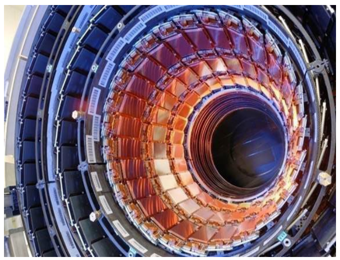
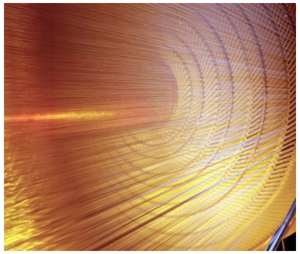
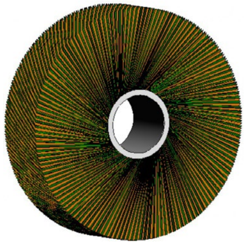
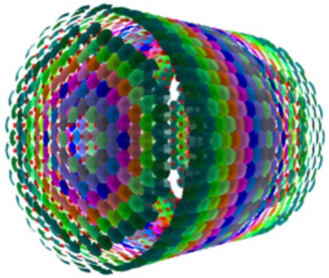
ECFA European Committee for Future Accelerators
NuPECC
APPEC
JENAS 2025, Apr 8 – 11, 2025
Harwell Campus, Didcot, Oxfordshire

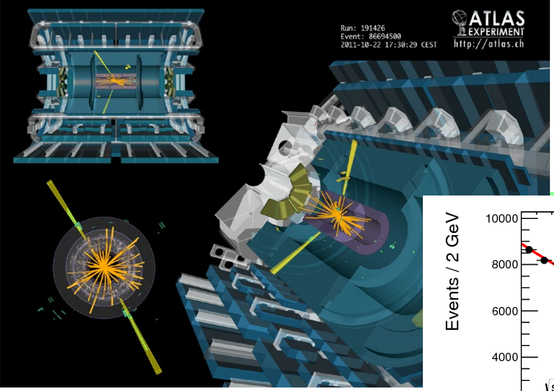



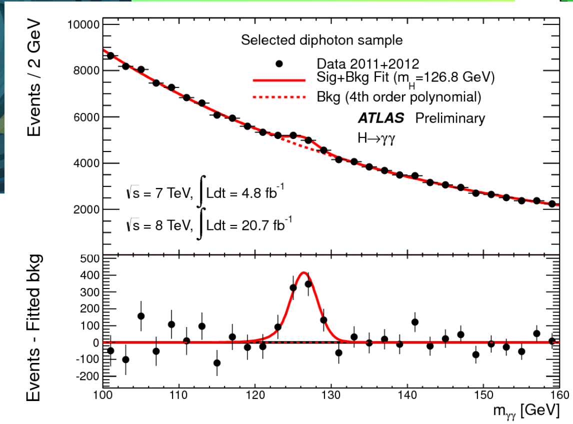
Detector R&D in Particle Physics

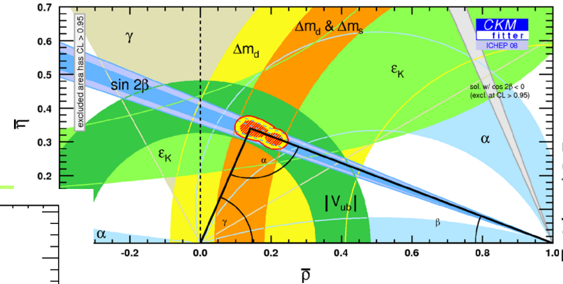
Univerza v Ljubljani

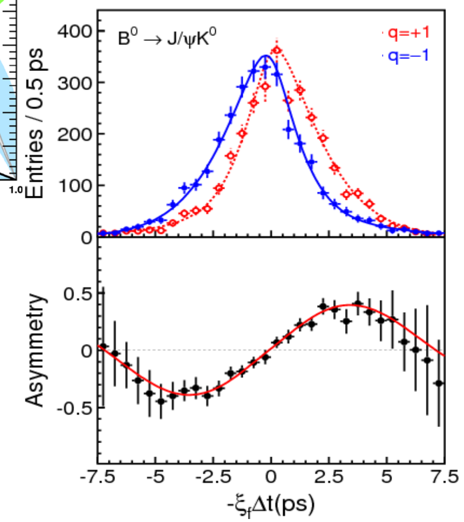
Peter Križan

University of Ljubljana and J. Stefan Institute

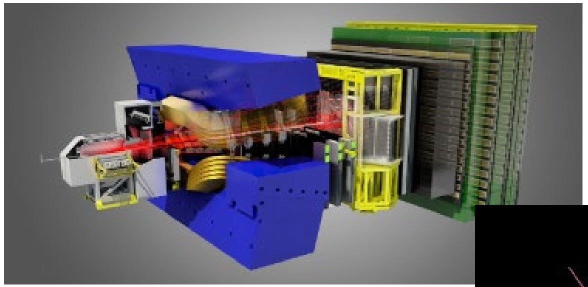


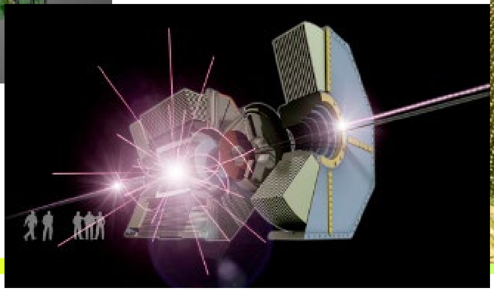


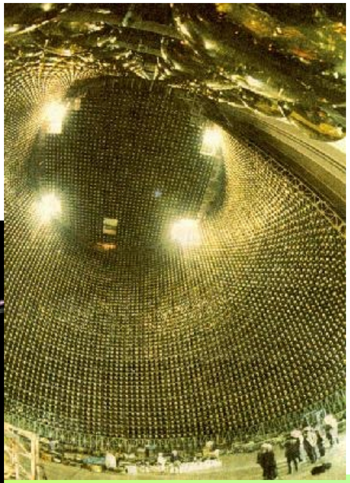


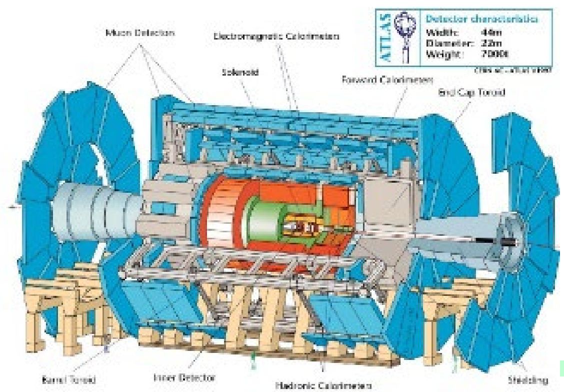


Detectors for particle physics experiments are our discovery tools – well-designed and well-functioning devices have been essential for our present understanding of elementary particles and their interactions.









Contents

Introduction: ECFA Detector R&D Roadmap and its implementation

Gas and semiconductor based tracking detectors

Photo-sensors and particle identification

Calorimetry

Electronics + Data acquisition

Quantum sensors

A very broad range of topics for a single talk – impossible to cover all interesting developments

Neutrino, DM detectors: talk by Roxanne Guenette

ECFA Detector R&D Roadmap

The ECFA Detector R&D Roadmap, developed following the 2020 European Strategy for Particle Physics, outlines a long-term vision to advance detector technologies critical for future particle physics experiments.

It emphasizes strategic planning and investment in areas like

- sensor development (gaseous, liquid, solid-state),
- photon detection,
- quantum sensing,
- calorimetry, and
- integrated electronics.

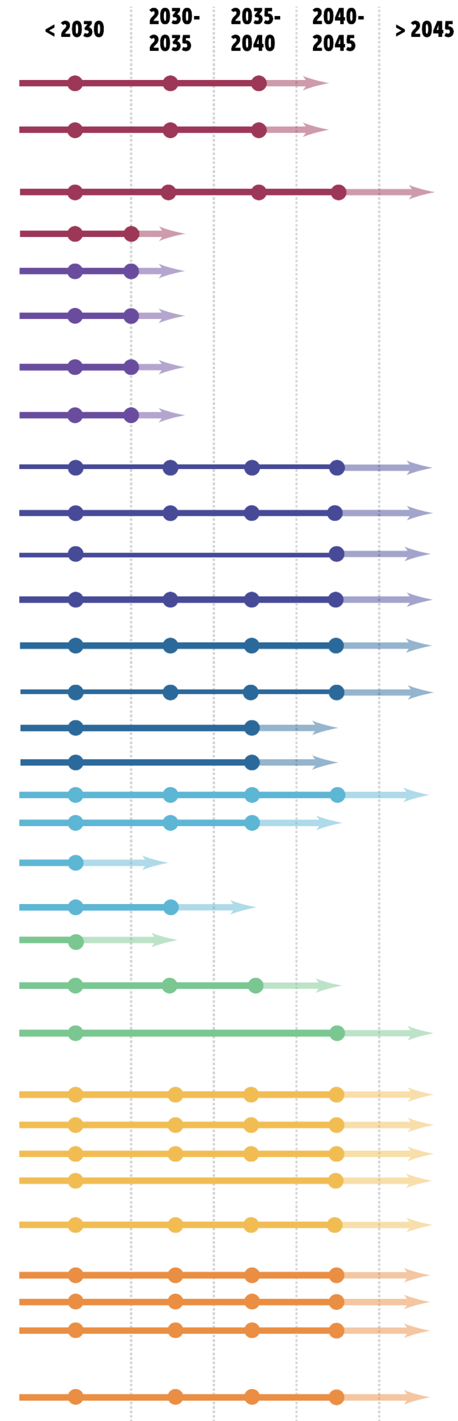
The roadmap highlights the need for coordinated European efforts, robust infrastructure, training, and industrial partnerships.

Strategic recommendations address challenges such as rising R&D costs, sustainability, and the retention of expert talent to ensure Europe remains a global leader in detector innovation.

It also provides a list of detector research and development themes - DRDTs

Detector research and development themes (DRDTs)

Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects



ECFA Detector R&D Roadmap implementation: Detector R&D (DRD) Collaborations

1. Gaseous

e.g.
time/spatial resolution;

environment friendly gases

2. Liquid

e.g.
Light/charge readout;

low background materials

3. Semiconductor

e.g.
CMOS pixel sensors;

High time resolution (10s ps)

4. PID & Photon

e.g.
spectral range of photon sensors;

Time resolution

5. Quantum

quantum sensors
- R&D, incl. beyond QFTP in conventional detectors

6. Calorimetry

e.g.
Sandwich;
noble liquid;
optical

7. Electronics

e.g.
ASICs;
FPGAs;
DAQ

8. Integration

tracking detector mechanics

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optical

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e.g.
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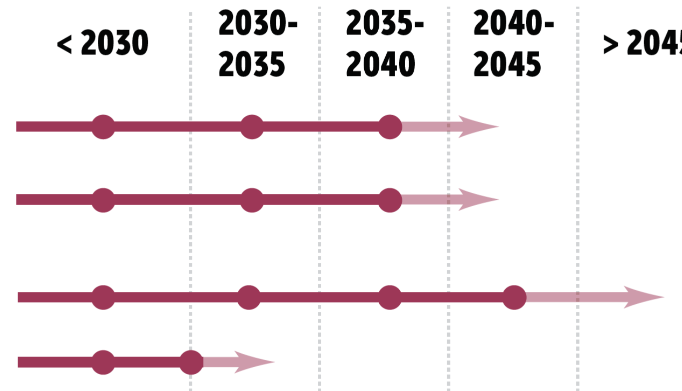
8. Integration

tracking detector mechanics

DRD collaborations have profited in their formation phase from
- experience in CERN RD Collaborations (e.g., RD50 and RD51)
- EU based large detector R&D projects like AIDAinnova

DRD1 – gaseous detectors

Detector R&D Themes (DRDTs)



Gaseous

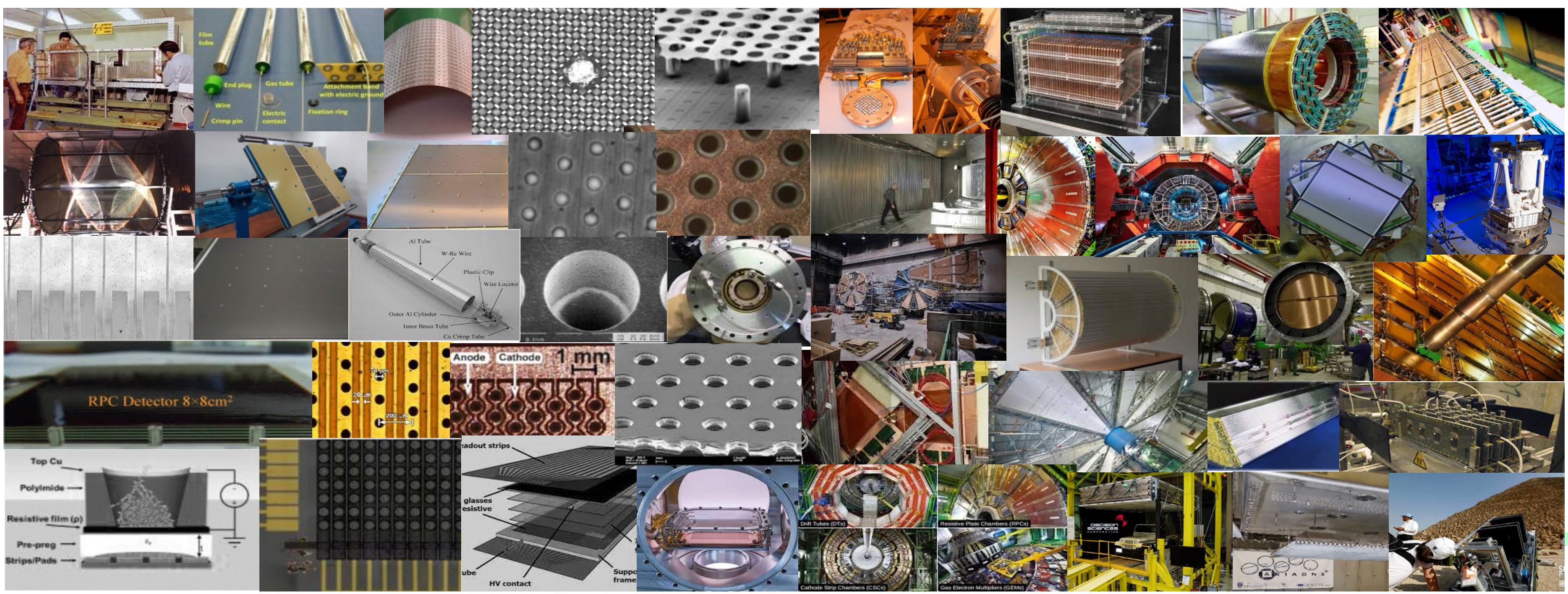
DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability

DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes

DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability

DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs

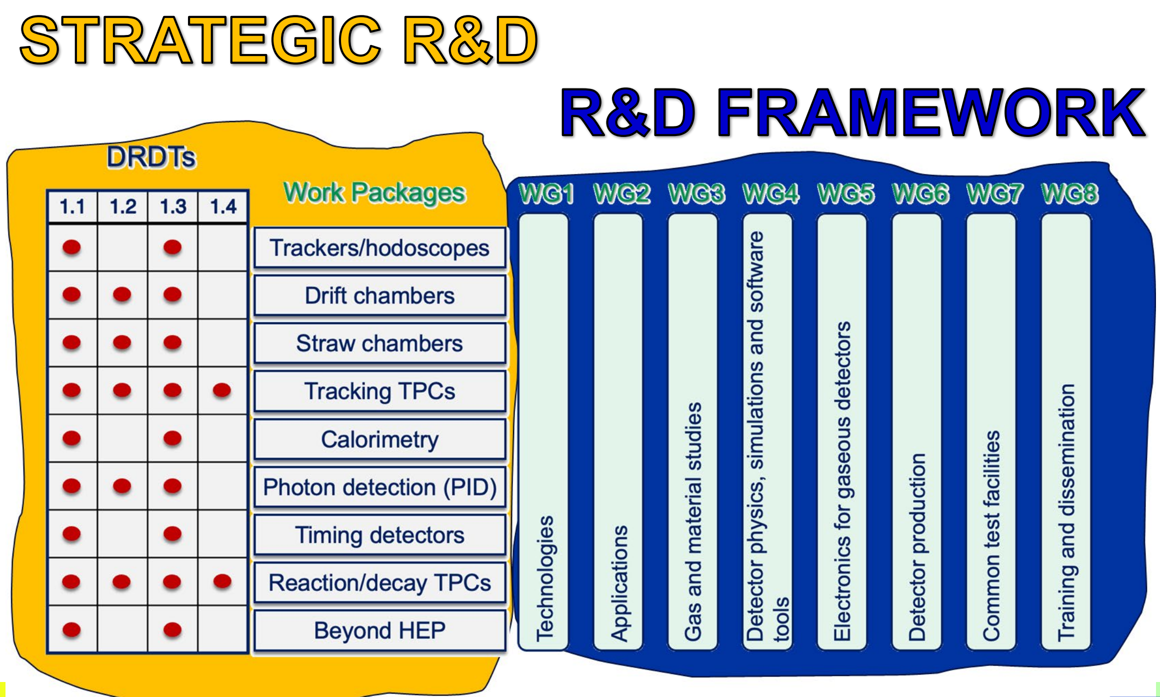
Builds on the experience of the very successful RD51 collaboration



DRD1 – gaseous detectors

- Working Groups: serve as the backbone of R&D: provide a platform for sharing knowledge, expertise & efforts by supporting strategic detector R&D directions, facilitating the establishment of joint projects between institutes
- Work Packages: reflect the ECFA DRDTs: long-term projects addressing strategic R&D goals, outlined in the ECFA Detector R&D roadmap with dedicated funding lines
- Common Projects: enhance synergies in "blue sky" and generic R&D between institutes: short-term blue-sky R&D or common tool development with limited time and resources, supported by the Collaboration

Strategic R&D and Long-Term Funding (FA) based on **Work Packages**

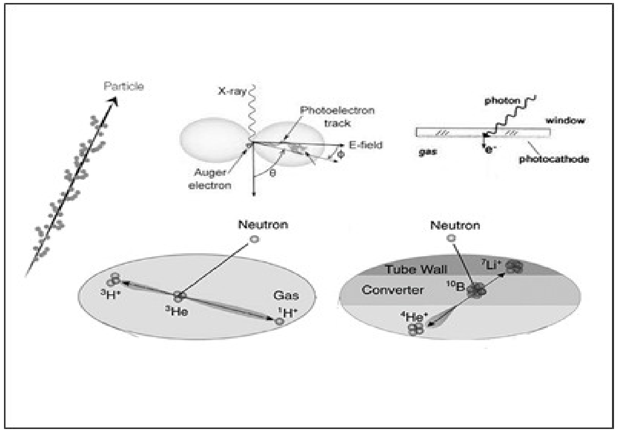


R&D framework based on **Working Groups** (RD51 legacy)

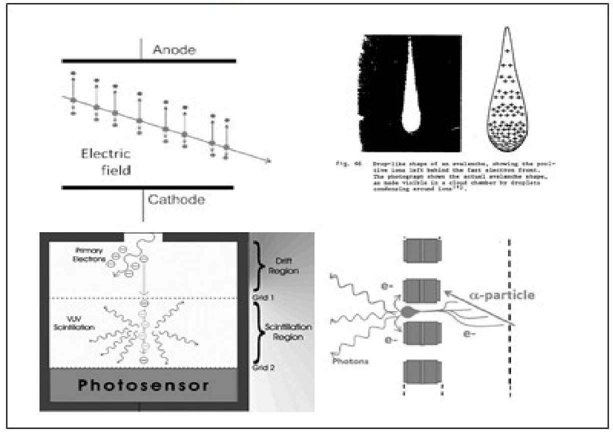
Maxim Titov, DRDC Nov 2024

Gaseous Detector R&D: Common Issues

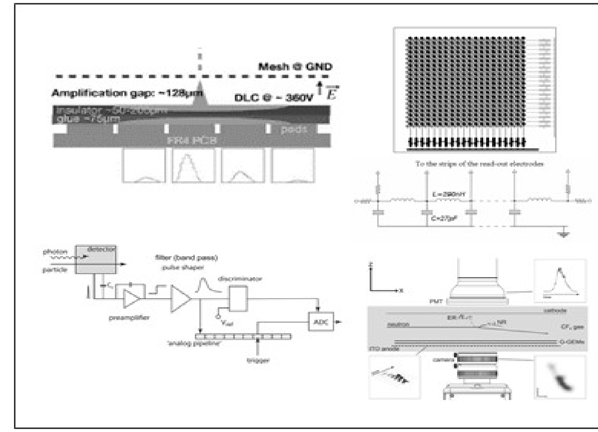
Ionization



charge drifting and amplification



readout



Despite the different R&D requirements, there is potential for overlapping in many aspects, allowing for a larger community of gaseous detectors to benefit. The most straightforward example are the ageing issues, but many others can be mentioned:

- MPGD- the main challenges remain large areas, high rates, precise timing capabilities, and stable discharge-free operation

- RPC - focus stays on improving high-rate and precise timing capabilities, uniform detector response, and mechanical compactness.

- Straw tubes- requirements include extended length and smaller diameter, low material budget, and operation in a highly challenging radiation environment.

- Large-volume Drift chamber with a reduced material budget in a high-rate environment requires searching for new materials. Avalanche-induced Ion Back Flow (IBF) remains the primary challenge for TPC applications in future facilities.

Maxim Titov, Corfu2024

DRD1 – gaseous detectors

Working group tasks

The collaborative structure of DRD1 keeps RD51 structure in Working Groups

Working-group conveners coordinate R&D tasks of the respective working groups. Two coordinators elected through a nomination process, approved by MB a

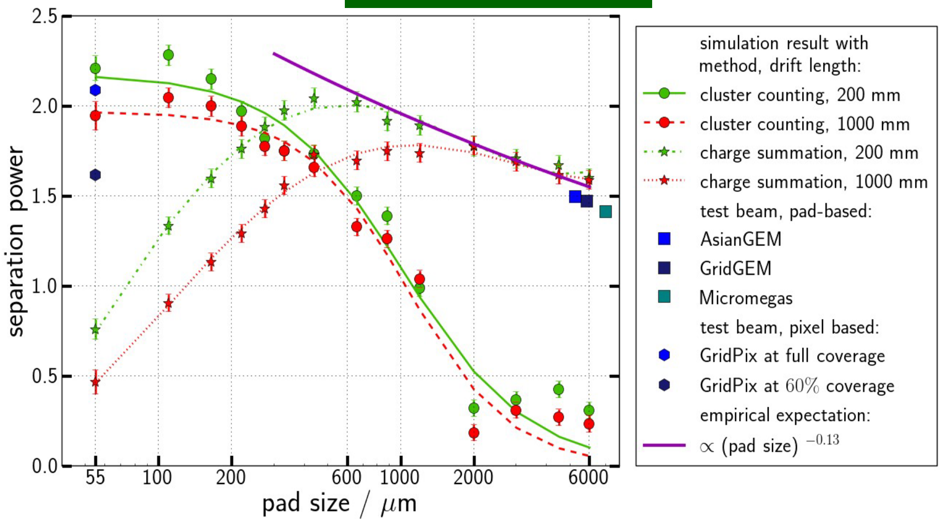
WG 1	WG 2	WG 3	WG 4	WG 5	WG 6	WG 7	WG 8
Technologies	Applications	Gas and material studies	Detector physics, simulations, and software tools	Electronics	Detector production	Common test facilities	Training and dissemination
Large Volume Detectors (Drift chambers, TPCs)	Trackers/Hodoscope	Measurement of Gas Properties	Garfield++	Front-End Electronics for Gaseous Detectors	Common Production Facilities and Equipments	Detector Laboratories Network	Knowledge Exchange and Facilitating Scientific Collaborations
MPGDs	Inner and Cenral Tracking with PID Capabilities: - Drift Chambers - Straw tubes - TPC	Studies on Eco-friendly Mixtures	Simulation of Large Charges and Space Charge	Modernised Readout Systems (DAQ): high performances	QA/QC	Test Beam Common Facilities	Training and Dissemination Initiatives
RPCs, MRPCs	Calorimetry	Ageing and Outgassing studies	Simulation of Detectors with Resistive Elements	Modernised Readout Systems (DAQ); FE Integration	Collaboration with Industrial Partner	Irradiation Common Facilities	Career Promotion
TPC	Photon Detector (PID)	Gas sytems	Modelling and Simualtion of Eco-friendly Mixtures	Modernised Readout Systems (DAQ): portability	Gaseous Detector FORUM (know-how)	Specialized laboratories (outgassing/ageing, gas analysers, photocathodes)	Outreach and Education
Straw tubes, TGC, CSC, drift chambers, and other wire detectors	Timing Detectors (PID & Trigger)	Materials studies: - novel material (nanomaterial) - new material for wire - new converter	Optimization of Simulations (time, hw/sw resources)	Instrumentation (e.g. HV,LV, monitoring)		Common instrumentation and sofware	
New amplifying structures	TPC as reaction and decay chambers	Photocathodes	Specific Proceses (e.g. Electroluminescence)				
	Beyond HEP - Medical Application - Neutron Science - Muography - Space Applicatios - Oher (Dosimetry, Beam Monitoring, Cultural Heritage, Homeland Security,..)	Precision Mechanics					

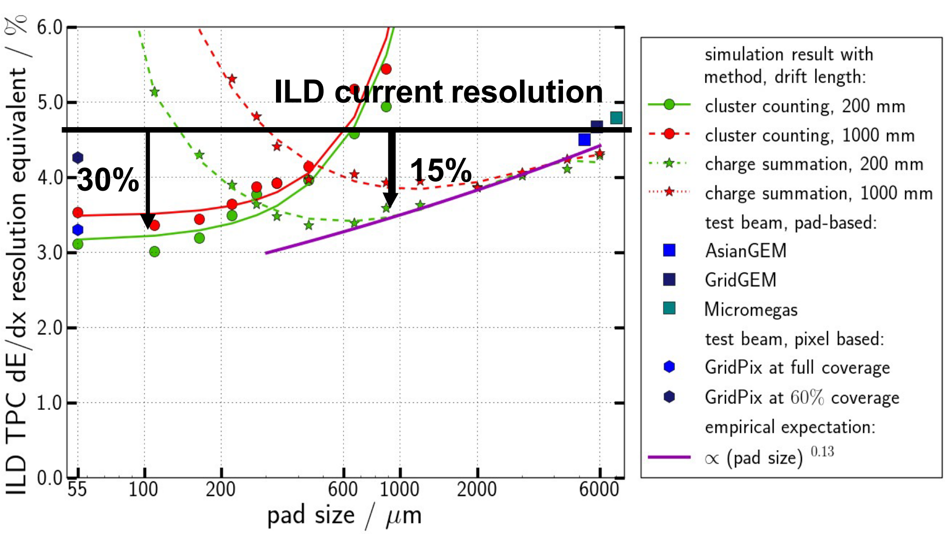
| Piotr Gasik | 1st meeting of the DRDC | DRD1 Proposal | CERN | 0

Cluster Counting / Charge Summation / Granularity

Simulation of PID with gaseous tracking and timing in ILD Prototype

arXiv: 2205.12160





Current full ILD reconstruction:

- ✓ 6 mm pads → 4.6 % dE/dx resolution
- ✓ 6 mm → 1 mm: 15% improved resolution via charge summing (dE/dx)
- ✓ 6 mm → 0.1 mm: 30% improved res. via cluster counting (dN/dx)

- ✓ Cluster Counting promises a few times better dE/dx resolution & separation power:
  - → in time (small drift cells): requires very fast electronics
  - → in space (TPC + pixelated endplates): requires good cluster finding algorithm

- ✓ Cluster Counting is an attractive option and is complementary to classical dE/dx by the spread charge

→ Some groups focus on it for CEPC, FCC-ee

Radiation Levels not Even Thought in '1980: from mC/cm → C/cm

'Low & Standard radiation levels' (LEP,HERA ep, BaBar/Belle,CDF/D0...)

- Basic rules for constructionare known and well tested
- Detectors are built and demonstrated to work
- Huge variety of gases are used
- If aging is nevertheless observed:
  - use oxygen-based (H20, alcohol) molecules to inhibit/relief/cure hydrocarbon polymerization (anode aging/Malter effect);
  - having identified the source of pollution, try to clean the gas system (e.g. operation with CF_4 decreases a risk of Si polymerization)

New classes of gas detectors – straws, MSGC, MPGD, CsI, RPC with their own specific aging effects evolved

MPGDs are much less sensitive to radiation- induced aging, compared to MWPC

'High radiation levels' – enormous R&D done (RD10, RD28, RD6, HERA-B, LHC, NP Exp…)

- Some basic rules are found
- There are clearly a lot of 'bad' and some 'usable' materials → careful choice of construction materials: radiation hardness and outgassing properties are of a primary importance
- Only a few gases are attractive candidates (noble gases, CF_4, CO_2, O_2, H_2O, alcohols) at high rates:
  - Hydrocarbons are not trustable for high rate exper.
  - Operational issues can be aggravated by CO_2 as a quencher and by the very high aggressiveness of CF_4 dissociative products (e.g. glass etching)
- Adequate assembly procedures, maximal cleanliness for all processes andquality checks for all system parts → personnel training, no greasy fingers, no polluted tools, no spontaneously chosen materials installed in the detector or gas system in the last moment, before the start of real operation
- Careful control for any anomalous activity in the detector: dark currents, variation of anode current, remnant activity in the chamber when beam goes away.

https://indico.cern.ch/event/1237829

DRD1: Common projects

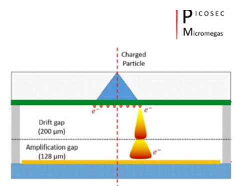
Common Project Example: Precise Timing with PICOSEC

- ✓ The PICOSEC concept overcomes timing limitations of gaseous detectors (goal is to achieve < 25 ps MIPs)
- ✓ Originally PICOSEC Micromegas initiated as the RD51 Common Project in 2015

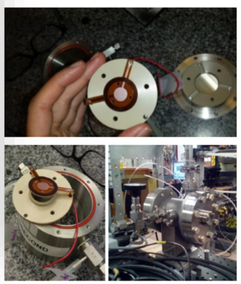
Precise timing with PICOSEC Micromegas

Primary charge production is localised in space and time by coupling Cherenkov radiator with photocathode and Micromegas amplification stage for precise timing.

Proof of concept started as **RD51 Common Project** in 2015 and initiated large collaborative effort addressing all aspects of detector optimisation and scaling: a... st photocathodes, readout electronics chain.

