Strategic Detector R&D for Particle Physics Experiments in Europe

(and by my research department at MBI Vienna)

Thomas Bergauer

Austrian Academy of Sciences, Marietta-Blau-Institute for Particle Physics (MBI; former HEPHY)

5 March 2026, CIEMAT Madrid

Disclaimer:
HEPHY becomes MBI

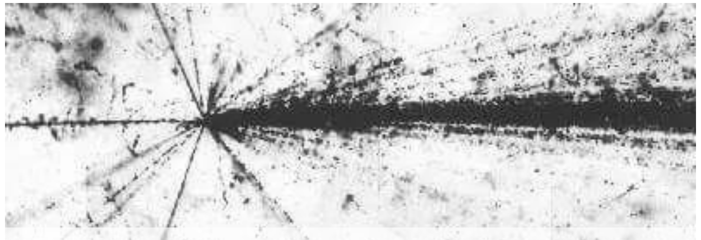
- Institute for High Energy Physics
  - CMS
  - Belle-II
  - Dark Matter (CRESST, COSINUS)
  - Gravitational Waves
  - Machine Learning, Theory
- Stefan Meyer Institute for Subatomic Physics
  - ALICE
  - Exotic Atoms & Antimatter at ASACUSA@AD

Since 1st September 2025:

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

http://www.oeaw.ac.at/mbi

Marietta Blau (1894 – 1970), Jewish Austrian physicist who developed nuclear emulsion techniques



nuclear disintegration stars (Zertrümmerungssterne)

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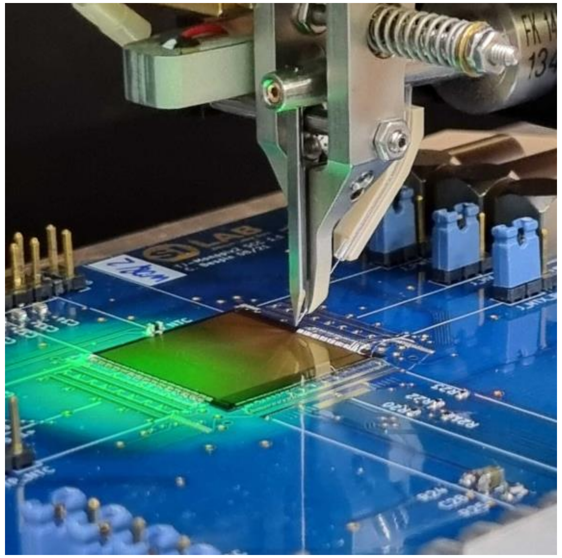
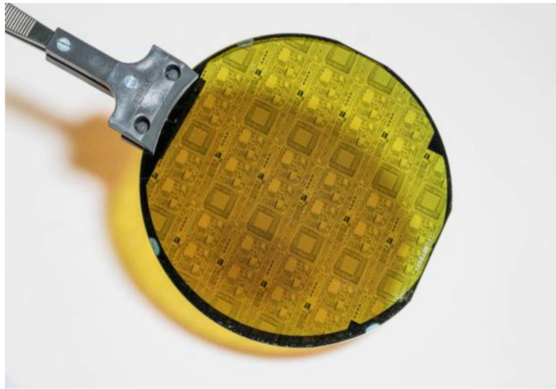
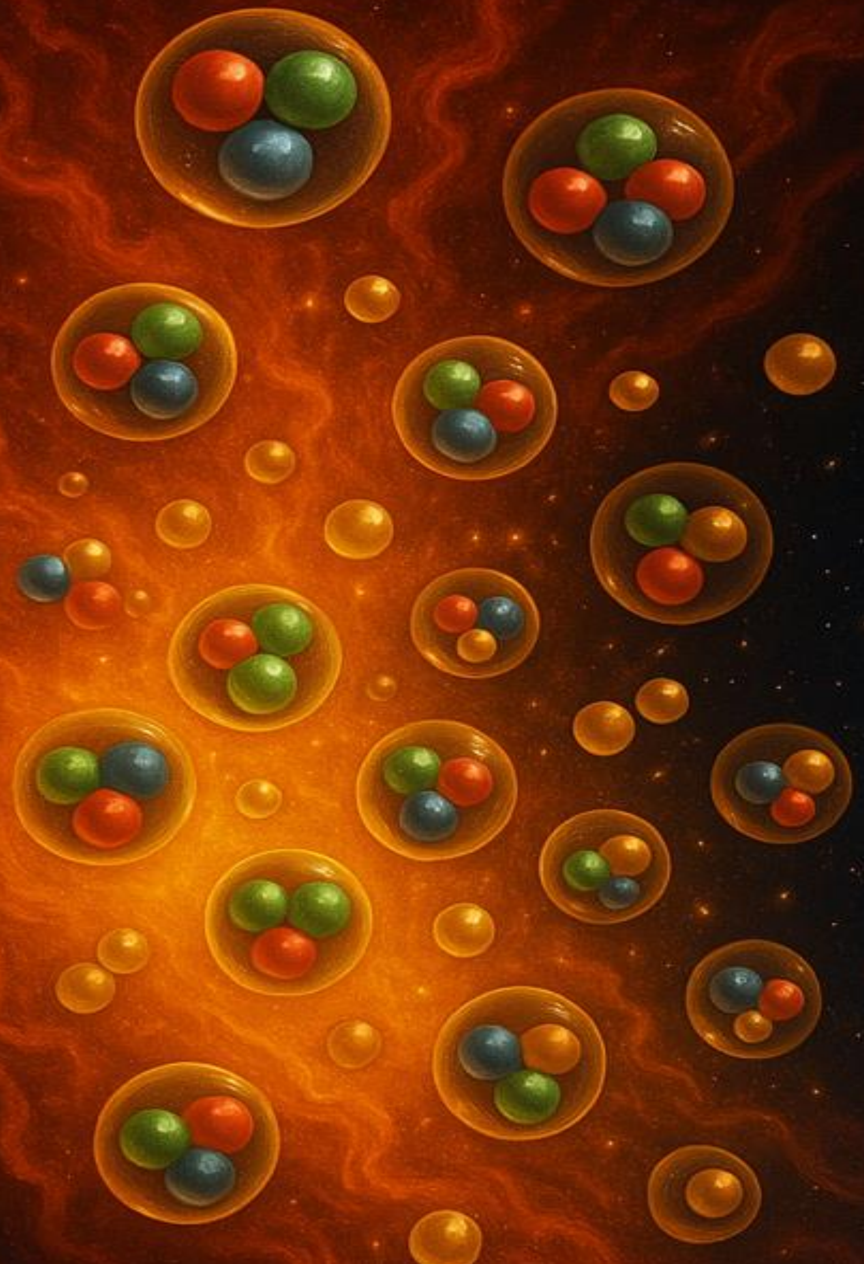
1. European Strategy for Particle Physics, ECFA Detector Roadmap & DRD Collaborations

2. Semiconductor Detectors at future experiments at what we do at MBI
   a) MAPS Sensors
   b) Silicon Carbide Detectors and Medical Applications







Particle, astroparticle and nuclear physics share the common goal of understanding the fundamental constituents of the universe and the forces acting between them

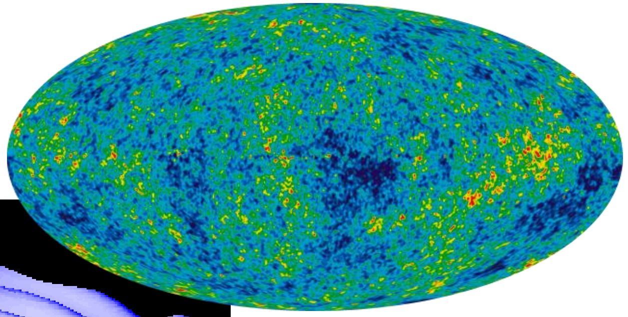
In the same way, we are united to develop and deploy many tools, as **observations** enable us to build an understanding of the universe.

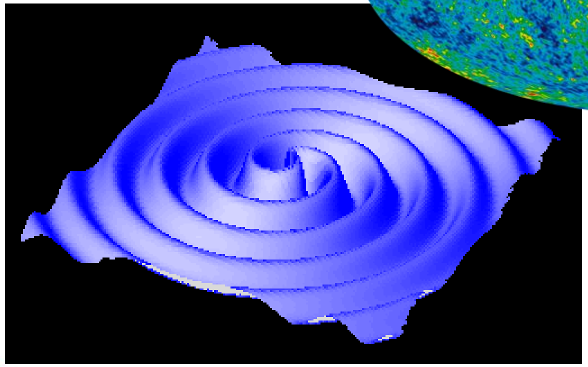
Challenges at a large

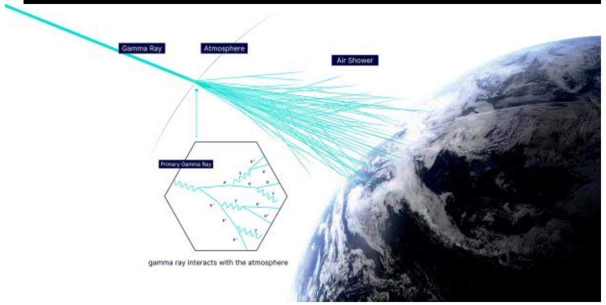
- **Images of the infant universe**: Cosmic microwave background, Quark-gluon plasma, gravitational waves

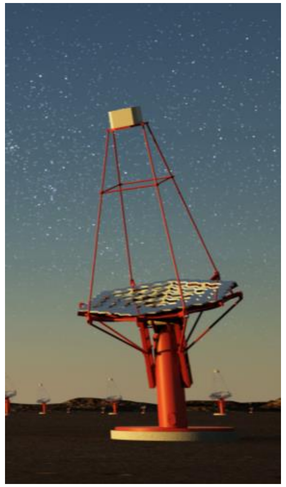
- **Matter of the Universe**: Testing the standard model, Matter-antimatter asymmetry, Dark Matter, Neutrinos

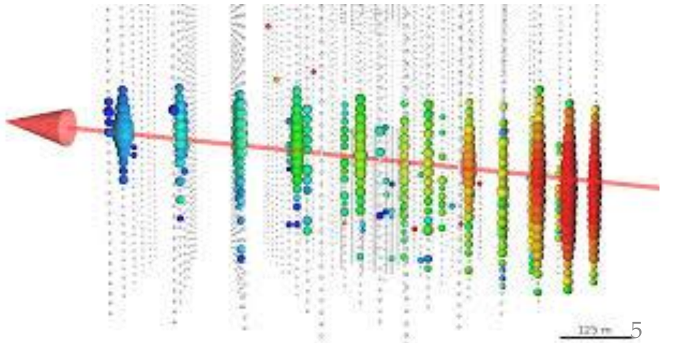
- **Using the universe as a laboratory**: astronomy with ground and space telescopes, gamma rays, UHE cosmic rays, neutrinos, dark matter







