DRD3/7

DRD7.6/3.1

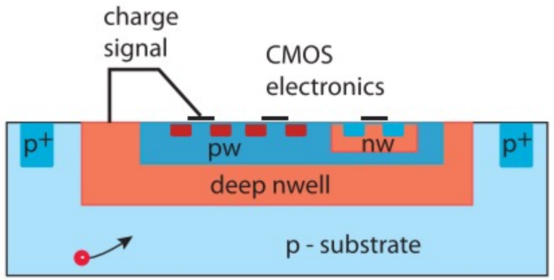
Sensor	*ASIC*
TCAD simulation Sensor design, optimization, characterization	TCAD simulation Architecture, design, verification, testing
Analog-on-Top designs	Digital-on-Top designs
Small scale prototypes in various technologies	Large scale demonstrators in selected/qualified technologies
Case-by-case access	Negotiated access framework, design flow, support

TWO approaches

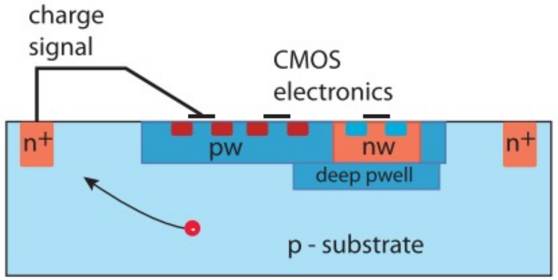
LARGE ELECTRODE DESIGN **SMALL ELECTRODE DESIGN**

$\tau \propto \frac{C}{g_m}$, $ENC_{\mathrm{thermal}} \propto \frac{kTC}{g_m}$ compensated by power (g_m)

taken from N. Wermes



- Large electrode: $C \approx 300\,\mathrm{fF}$
- Strong drift field, short drift paths, large depletion depth
- Higher power, slower
- Threshold $\sim 2000\,e^-$



- Small electrode: $C \approx 3\,\mathrm{fF}$
- Low analogue power
- Faster at given power
- Difficult lateral depletion, process modifications for radiation hardness
- Threshold $\sim 300\,e^-$

WG1/WP1: Monolithic silicon sensors

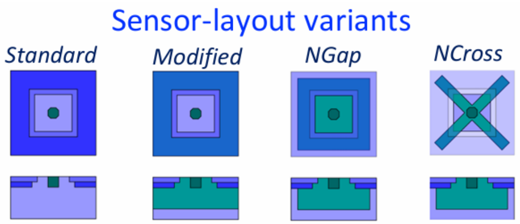
Projects **running**, **proposal draft submitted (work ongoing)**, **proposals in preparation (work ongoing):**

55 nm SMIC
- Development of HVCMOS sensors using 55nm process - COFFEE

65 nm TPSCo technology (in co. with DRD7.6a):
- OCTOPUS - Optimized CMOS Technology for Precision in Ultra-thin Silicon
- MANTA - Versatile MAPS
- TPSCo 65nm MCMOS with high precision timing

150 nm LF technology
- Towards large electrode CMOS sensors with intrinsic amplification for ultimate timing performance
- Radiation hard HVCMOS detectors
- Passive large area strip sensors

180 nm TJ technology
- CMOS Active SenSor with Internal Amplification - "CASSIA"
- Radiation hard read-out architectures

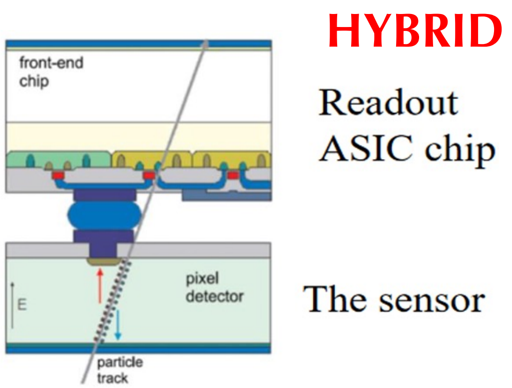


Main challenges (from DRD3 point):
- availability of the active volume (60-80 e-h/mm)
  - epitaxial layer decreases with smaller node processes (350 nm->28 nm). Also, the lateral drift becomes even bigger problem for thin epitaxial layers.
  - few foundries are/will be open to use high resistivity substrate wafer
- costs increase rapidly with the smaller node (MPW runs may not be available)
- allocating the vendors that are open to our needs
  - minimum information about the process which allows for simulation of particle detection in the devices.
  - adaptation of the process
- accessibility to the processes – licensing (access to process development kits - PDK)
- requirements of additional processing (back side processing), back side metallization …