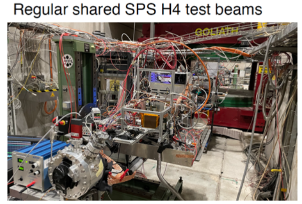


Picosec detection concept



Proof of concept with small prototypes

Regular shared SPS H4 test beams

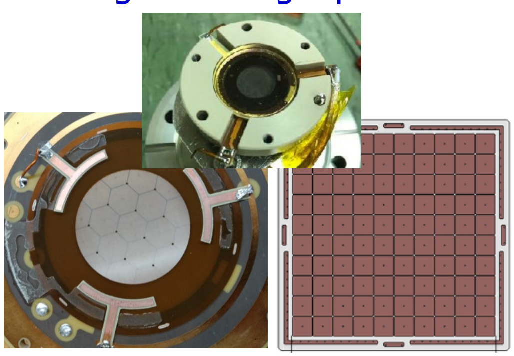


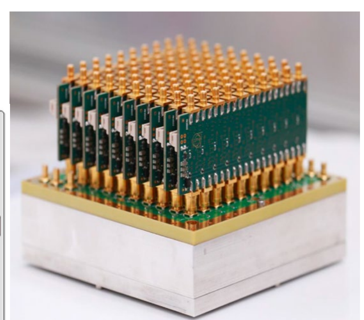
TODAY: Active collaboration with multiple developments ongoing <u>in >10 institutes</u> working on PICOSEC technology including lab tests and common test beam activities:

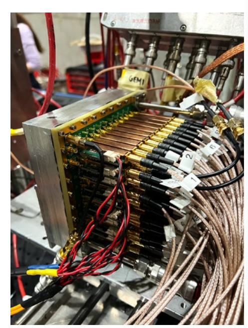
-Tileable 10x10 pad detector modules have been tested in MIP test beams and provide good timing resolution also for signals shared across pads.

-Robust photocathodes (B_4C, DLC), **resistive multi-pad** Micromegas, and scalable readout electronics are implemented in 100-channel detector modules.

Scaling from single-pad detectors to tileable multi-pad modules







Future developments

Spatial resolution: optimised pad size, charge sharing (resistive/capacitive)

Secondary emitters: minimise material budget, robustness against ion-back flow

Amplification structure: optimised double/single gaps, mesh geometries/technologies, μRWELL

Electronics: waveform digitisation vs. threshold based timing, FE ASICs

Maxim Titov, DRDC Nov 2024

DRD3 – semiconductor detectors

Detector R&D Themes (DRDTs)

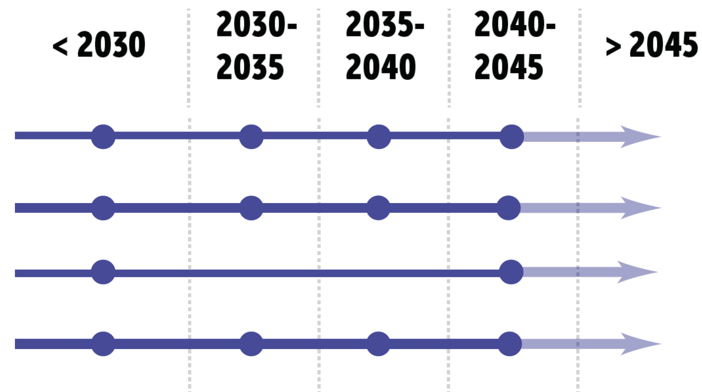
Solid state

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

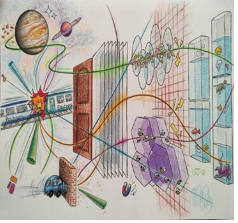
DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry

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

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

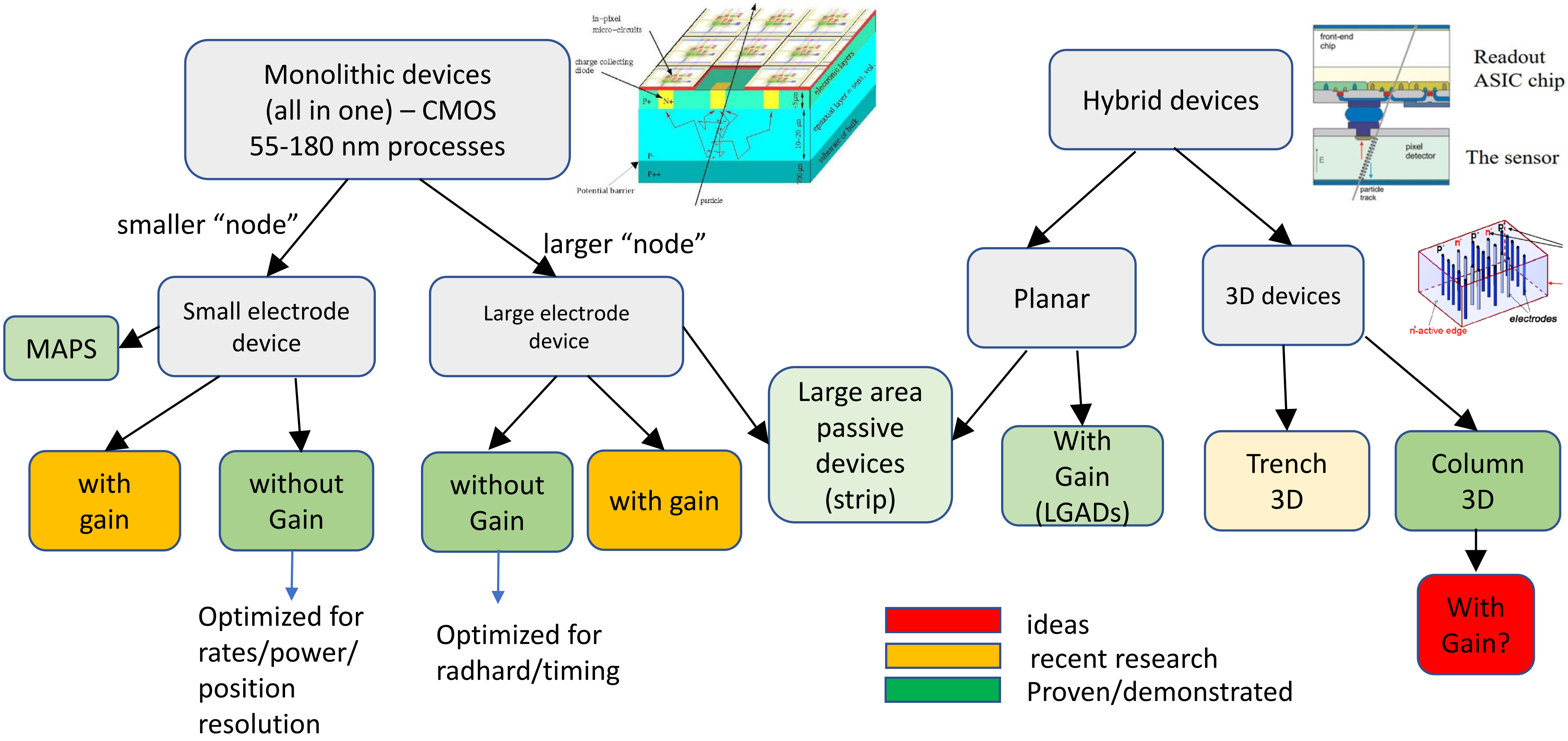


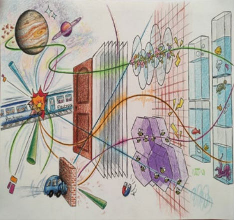
Builds on the experience of the very successful RD50 collaboration



Paths of present R&D

DRD 3

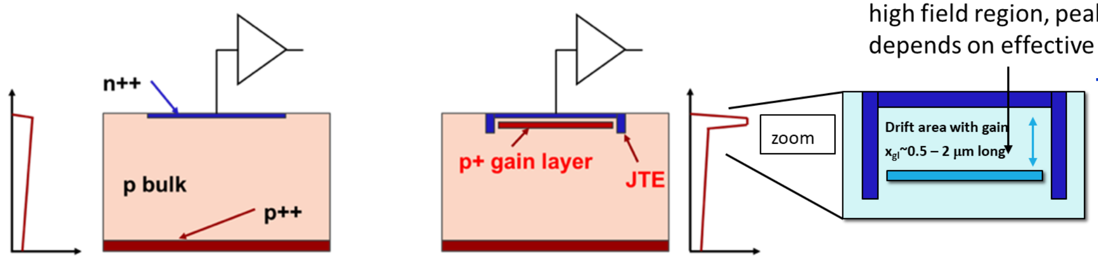




Hybrid silicon technologies towards 4D tracking - LGADs

DRD 3

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)



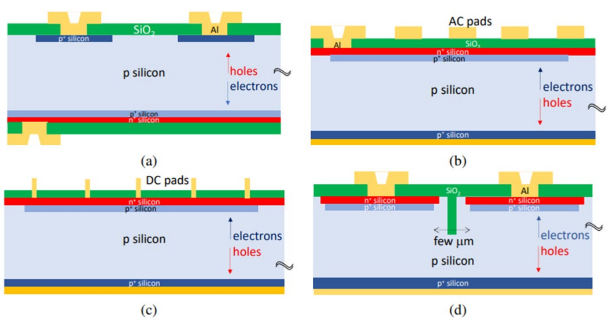
Typically 20-55 μm thick with signals of 20fC (G~40)

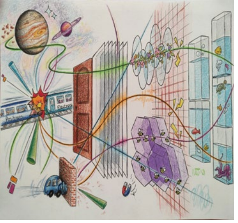
Limitations for conventional LGADs:

- Fill factor (large cell devices) due to JTE
- Radiation hardness – currently to ~3e15 cm^{-2}

Improvements in radiation hardness: co-implantation of carbon in the gain layer (reduction of acceptor removal), was successfully mastered by several vendors

Fill factor: several different technologies proposed where the gain layer is not segmented and hence no gap in efficiency for small pitch devices: (a) Inverse LGADs, (b) AC-LGADs (c.) RSD LGADs and (d) Trench isolated LGADs





Hybrid silicon technologies towards 4D tracking – 3D detectors

DRD 3

3D technology as timing detectors:

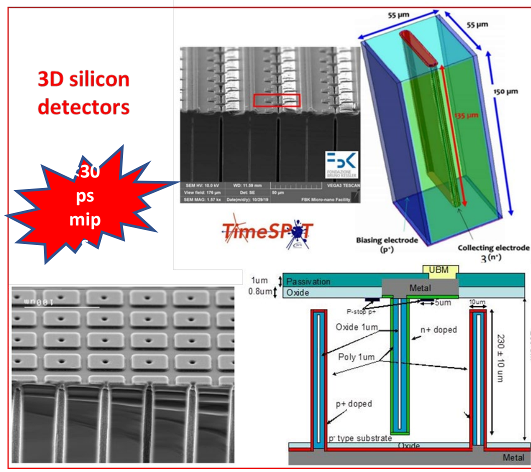
- They have fill factor ~100% (inclined tracks)
- They are fast (small distance) and can be thick (LF less important)
- The radiation tolerance of small cell size devices is large (for signal) and allows operation at higher bias voltages – shown up to ~1e17 cm^{-2}
- Technology is already mature – the latest 3D detectors are done in single-sided processing

Directions of research – 3D sensors with gain

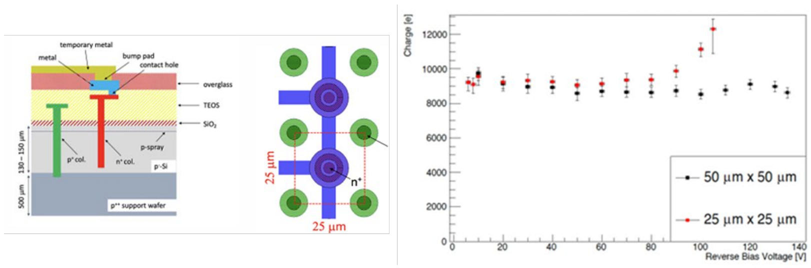
- reduction of cell size
- very small column width ("silicon wire proportional chamber")

Trench 3D
(INFN – FBK/IME)

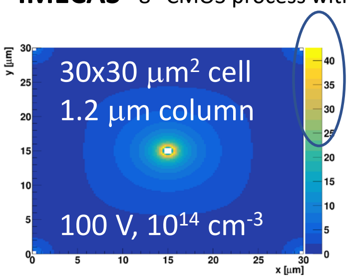
Column 3D
(CNM/FBK/Sintef/IME…)

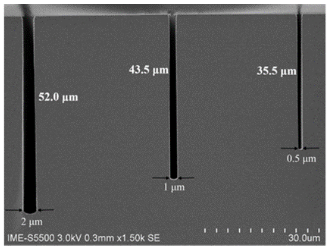


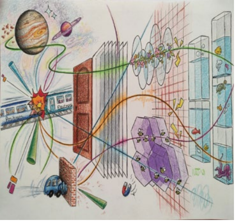
FBK production



IMECAS - 8" CMOS process with aspect ratio of **>70**





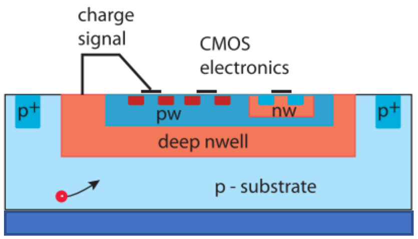


Monolithic technologies – CMOS MAPS

DRD 3

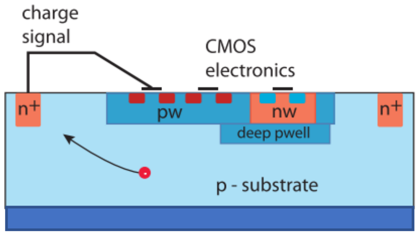
LARGE ELECTRODE DESIGN **SMALL ELECTRODE DESIGN**

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



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

Timing: large jitter and small distortion component - ~100 ps



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

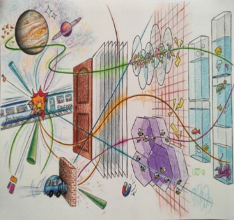
Timing: small jitter and large distortion/landau component ~ 1ns

taken from N. Wermes

The aim is to advance the performance of monolithic CMOS, combining sensing and readout elements, for future tracking applications, tackling the challenges of:

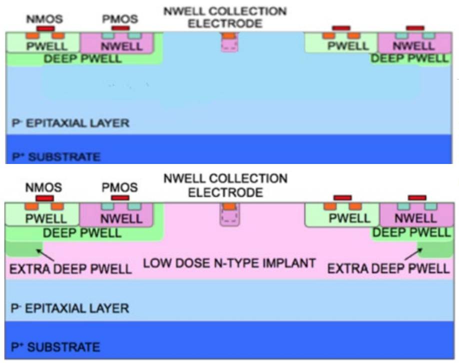
- very high spatial resolution;
- high data rate;
- high radiation tolerance;
- low mass;
- covering large areas;
- reducing power;
- keeping an affordable cost;

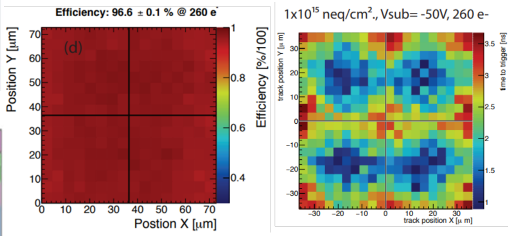
and ultimately combining these requirements in one single sensor device.