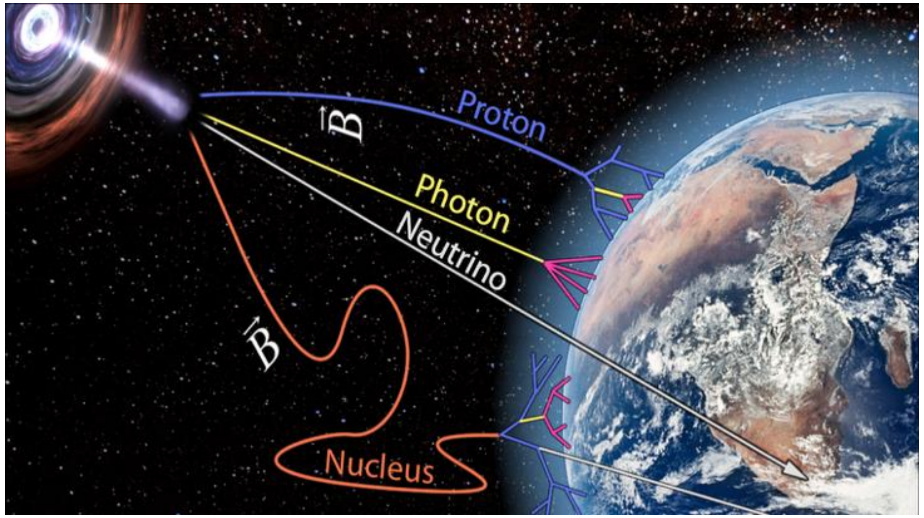


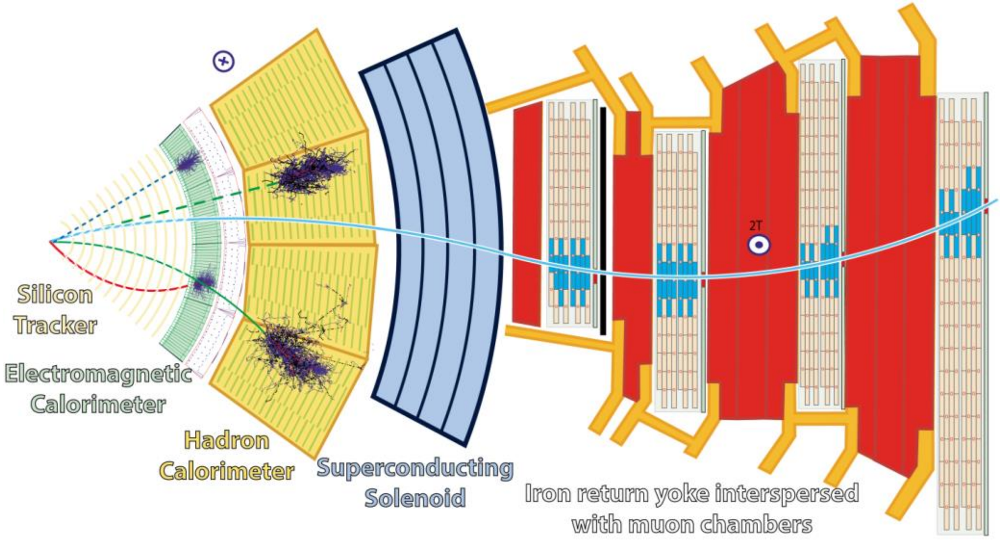


Particle Detectors

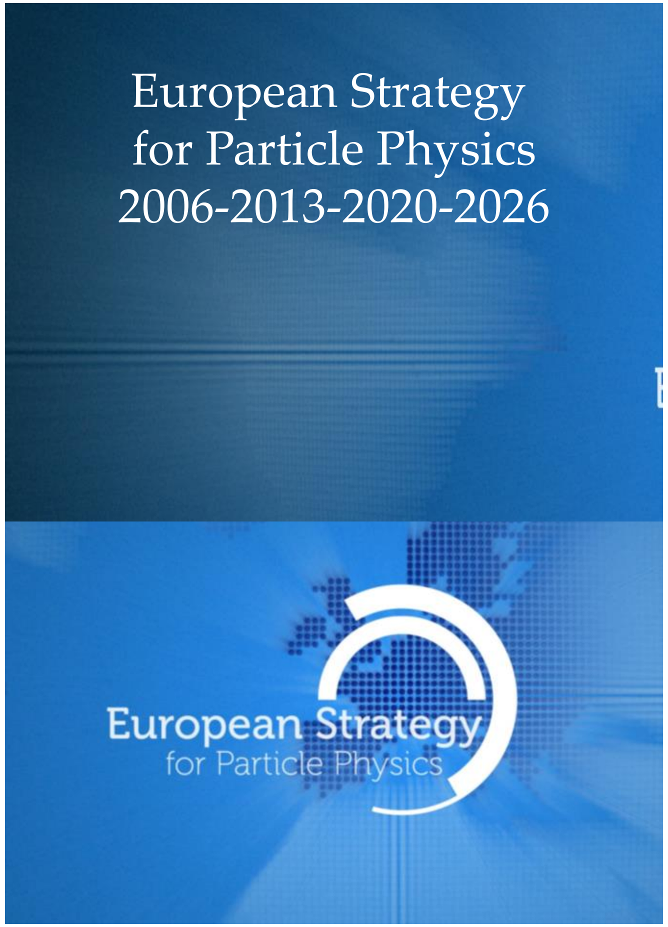
- The particles, whether produced in accelerator collisions, in non-accelerator experiments, in cosmic rays or space are:
photons, electrons, protons, neutrons, neutrinos, pions and kaons
  - Typical HEP/nuclear detectors needs: *Vertexing, Tracking, Calorimetry, Photon detectors, Low-weight mechanics, Large-Area coverage & scalability, Radiation hardness & Longevity*
  - Astroparticle: *Photon detectors, Cryogenics*

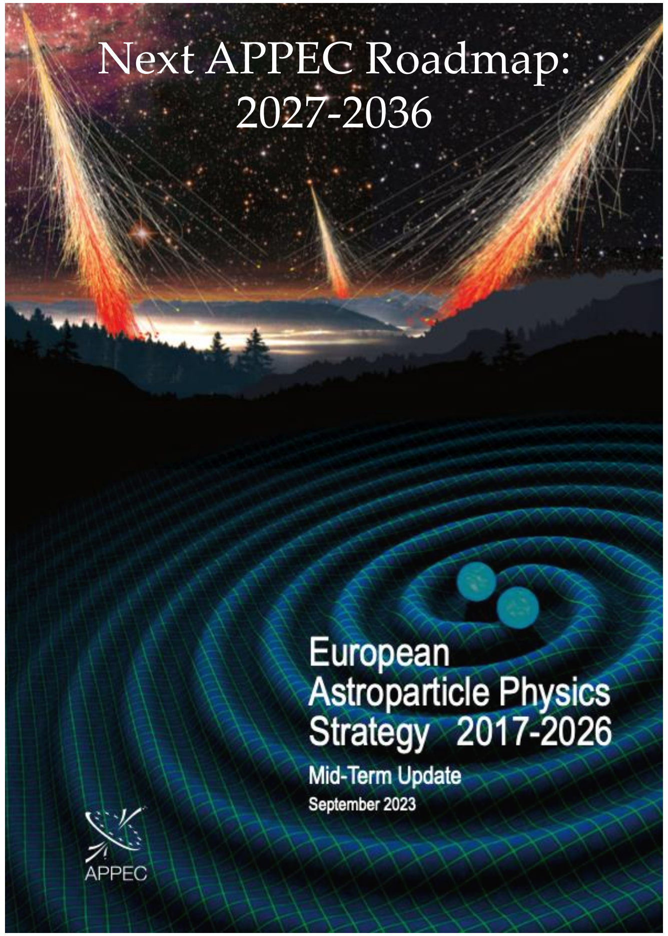
- Moreover, modern technologies cover:
  - gravitational waves detection needs *interferometry* with *high-precision optics, mirrors*
    Synergy: fast triggering, vacuum technology
  - Quantum technologies





Strategies





1991-1997-2004-2010-2017

European Strategy for Particle Physics Update 2020

- *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..*

→ Brought us the ECFA Detector Roadmap (see later)

- Successful completion of High-Luminosity LHC must remain key focus

Strategy Update 2026

http://europeanstrategy.cern and https://europeanstrategyupdate.web.cern.ch

263 input proposals

End September 2024
Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024
Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025
Deadline for the submission of main input from the community

26 May 2025
Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025
Open Symposium

End September 2025
Submission of the "Briefing Book" to the **ESG**

14 November 2025
Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025
ESG Strategy Drafting Session

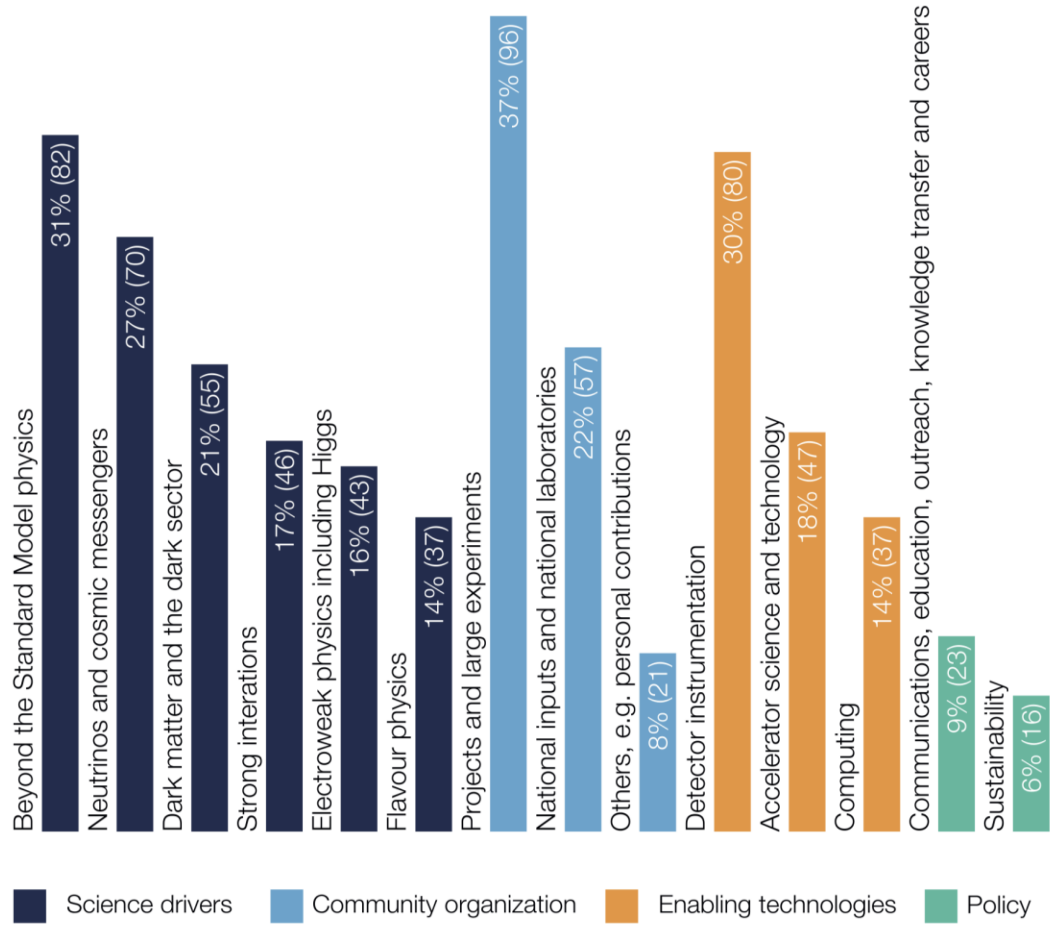
End January 2026
Submission of the draft strategy document to the Council

March and June 2026
Discussion of the draft strategy document by the Council and **updating of the Strategy**

ÖAW AUSTRIAN ACADEMY OF SCIENCES

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

Input Proposals submitted



Full text of all input proposals at this link or use Input Explorer, an AI-enhanced search tool

- **National inputs**: official statements of CERN member states about their preference for the next collider
- **Topical inputs** on:
  - **Accelerator projects:** Linear Collider (#140),CLIC (#78), LEP3 (#188), LHeC (#174,#214), CLIC (#78), Muon Collider (#152, #207), FCC integrated program (#241)
  - **Full detector concepts and study reports**: ePIC (#17), ATLAS Upgrade (#189), ALICE3 (#70), LHCb Upgrade II (#148), Belle II (#205), [MUSIC Muon Collider Detector (#32)], SHiP (#145)
  - **FCC/Higgs Factory projects**: Physics Experiments and Detector (PED) of FCC feasibility study (#95), ECFA HET Study (#141), SiD (#94), ILD (#102), ALLEGRO (#211)
  - **Subdetectors**: Si-W ECAL (#77), Muon Detectors for ALLEGRO (#133), Straw tracker (#142), beamstrahlung-monitoring (#160), MAPS-ToF (#262), 3D-pixel-Calo (#266)
  - **DRD Collaborations**: ECFA Detector Panel (#157), DRD1-gas (#229), DRD6-calo (#108), DRD5-quantum (#204)

Open Symposium and Briefing Book

Open Symposium Venice

CERN-ESU-2025-001
30 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

https://cds.cern.ch/record/2944678

250-page summary of input proposals, discussion topics and community view, compiled by Physics Preparatory Group and contains chapters on

- Intro and Theory
- Six Physics PPG groups: Electroweak, QCD, flavor, neutrino, cosmic messenger, BSM, dark sector
- Technology PPGs: accelerators, computing, detector instrumentation
- Projects comparison (based on ID281)

Work to come to this conclusion

ESG WG 2a: Assessment of large-scale accelerator projects at CERN

Key findings:

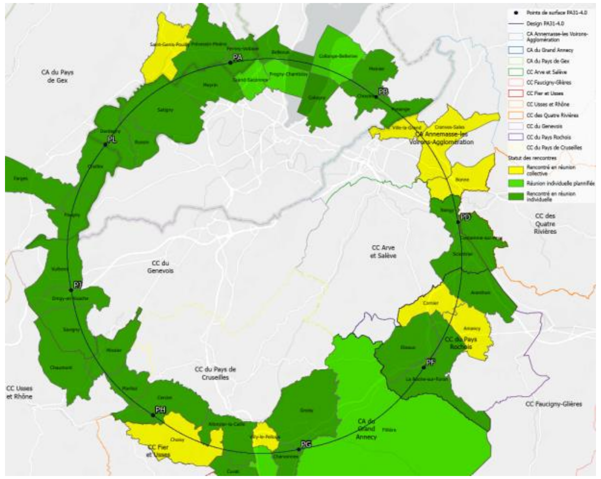
Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
CLIC 380GeV, 1.5TeV		4 - 6 / 5.2							
FCC-ee 91-365GeV		4 - 7 / 6.0							
FCC-hh 85TeV		4 - 7 (Nb_3Sn) / 4.3 2 - 7 (HTS) / 3.2							
FCC-hh - SA 85TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250-550GeV		5 - 7 / 5.5							
LEP3 91-230GeV		3 - 6 / 4.0							
LHeC: HL-LHC+50GeV ERL		3 - 6 / 4.5							
MC 3.2TeV, 7.6TeV		3.2TeV: 3 - 5 7.6TeV: 2 - 5							