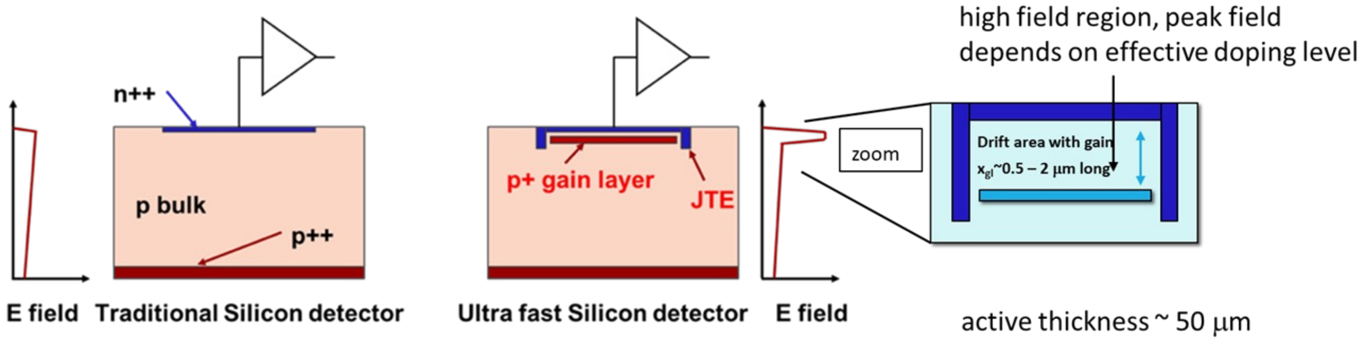
The work is ongoing in all of the projects:
- Resources are at least partially secured
- TPSCo 65 nm (organization together with DRD7/ESE in 2026/27)
- LF15 run is coming in 2026 with resources secured (RD50 legacy)
- TJ180 MPW runs

WG2/WP2: Hybrid silicon technologies and 4D tracking

By "4D tracking" we mean the process of assigning a space and a time coordinate to a hit - ~10-30 μm position **and ~10-30 ps time resolution** – simultaneously (many benefits in dense particle environment for tracking and PID)

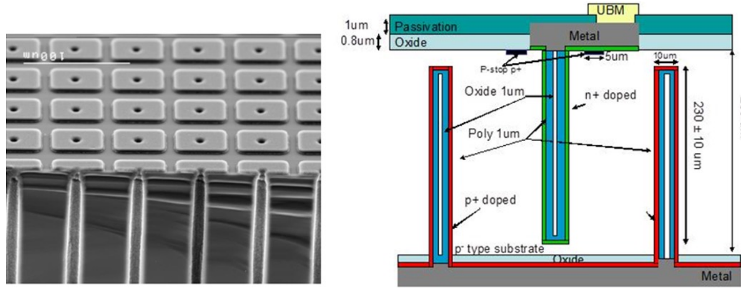


The above goals can be achieved in planar technology with gain or 3D (requirement - high signal and short collection time)

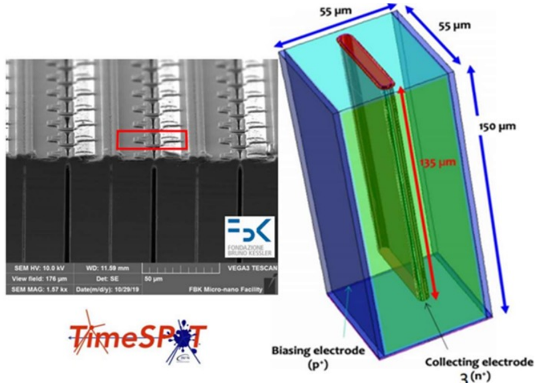


4D tracking (not only track timing)