Monolithic technologies – CMOS MAPS

DRD 3

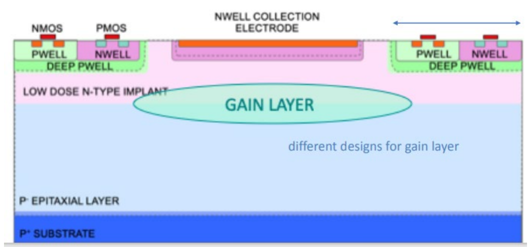




The main directions in MAPS research

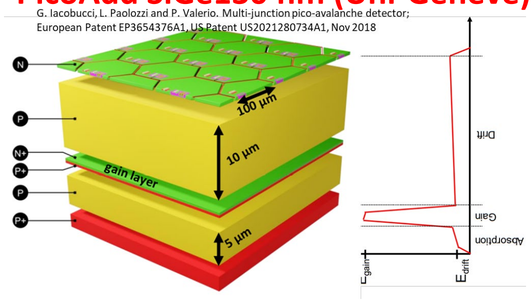
- **Development of modified processes – uniform efficiency over the cell (not needed for visible light – cameras) for small cell devices**
- Develop timing capabilities for large cell design ~50 ps
- **CMOS sensors with gain (faster, less power, better resolution)**

Cassia (CERN)



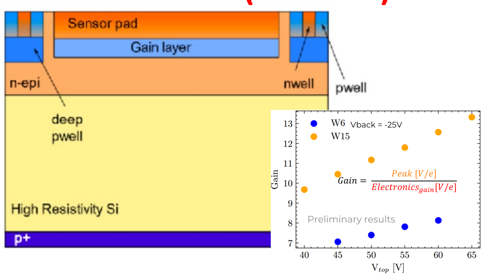
"deep junction" gain layer design in TJ180

PicoAdd SiGe130 nm (Uni-Geneve)

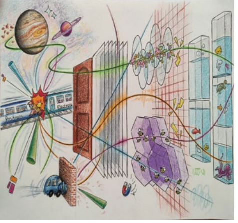


- SiGe bipolar amplifiers – fast (good timing)
- CMOS for digital electronics (monolithic)
- Gain-layer removed from the surface allowing very good spatial resolution without dead area

ARCADIA LF110 nm (INFN-TO)



- Back side processing
- High-field grows from the back side – high drift field at the back.
- First results Gain 7-13 – more soon!

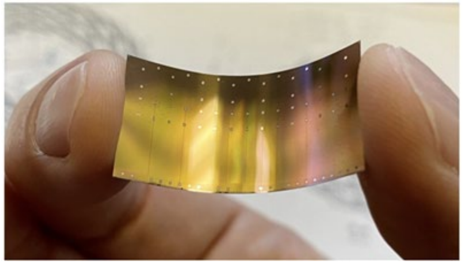


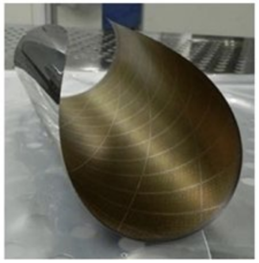
Monolithic technologies – CMOS MAPS

DRD 3

The main directions in MAPS research (cont.)

- Wafer area stitched sensors thinned down to few tens μm foldable vertex detector (65 nm TPSCo technology, for ITS-3)

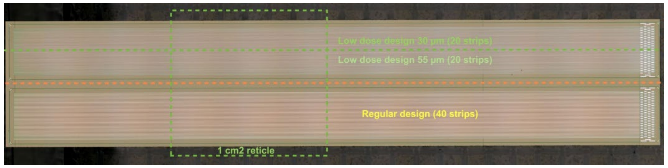




- Large area CMOS strip detectors

(Reduced material budget, easier integration, potentially low cost and availability)

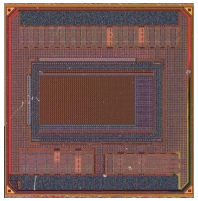
LFA150 nm - Resistivity of wafer: >2000 Ω·cm
ASIC can be implemented at the sides

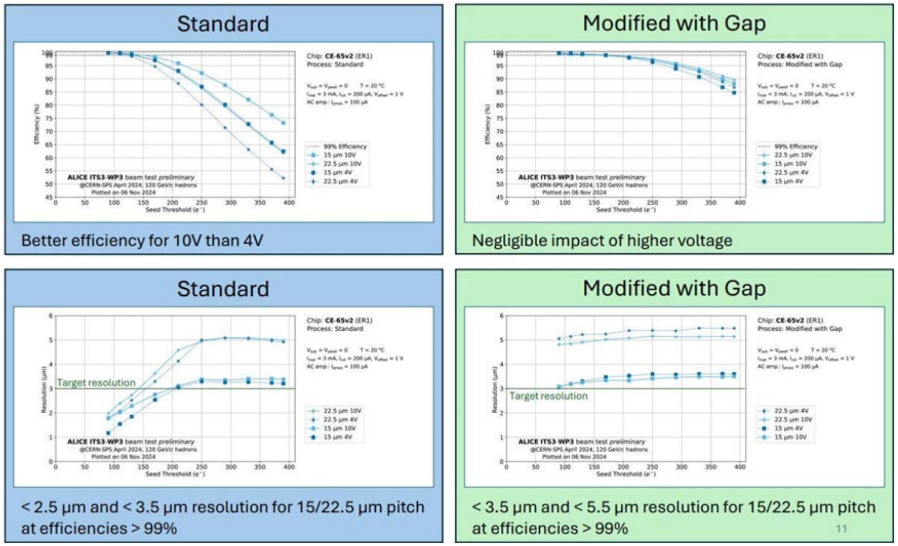


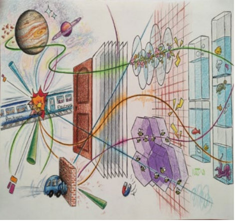
(Dortmund, Freiburg, DESY, Bonn)

- Fine pitch resolution sensors in TPSco 65 nm technology (ALICE groups)

15 μm pixel pitch, modified design electrode, ITS-3



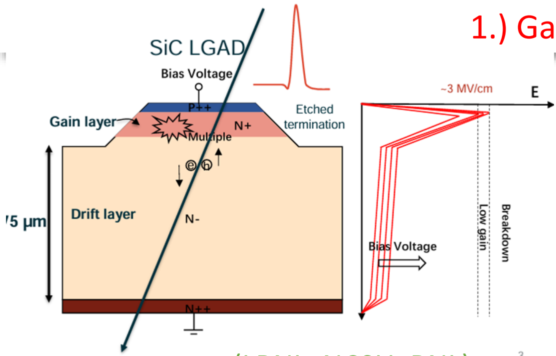




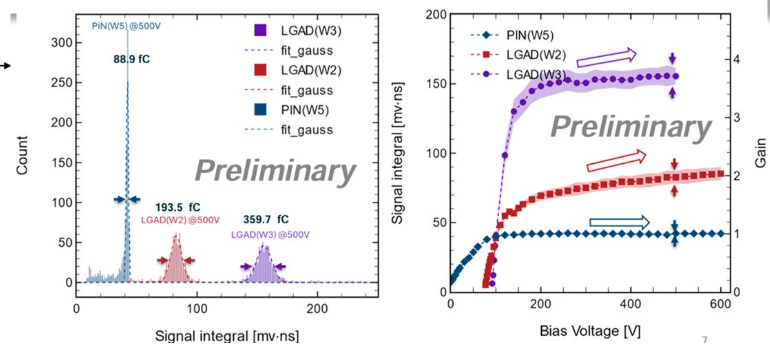
Silicon carbide developments

DRD 3

1.) Gain achieved with SiC-LGADs

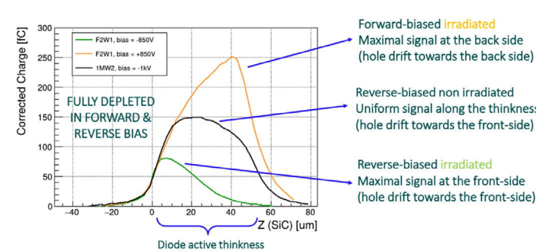


(LBNL, NCSU, BNL)

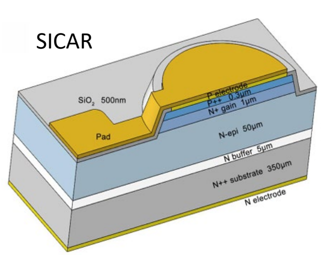


3.) Irradiated SiC detectors in forward bias – discovery of charge multiplication

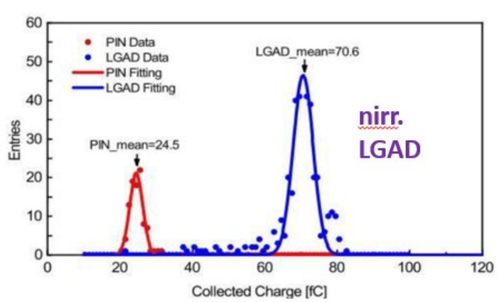
(IFCA)

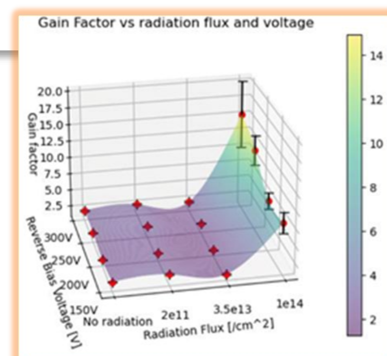


2.) Gain increases with irradiation!

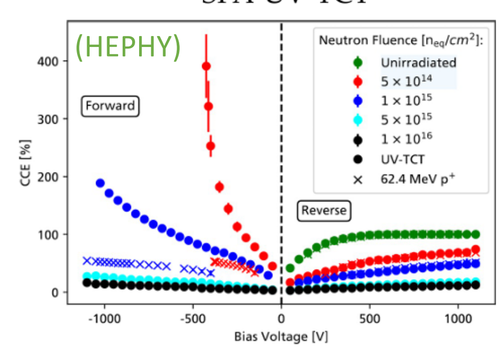


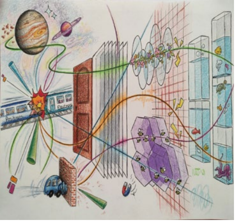
IHEP, Shanghai, Hefei





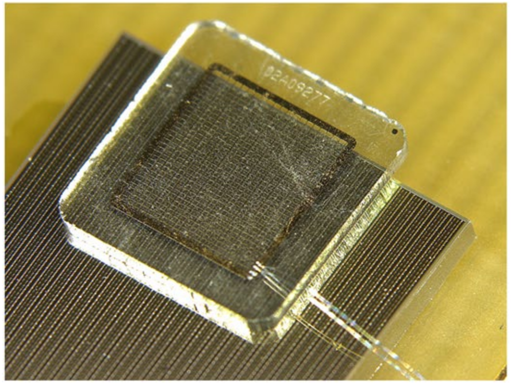
SPA-UV-TCT



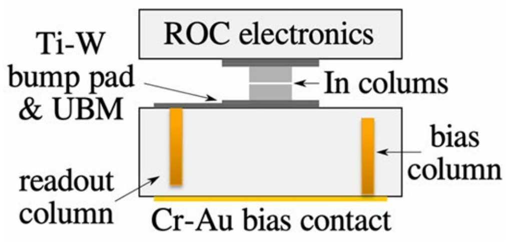


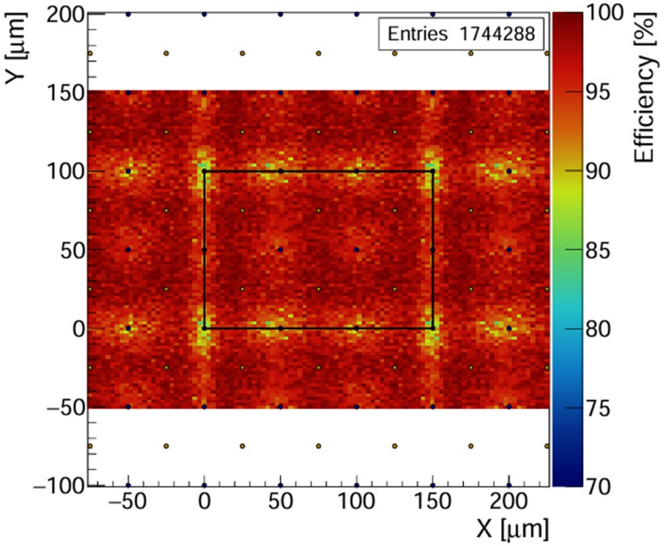
Diamond detector developments

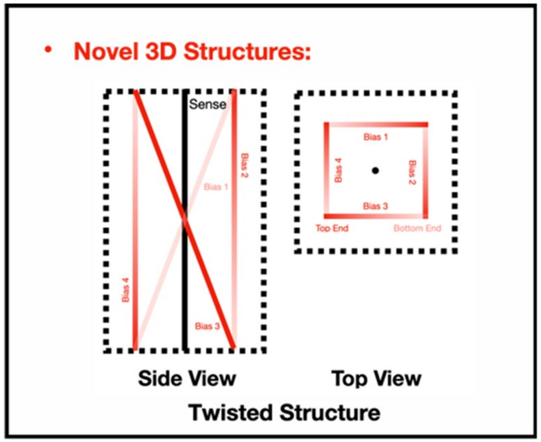
DRD 3

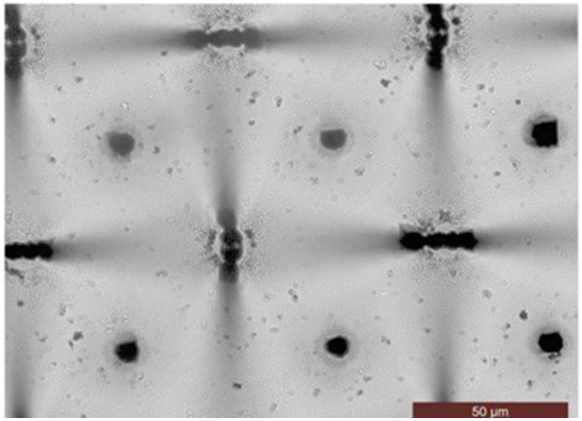


3D diamond detector connected to CMS pixel ASIC









3D electrodes made with laser (graphitization when focused light pulls through the diamond – slow)

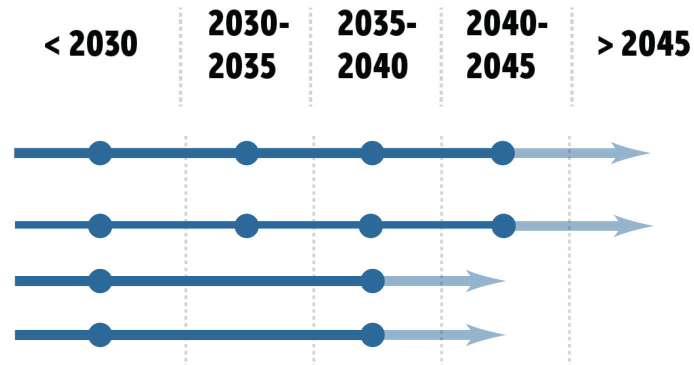
Twisted structure would improve timing performance and reduce the impact of the pCVD grains.