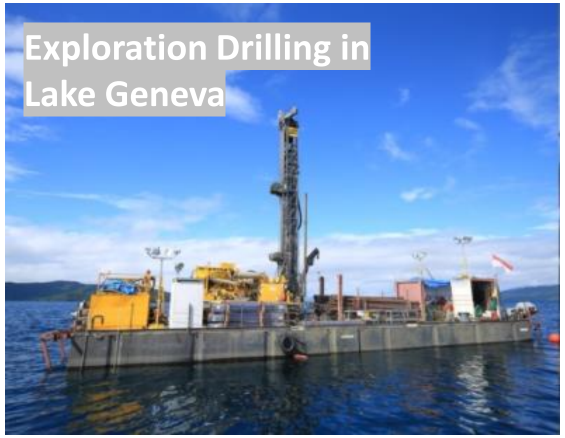
FCC Feasibility Study (2020-2025)

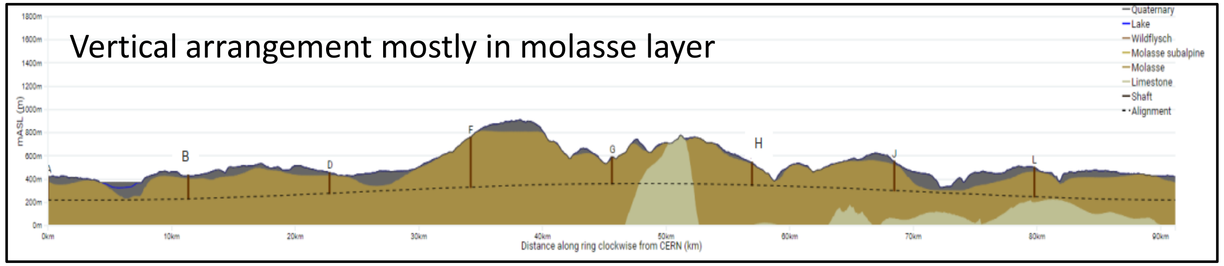
Feasibility Study Reports released 31 March as input to ESPP:
- Vol. 1: Physics, Experiments and Detectors (~200 pages)
- Vol. 2: Accelerators, Technical Infrastructures, Safety Concepts (~400 pages)
- Vol. 3: Civil Engineering, Implementation & Sustainability (~200 pages)

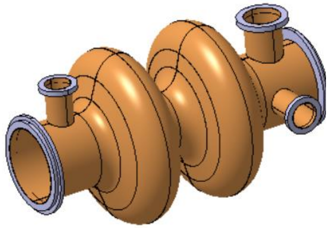
Reference layout and implementation: PA31 - 90.7 km
- Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment, (protected zones), infrastructure (water, electricity, transport), machine performance etc.
- Meetings with municipalities
- Site investigations to identify the exact location of geological interfaces with >30 drillings
- Excavation material: transformation from waste to resource
- Machine optimization: RF cavities, optics, Machine-Detector-Interface (MDI) with final focussing magnets far into experiments

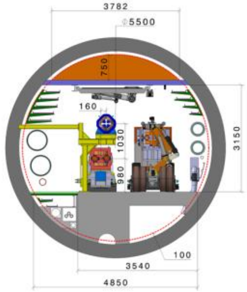
Futher info in talk by M.Benedikt

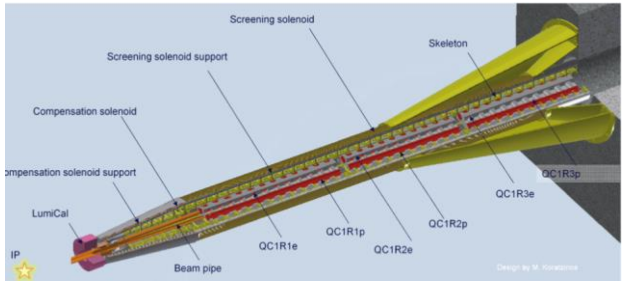







400MHz cavity for Z, W, ZH


Tunnel cross section



MDI with final focus

Proposed projects

FCC-ee

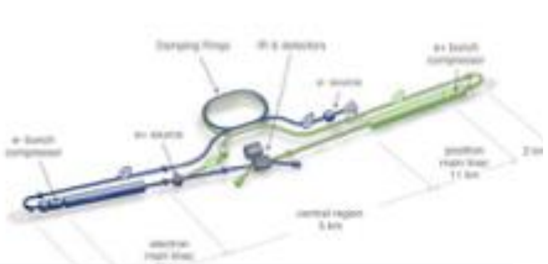
e⁺e⁻ colliders
("Higgs factories")

Up to 365GeV

FCC-ee (e⁺e⁻, circular, 91 – 365 GeV)

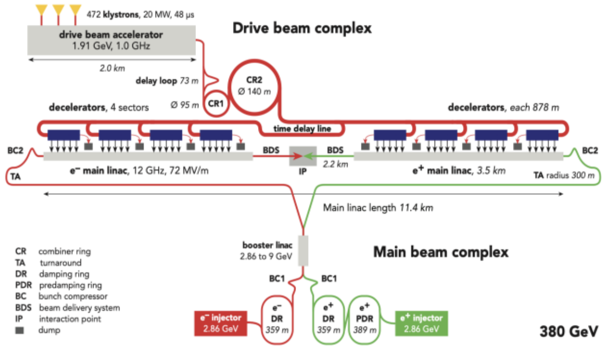
Cost: 15.3 billion CHF
(incl. 4 experiments)

Linear **C**ollider **F**acility (based in ILC technology)



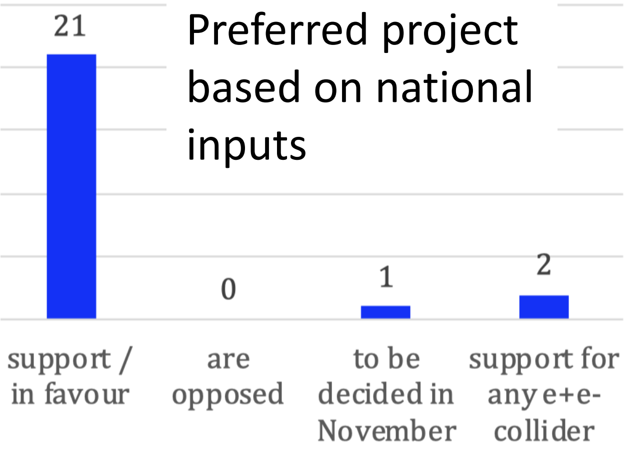
Cost: ~9.3BCHF (250GeV)
+5.4 BCHF (550 MeV upgrade)

CliC w/wakefield acc.



Cost: ~8.2 BCHF (380GeV)
+7.1 BCHF (1,5TeV upgrade)

CERN Member States (MS)



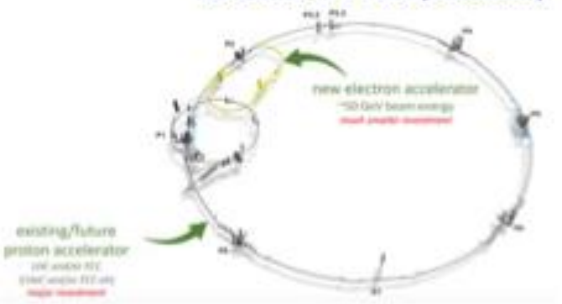
Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LEP3 (e⁺e⁻, circular, 91 – 230 GeV)

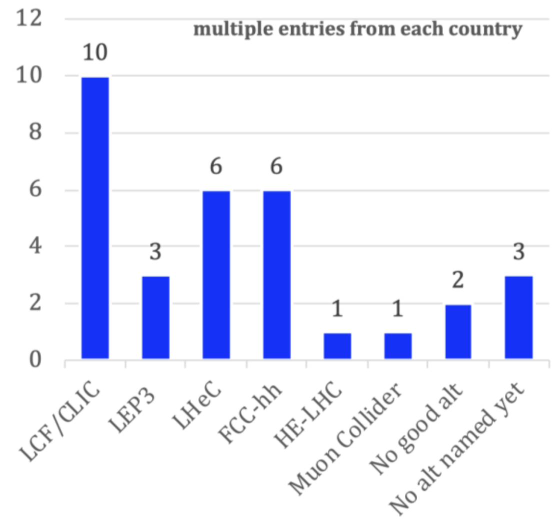
Cost: 4 billion CHF
(with upgrades of two existing Xpts)

LHeC (ep, circular, electron ERL, 50 GeV e⁻, > 1 TeV ep collisions)



Cost: ~2.4 billion CHF
(including 1 exp)

Alternative project:

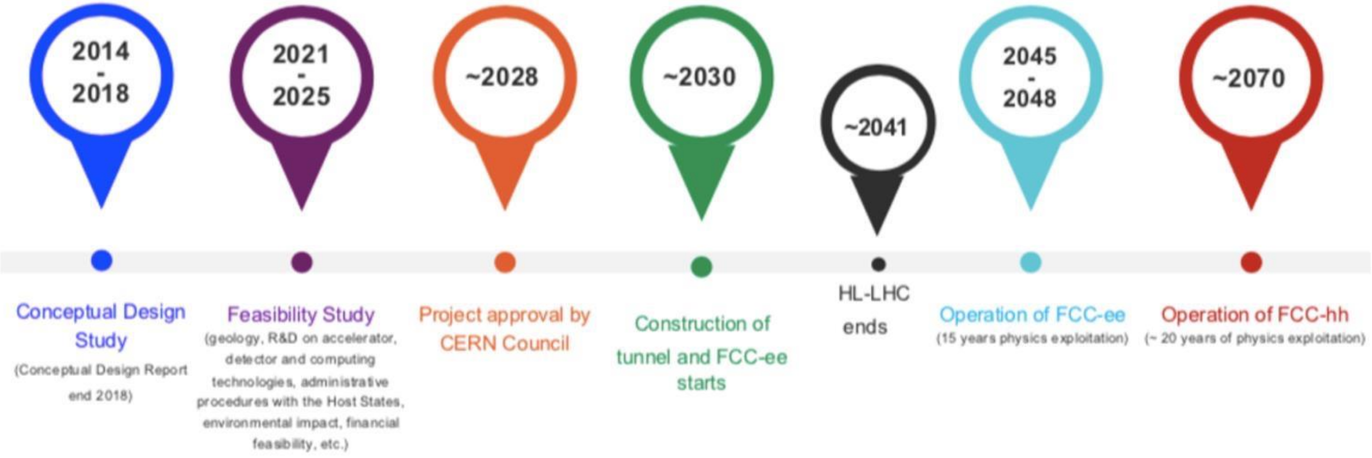


Cost numbers from Future Colliders Comparative Evaluation - Working Group Report ID281

(Possible) Next Big Collider

Recommendations from Drafting Session of ESPPU 2026:

- *A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.*
- *B. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.*



FCC Integrated Program:

Stage 1, Precision Frontier: **FCC-ee**

electron-positron collisions at 88-365 GeV

Construction: 2030-2045/48

Physics operation: 2045/48-2060

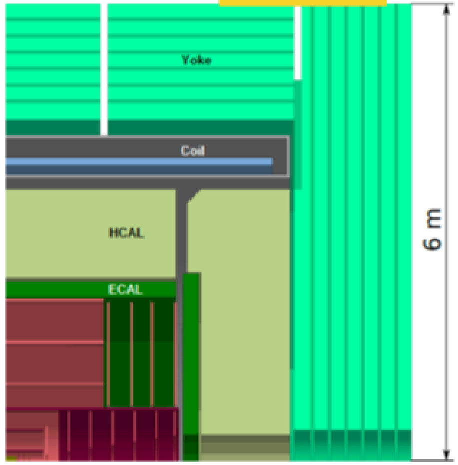
Stage 2, Energy Frontier: **FCC-hh**

proton -proton collisions at $\gtrsim$ 100 TeV

Physics operation: $\sim$ 2070

Detectors for FCC-ee

CLD (ID#95)

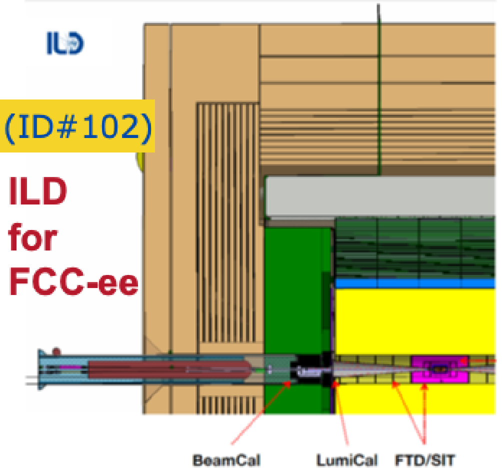


- VTX MAPS
- Main Tracker: Silicon
- Very high granularity (CALICE) inside the Solenoid
  - ECAL Si+W
  - HCAL Fe+scintillator
- PID: RICH and TOF
- Muons ID with RPC