Column-3D detectors



Trench-3D detectors



WG2 research goals <2027	
	Description
RG 2.1	Reduction of pixel cell size for 3D sensors
RG 2.2	3D sensors for timing (50 × 50 μm, < 50 ps)
RG 2.3	LGAD for 4D tracking < 10 μm, < 30 ps, wafer 6" and 8"
RG 2.4	RSD for ToF (Large area, < 30 μm, < 30 ps)

WG2/WP2: Hybrid silicon technologies and 4D tracking

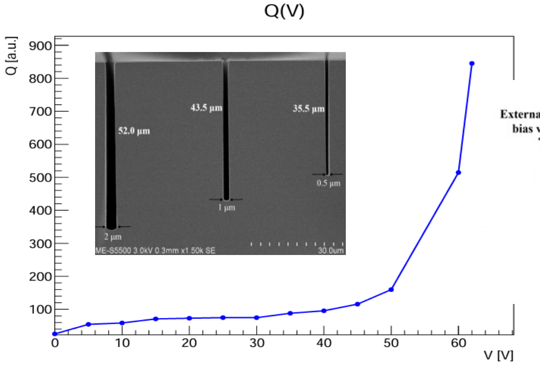
Projects **running**, several in preparation

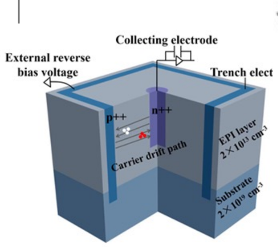
LGAD projects

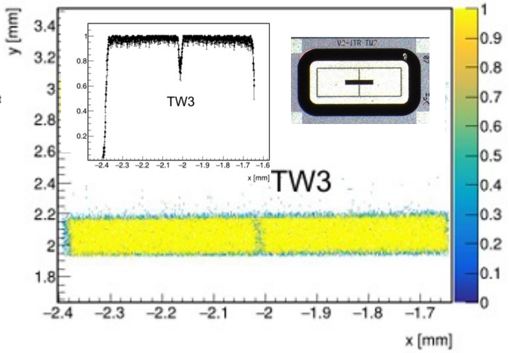
- LGAD based timing tracker development for future electron collider
- Development of Ultra Fast-Time Low Mass Tracking Detectors
- Development of TI-LGADs for 4D Tracking

3D projects

- Development of very small pitch, ultra rad-hard 3D sensors for tracking & timing applications at FBK
- Novel silicon 3D-trench pixel detectors based on 8-inch CMOS







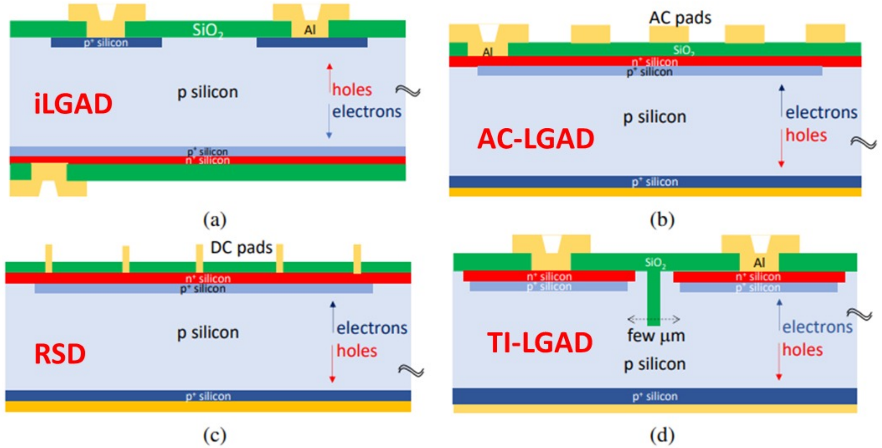
Main challenges and developments:

3D detectors:

- increase of column-depth/width ->100 – narrower columns/trenches (~0.5-1 mm) that would allow for controlled multiplication/gain device (**recently achieved in WP2 project**)
- Scalability to 8″ wafers **(ongoing)**
- Reduction of cell sizes to 25x25 mm^2 and thickness with gain leading to smaller capacitance **(ongoing)**
- Optimization of geometry for best timing performance

LGADs:

- Solution to fill factor problem – 100% surface efficiency. Addressed in several WP2 projects: TI-LGADs, RSD (AC/DC) LGADs
- Addressing the radiation hardness – defect engineering
  - Co-implantation of impurities (Carbon) – addressed in WG3
  - Compensated LGADs – addressed in WG3

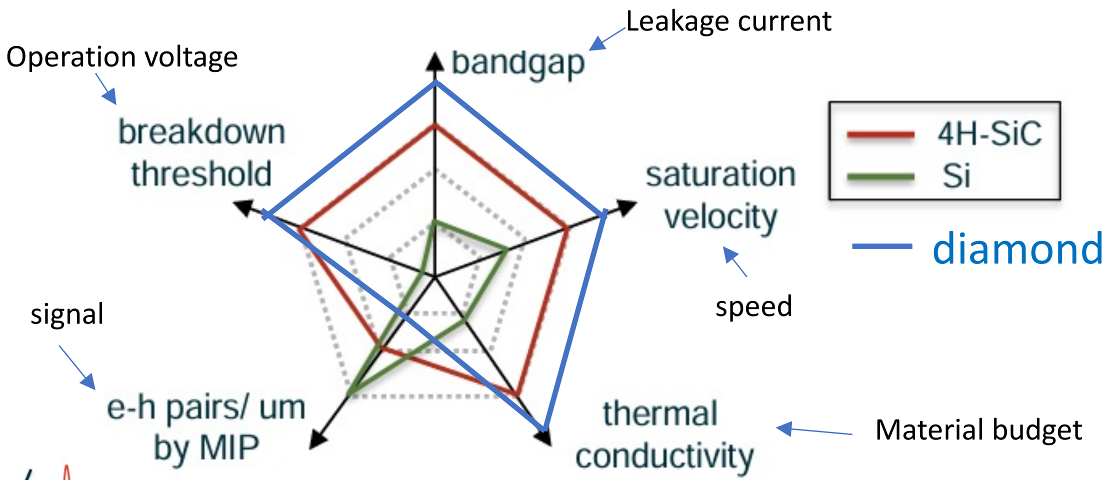


<u>**The work is ongoing in all of the projects:**</u>

- Resources are at least partially secured (initial runs possible)
- Several WP projects and also CCF in preparation

WG3,6/WP3: extreme fluence and WBS

Improve the radiation hardness of the semiconductor detectors and exploitation of the benefits of WBS for particle physics



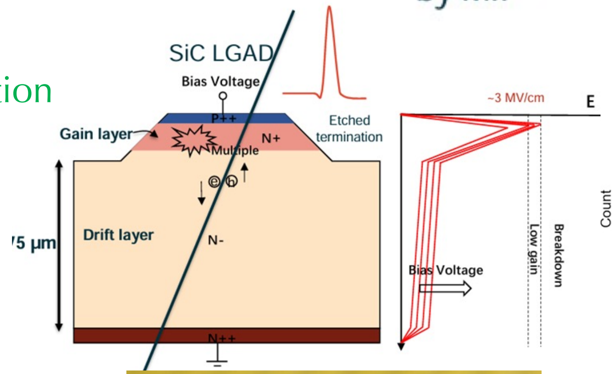
Projects **running**, **proposal draft submitted (work ongoing)**, **proposals in preparation (work ongoing):**

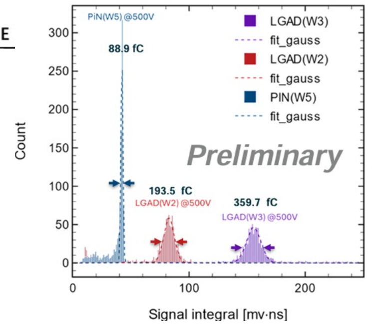
Understanding silicon at extreme fluences
(**devices developed with in WP2**)