DRD4: photon detectors and PID

Detector R&D Themes (DRDTs)

PID and Photon

DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2	Develop photosensors for extreme environments
DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4	Develop compact high performance time-of-flight detectors

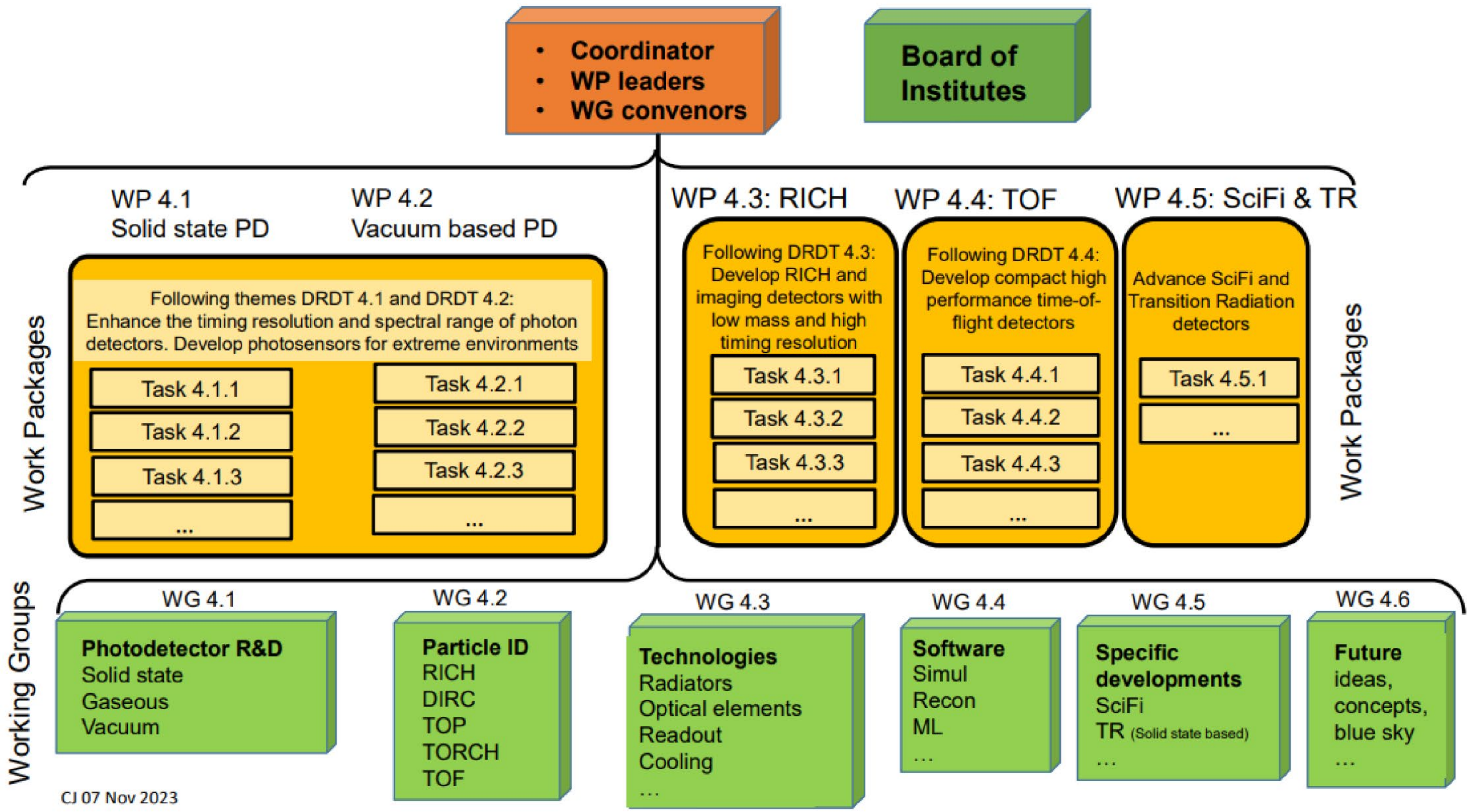


- Single-photon sensitive photodetectors (vacuum, solid state, hybrid)
- PID techniques (Cherenkov-based, Time of Flight)
- Scintillating Fiber (SciFi) tracking
- Transition Radiation (TR) using solid state X-ray detectors

DRD4 : photon detectors and PID

Organization:

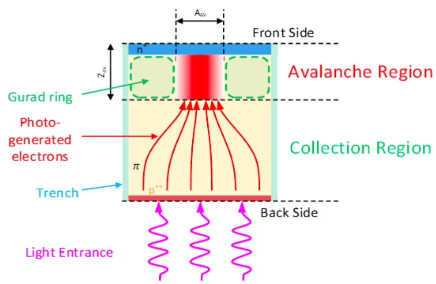
- Work packages: projects
- Working groups: discussion forums

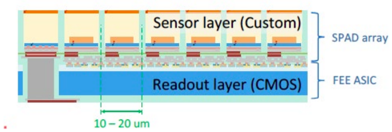


DRD4: Solid-State Photodetectors

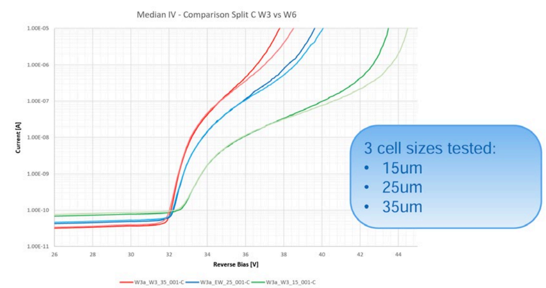
- Task 1 -SSPD with new configurations and modes: Development of back-side illuminated SiPM (potential for better PDE and radiation tolerance); development of ultra-granular SiPM that integrates with the electronics by using 2.5D or 3D interconnection techniques; development of CMOS-SPAD light monolithic sensors for HEP; study of new materials for light detection
- Task 2 -Fast radiation hard SiPMs: Standardize procedures for quantification of radiation effects; irradiated SiPMs characterization in wide temperatures range (down to -200 °C); study of annealing; study and quantify other measures enabling the use of SiPM in highly irradiated areas (e.g. smaller SiPMs, macro-and micro-light collectors)
- Task 3 -Timing of SSPD, including readout electronics: Study and improve the timing of SiPMs; co-design of a multi-ch. readout ASIC exploiting the timing potential; integration and packaging with integrated cooling; vertical integration of SiPM arrays to FEE (better timing via reduction of interconnections' parasitic induct+capac)

Backside illuminated (BSI) SiPMs: potential for an enhanced PDE and a better radiation tolerance.



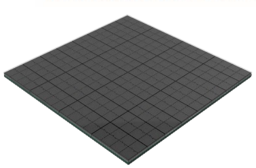


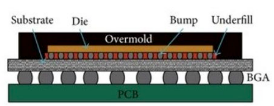
The first results of the FBK IBIS Run samples



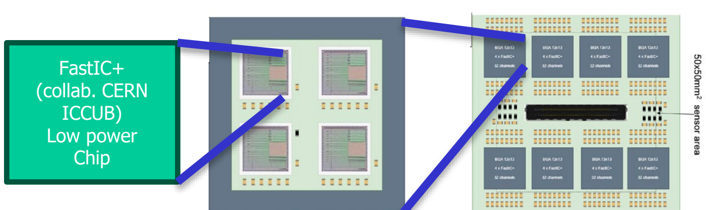
Timing of SSPD & Developing ultra-granular SiPM that integrates with the readout electronics

ICCUB Institute of Cosmos Sciences — Excelencia María de Maeztu





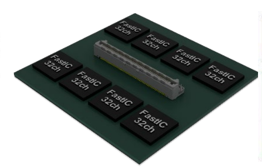
3x3mm2 SiPM Array

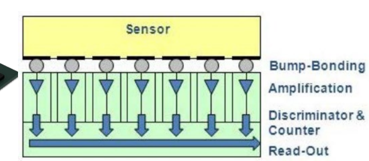


2024 Produced and evaluated

design & production 6.2025

256 Ch 5x5cm2 Module proposal





Ultra granular SiPMs

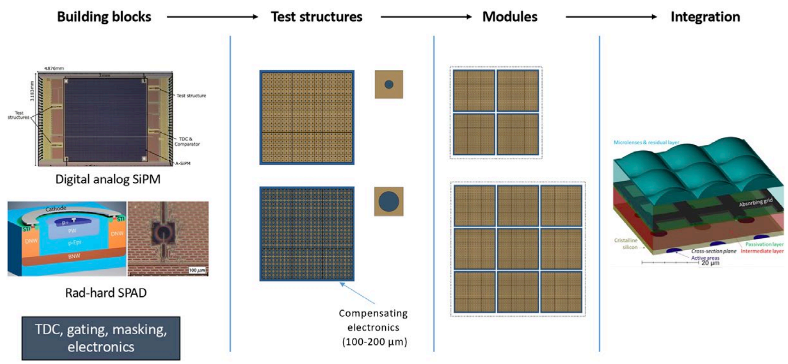
DRD4 -Solid State Photon Detectors

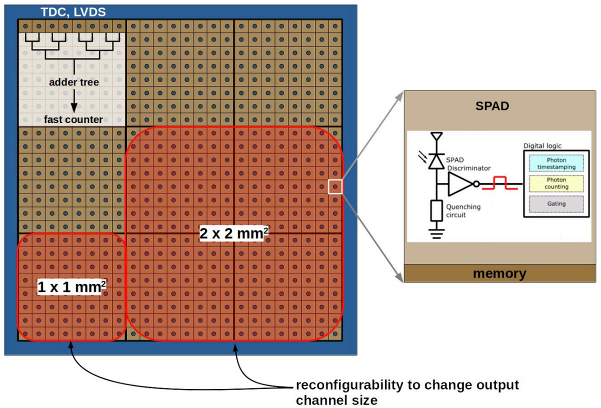
CMOS-SPAD light sensors: co-integration of SPADs and electronics, digitised output signals

spadRICH - Radiation-hard digital analog silicon photomultipliers for future upgrades of Ring Imaging Cherenkov detectors

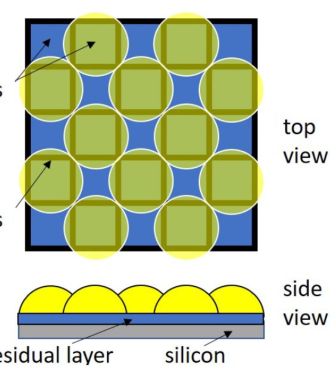
aqualab
EPFL

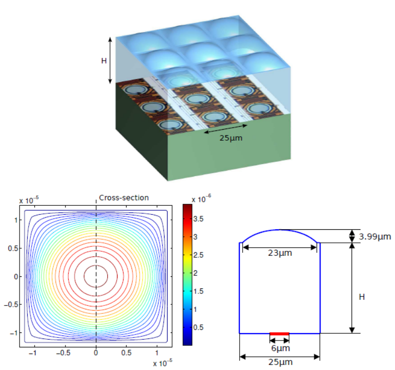
Institut "Jožef Stefan" Ljubljana, Slovenija



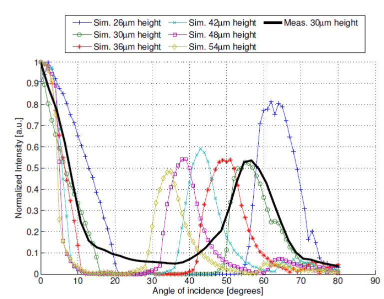


Increase the active area fraction – use microlenses or light collection

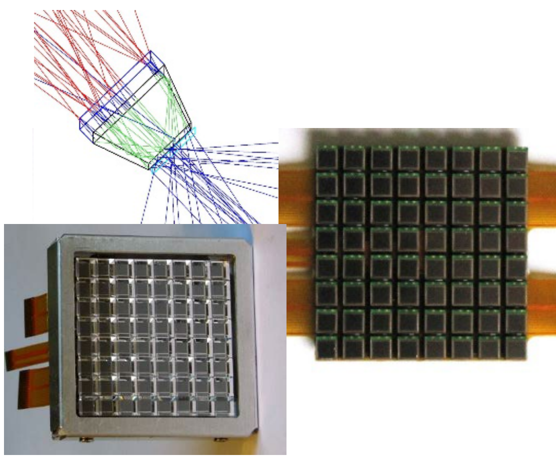




G. Haefeli et al., TNS, DOI 10.1109/TNS.2025.3542597



J.M. Pavia et al. Opt.Exp. 22-4(2014)4202



E. Tahirović et al., NIM A787 (2015) 203

DRD4: Solid State Photon Detectors

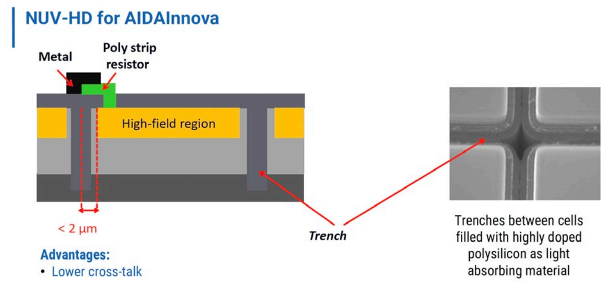
Fast & radiation hard SiPMs - enabling the use of SiPM in highly irradiated areas

Experimental structures, AidaInnova Run – exp. May 2025

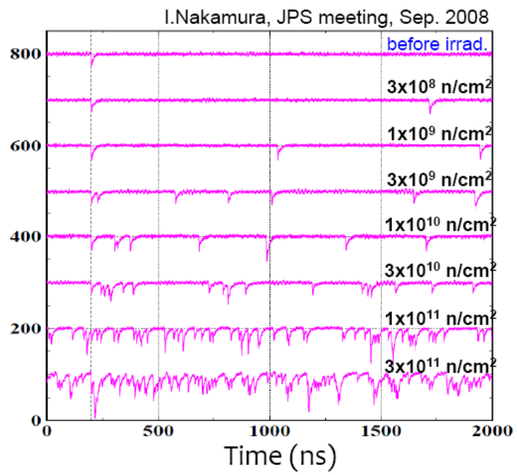
Two different technologies:

- Low electric field
- Ultra Low electric field

Cell pitch: 15, 25, 40, 75um; SiPM sizes: $(0.25, 0.5,1,2,3)^2$ mm^2

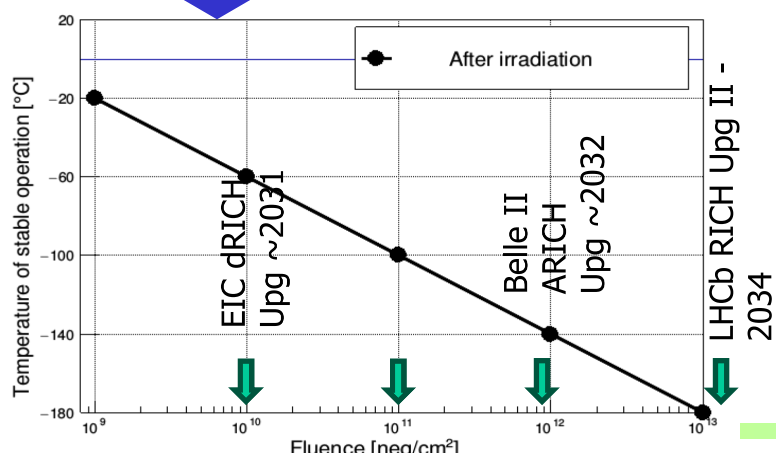


Operation of highly irradiated SiPMs for single photon detection – cooling and annealing



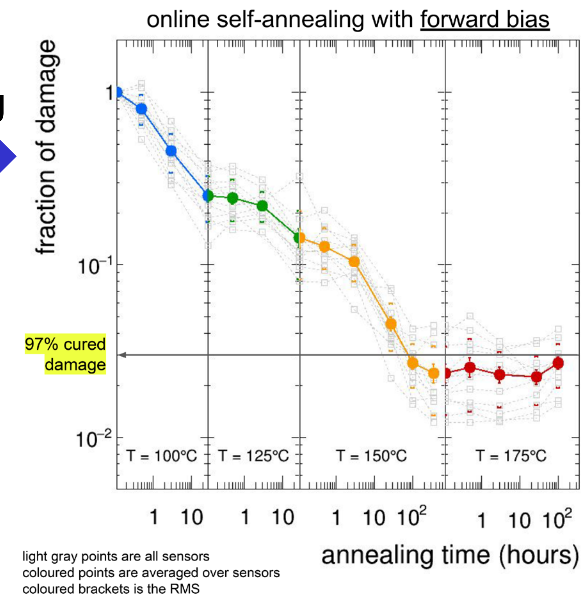
Waveforms from irradiated SiPMs

Cooling: Temperature at which the SiPMs are "usable", i.e. where the single photo electron peak @ 9V Over Voltage is separated from the background.