(ID#211) ALLEGRO

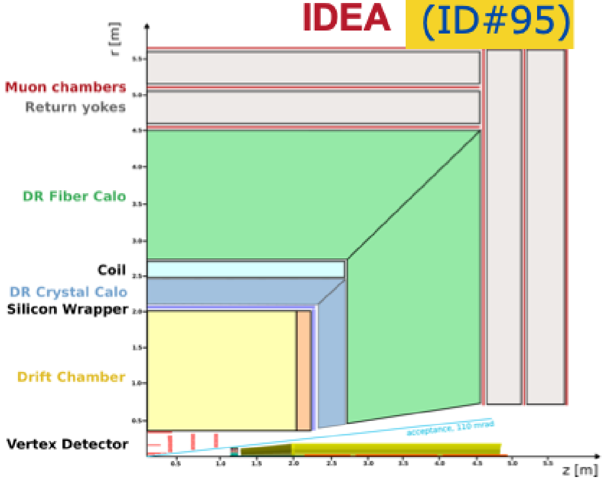
- VTX MAPS
- Main Tracker:
  - Drift Chamber/Straw/Si
- Si/LGAD wrapper (TOF)
- ECAL: Pb+L-Ar/W-L-Kr
- HCAL: Fe+scintillator outside the Solenoid
- PID: RICH (in case of Silicon main tracker)
- Muons with RPC

(ID#102) ILD for FCC-ee



- VTX MAPS
- Main Tracker: TPC
- Very high granularity (CALICE) inside the Solenoid
  - HCAL Fe+scintillator
  - ECAL Si-W
- Muons with scintillator

IDEA (ID#95)

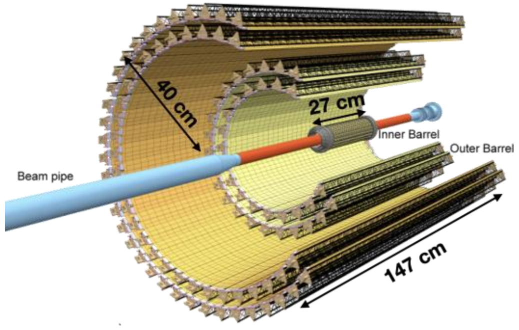


- VTX MAPS
- Main Tracker:
  - He+Isob drift chamber
- Si/LGAD wrapper (TOF)
- DR calorimetry (fibres):
  - ECAL: Crystals
  - HCAL: Iron **outside** the Solenoid
- HTS Solenoid (up to 3T)
- Muon ID: μ-RWELL

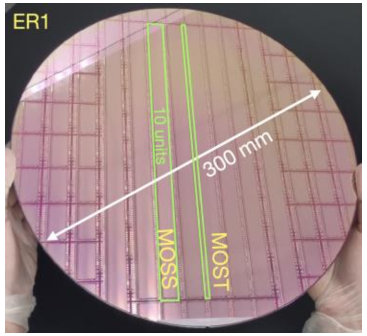
Vertex Detector Requirements of FCC-ee Exps., ALICE, ePIC, Belle II,..

Vertex Detectors for FCC-ee have **similar requirements** to **other experiments starting in the 2030ths** (ALICE3, ePIC, BelleII)

- Resolution (special single point: 3 µm, time: 5 ns)
- Hit rate/density (up to) 200 MHz/cm^2
- Power consumption < 50 mW/cm^2
- Radiation hardness TID: 100 kGy, NIEL: ~ 10^{13}/ cm^2
- Material budget: very low 0.3% of radiation length per layer



ITS3



	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW / cm^2)	35	70	20	<40	50
Hit density (MHz/cm^2)	8.5	96	0.6		200
NIEL (1 MeV n_{eq}/cm^2)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	˜0.3%
Pixel size (μm)	20	10	50	20	15-20

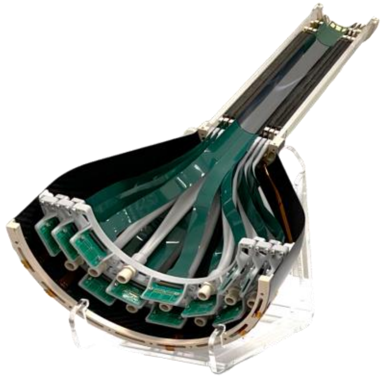
European Strategy Input ID Submission ID #70

“Eras” of HEP Experiments

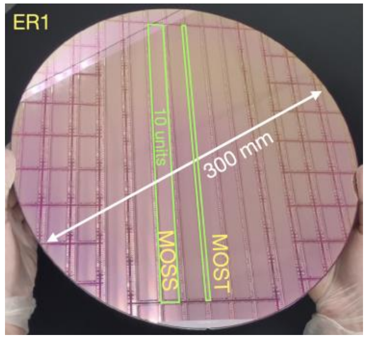
- **Experiments with similar requirements:**
  - **Era 1: Experiments/upgrades starting in the mid-2030s**: ALICE3, LHCb Upgrade 2, ePIC@EIC, Belle II Upgrade
    - Acting as “stepping stones” towards FCC
  - **Era 2:** mid-2040s: Higgs/Electroweak/Top factory detectors at FCC

  Commonalities: Vertex detector based on Monolithic Active Pixel Sensors, High-granular Calorimeter, Gas-detector tracker, PID with RICH and ToF → common developments useful (compare to RD53 for common ATLAS/CMS pixel ASIC)

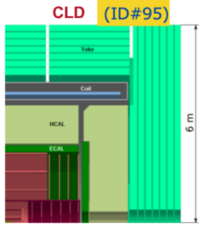
- **Era 3**: future hadron collider



ALICE ITS3



ALICE wafer-scale ITS3 sensor prototype



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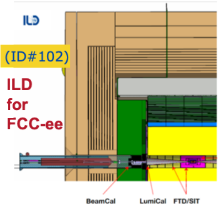

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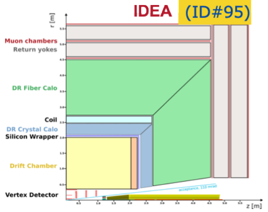

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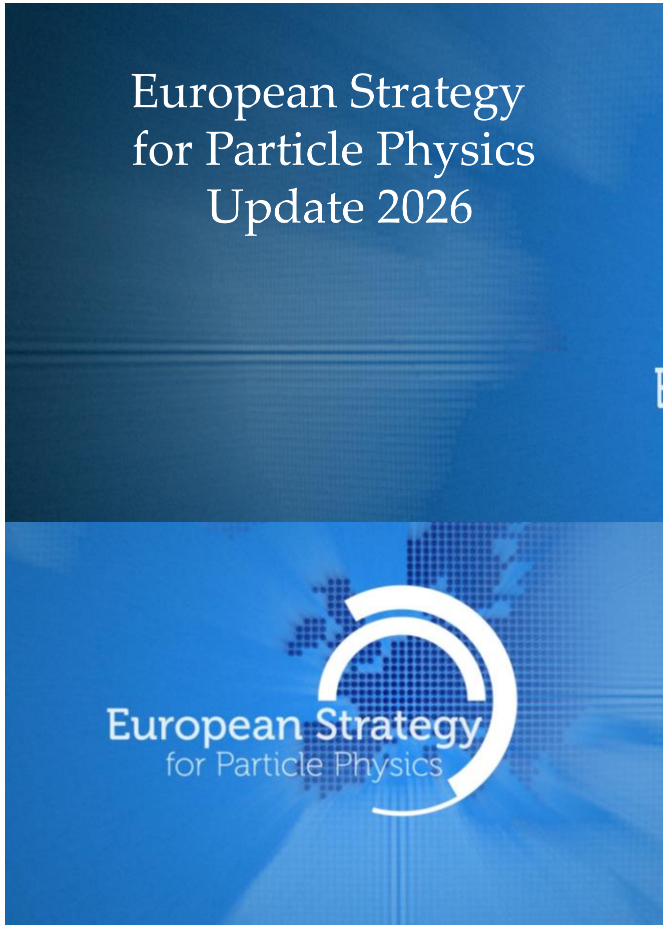
DRDs in Strategy Update

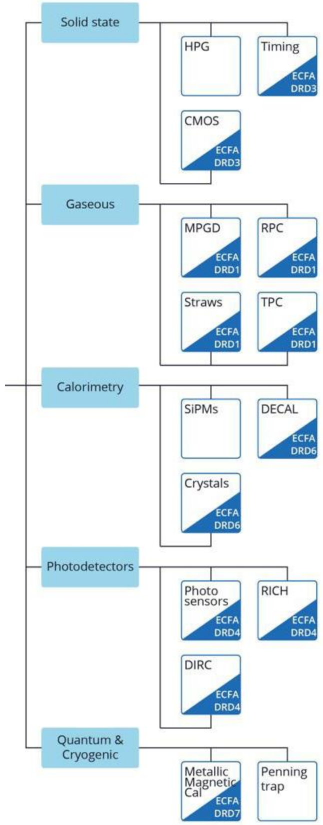


DRD collaborations are often referenced and seen as an already **established concept** in many input proposals (e.g. in many national submissions)

Neighboring fields:

- **Nuclear Physics**: large overlap with all DRD collaborations for high-energy NP, referenced in NuPPEC long-range plan 2024 in detail; Also e.g. 40% groups in DRD1
- **Astroparticle physics**: connection with DRD2 and DRD4, Intensifying cooperation suggested (e.g. German astroparticle submission #126,..)

APPEC welcomes the 2021 ECFA detector R&D roadmap for particle physics and acknowledges the synergy with particle physics detector R&D
(APPEC Roadmap Update 2023)

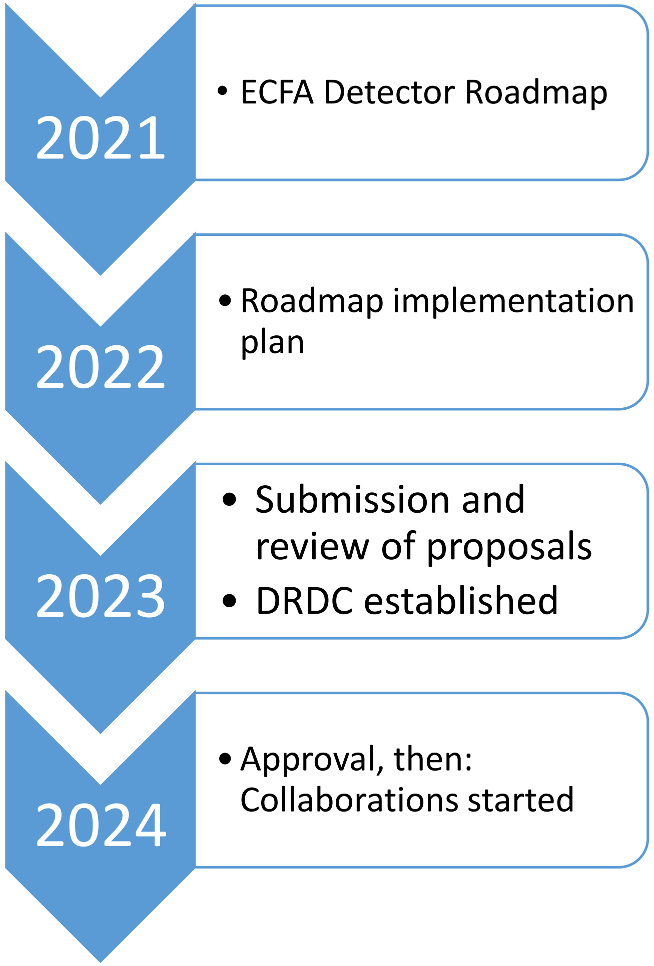


Instrumentation since ESPPU 2020

- ***ECFA Detector Roadmap*** as result of last ESPP Update 2020
  - Most of the chapter's convenors ("Task Forces") from ECFA Roadmap process became part of *Proposal Writing Teams* for new DRD collaborations

- ***Roadmap implementation plan*** defined that CERN will host the DRD collaborations
  - Approved by CERN SPC and Council in fall 2022 (CERN/SPC/1190 ; CERN/3679)
  - DRDC created as new committee at the same level as LHCC, SPSC and others; ECFA Detector panel kept an "advising role"

- **Approval of DRD collaborations** by CERN RB for an initial period of three years:
  - DRD 1,2 4 & 6 in December 2023 –> **2 years have passed already; renewal in Dec. 2026**
  - DRD 3, 5 and 7 in June 2024
  - DRD 8 in December 2024