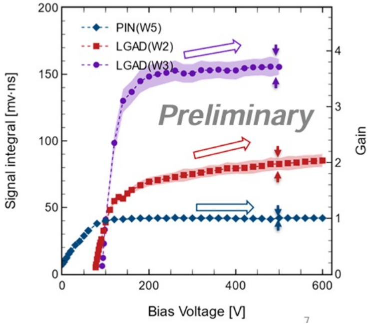
- Radiation damage in Si PiN and LGAD sensors
- Many RD50 projects running on the radiation hardness

Wide-Bandgap-Semiconductors

- SiC LGAD Detector (one running one in preparation)
- Development of radiation-hard GaN devices for MIP detection
- Radiation hardness of 25um 3D diamond detectors
- Graphene/SiC Detector







Main challenges and developments:
Silicon at extreme fluences:

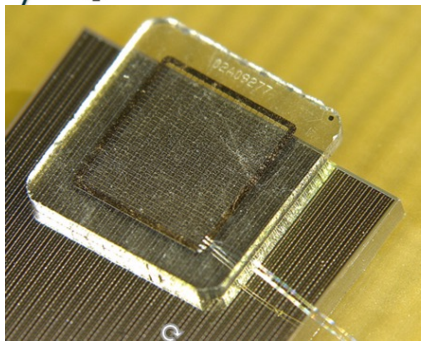
- understanding material properties (impact ionization, mobility, trapping…)
- understanding the operation

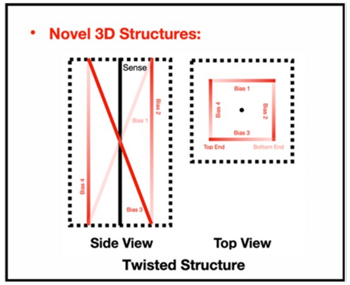
SiC/GaN

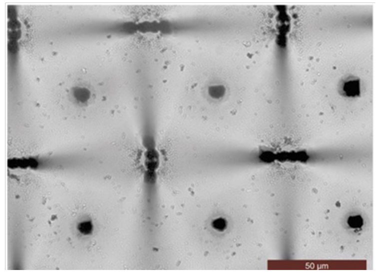
- understanding the material properties – defects formation
- processing of large device SiC-LGADs

Diamond:

- scalability of 3D column processing
- availability of high-quality large diameter wafers







WG7/WP4: 3D-integration and interconnections

The goal of the DRD3 interconnection task is to organize the different technological 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.

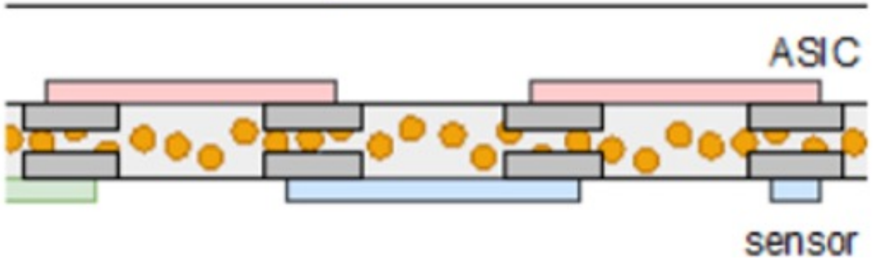
Projects **running**

- In-house plating, hybridization and module-integration technologies for pixel detectors

CCF project:

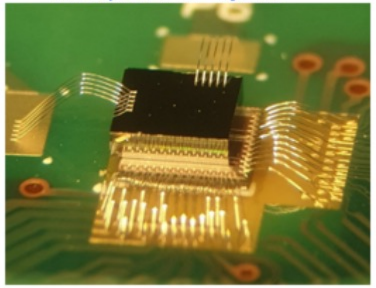
- CMOS Pixel Detector Demonstrator with Serial Powering and Innovative Interconnections

