ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Detector Development

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10 June 2024

European Strategy on Particle Physics

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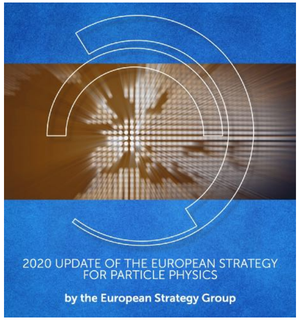
http://europeanstrategy.cern



Continuous process driven by the community

- First defined **2006**
- **Update 2013** brought us HL-LHC decision
- **Update 2020** brought us decisions for post-HL-LHC times:
  - *Europe, together with its international partners, should investigate the technical and financial feasibility of* ***a future hadron collider at CERN*** *with a centre-of-mass energy of at least* ***100 TeV*** *and with an* ***electron-positron Higgs and electroweak factory*** *as a possible* ***first stage****.*
  - ***Detector R&D programmes*** *and associated infrastructures should be supported at CERN, national institutes, laboratories and universities.* ***Synergies*** *between the needs of different scientific fields and* ***industry should be identified*** *and exploited to boost efficiency in the development process and increase opportunities for more* ***technology transfer benefiting society*** *at large. [... The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels..*
  - Successful completion of High-Luminosity LHC must remain key focus
- **Update 2026** on the horizon with input proposals by spring 2025

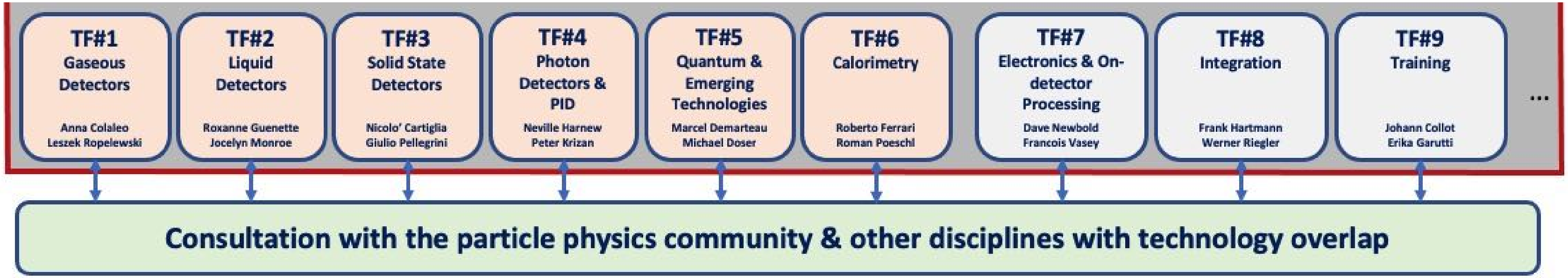
http://dx.doi.org/10.17181/CERN.JSC6.W89E

ECFA Detector Roadmap

European Committee for Future Accelerators (ECFA) released in 2021 a full document (200 pages) and synopsis (~10 pages) based on a community-driven effort

The full document can be referenced as DOI: 10.17181/CERN.XDPL.W2EX

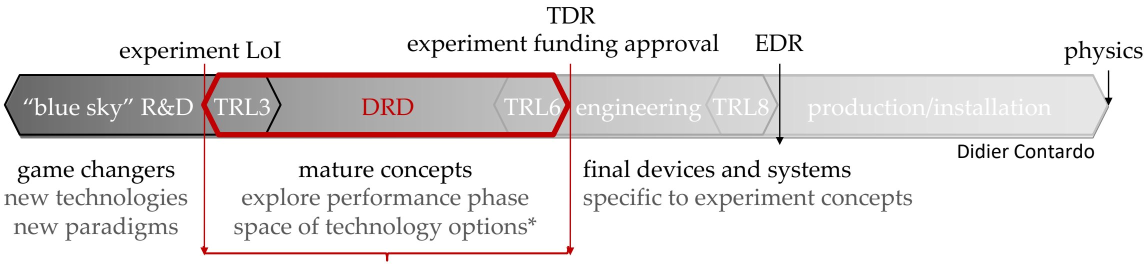
- Overview of **future facilities** (EIC, ILC, CLIC, FCC-ee/hh, Muon collider) or major **upgrades** (ALICE, Belle-II, LHC-b,…) and their **timelines**
- Ten "**General Strategic Recommendations**" (full list in backup slides)
- **Nine Technology domains** with **Task Forces** areas
  - The **most urgent R&D topics** in each domain identified as **Detector R&D Themes** (DRDTs)



Aim: Strategic R&D

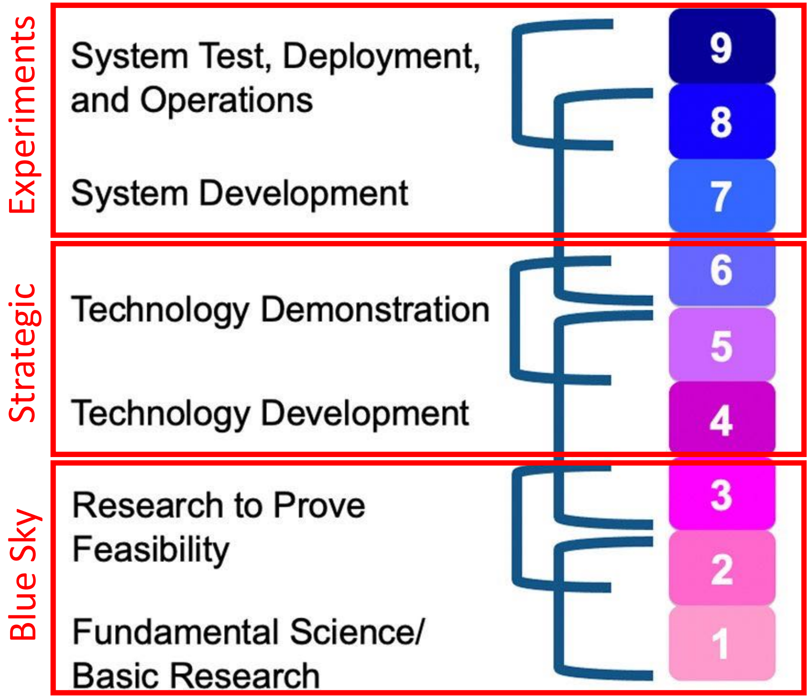
Strategic R&D bridges the gap between the idea ("**blue sky research**", TRL 1-3) and the **deployment and use in a HEP experiment** (TRL 8-9)

- Detector R&D Collaboration should address TRLs from 3 to 7, before experiment-specific engineering takes over
- Covers the development and maturing of technologies, e.g.
    - Iterating different options
    - Improving radiation hardness
    - Scaling up detector area, number of layers,..
- Backed up by **strategic funding**, agreed with funding agencies



Technology Readiness Levels (TRLs) 1-9:

Method for estimating the maturity of technologies



Overview DRD Collaborations

Fully Approved for an initial period of 3 years by CERN Research Board in December 2023

- Gaseous Detectors (DRD1) [ex RD51]
- Liquid Detectors (DRD2)
- Photodetectors & Particle ID (DRD4)
- Calorimetry (DRD6)

Reports at March open DRDC session: https://indico.cern.ch/event/1356910/
Full Proposals in CERN CDS

Fully Approved for an initial period of 3 years by CERN Research Board in June 2024

- Semiconductor Detectors (DRD3) [ex RD50, RD42,..]
- Quantum Sensors (DRD5)
- Electronics (DRD7)

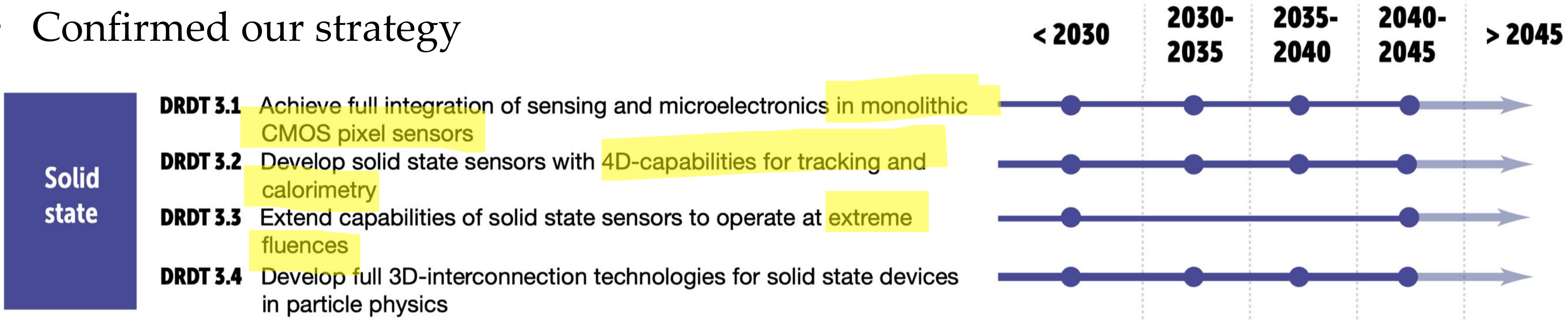
Reports at June open DRDC session: https://indico.cern.ch/event/1406007/