ECFA Detector Roadmap

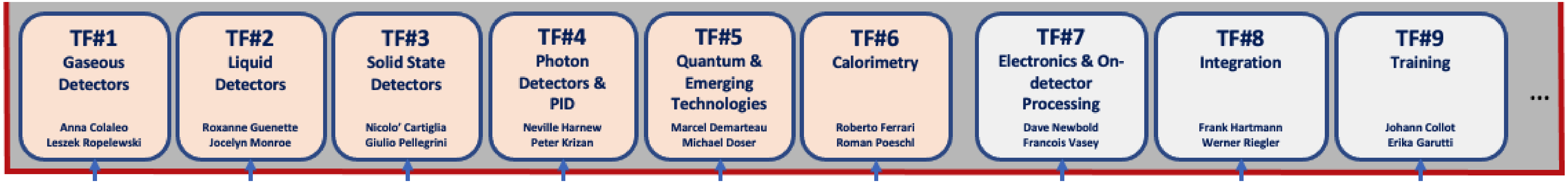
The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels. ***ESPPU 2020***

ECFA detector roadmap released in 2021 with full document (200 pages) and synopsis (~10 pages) based on a **community-driven effort** with many community meetings

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

Document contains:

- 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**" (GSRs) see next slide….
- **Nine Technology domains** with **Task Forces (TF)** areas:
  - The **most urgent R&D topics** in each domain, identified as **Detector R&D Themes** (DRDTs)



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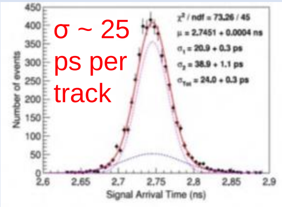
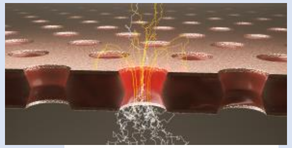
Strategic R&D: DRD Collaborations

DRD1: Gaseous Detectors

Large · Fast · eco-friendly gases · MPGD, e.g. GEMs

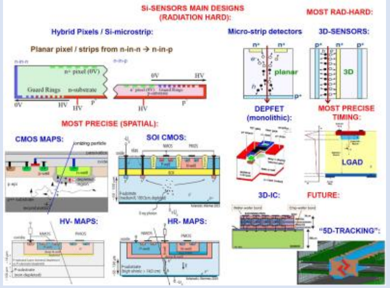




PICOSEC: NIMA903 (2018) 317

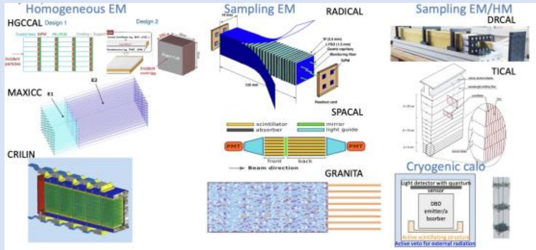
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.



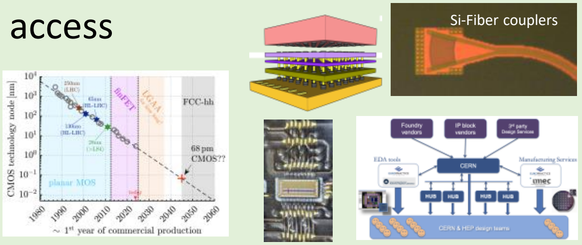
DRD6: Calorimetry

Energy resolution · High granularity · dual readout · particle flow · sandwich · optical



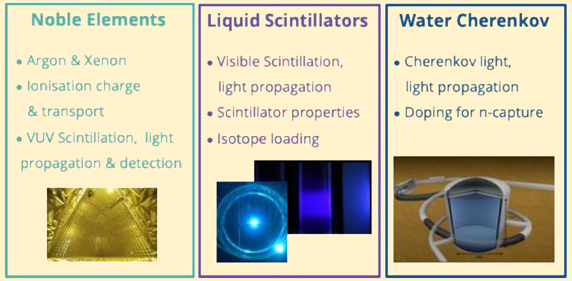
DRD7: Electronics

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access



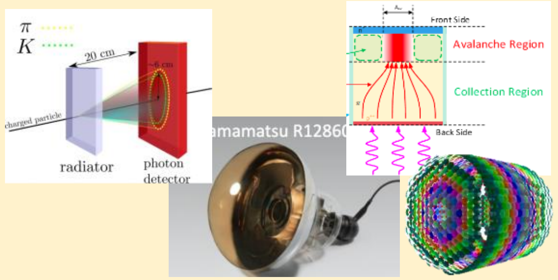
DRD2: Liquid Detectors

for Neutrinos · Dark Matter · 0vbb



DRD4: Photon detectors

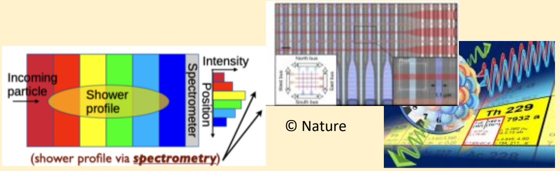
vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID, RICH, tracking



DRD5: Quantum Sensors

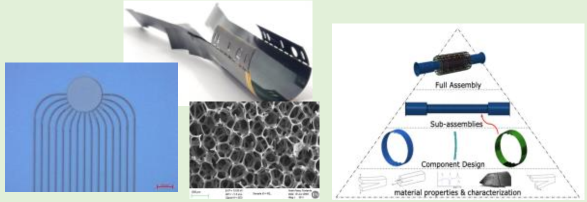
Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks

Applications in LEPP, first projects in HEPP happening



DRD8: Mechanics

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality



The DRD Collaborations

Eight DRD collaborations have been approved for an initial period of 3 years (extendable) with different histories and "maturity":

Just subscribers of e-groups.
Active people much less

- Based on previous R&D collaborations:
  - **DRD1: Gaseous detectors** (based on RD51): *161 institutes, 700++ people*
  - **DRD3: Semiconductor Detectors** (previously RD42, RD50): *145 institutions / 700++ people*
  - **DRD6: Calorimetry** (CALICE, other proto-experiment collabs.): *135 institutes*

- Completely new: (community building, building trust, and finding benefit of being "CERN hosted")
  - **DRD2: Liquid Detectors:** *86 institutes, 205 members*
  - **DRD4: Photodetectors & PID:** *74 institutes*
  - **DRD5: Quantum Sensors and emerging technologies:** *112 involved groups*

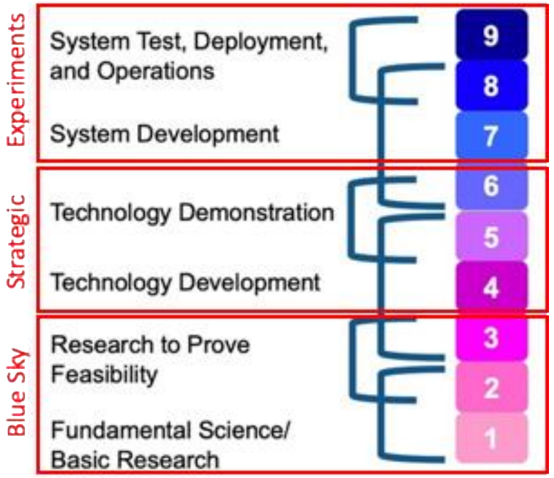
- Transversal activities: no service provider, but with genuine R&D interest (TF9 → ECFA Training Panel)
  - **DRD7: Electronics:** *67 Institutes*
  - **DRD8: Mechanics & Integration:** *38 institutes*

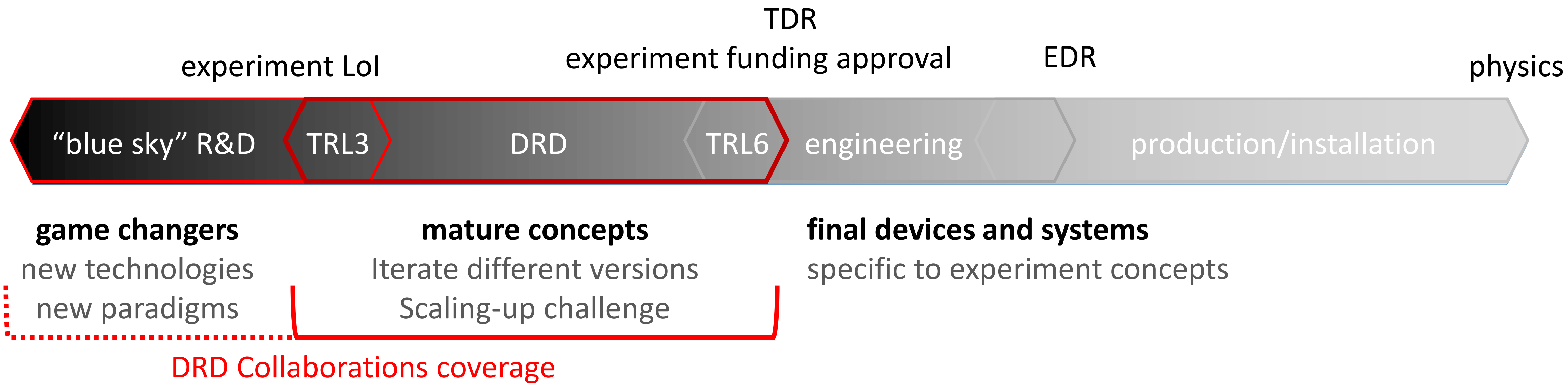
Detector Dev. covers low TRLs

- **“Blue Sky” R&D** develops new technologies (TRL 1-3)
- **Strategic R&D** (TRL 3-6) bridges the gap between “blue sky” and the deployment and use in a HEP experiment (TRL 8-9)

  covers the **development and maturing of technologies**, e.g.
  - Iterating through different options
  - Improving radiation hardness
  - Scaling up: detector area, number of channels, layers,..
  - …

Technology Readiness Levels (TRL):





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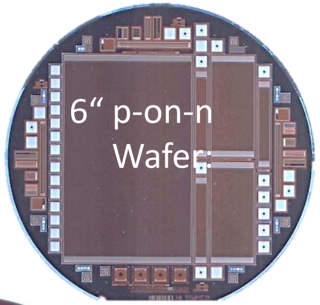
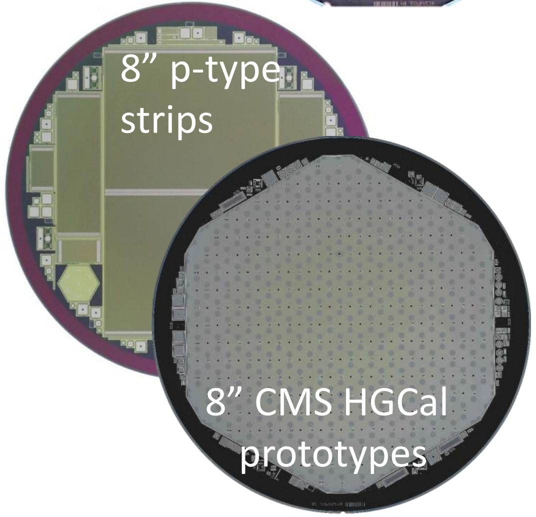
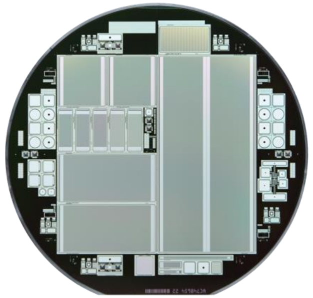
Collaboration Infineon - HEPHY

- We worked (under old name HEPHY) for almost a decade with Infineon on large-area planar Si sensors, targeting Phase-II Upgrades of LHC experiments at CERN
  - Attracted a lot of attention (CERN, Infineon Austria CEO)
  - 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:
  - Several more lots would have been necessary to mature the technology
  - No proper funding model





6” CMS PS-S prototypes




Infineon CEO together with HEPHY and CERN representatives


Former CERN DG R. Heuer with Infineon and HEPHY staff

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Recommendations on Detectors

Detector R&D is essential for realising future experimental research programmes. This effort is strengthened by the Detector R&D (DRD) collaborations, which have recently been established in accordance with the ECFA Detector R&D Roadmap as a result of the 2020 Strategy update. The roadmap outlined ten General Strategic Recommendations, including sustainable support of R&D facilities, such as test beam and irradiation centres, promoting distributed R&D activities and open science, maintaining engineering support and investing in blue-sky R&D.