In-house hybridisation

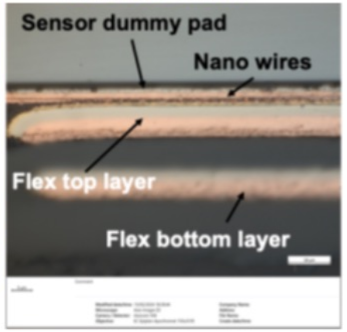


Plating

Timespot1 ACF hybrid

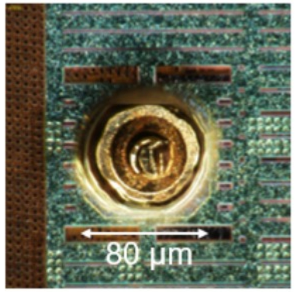


Nanowires on flex

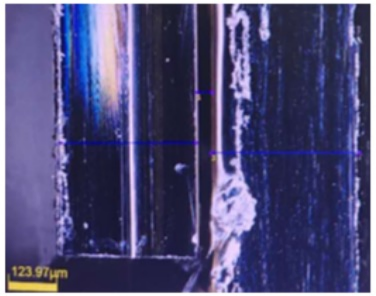


In-house hybridization, module integration
- Exploring innovative **bonding** methods, adapted to the requirements of various projects
  - **Conductive adhesives (ACF / ACP)**
    → good results for <1cm^2 devices and >~50 µm pitch
  - **Nano wires**
    → successful bonding of MALTA2 to flex
  - **Gold studs** + epoxy
    → successfully used for large (>100 µm) pitch
    → developed **low-temperature bonding process** suitable for **irradiated samples**

Gold-stud on ALTIROCA

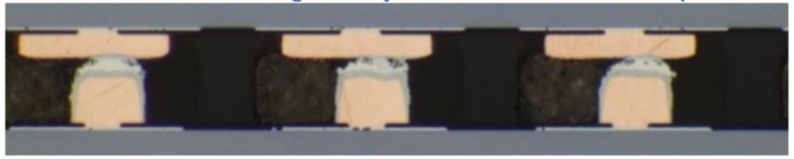


ALTIROCA + irradiated LGAD



Wafer-to-wafer bonding
- Target: ultra-thin hybrid detectors with TSV
- Pilot project U Bonn / IZM: passive CMOS sensors + Timepix3

Wafer-to-wafer bonding of daisy-chain test wafers with Cu pillars



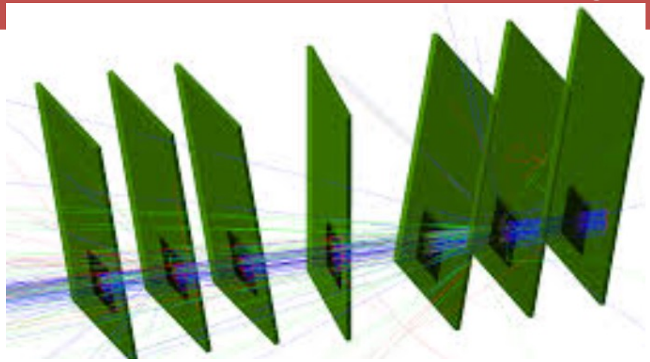
WG4: Simulations

Simulations are essential for planning, understanding the performance and designing of devices. Aim to develop tools that could be (easily) implemented to simulate any specific detector or measurement.

"Monte Carlo"
(predicting the performance of complex detector assemblies)

AllPix2 / Garfield++ as the main tool
complement by other ones (also RASER, KDetSim…)

GOALS:
- Implementation of improved semiconductor models (e.g. mobility, impact ionization, trapping …)
- Adaptation of WBS sensors
- Adaptation of dynamic /adaptive E, E_w
- Implementation of common electronics/digitization



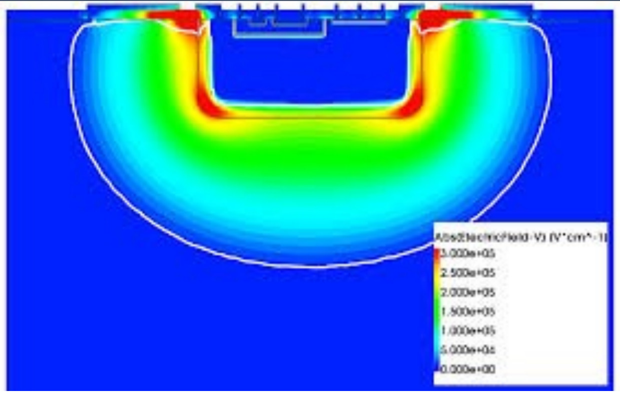
GEANT4

E , E_w

TCAD
(understanding the sensors)