Letter of Intent submitted

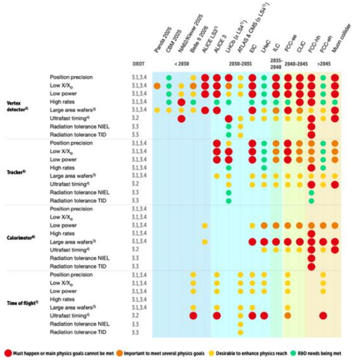
- Integration (DRD8) Full Proposal to be written by the end of 2024

ECFA Roadmap: solid-state (DRD3)

- Four Detector R&D Themes (DRDTs) defined for solid-state detectors
  - We were involved in most of the research topics for solid-state detectors defined by ECFA already before the document got released
  - Confirmed our strategy

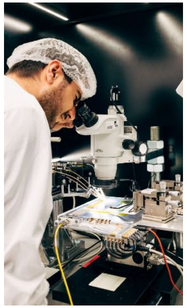


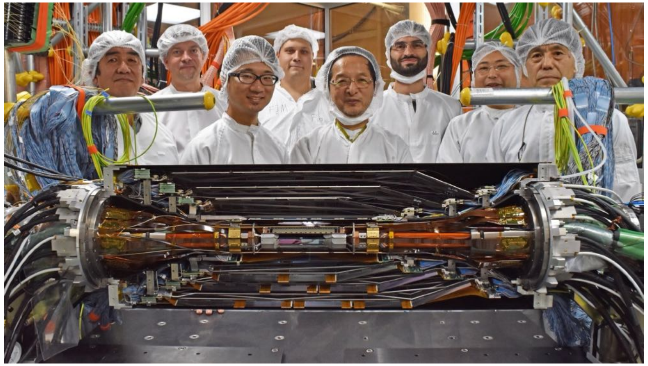
- Additional topics mentioned in the roadmap document:
  - Wide band-gap semiconductor



HEPHY Vienna

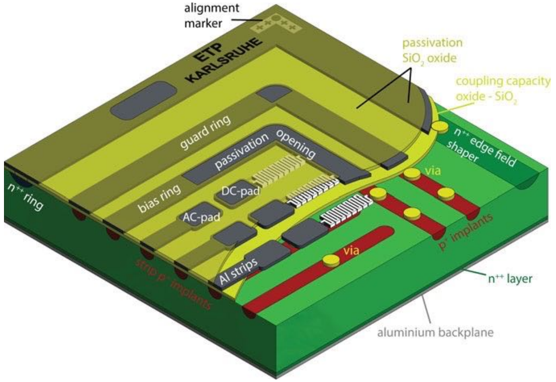
- Experimental Involvements:
  - CMS Experiment at LHC
    - Silicon sensors, module assembly, tests
  - Belle Experiment at KEK
    - Silicon Sensors design, tests
    - Modules/Ladder Design and Assembly
    - DAQ System design, production, deployment
  - Medical Applications





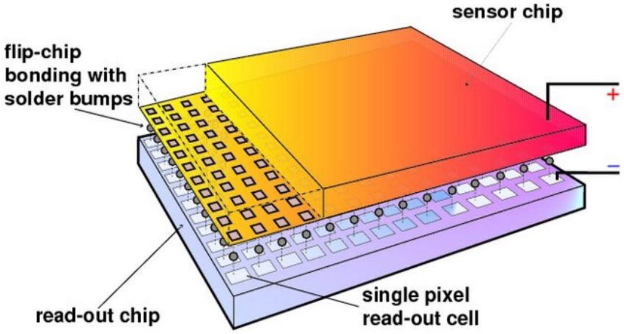
Particle Detectors Concepts

Strip Sensors



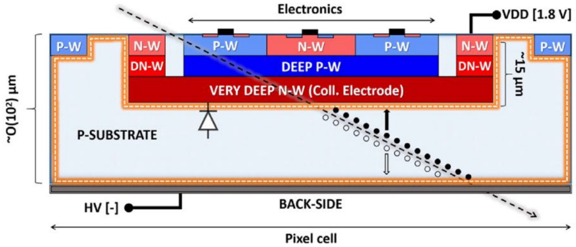
- One-dimensional position resolution
- Readout electronics wire-bonded at the side
- Simple (1 mask layer for each implant, metal layer, contacts, polyresistors, passivation)

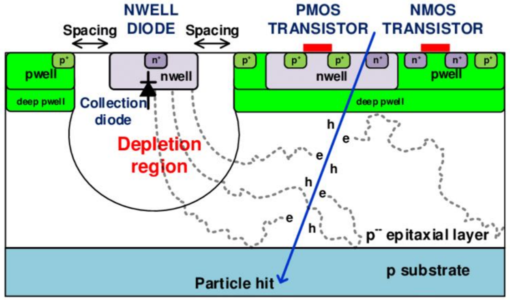
Hybrid Pixel Sensors



- Two-dimensional position resolution
- CCD too slow, so each pixel is read out individually
- Sensor top
- Front-end ASIC bottom
- Fine-pitch bump bonding (50μm pitch, expensive and error-prone)

Monolithic Pixel Sensors

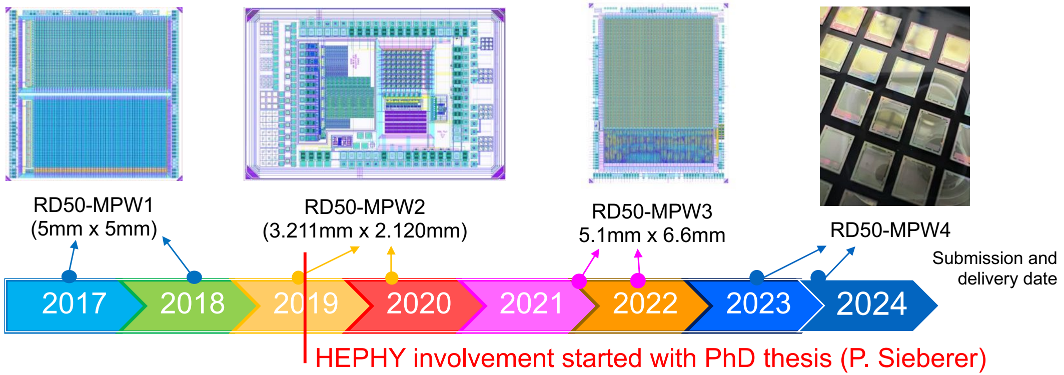




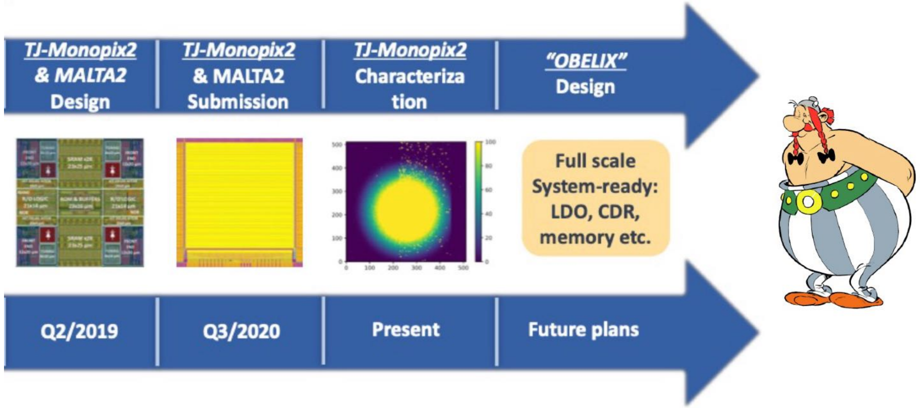
- Integration of sensor and Front-end electronics (analog amplifiers, shaper, ADC or comparator, digital memory,..) in one Die