D. Consuegra-Rodrigez et al., Eur. Phys. J. C 84, 970 (2024)

Annealing



R. Preghenella, PD24

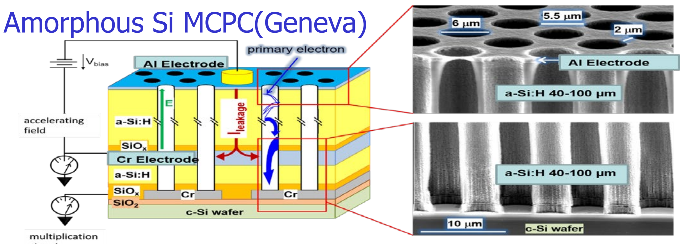
DRD4: Vacuum-based Photodetectors

■ Task 1 -New materials, coatings, longevity and rate capability studies: Develop new materials and techniques to increase MCP-PMT tube lifetime and improve rate capabilities; use new techniques with new materials to achieve high aspect ratio with small diameter for better gain, time, and spatial resolution
■ Task 2 -New photocathode materials, structure and high QE VPD: Search for new materials with the required characteristics to be used as photocathodes; develop photocathodes with new structures
■ Task 3 -VPD time and spatial resolution performance: Development of large area MCP-based photodetector with combined excellent timing and position resolution, including electronics integration

New material, new coatings, longevity and rate capability study

This concerns the R&D on new materials to produce VPD, new shapes and new coatings and their consequences on their longevity and rate capability

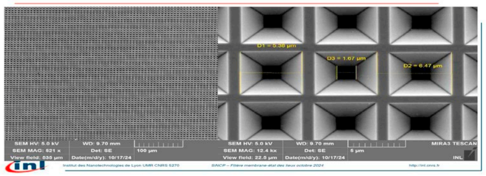
Amorphous Si MCPC(Geneva)



A. Franco *et al.* Sci. Rep. 1 (2014).

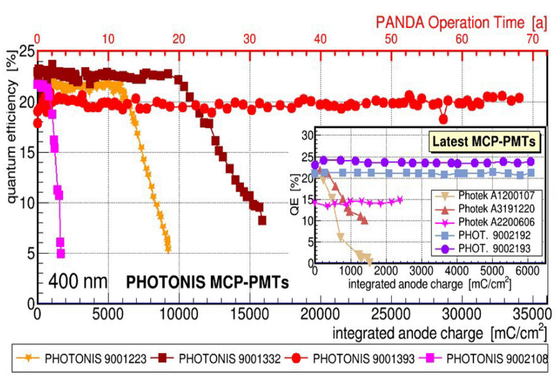
New photocathode materials, structure and high quantum efficiency

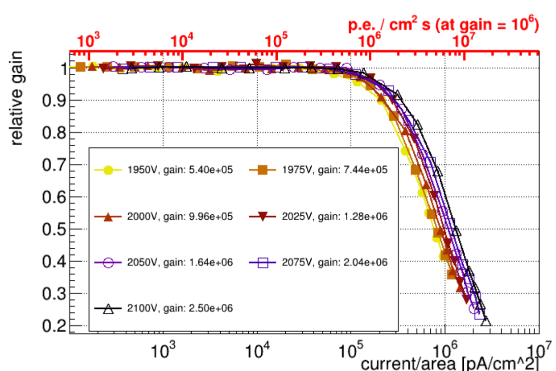
New photocathode materials, new structures and their impact on improving the quantum efficiency for different wavelengths



Si nanometric structure for reflective photocathode (Lyon)

Aging and high rate performance studies



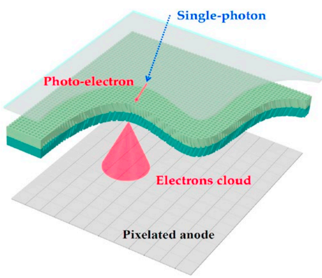


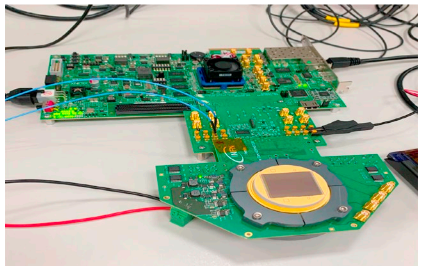
A. Lehman et al., https://arxiv.org/abs/2403.13938

DRD4 – Vacuum-based Photon Detectors

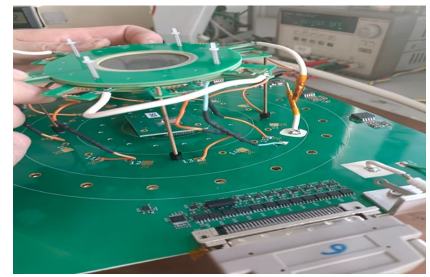
Time and spatial resolution performance

Study of timing and spatial performance using appropriate readout electronics and appropriate anode structure

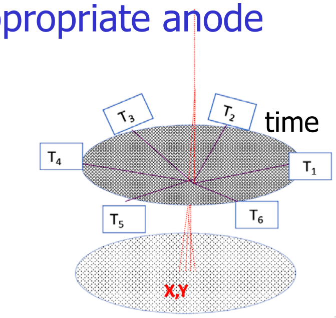




MCP+Timepix4 (Ferrara)



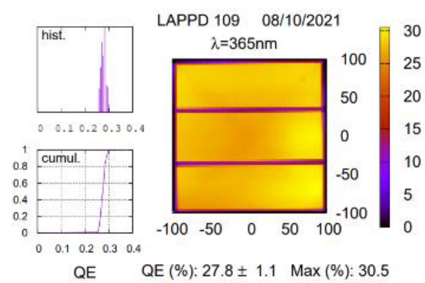
MCP+PICMIC concept (Lyon)



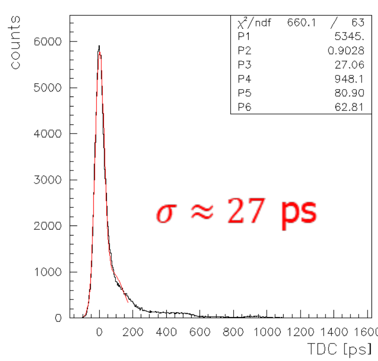
Woven strips

LAPPD (large area picosecond photodetector) Gen II by INCOM

- Fast MCP PMT based detector
- 230mm x 220mm active area
- Readout: capacitive coupling
- Nice agreement between modeling and measurements

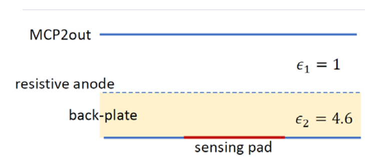


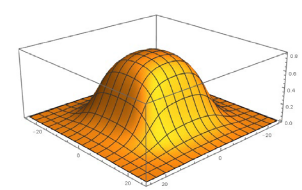
QE and timing

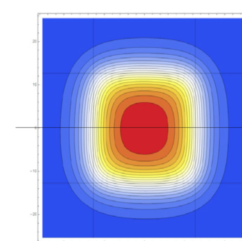


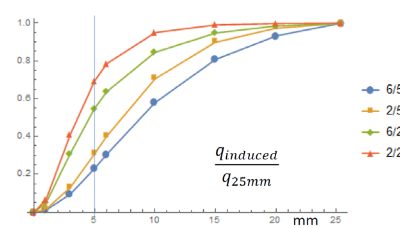
LAPPD charge sharing

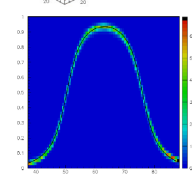
- calculation of charge sharing for different MCP2out-resistive andode/resistive anode-sensing electrode distances (6/5-measured, 2/5, 6/2, 2/2)
- fraction of the charge induced vs. square pad size when signal is produced in the centre of the pad

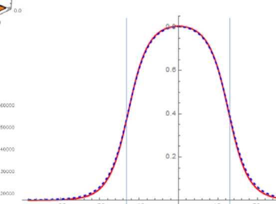












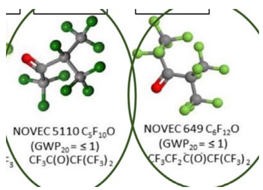
RAL

S. Korpar, DRD4 Coll.
Meeting April 2025

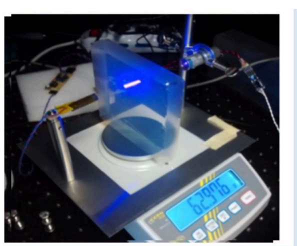
DRD4: RICH and other imaging detectors

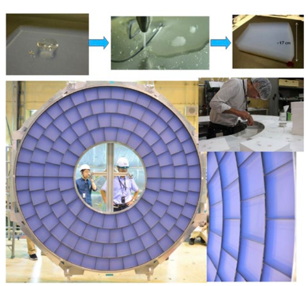
- Task 1 -New Materials Radiators and Components: Gas alternatives; optimized aerogel modules; precise interferometric measurement of refractive index
- Task 2 -Development of new RICH detector concepts for improved performance: High-pressure gas radiator; fast timing, combined RICH/TOF; cryo-RICH; modular RICH; technological demonstrators & proof of concepts
- Task 3 -Prototype Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems: Fully functional autonomous modules; scalable R/O electronics; integration to arrays with cooling; on-detector calibration/alignment/monitoring
- Task 4 -Study of RICH detectors for future e^+e^- colliders: Prototype a cell for the ARC concept
- Task 5 -Software and Performance: Fast simulation; reconstruction for high occupancy, high background

Study of gas alternatives to perfluorocarbons or eco-friendly fluorocarbon gas system

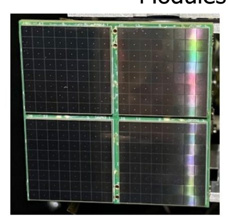


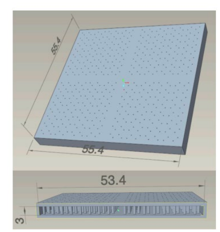
Optimized Aerogel Radiator Tiles

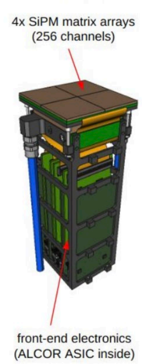


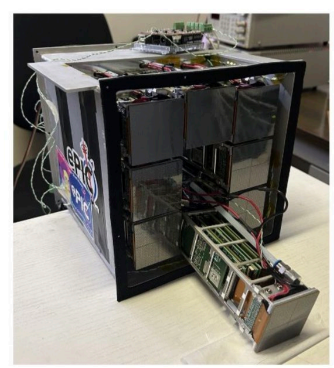


Prototype Single-Photon Sensitive Modules

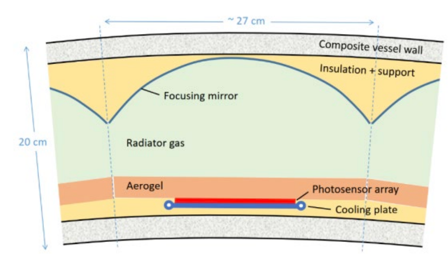


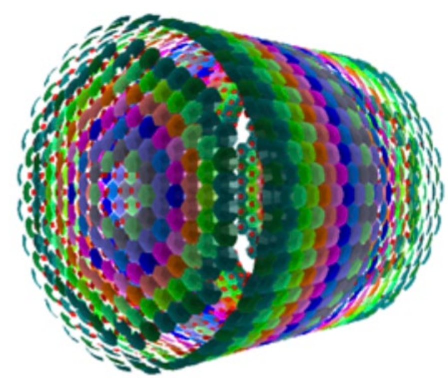






ARC detector concept for FCC-ee





DRD4– Time of Flight Detectors

■ Task 1 -Study the coupling of a thin Cherenkov radiator to a single-photon detector array, for TOF of charged particles: High precision timing (~10 ps) using high refractive index solid Cherenkov radiators coupled to SiPMs arrays or MCPs

■ Task 2 -Develop a SiPM array for single-photon detection, with mm-scale pixelation, suitable for use in TOF prototypes: Integration of SiPM arrays with multichannel R/O electronics to provide mm-scale position sensitivity and fast timing of Cherenkov light at the very high rates expected with HL-LHC and future colliders

■ Task 3 -Develop lightweight mechanical supports for DIRC-type TOF: Development of prototype support using lightweight materials with minimal distortion of quartz, detectors, electronics

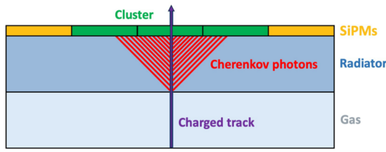
■ Task 4 -Develop techniques for measuring the optical properties of optical components for TOF detectors: Develop precision measurement characterization of quartz Cherenkov radiators; share existing facilities

Cherenkov-based timing measurements

Principle of operation

- Implementation of a Cherenkov radiator coupled to SiPM layer
- Benefit of single photoelectron statistics for precise MIP timing

Possibility of achieving time resolutions down to ≈ 20 ps with ≈ 100 % charged particle detection efficiency !!!