Synopsis, Silvaco

GOALS:
- Developing and verification of damage models (effective and defect based)
- Establish how to benchmark/evaluate the models against the measured properties (important milestone)
- Improving the TCAD with new findings (WBS, extreme fluences)
- Develop a flexible framework to simulate performance of different processes (CMOS)



WG5: R&D on new techniques, common infrastructures, and characterization facilities

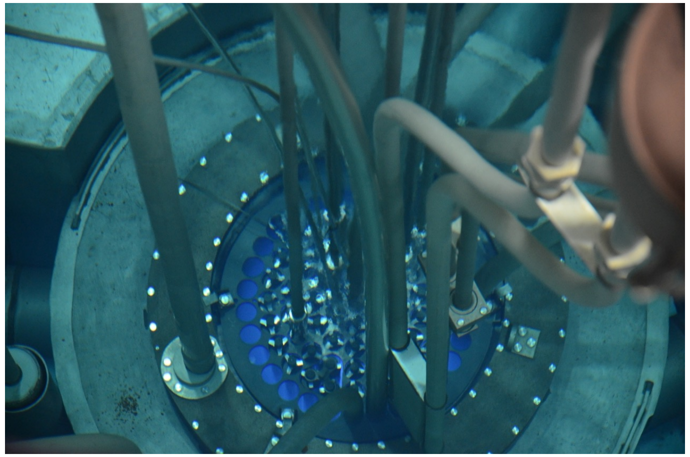
Lines of actions

- Development/improvement/diffusion of **methods and techniques for characterizing sensors** (those for defects spectroscopy DLTS,TSC, EPR…. as well those for characterization TCT, Beta-scope…)
- Joint research activities for the **delivery of common infrastructures for sensor testing** (common sensor readers, jigs, test fixtures,…)
- Promoting the **use of unique irradiation and characterization facilities.**

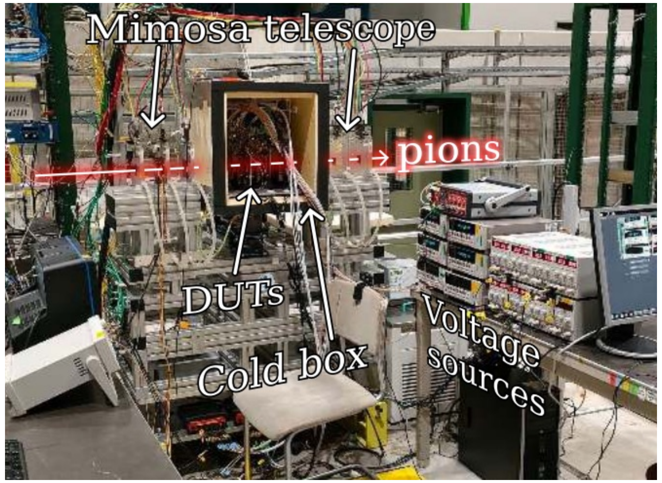
Activities in the last year:

- Centrally organized irradiations to 10^{18} cm^{-2} with reactor neutrons, now also PS and FNAL irradiations
- Centrally organized TB campaign (many DRD3 groups benefited)
- Setting up know-how and infrastructure at ELI-beams
- Development new techniques e.g DB-TCT
- …

Irradiation facilities (e.g. JSI reactor)



Test beam activities (CERN/DESY)