CMOS ASICs and MAPS Sensors

- RD50-MPW developments
  - R&D development using Lfoundry 150 nm process via Europractice
  - “large collection electrode”
  - Caribou DAQ System

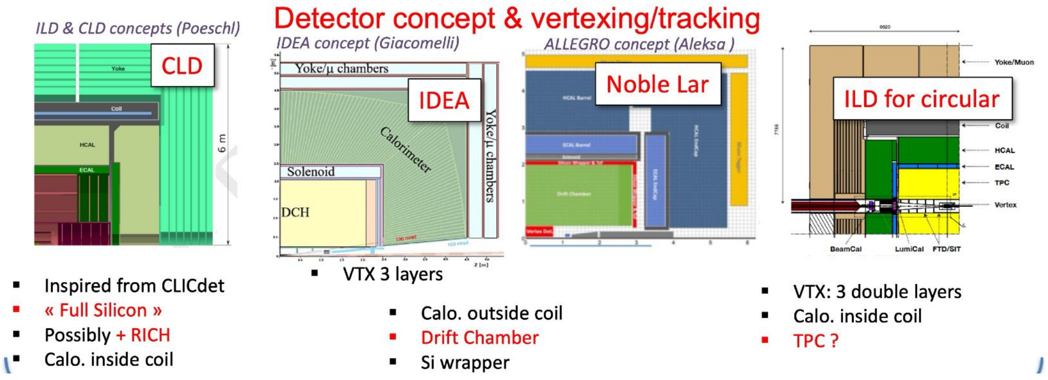


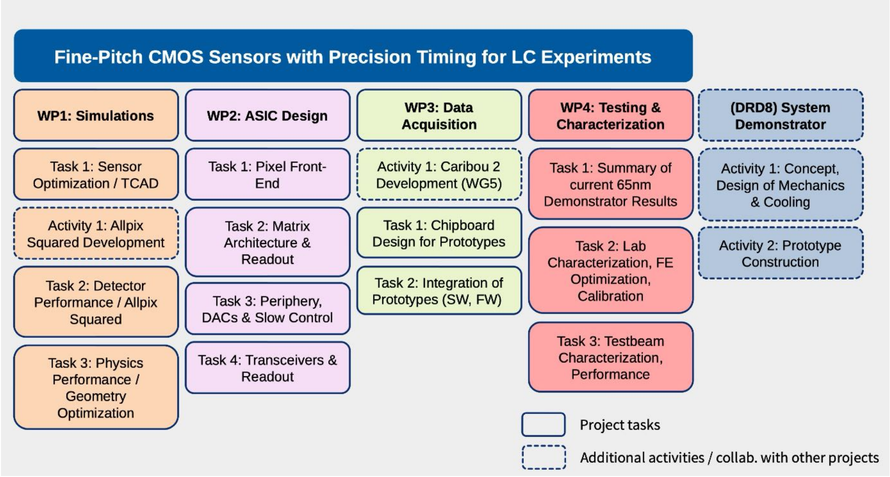
- Monopix2 → OBELIX
  - Targeting Belle-II VTX Upgrade
  - Tower 180 nm modified process accessible directly / via CERN
  - “small collection electrode”



CMOS Activities in DRD3

- TPSCo 65 nm process identified to meet the FCC-ee requirements:
  - Position: 3 μm single-point resolution
  - Timing: down to 5 ns time resolution
  - Material budget ~< 0.15% X_0 (per layer) needs thinning to 50μm
  - Power: average power consumption below 50 mW/cm^2
- DAQ System: Caribou
- Intermediate goal: build a beam telescope out of these sensors
- Successor of German "Tangerine" project proposed for DRD3 project

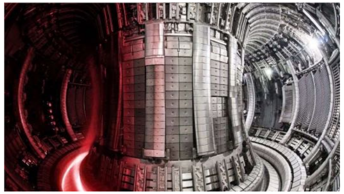
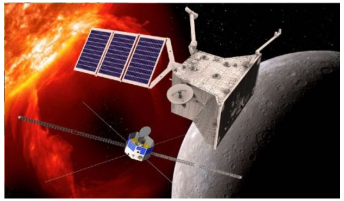




Silicon Carbide Detectors

- Wide bandgap semiconductor (3.26 eV) : Low leakage currents, insensitivity to visible light
- Renewed interest: High quality wafers from power electronics industry

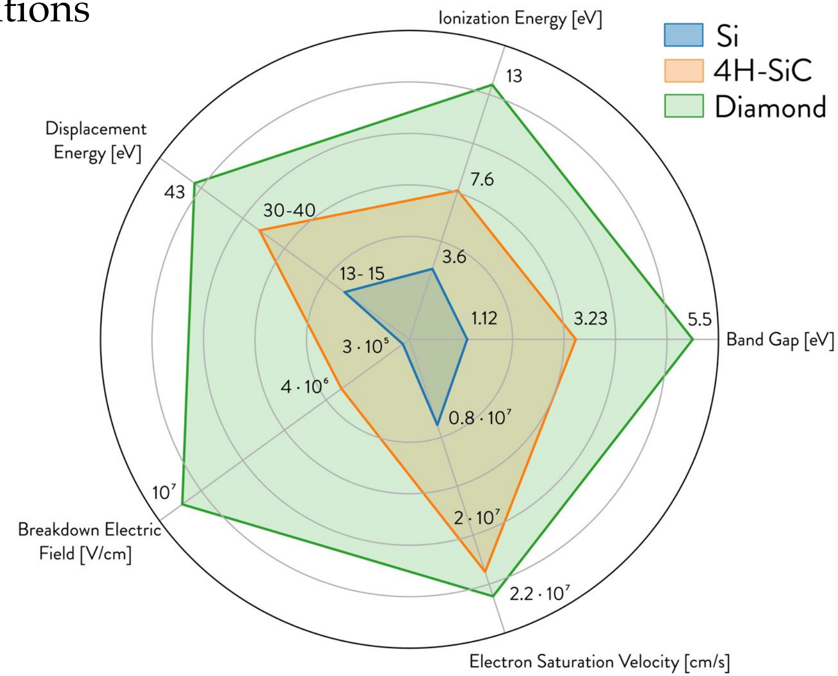
+ High breakdown field and saturation velocity : timing applications
+ Potentially higher radiation hardness (displacement energy), no cooling needed after irradiation
- Higher ionization energy (~30% less signal per μm)
- Limitations in epi layer thickness and resistivity


Dosimetry: μDOS, FLASH

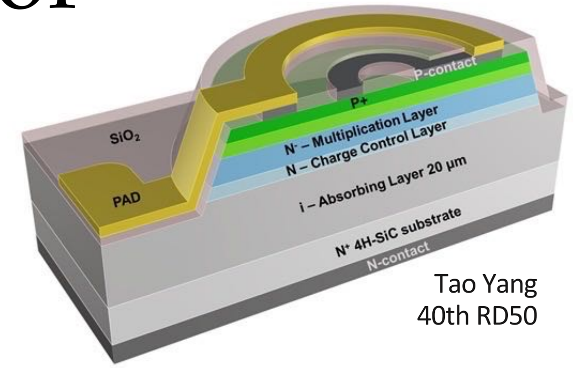
Space, harsh environments (fusion)

Beam monitoring, radiation hard large area detectors



Advantages and disadvantages of 4H-SiC compared to Si

SiC towards HEP Detector



Tao Yang
40th RD50

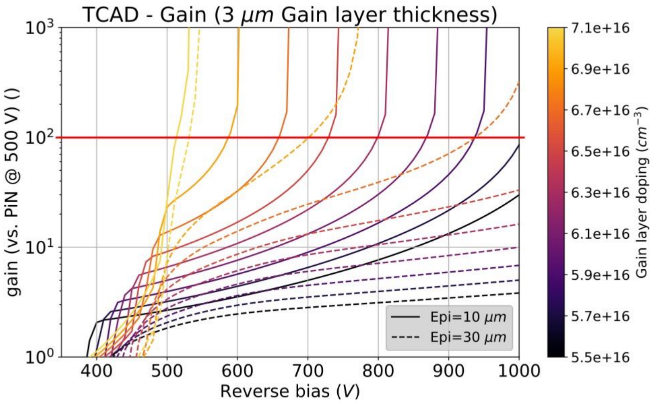
Differences Si vs. SiC for MIP detection