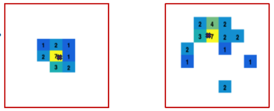
Radiator choice

- Use high refractive index material to minimize Cherenkov thresholds and to enhance photon yield and cluster size

1 mm SiO_2 (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 mm² SiPMs

MIP at 0° incidence

MIP at 50° incidence



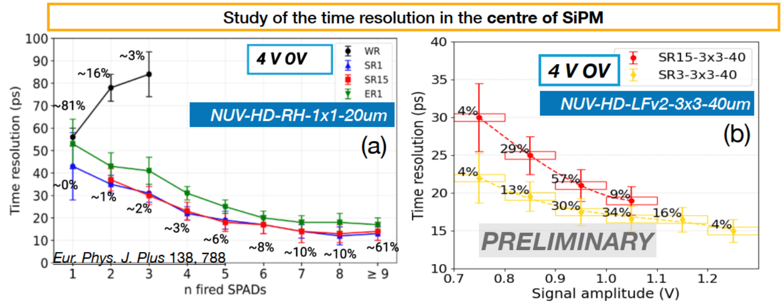
Material	Refractive index at 400 nm	$\beta_{thr.}$	$p_{thr.,\pi^\pm}$ [MeV/c]	Max θ_c [degree]	$N^*_{p.e.}$ at saturat. [mm⁻¹]
NaF	1.33	0.75	159	41.3	13
MgF_2	1.40	0.71	142	44.3	14
SiO_2	1.47	0.68	129	47.9	16
Silicone resin	1.50	0.66	124	48.2	16
Epoxy resin	1.55	0.64	117	49.8	17
High-n Corning	1.84	0.54	90	57.1	21

*Assuming PDE of S13360-3050CS SiPMs at V_{ov}= 3V
* Neglecting material absorption in the calculation

Nicola Nicassio – University and INFN Bari, Italy 4

INFN Bari

Time resolution wrt n SPADs



- SiPMs with protection layers: larger n fired SPADs -> better time resolution
  SiPM without protection layer: larger n fired SPADs -> worse time resolution (events are mainly due to intrinsic CT)
- In (a) -> n SPADs directly discriminated
- In (b) -> n SPADs not directly discriminated [~0.7-1.2 V corresponds to ~10-20 SPADs].
- Sensors in (b) under study for possible inhomogeineities in the samples

Time resolution trend improving as number of SPADs increase: → 20 ps for more than a few SPADs firing where the majority of events lie.

TOF sensors R&D: SiPMs | B. Sabiu | DRD4

INFN Bologna

DRD6: calorimeters

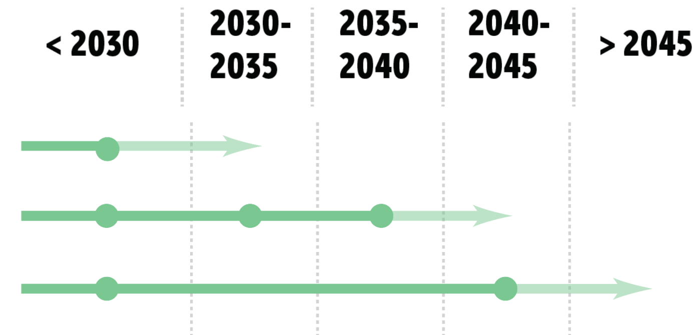
Detector R&D Themes (DRDTs)

Calorimetry

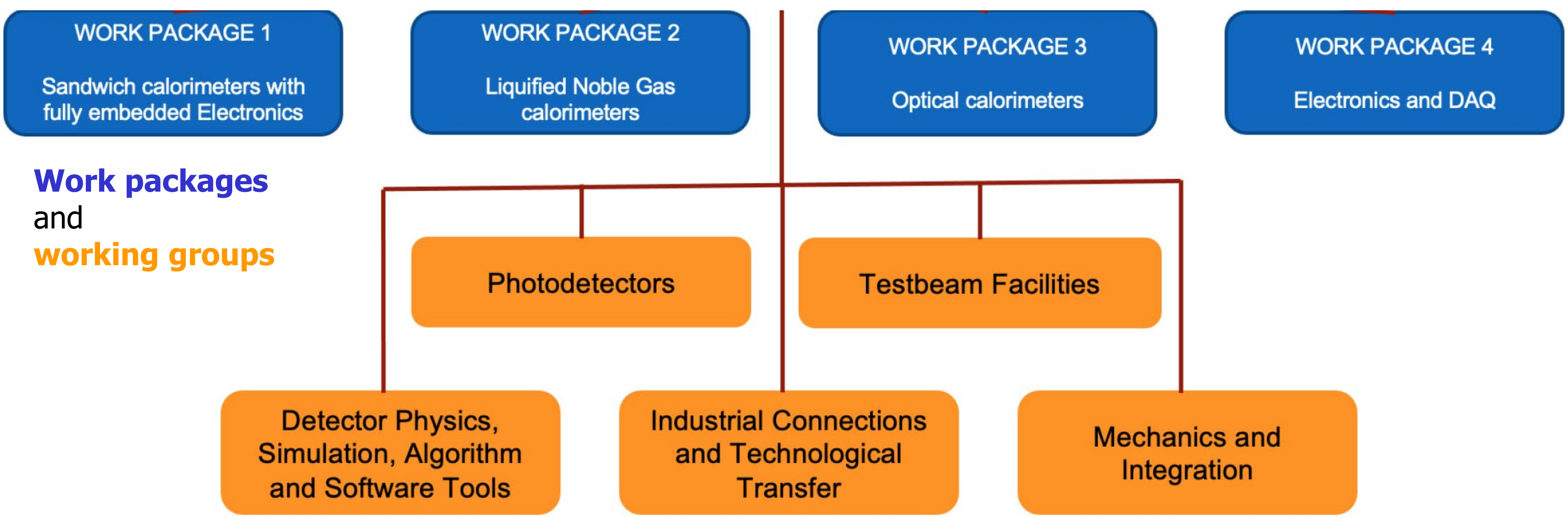
DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution

DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods

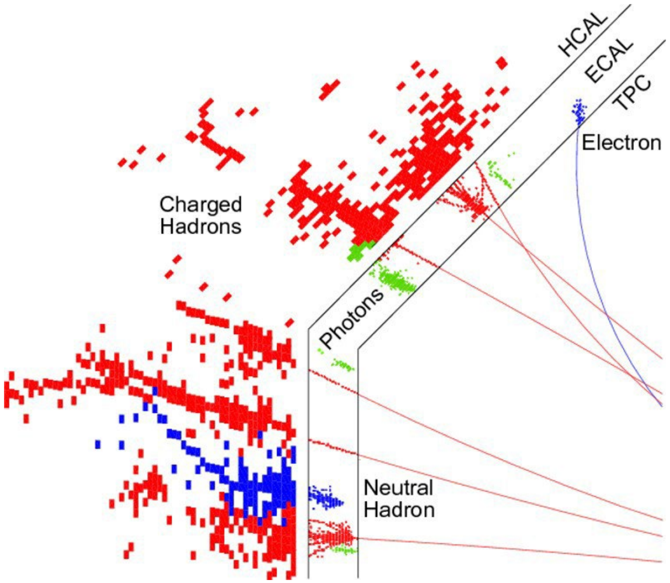
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments

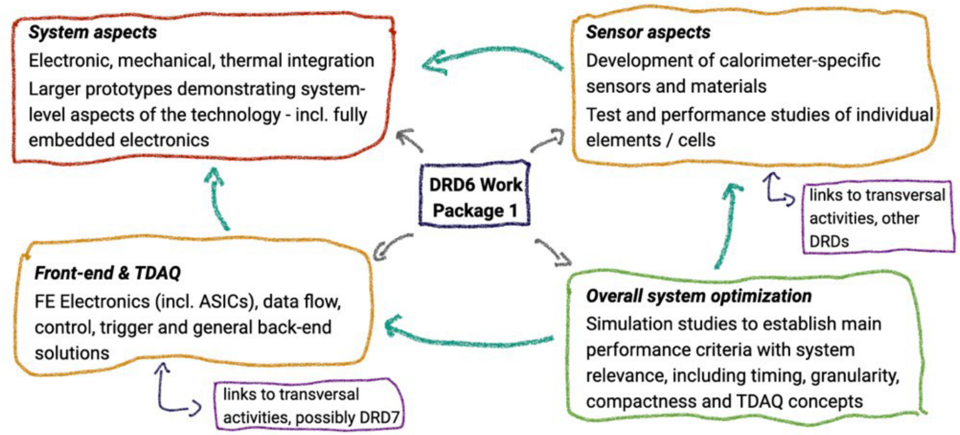


Work packages
and
working groups



DRD6: sandwich calorimeters with embedded electronics





- Challenges:
  - High pixelisation, 4π hermetic -> little room for services
    - Detector integration plays a crucial role
- New strategic R&D issues
  - Detector module integration
  - Timing
  - High rate e+e- collider (such as FCC-ee)

- Imaging calorimeters live on the high separation power for Particle Flow
- One calorimeter - Subdivided into electromagnetic and hadronic sections

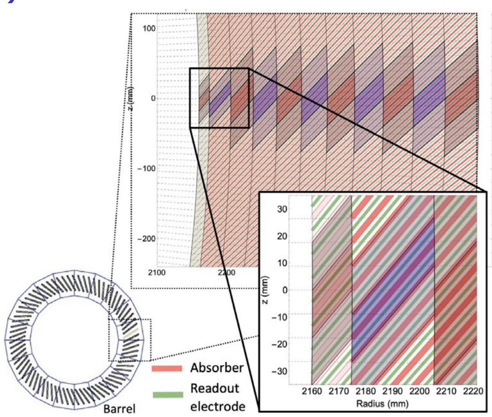
R. Pöschl, DRDC Nov 2024

DRD6: liquefied noble gas calorimeters

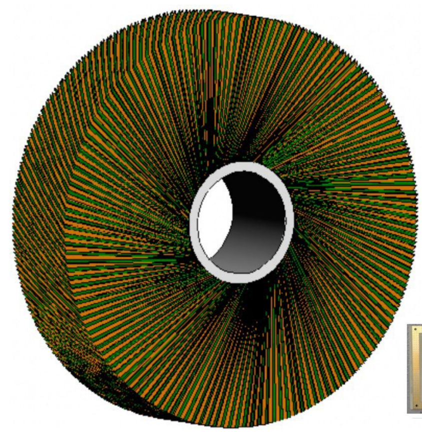
- Focused on R&D on noble-liquid calorimetry
- The main target in the foreseeable future: sampling EM calorimeter for e^+e^- factories – one of the key features of the “ALLEGRO" detector concept for FCC-ee (https://allegro.web.cern.ch/)

  •highly granular calorimeter with absorber planes inclined in r-phi (barrel) / arranged in turbine-like structure (endcap)

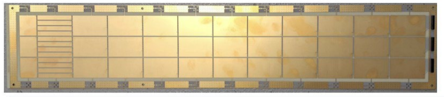
  •readout by segmented PCB planes alternated to Pb (or W) absorbers, gaps in between filled with LAr (or LKr)



barrel



endcap

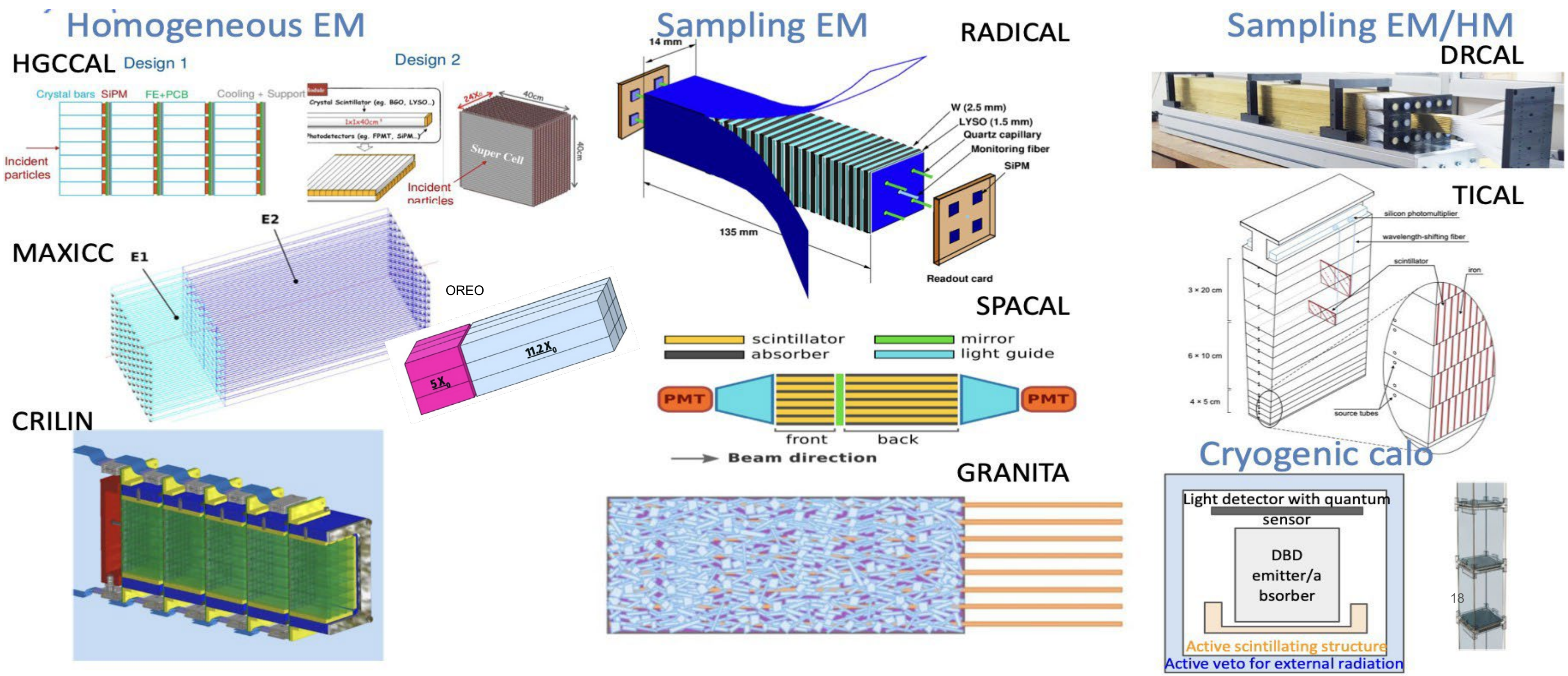


PCB (readout)

R. Pöschl, DRDC Nov 2024

DRD6: optical calorimeters

Involvement from ~70 institutes working on 11 different projects
The goal: explore, optimize, and demonstrate with full shower-containment prototypes, new concepts of sampling and homogeneous calorimeters based on scintillating materials



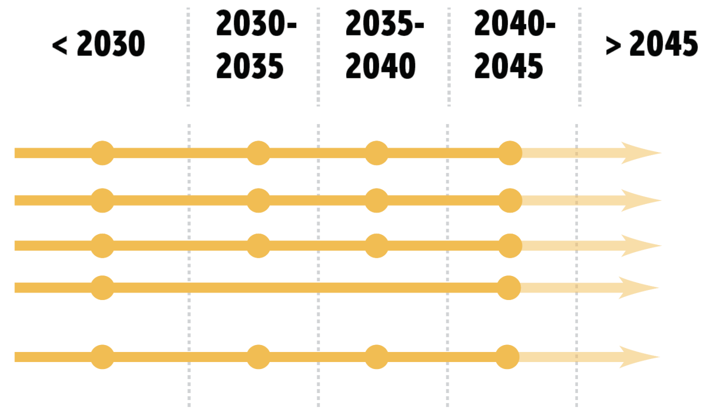
R. Pöschl, DRDC Nov 2024

DRD7: electronics

Detector R&D Themes (DRDTs)

Electronics

DRDT 7.1	Advance technologies to deal with greatly increased data density
DRDT 7.2	Develop technologies for increased intelligence on the detector
DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies



DRD7 – Electronics, projects

- 7.1 Data density and power efficiency
  - 7.1a Silicon photonics transceivers
  - 7.1b Powering next generation detector systems
  - 7.1c Wireless allowing data and power transmission
- 7.2 Intelligence on detector
  - 7.2b Radiation Tolerant RISC-V SoC
  - 7.2c Virtual Electronic System Prototyping
- 7.3 4D and 5D techniques
  - 7.3a High Performance ADCs and TDCs
  - 7.3b Characterizing and calibrating sources impacting time measurements
  - 7.3c Timing distribution techniques
- 7.4 Extreme environements
  - 7.4a: Modelling and development of cryogenics PDKs and IPs
  - 7.4b Radiation resistance of advanced CMOS nodes
  - 7.4c Cooling and cooling plates
- 7.5 Back-end systems and COTS
  - 7.5a: DAQOverflow
  - 7.5b: From front-end to back-end with 100 GbE
- 7.6 Complex imaging ASICs and technologies
  - 7.6a: Common access to selected imaging technologies
  - 7.6b: Shared access to 3D integration