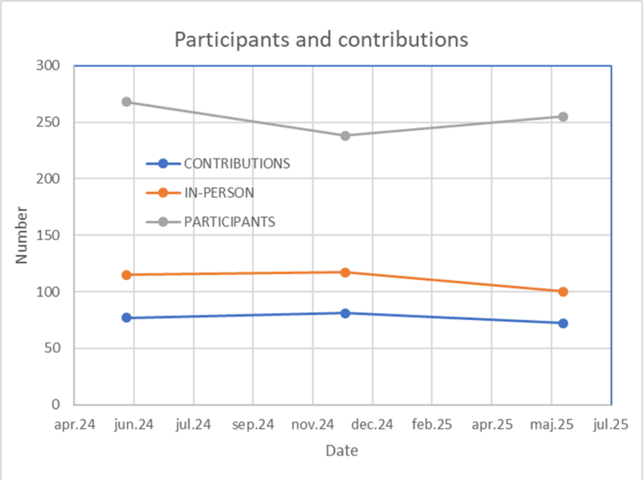
fs high intensity laser facilities (ELI Prague, SGIKER Bilbao…)

WG8: Outreach and visibility

Keep all information on DRD3 web (drd3.web.cern.ch):

- announcements of schools/conferences/workshops
- open positions
- repository of relevant literature and documents
- links to CDS records of proposals and internal documents

DRD3 weeks
our main events
open to everyone

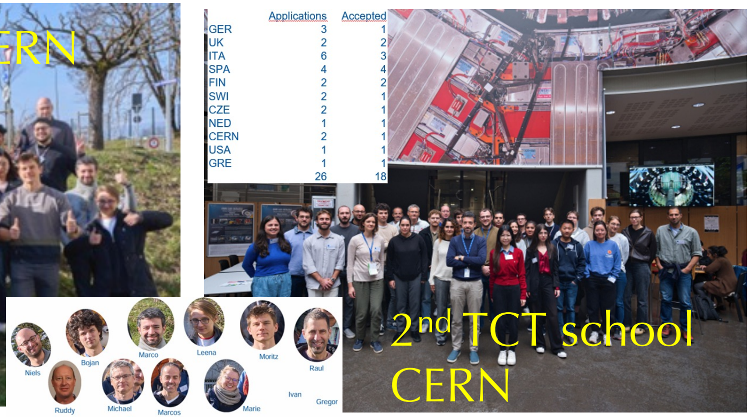


Presentations:

- at student lectures/schools
- several overview presentations at various conferences/workshops

Schools organized within/by DRD3 in last year:

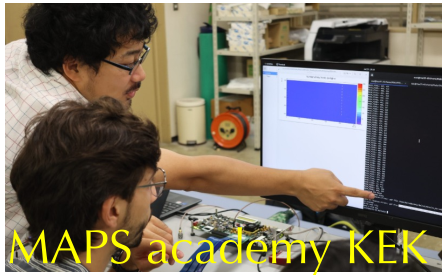
- 1st DRD3 TCT School (March 2025)
- MAPS academy (July 2025)
- 2nd DRD3 TCT School (September 2025)



	Applications	Accepted
GER	3	1
UK	2	2
ITA	6	3
SPA	4	4
FIN	2	2
SWI	2	1
CZE	2	1
NED	1	1
CERN	2	1
USA	1	1
GRE	1	1
	26	18

Next Week:

4th DRD3 week
10-14 Nov @CERN



Conclusions & outlook

- We are large fully functioning collaboration with MoU in the last phases of preparation.
- We have very active R&D going on:
  - approved and running in **total 12 WP projects** with several in making (**not all the projects have fully assured finances – most critical is financing of prototype runs**)
  - small DRD3 CCF projects
  - small RD50 CCF running projects
- More than 700 people are engaged with person-power of around 320 (full engagement) – we **hope that at least this level of involvement in R&D will be kept or even increased** after completion of HL-LHC.
- **CCF** is as vital for promotion of new ideas, integration of smaller groups, facilitation of activities, and increase of mobility.
- We would like to expand the sensors technologies developed in the DRD3 to the other fields of science for which adaptation we would need more resources.

> *"Far better it is to dare mighty things, to win glorious triumphs, even though checkered by failure, than to take rank with those poor spirits who neither enjoy much nor suffer much, because they live in a gray twilight that knows not victory nor defeat."*
>
> -- *Theodore Roosevelt, 1899*