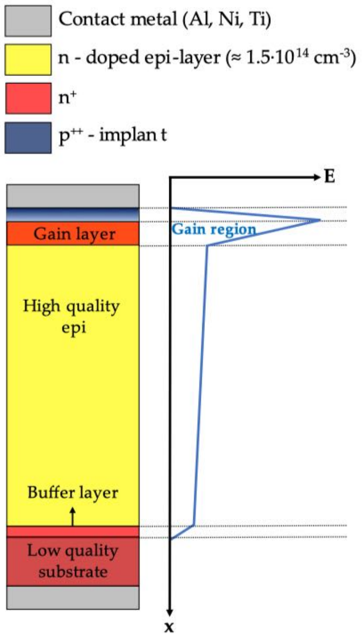
- Silicon: 300μm thick, mip signal: 22ke⁻
- SiC: 50μm thick, mip signal 2.7ke⁻

12% signal only

Mitigation: charge amplification by impact ionization

- Technology: **LGAD: Low Gain Avalanche Detector**
  - Implement a gain layer into Silicon Carbide to mitigate the small signals
  - Technological challenges
  - TCAD simulations needed to optimize gain layer
- SiC-LGAD development running as RD50/DRD3 common project under HEPHY leadership
- Potential very radiation hard → optimally suited to mitigate the unprecedented pile-up of FCC-hh

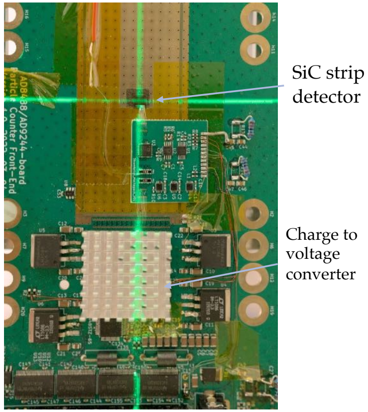


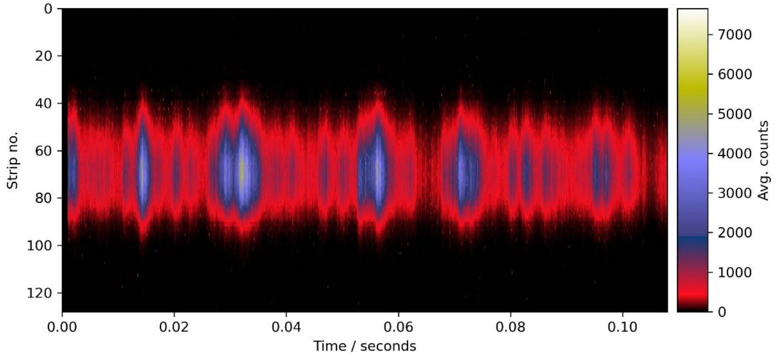


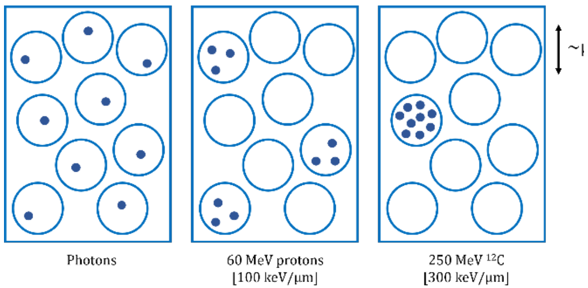
SiC outside HEP: Medical Appl.

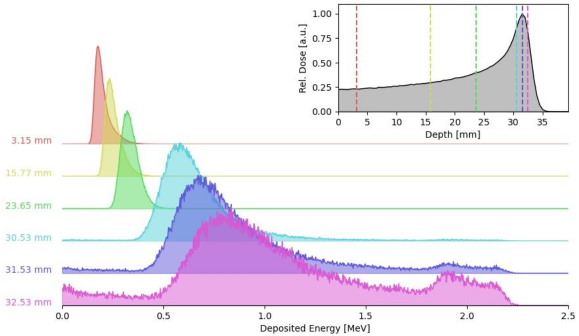
Take advantage of access to **MedAustron**

- Beam position and intensity monitor
  - High dynamic range (HiBPM project): ASIC and electronics development, SiC strip sensor
  - FLASH dosimetry: 40Gy / s
- (Micro-) Dosimetry
  - Stochastic nature of energy loss





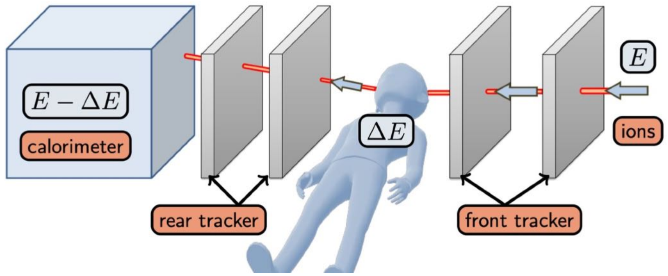


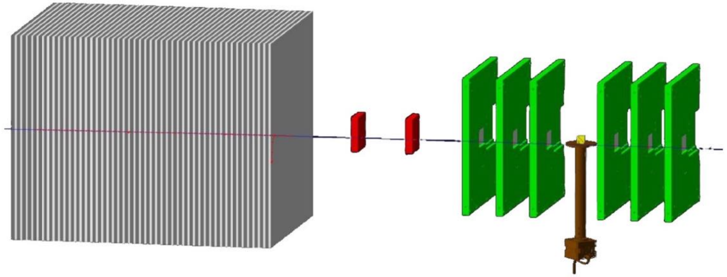


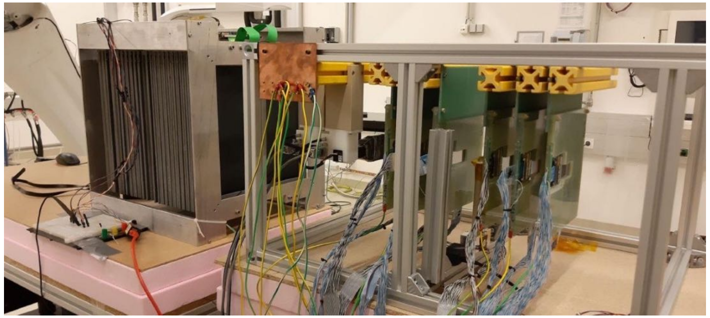
Ion Imaging @ MedAustron

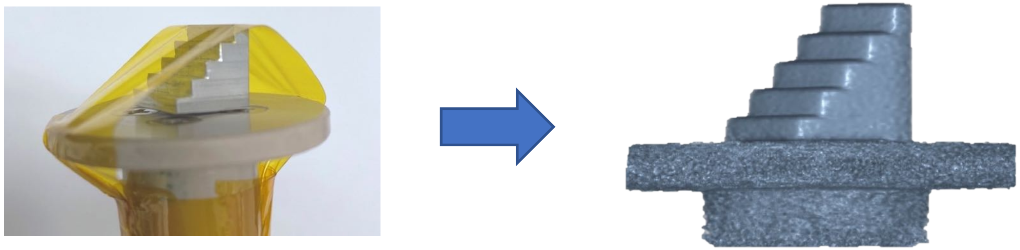
Radiotherapy treatment planning for tumor location determination
- Conventional X-ray CT measures Hounsfield units
- "Ion CT" directly determines energy loss in the object per voxel and does not need erroneous conversion.

Hardware required for "Ion-CT":
- Spatial resolution detectors: HEPHY DSSDs now, CMOS MAPS in future
- Calorimeter to measure residual energy: classical sandwich scintillator calorimeter → ToF using LGAD sensors
- Image reconstruction: GPU-based software initially developed for cone-beam CT extended for Ion-CT









Phantom

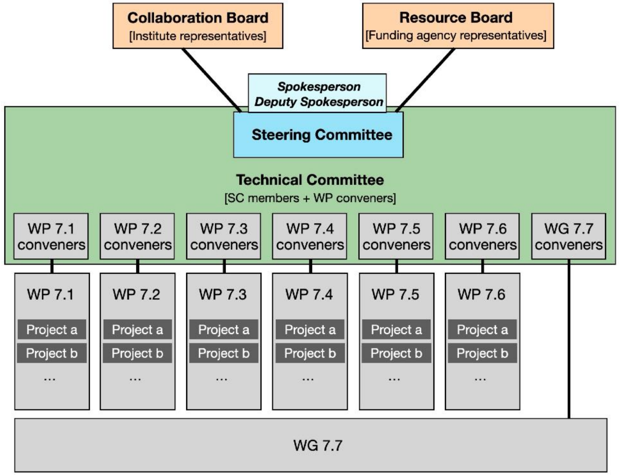
Reconstructed image

DRD7: Electronics

- Full proposal submitted by 21 May 2024; **approved on 5 June 2024**
- Objectives: Carry out strategic R&D in electronics, fulfilling DRDTs, Coordinate cross-European access to technologies, tools and knowledge, Interface with other DRDs
  - No orthogonal "Service-Provider" for other DRDs
- Organization:
  - 19 countries, 68 institutes
  - 1st workshop in March, 2nd workshop in Sept. 2023; 1st collaboration meeting planned 9-10 Sept 2024