- *E. For the DRD collaborations to address the requirements of future flagship projects, they* ***must receive adequate funding****. New R&D topics and initiatives should be integrated in the DRD scheme. The* ***General Strategic Recommendations*** *in the roadmap must be fully addressed by dedicated initiatives coordinated across the DRD collaborations.*
- *F. A coherent, strategic approach and sufficient resources to support* ***close cooperation with industry*** *are required to address the rising costs and growing complexity in engineering, particularly in* ***microelectronics****.*
- *G. To enhance efficiency and align developments with global technology trends in other fields,* ***standardised, off-the-shelf solutions*** *should be prioritised over custom designs, where applicable.*

Generic Strategic Recommendations

Formulated in the ECFA Detector Roadmap as ten "action items"

- **International coordination** and organization of R&D activities (GSR 4)
- Establish long-term strategic **funding programs** (GSR 6) → ongoing
- Support "**Blue-sky**" R&D (GSR 7) → ongoing

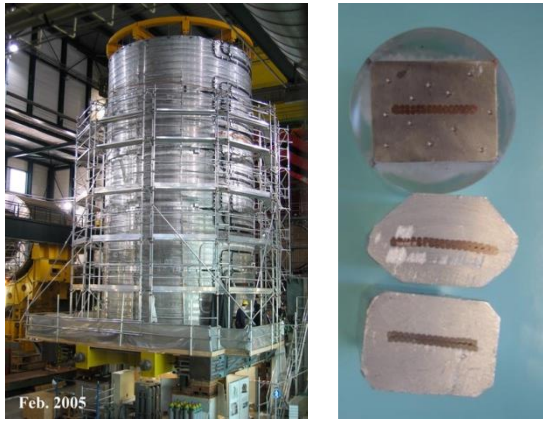
DRD Collaborations

- Supporting **R&D facilities**: test beams, large-scale prototyping, irradiation (GSR 1)
- **Engineering support** for detector R&D (GSR 2)
- Specific **software** for instrumentation (GSR 3)
- Distributed R&D activities with **centralized facilities** (GSR 5)
- Attract, nurture, recognize, and sustain the **careers of R&D experts** (GSR 8)
- Establish and maintain **Industrial partnerships** (GSR 9)
- Support **Open Science** (GSR 10)

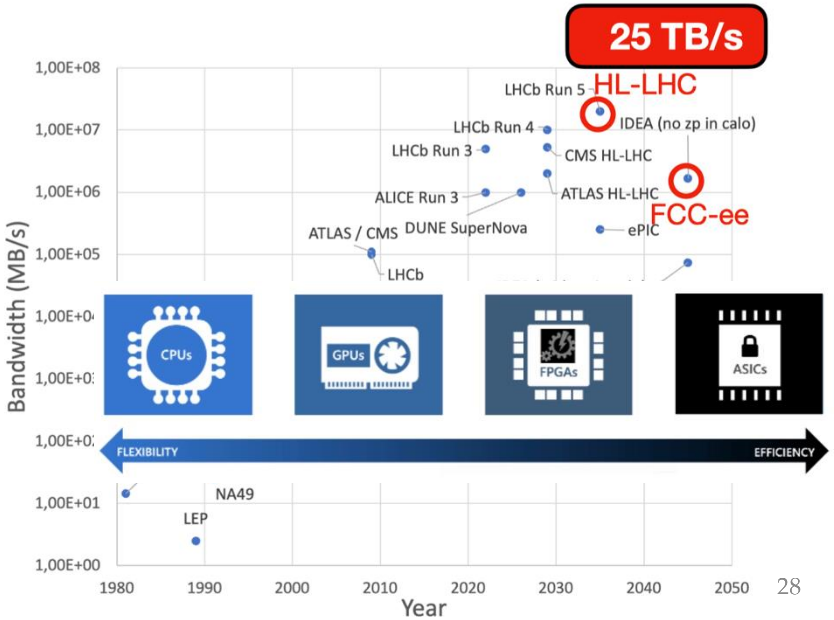
All topics still valid and highly relevant

What is beyond the current DRDs?

- **Superconducting Experimental Magnets (initial in TF8)**
  - Al-stabilized Nb-Ti conductor technology used >20 years ago for LHC experiments, worldwide no vendor now, but ALICE3 and ePIC need
  - Research aligned with CERN activities, see 2022 workshop and arXiv:2203.07799
  - HTS as an alternative with possible synergy to accelerator magnet R&D
- **Rare event detectors**
  - Several submissions (e.g. #112 proposing a high-TRL R&D network)
  - DRD5 would also provide a suitable host for e.g. bolometers
- **New TDAQ methods** with AI, intelligence on the detector
  - "triggerless" DAQ creates high data rate, throughput challenge (e.g. #127)
  - AI-RDs collaborations proposed as a parallel structure to DRDs (#167)
  - Personal comment: I would not create several AI-RDs, s
- New approach in **microelectronics**
- **Attracting more person power, funding**, and engaging new communities



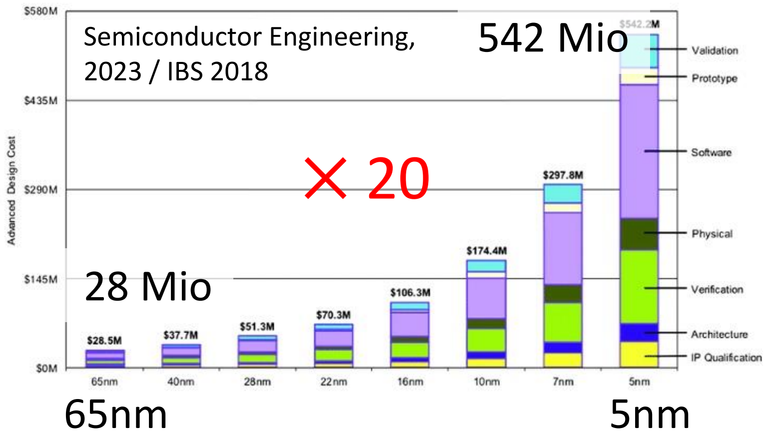
CMS Solenoid 2005



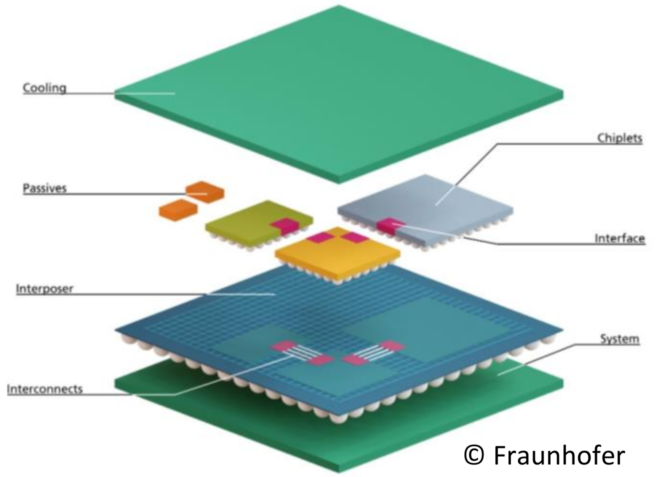
Microelectronics Challenge

#161, GSR 2, GSR 5, GSR 9

- The **cost and complexity** of developing advanced CMOS technologies have risen dramatically. **HEP is now lagging behind commercial technology**
  - In 1999: APV25 (CMS Tracker ASIC) and Pentium-III shared the same technology (250 nm)
  - Now: 3 nm at TSMC (e.g. Apple M4) vs. 28 nm in FE-ASIC and 65 nm in MAPS
- Mitigation by **seeking resources beyond HEP** and forming **broader collaborations**, actively encourages cross-disciplinary developments
  - **Fewer, common developments with higher volumes**
  - Use modern technologies with standardized, common **chiplets** combined to chips tailored to different needs



Recommendation: A **strategic, coherent approach** is needed to address the increasing costs and complexity in **microelectronics and ASIC development**.



© Fraunhofer

Broadening the community

- New technologies and scientific fields have emerged in recent times, including quantum sensing/computing, and communication, as well as gravitational waves. However, the number of STEM students has not grown significantly
  - Attract, nurture, recognize, and sustain the careers of R&D experts (GSR 8)
  - **Biggest threat in my opinion!**

- Bring in disruptive ideas and technologies, e.g. in quantum sensing → Blue Sky funding (GSR 7)
- Involve the industry early in R&D processes and co-develop (GSR 9)

- HEP needs to welcome expertise from outside the traditional domain: Chip design, material science, advanced manufacturing, mechanics, QA,…
- Cooperate with overlapping domains: astro-particle, medical physics

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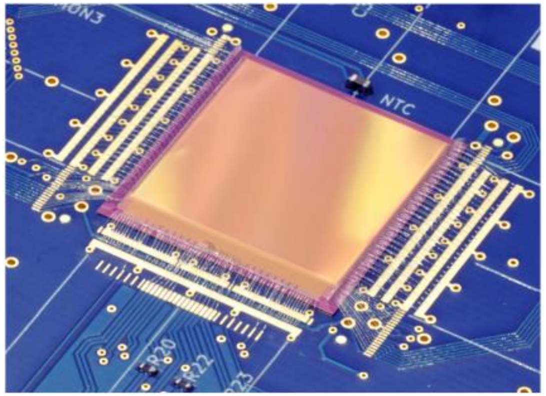
Semiconductor Detectors at MBI

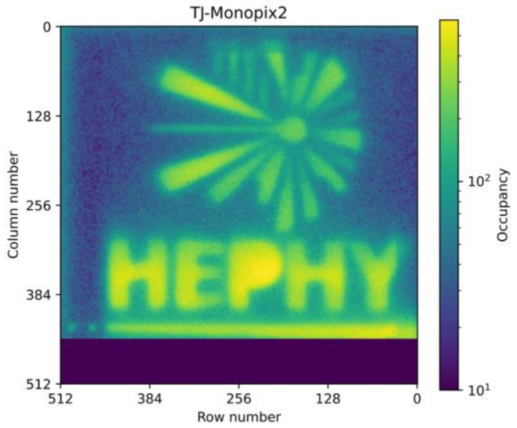
Detector Technologies at MBI

Research topics at MBI on solid-state detectors:

Monolithic Active Pixel Sensors

- Sensor design becomes chip design
- Applied to the planned Belle-VTX upgrade (OBELIX), FCC-ee vertex detector (OCTOPUS), and possibly ALICE3 OT
- Using Towerjazz 180 nm and TPSCo 65nm processes

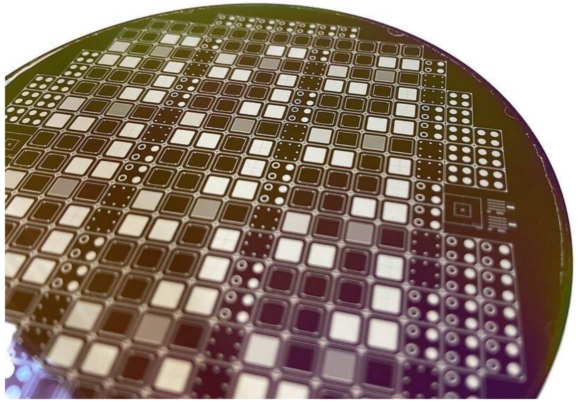


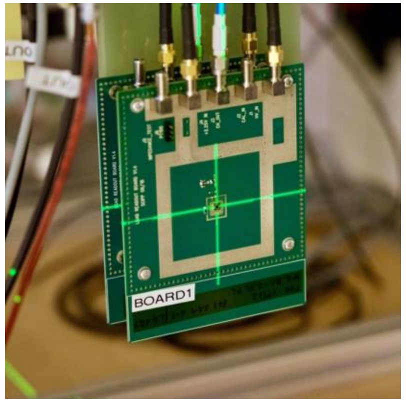


Exposure with ^{90}Sr Source above 15 mm PLA Mask.