Attilio Andreazza, report to the DRDC, Feb. 2025

DRD5: quantum sensing

Detector R&D Themes (DRDTs)

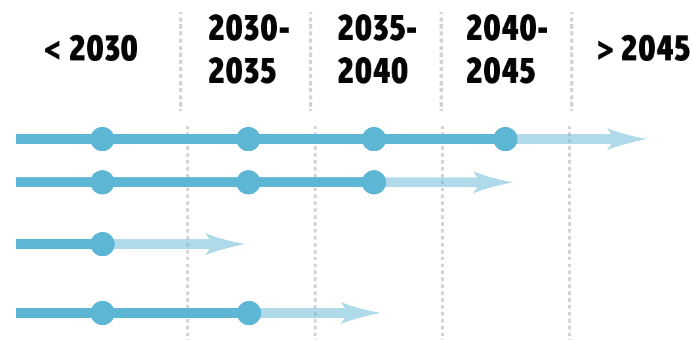
Quantum

DRDT 5.1 Promote the development of advanced quantum sensing technologies

DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics

DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies

DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure



WP1 — Exotic systems in traps & beams (HCI's, molecules, Rydberg systems, clocks, interferometery, …)

WP2 — Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)

WP3 — Quantum superconducting systems (4K electronics; MMC's,TES, SNSPD, KID's/…; integration challenges)

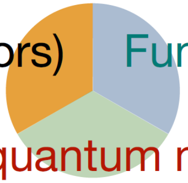
WP4 — Scaling up to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,…)

WP5 — Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

WP6 — Capability expansion (cross-disciplinary exchanges; infrastructures; education)

Michael Doser, report to the DRDC, Feb 2025

Potential HEP impact

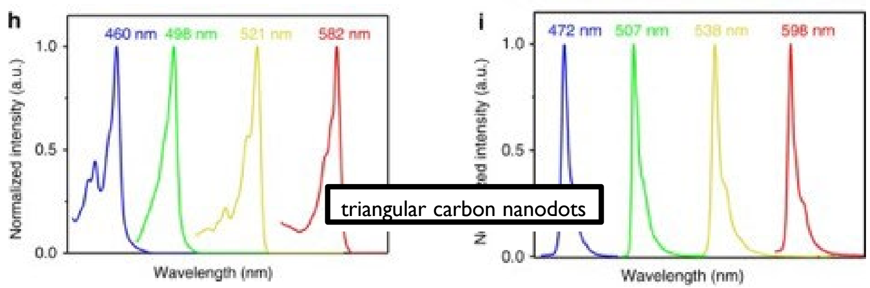


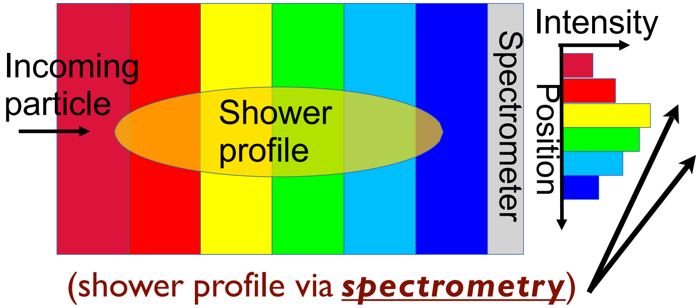
HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	"DotPix"; improved GEM's; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip's)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

(under way; in preparation; under discussion or imaginable applications; long-range potential)

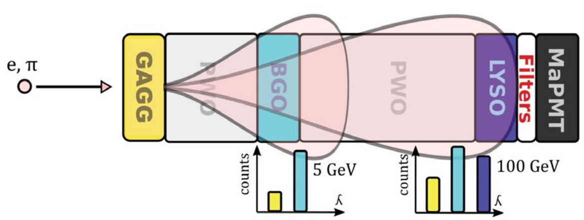
Michael Doser, report to the DRDC, Feb 2025

DRD6: an example of a potential particle physics impact:
WP-2 chromatic calorimetry



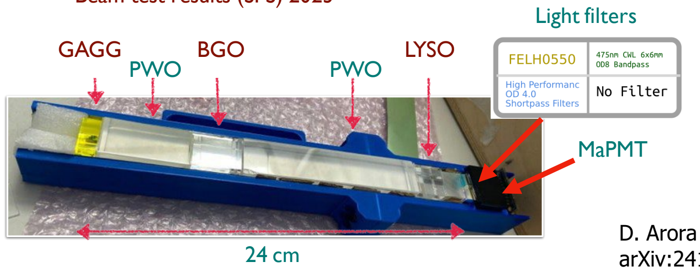


(shower profile via ***spectrometry***)

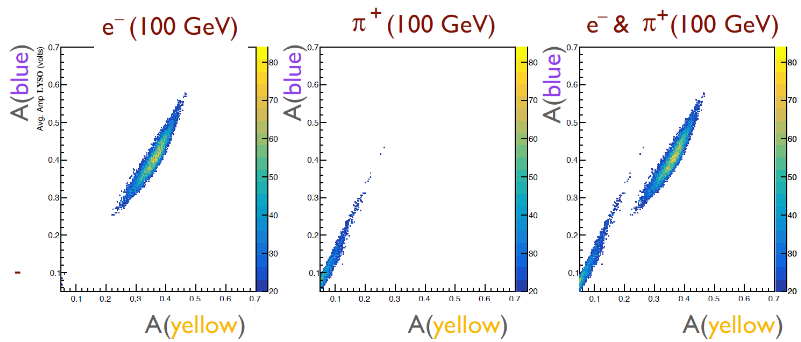


Proof of concept

Beam test results (SPS) 2023



"Chromatic" electron–pion discrimination



86% "chromatic" electron - pion discrimination

D. Arora et al, EPJ Web Conf. 320 (2025) 00029; arXiv:2411.03685 [physics.ins-det]

Michael Doser, report to the DRDC, Feb 2025

Blue-sky research

Innovative instrumentation research is one of the defining characteristics of the field of particle physics.

Blue-sky (more explorative, without addressing immediate detector specifications) R&D has often resulted in game-changing developments which could not have been anticipated even a decade in advance.

Examples include micro-pattern gas detectors, SiPMs and new technologies for very fast (10 ps) timing coupled with accurate spatial information - 4D-detectors.

Blue-sky developments have often been of broad application and had immense societal benefit (World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science).

From ‘The 2021 ECFA Detector Research and Development Roadmap‘

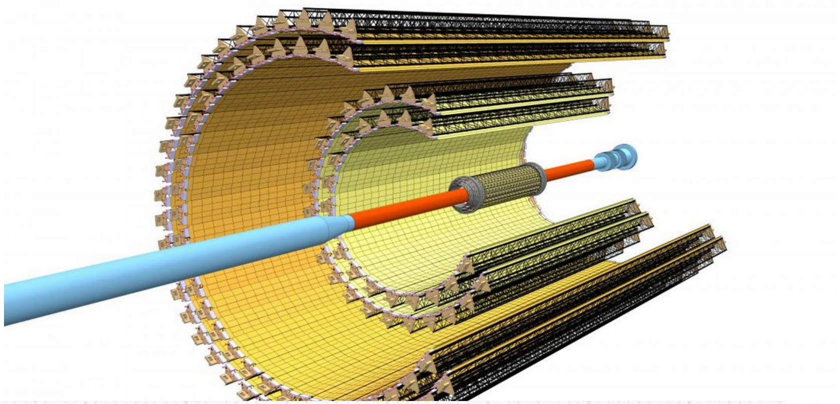
Blue-sky research, example: Wireless data acquisition

Physics events propagate from the collision point radially outwards – while the detectors are read our axially

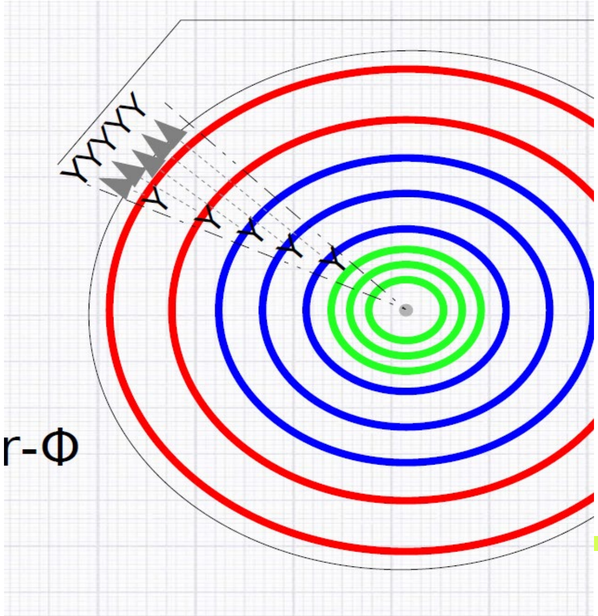
→ Not optimal for triggering

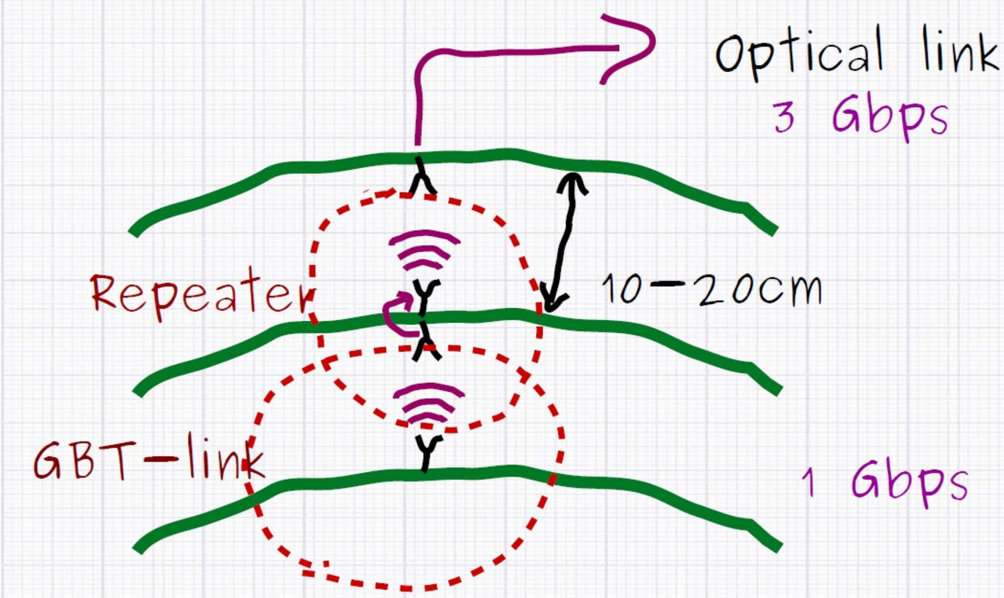
→ Not optimal for material distribution

(in particular at the barrel-endcap boundary)



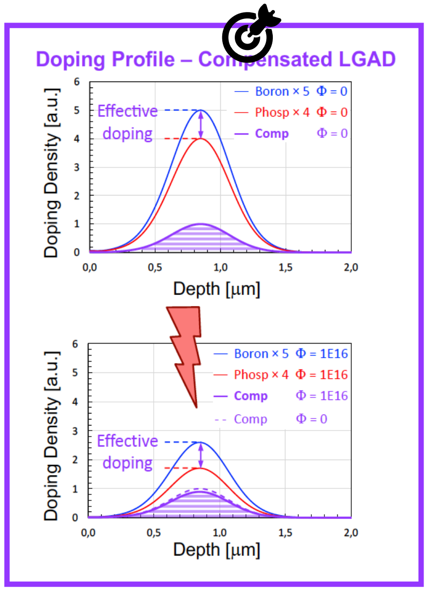
Idea: read out wirelessly





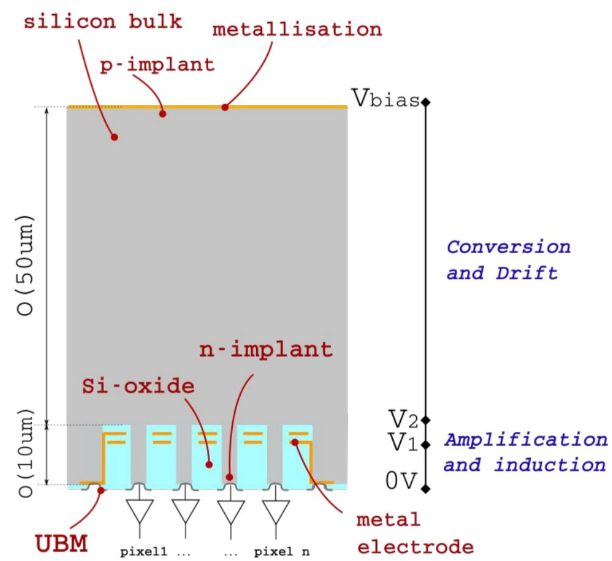
AIDAinnova Blue Sky projects

AIDAinnova is a large EU-funded detector R+D project hosted by CERN. Most of the effort is targeted research, but one of the work packages is devoted to blue-sky research.

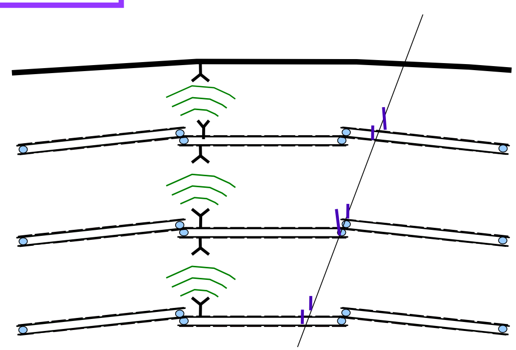


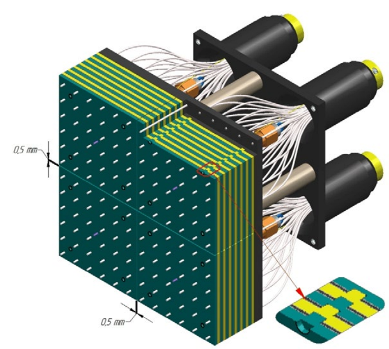
Radiation resistance of Si sensors through:

- Clever doping – compensated LGAD
- Amplification through electrodes in Si - SiEM



Wireless read-out





Shashlik calorimeter with nano-composites in polymer or glass matrix; decay times O(100 ps), radiation hard to O(1 MGy)

Summary

Detectors for particle physics experiments are our discovery tools – well-designed and well-functioning devices have been essential for our present understanding of elementary particles and their interactions.

A very vibrant research area: many new methods and techniques are under development, have been developed recently, or are getting ready for upgrades.

New challenges are waiting for us when planning the next generation of experiments as documented in the ECFA Detector R&D Roadmap. The DRD collaborations are helping the community to get organized in a structured way.

Blue sky research has traditionally been an important driver of progress in particle physics – and has to be supported also in the future. Many blue sky studies of today will become mainstream tomorrow.

Novel ideas will also come from discoveries in condensed matter physics, advanced materials, needs in medical imaging, and innovations in the industry.

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