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

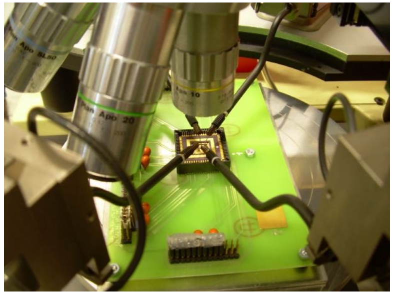
WP 7.6 Complex imaging ASICs and technologies
WG 7.7. Transversal Tools and Technologies

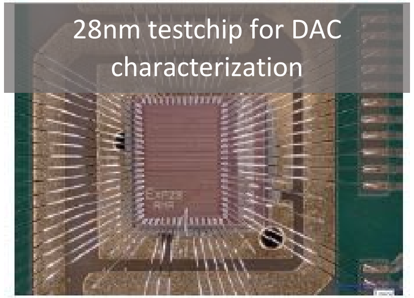


TU Graz Contributions to DRD7

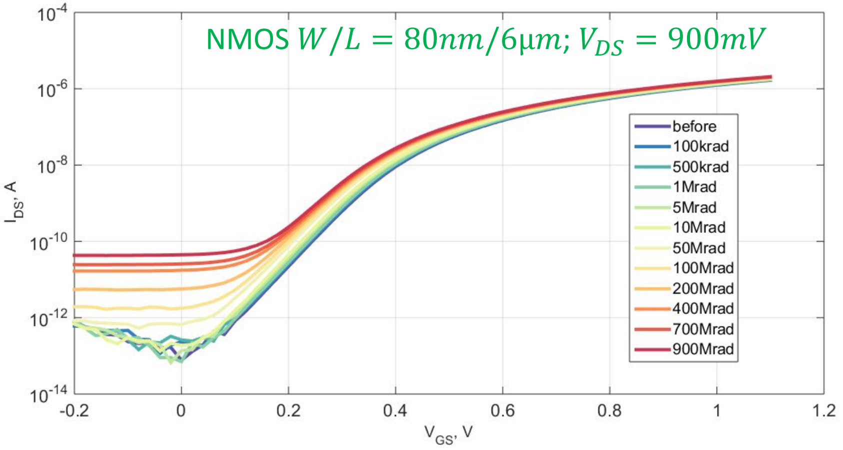
- Graz University of Technology – Institute of Electronics:
  - **Cadence IC design software** for the complete mixed-signal design flow from schematic through physical layout to IC evaluation
  - **Instruments** for characterization of various IC parameters
  - Every year **fabrication** of 1-2 custom integrated (test)chips from 350µm down to 28nm CMOS
  - In-house, **X-ray test facility**, suitable for tests up to Grad TID

- Projects within DRD7:
  - Project 7.1.b Powering Next Generation Detector Systems
  - Project 7.3.a High-Performance TDC and ADC Blocks at Ultra-Low Power
  - Project 7.4.a Device modelling and development of cryogenic CMOS PDKs and IP
  - Project 7.4.b Radiation resistance of advanced CMOS nodes





Ionizing radiation effects on CMOS,



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Summary

- CERN-hosted Detector R&D (DRD) collaborations are currently being set up following ECFA Detector roadmap and Austria is involved in
  - DRD3 (Semiconductor Detectors) at HEPHY
  - DRD7 (Electronics) at TU Graz
- R&D in Austria is in line with work in these DRD collaborations:
  - Monolithic CMOS sensors to meet the physics requirements of FCC-ee
  - Radiation Hardness towards FCC-hh
- More funding is currently being acquired outside HEP (Medical appl.)

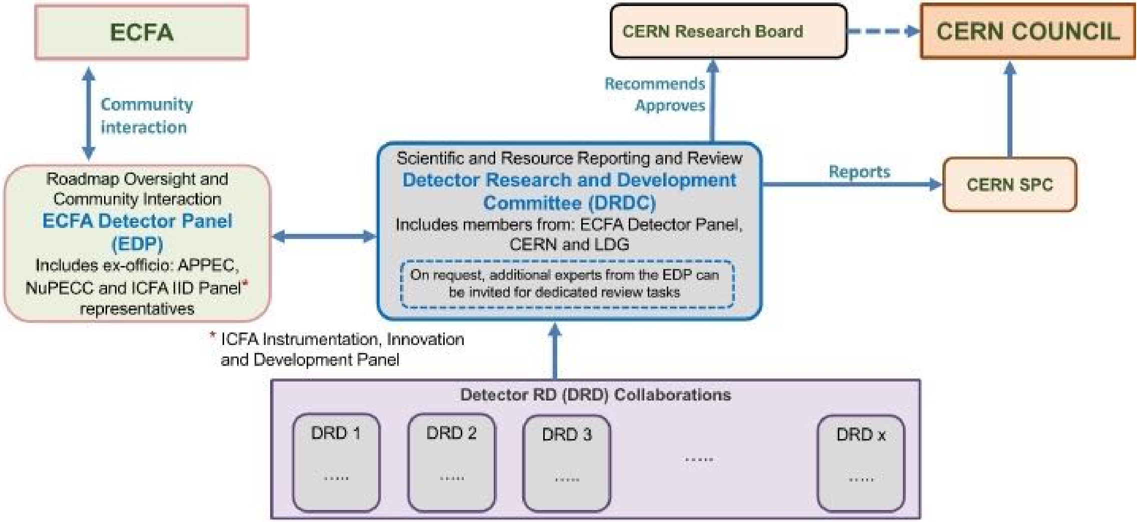
The End.

Thank you for your attention

Roadmap implementation plan

- Approved by CERN SPC and Council in fall 2022 ([CERN/SPC/1190 ; CERN/3679]())
- **CERN will host DRD collaborations**
  - Interaction between DRD collaborations and committees through DRDC
  - Interface to ECFA via ECFA Detector panel EDP: https://ecfa-dp.desy.de

- Distinction between reviewing body (DRDC) and advising body (EDP)
- [ECFA Detector Panel]()(EDP) interfaces to ECFA
  - Organizes “DRD managers forum”
  - provides input to the next Strategy update



From ECFA Task forces to DRD collaborations

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- Chapters convenors (Task Force) from ECFA Roadmap became part of Proposal Writing Teams for new DRD collaborations
- Collected input from the communities in open meetings happening in the beginning of 2023

- Summer 2023: **Submission deadline of DRD proposals**
  - The DRDC (DRD Committee) was appointed at the same time only
  - Review of first DRD proposals by DRDC in autumn 2023
  - Intense phase of work as also DRDC mandate and tasks had to be defined first

- **Approval of first DRD collaborations in December 2023 RB**
- Once approved, DRD collaborations started in 2024
  - Collaborations have kick-off meetings, elect management positions,…
  - Setting up MoU and collecting signatures from Funding Agencies

Q1/2023	• Community input by open meetings
End 07/23	• Submission of proposals to DRDC
Fall 2023	• Review by CERN DRDC, assisted by ECFA EDP
End 2023	• Approval, then: • Collaboration starts
2024	• MoU negotiations and signature collection
2024ff	• annual status reports and monitoring to DRDC