Wide-bandgap Semiconductor

- Studies to better understand material properties (ionization energy, charge carrier mobility, rad. hardness,..)
- Aim to develop HEP-compatible detector
- Many applications outside HEP





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DRD3 R&D Topics and DRDTs

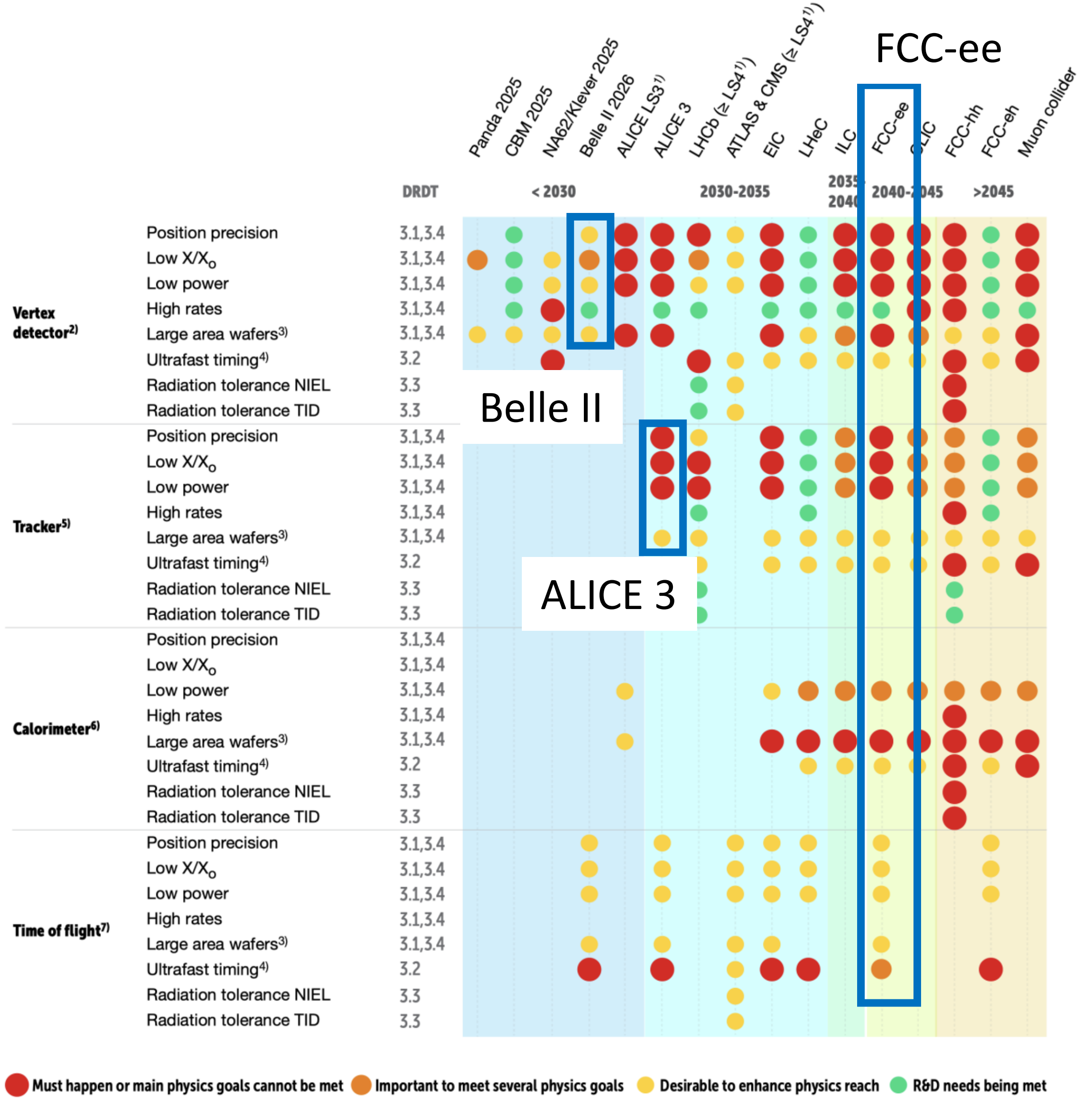
- **Detector R&D Themes (DRDTs)** were formulated as high-level deliverables:

Solid state

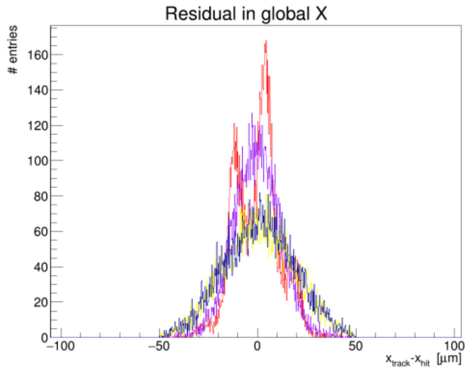
DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics

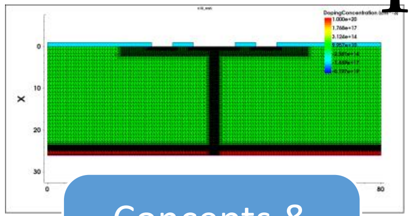
At MBI/DD we cover three of those

The most urgent R&D topics are identified by **Detector Readiness Matrix** in the ECFA Detector roadmap

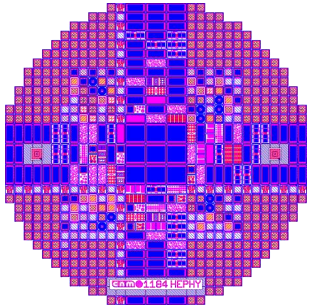


Our Sensor Development Cycle



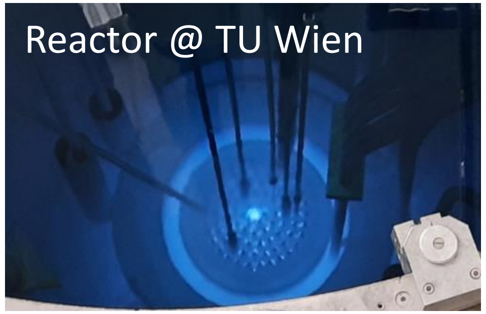


Concepts & Simulations



Sensor Design

Results: Analysis & Paper

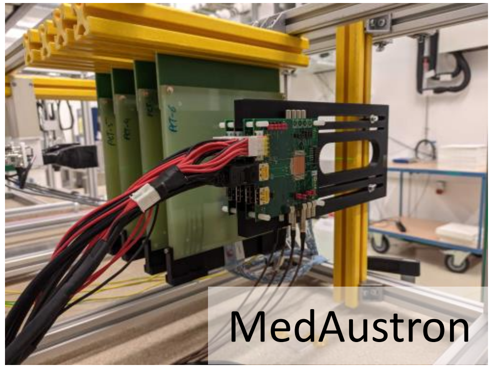


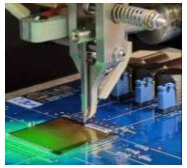
Irradiations n/p/gamma

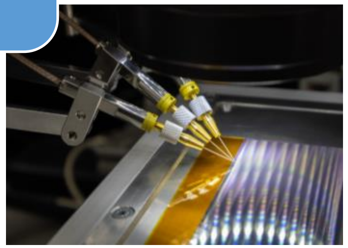
Production (extern)

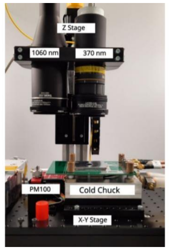
Beam tests MedAustron/ DESY/CERN

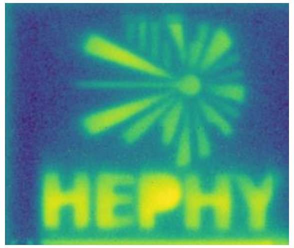
Characterization Electrical, Laser & Sources











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Necessary Infrastructure

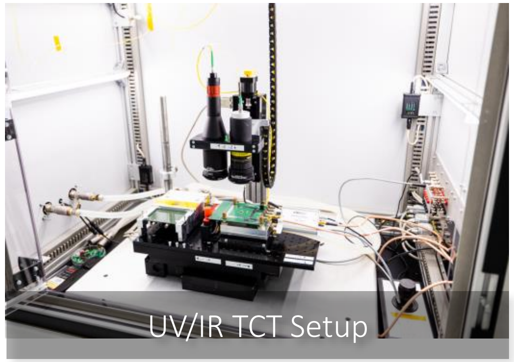
We are using high-level equipment for sensor characterization and module construction

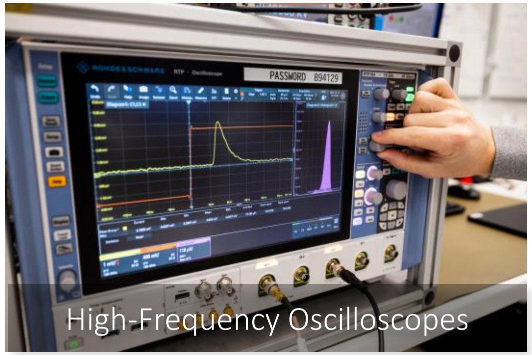
- Several custom probe stations for sensor tests
- TCT Setup with lasers for signal generation (IR/UV)
- Fully automatic thin-wire bonding machine
- Climatic chamber, different Microscopes (a.o. 3D confocal laser)
- DAQ Systems, Digitizers, HF Oscilloscopes, …….
- Radioactive sources (Sr-90, Am-241, Tri-Alpha, Fe-55,..)
- Software for sensor, chip, and electronics design and simulation


Thin-wire bonding machine


Climatic Chamber


Alpha/Vacuum Setup


UV/IR TCT Setup

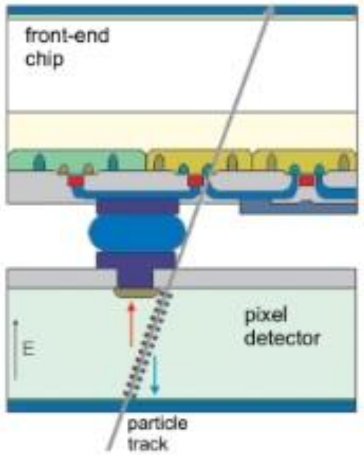

High-Frequency Oscilloscopes


HF Shielding Box

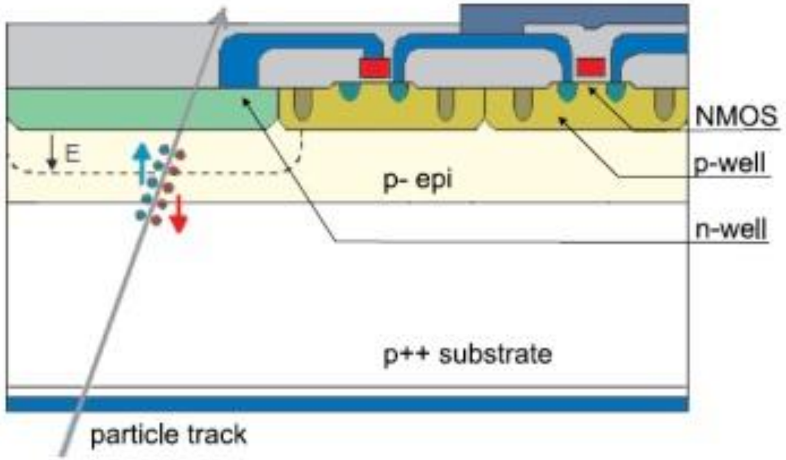

3D confocal microscope


Radioactive Sources

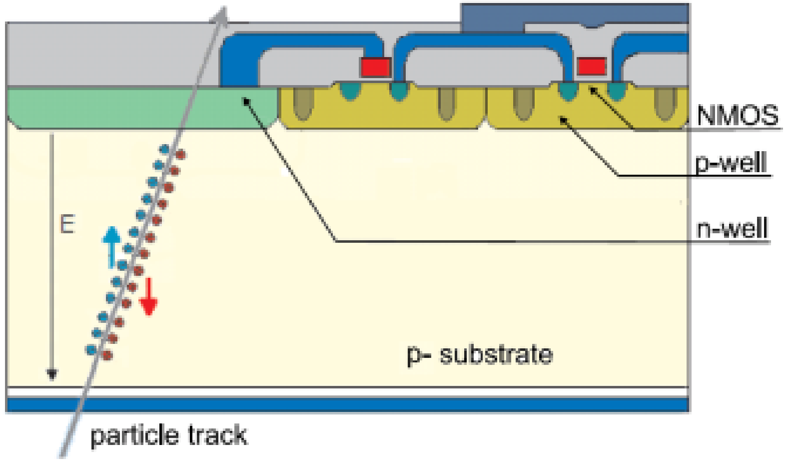
Monolithic Active Pixel Sensors



Hybrid pixel sensor



MAPS: ”low” HV ~6 V
so that charge collection is drift/diffusion



Depleted MAPS:
Fully depleted bulk
“HV-CMOS” ~100 V

- ***(Depleted) Monolithic Active Pixel Sensors*** (MAPS) merge charge-collecting electrodes and CMOS-based front-end electronics into one silicon die, which results in several advantages
  - Avoiding expensive and error-prone bump-bonding technology in hybrid pixel sensors
  - Lower material budget → better tracking performance
  - High granularity → high spatial resolution; Higher hit rate → higher luminosity

MAPS Projects at MBI

Monolithic Active Pixel Sensors Projects

LFoundry 150 nm
"large collection electrode"

RD50-MPW series

- Digital Periphery
- Caribou DAQ System
- Firmware

C Irmler, B Pilsl,
C Hahn, H. Steininger

Tower 180 nm
"small collection electrode"

Belle II Upgrade

- "OBELIX" Sensor design
- TJ-Monopix2 studies

M. Babeluk → R. Russo
C Irmler, H. Steininger

TPSCo 65 nm
"small collection electrode"

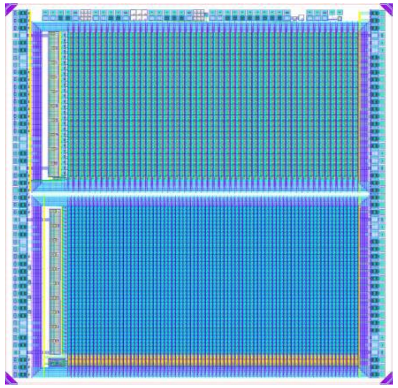
DRD3 Projects

- OCTOPUS (FCC-ee)
- MANTA for a "versatile" MAPS Sensor
- Caribou DAQ

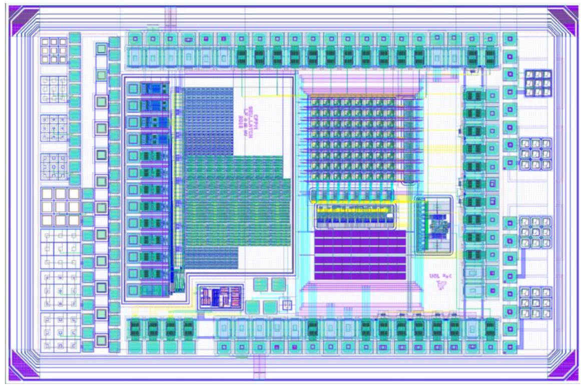
C Irmler, R Russo, J Habala

- Our Expertise: Digital End-of-Column logic, digital Periphery (ASIC-side), deserializer (FPGA DAQ Side), DAQ System FPGA firmware