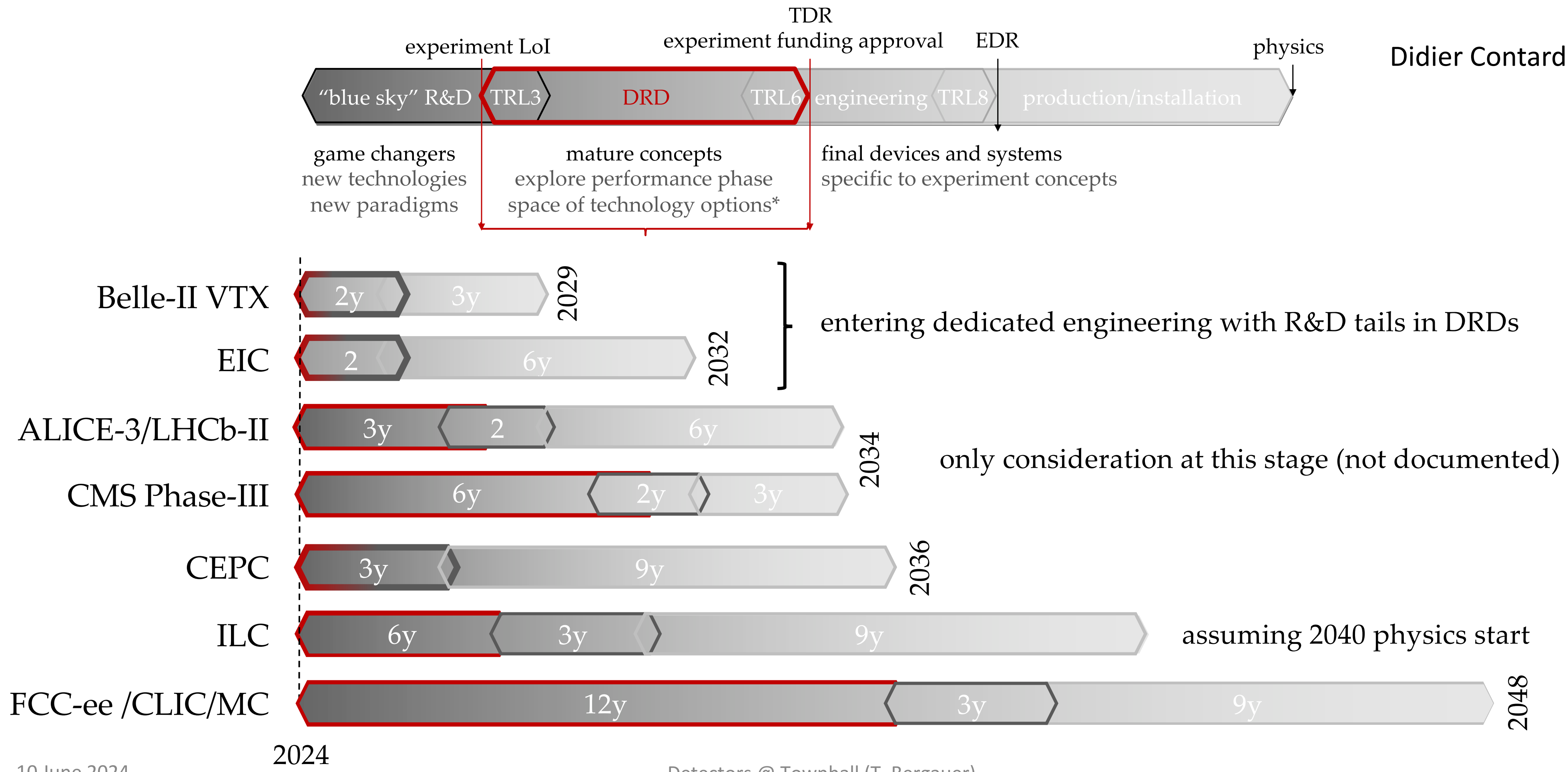
General Strategic Recommendations

The General Strategic Recommendations (GSR) topics are:

- GSR 1: Supporting R&D facilities (**test beams, large-scale generic prototyping and irradiation)**
- GSR 2: **Engineering support** for detector R&D
- GSR 3: Specific **software** for instrumentation
- GSR 4: **International coordination** and organisation of R&D activities
- GSR 5: Distributed R&D activities with **centralised facilities**
- GSR 6: Establish long-term strategic **funding programmes**
- GSR 7: "**Blue-sky**" R&D
- GSR 8: Attract, nurture, recognise and sustain the **careers of R&D experts**
- GSR 9: **Industrial** partnerships
- GSR 10: **Open Science**

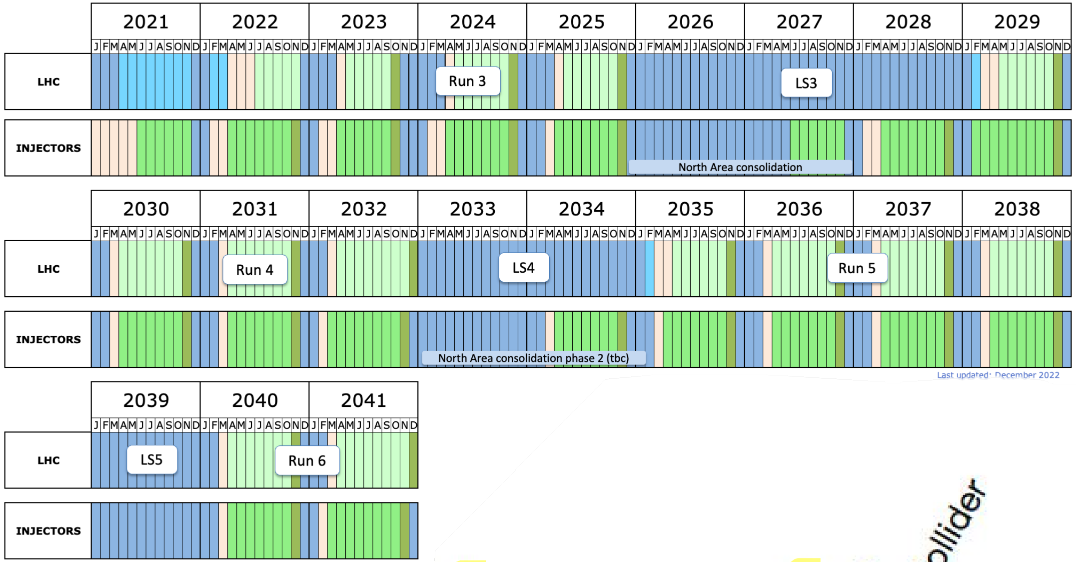
Broad timelines for future HEP Projects

Didier Contardo

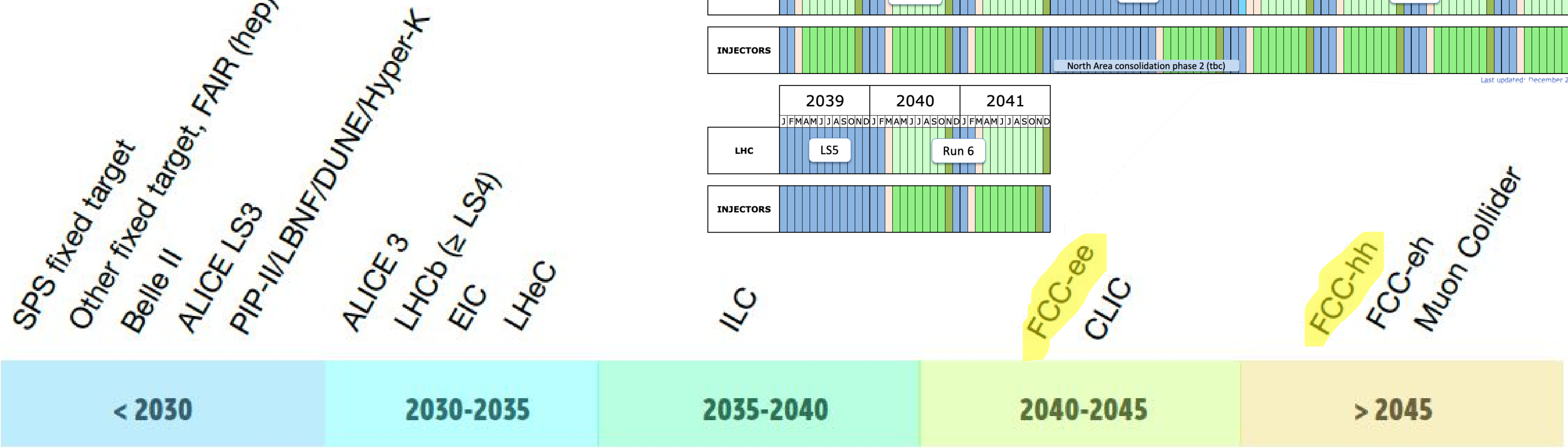


Future Large Experiments

(HL-)LHC timeline:



- Five Time periods defined



LHC LS3

LHC LS4

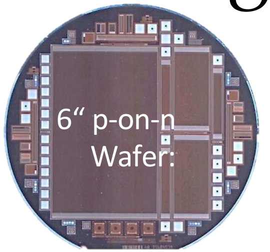
Example for the need of strategic R&D

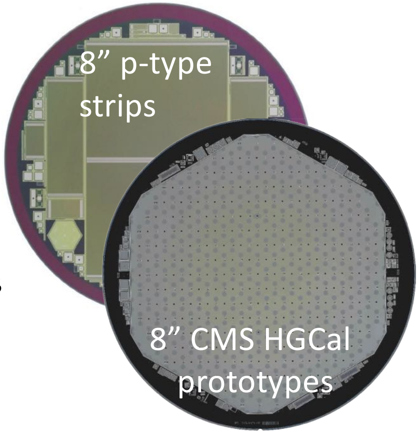
My group worked for almost a decade with European semiconductor industry to find a "second source" for large-area planar Si sensors (targeting Phase-II Upgrades)

- Attracted a lot of attention
- Pushed HPK into developing 8" process
  → now being used for CMS HGCal
- Milestones:
  - 2009: re-produce 6" p-on-n strip sensors
  - 2015: First AC-coupled strip sensors on 8" wafers
  - 2016/17: production of first 8" hexagonal HGCal sensors
  - 2018: **program stopped due to economic reasons**

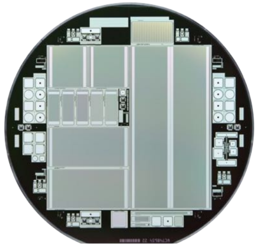
Reason for termination of program before series production:

- O(10) more wafer runs (~150k€ each) would have been necessary to mature the technology
- Strategic R&D funding for R&D costs → reduction of series production costs





6" CMS PS-S prototypes




Infineon CEO together with HEPHY and CERN representatives

Similar effort driven by INFN with STMicroelectronics quite some time ago for planar sensors of LHC ("Phase-0")

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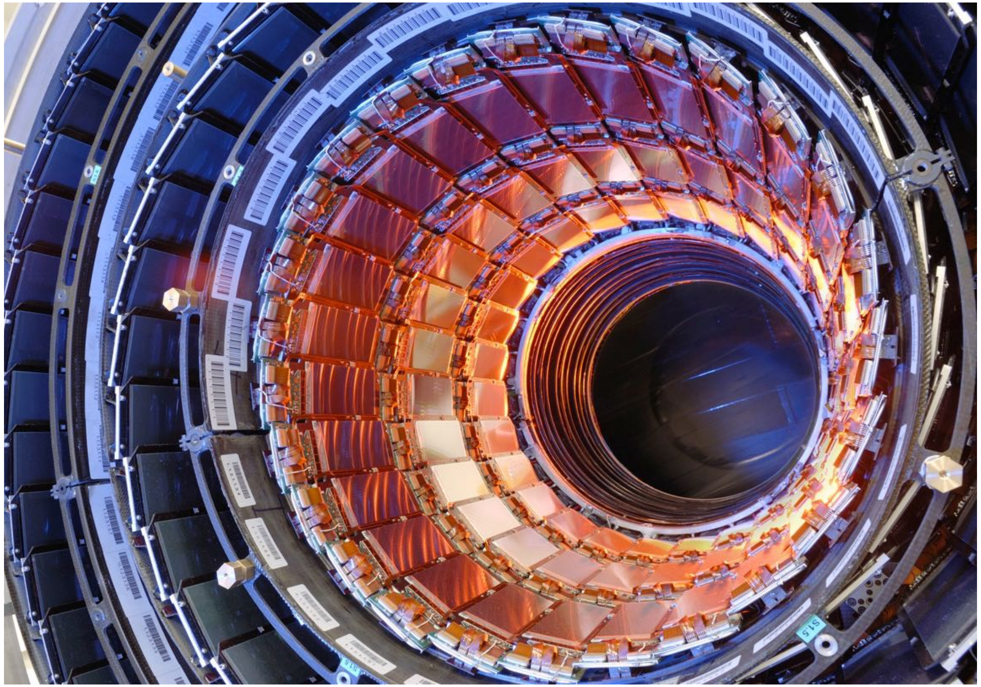
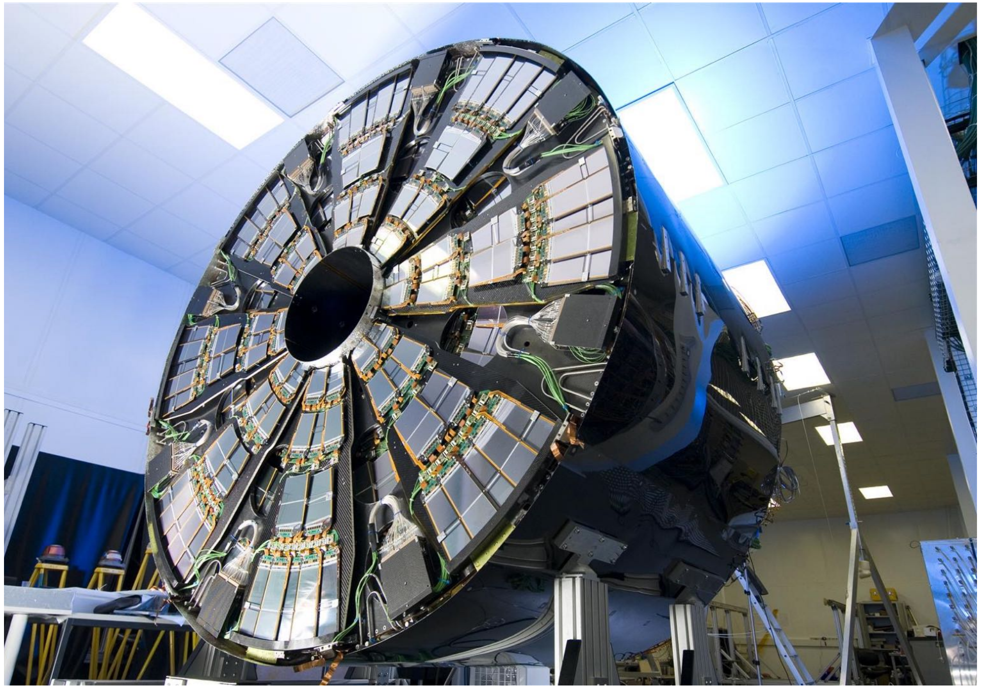
Particle Detectors at CERN

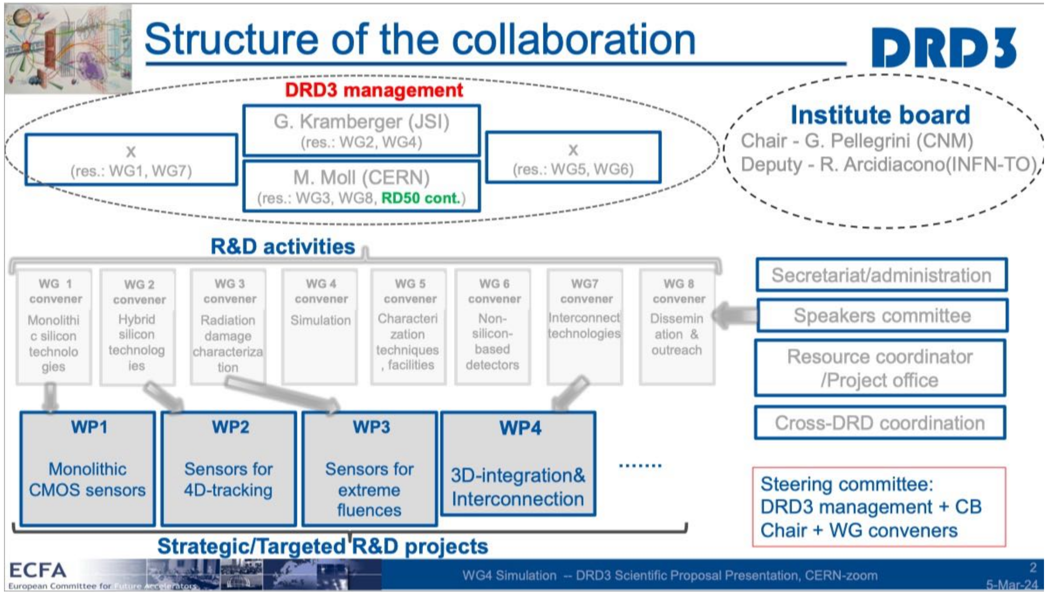
- Pictures of CMS Tracker barrel (left) and endcaps (right)
- 30000 individual Si strip sensors, each 10 x 10 cm^2





DRD3: Semiconductor Detectors

- DRD3 benefits from existing RD50 collaboration, extended by diamonds (RD42) and 3D integration
  - Focus widened from pure radiation hardness (HL-LHC Ph-2 upgrades) to lepton collider needs
  - Large interest in CMOS (DMAPS) sensors
- Large Collaboration: 132 institutes from 28 countries
  - ~900 interested people
  - ~ 70% are from Europe, 15% from North America,
  - Compare: RD50: 65 institutes and 434 members
- Budget: ~5 MCHF/y (existing), ~8 MCHF/y (additional needed)
  - 327/170 FTE (existing / additional needed)



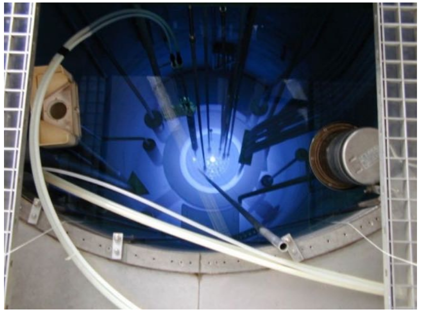
- CB Board chair : Giulio Pellegrini (CNM Spain)
- Spokesperson: Gregor Kramberger (JSI Slovenia) with deputies (Sally Seidel, Michael Moll, n.n.)
- Webpage: https://drd3.web.cern.ch/

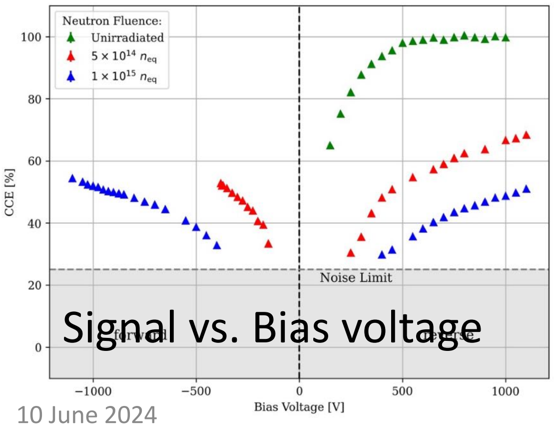
- Recently started with WG/WP meetings to organize work towards 1st DRD3 collaboration meeting (17-21 June 2024)

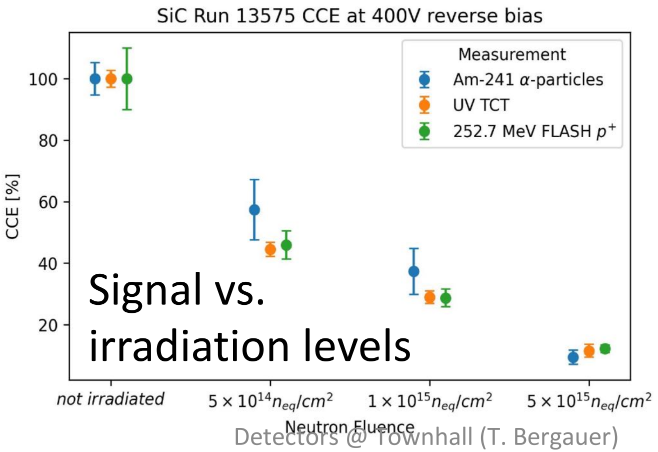
SiC Radiation Hardness

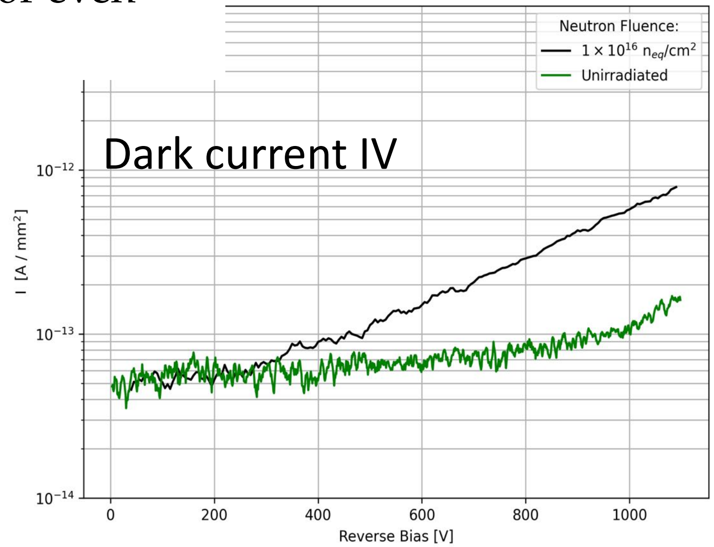
- Each particle detector development need to take irradiation damage into account ab initio
- We have access to the Triga Mark II nuclear reactor of Atominstitut (ATI) of TU Wien nearby

- SiC Advantage: low dark current, even after irradiation (in contrast to Si)
- However, loss in signal heights after irradiation exist similar (or even worse) to silicon







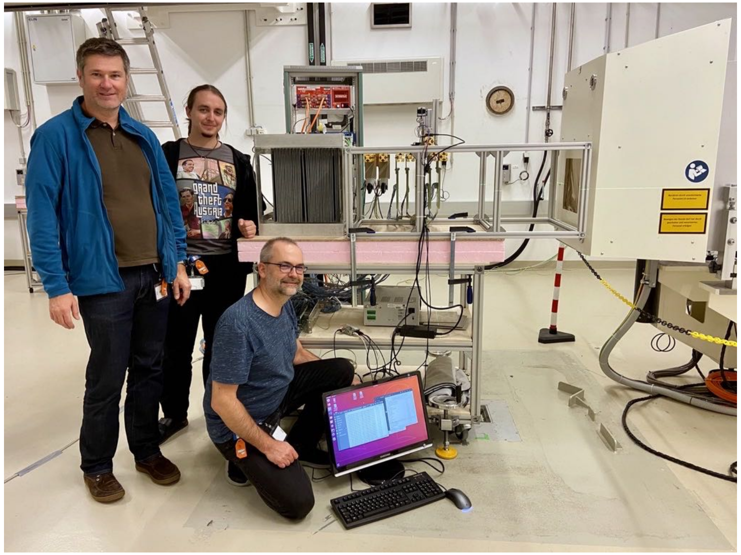


MedAustron

Particle therapy center in Wiener Neustadt

- Located 50km away from Vienna city center
- Protons (since 2016) and carbon ions (2019) are available
  - Helium currently commissioned
- For protons:
  - Flux from kHz/cm² ("low flux settings") to 10^{12} protons/cm² (FLASH)
  - Energies from 62.4 MeV to 800 MeV (1.2 mip particle equivalent)
  - Technical maximum energy 1.2 GeV (legally not approved)

- We use it as test beam facility, but also develop medical applications
  - On weekends only
  - 8h shift slots. Completely different to typical HEP beam test (1 week)
  - ~10-15 8h-shifts per year for HEPHY in total
  - Hard to sustain with given manpower, equipment and transportation possibilities



Committee Members

ECFA Detector Panel (EDP):

- Co-chairs: ***Phil Allport*** *(Birmingham)*, ***Didier Contardo*** *(Lyon)*
- Scientific secretary: *Doris Eckstein (DESY)*
- Gaseous Detectors: *Silvia Dalla Torre (Torino)*
- Liquid Detectors: ***Inés Gil Botella*** *(CIEMAT)*
- Solid State Detectors: *Doris Eckstein, Phil Allport*
- PID & Photon Detectors: ***Roger Forty*** *(CERN)*
- Quantum and emerging Technologies.: *Steven Hoekstra (Groningen)*
- Calorimetry: ***Laurent Serin*** *(IJCLab)*
- Electronics: *Valerio Re (Bergamo)*
- Ex Officio: *ECFA Chair (Paris Sphicas), ICFA Detector Panel (Ian Shipsey), DRDC chair (**Thomas Bergauer**), APPEC & NuPECC observers*

Detector R&D Committee (DRDC):

- ***Thomas Bergauer*** (HEPHY Vienna), Chairperson
- *Jan Troska* (CERN), scientific secretary
- *Stan Bentvelsen* (NIKHEF; LDG contact)
- *Shikma Bressler* (Weizmann)
- *Dimitry Budker* (Mainz)
- *Roger Forty* (CERN; RB contact)
- *Claudia Gemme* (INFN and U. Genoa)
- ***Inés Gil Botella*** (CIEMAT)
- *Petra Merkel* (Fermilab; US contact)
- *Mark Pesaresi* (Imperial College)
- ***Laurent Serin*** (IJCLab)
- Ex-officio: **P. Allport, D. Contardo** (EDP)

Names in bold in both committees