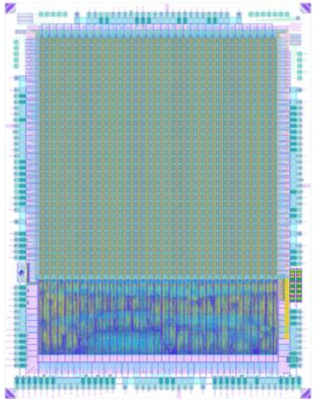
RD50 DMAPS Timeline



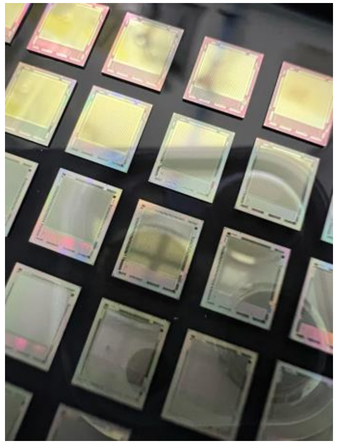
RD50-MPW1
(5mm x 5mm)



RD50-MPW2 (3.211mm x 2.120mm)



RD50-MPW3
5.1mm x 6.6mm



RD50-MPW4

MPW3/4 specs:

- 64x64 pixel matrix arranged in 32 FEI-3 style double columns
- Active area of $4x4mm^2$
- Pixel pitch of $62x62\mu m^2$
- 8-bit timestamp based on 25ns clock

HEPHY involvement started with PhD thesis (P. Sieberer) and Christian Irmler (Electronics group)

Submission and delivery date

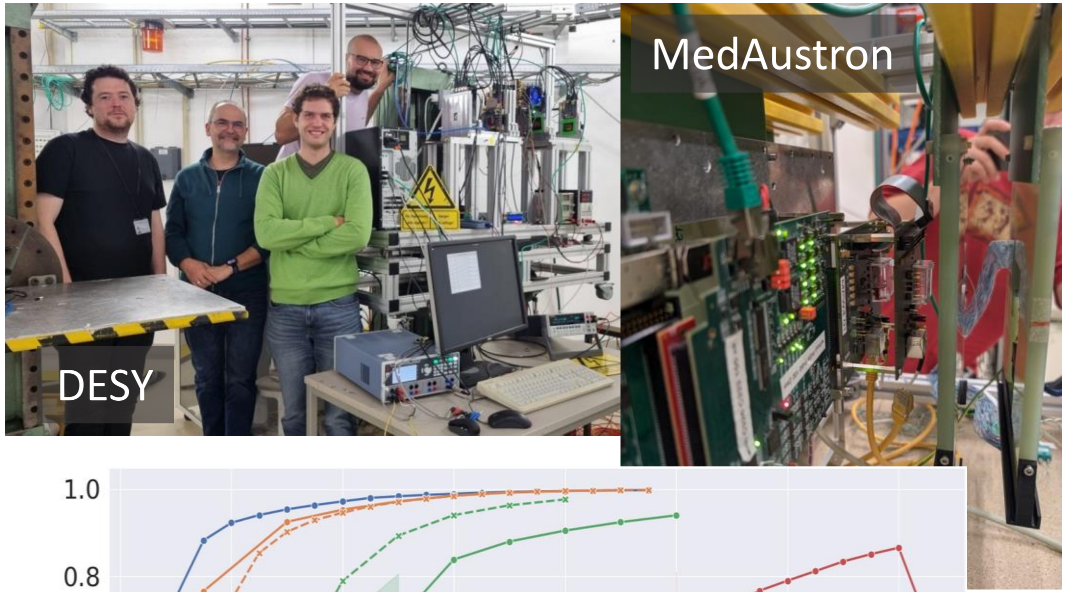
- RD50-MPW 1: started with DAQ System developments at HEPHY (backup slides)
- RD50-MPW 2: lab measurements, performed beam tests (backup slides)
- RD50-MPW 3 & 4: designed digital periphery, firmware programming

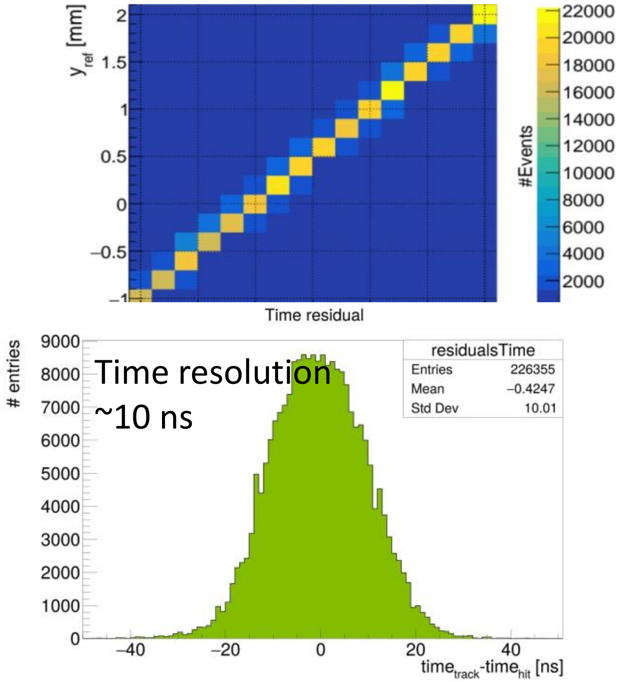
RD50-MPW4 Test-beam performance

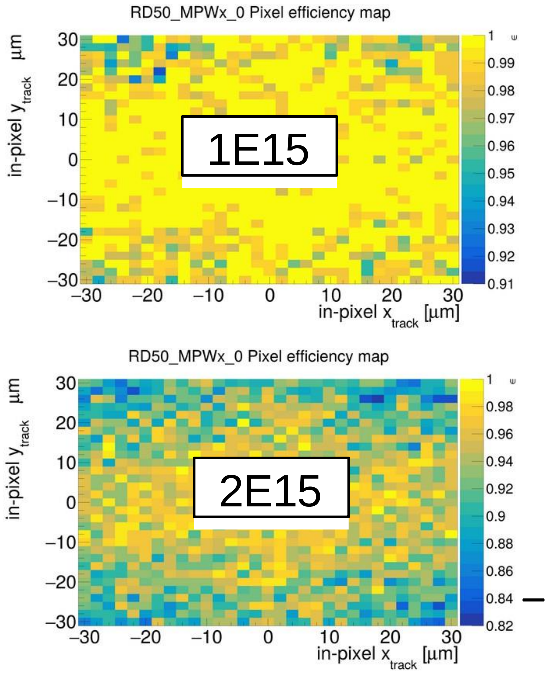
B Pilsl, H. Handerkas, C. Irmler et. Al [NIMA (2025), NIMA (2024),..]

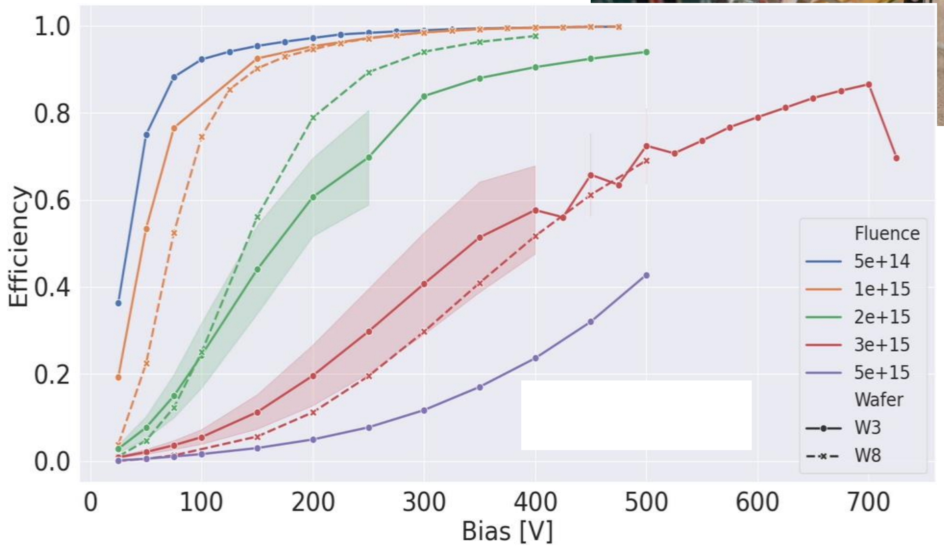
Various beam tests at MedAustron and DESY

- Samples got neutron irradiated to fluences from $1\times10^{14} - 1\times10^{16}$
- Irradiated devices need to be cooled: Peltier element-based cooling setup









- Efficiency drops to ~96% at 2×10^{15}
- Spatial resolution drops from 15.9µm to 17.9µm

DAQ Systems for DMAPS

C. Hahn / B. Pilsl (recent talk at OCTOPUS Meeting)

- Caribou DAQ System
  - Consists of a commercial FPGA evaluation board, self-made “CaR” main board, ASIC-specific chipboard
  - We proposed to use the Caribou system for the readout of MPW1
  - Baseline DAQ system for OCTOPUS, possibly also for MANTA

- HEPHY contribution:
  - Custom FPGA firmware for low-level chip debugging (electronics engineer)
  - Software development on integration in EUDAQ
  - Implemented fast data path: FPGA dispatches UDP packages, dedicated EUDAQ producer

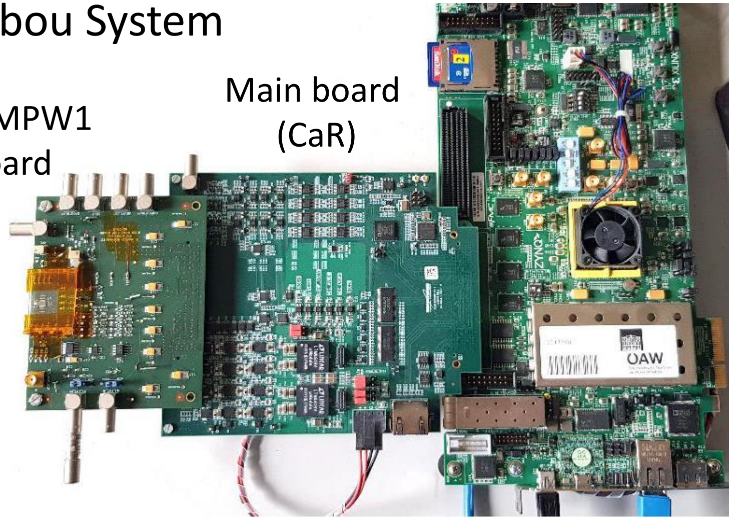
  - Porting to new FPGA evaluation board (Peary), S-curve, Trim-DAQ implementation

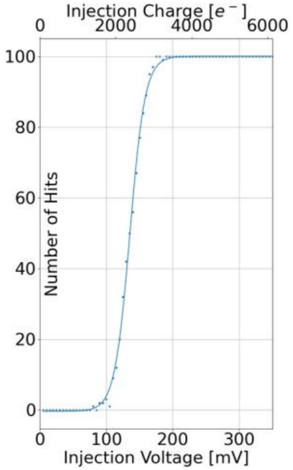
FPGA evaluation board

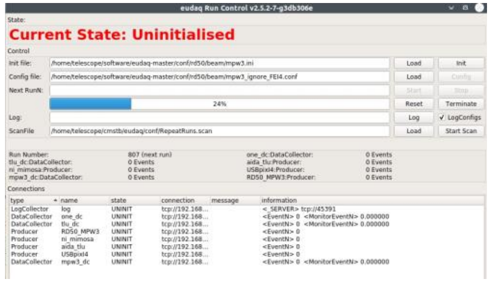
Caribou System

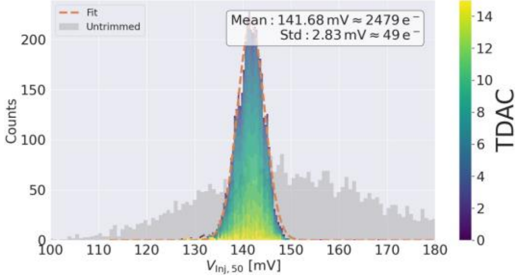
Main board (CaR)

RD50 MPW1 chipboard



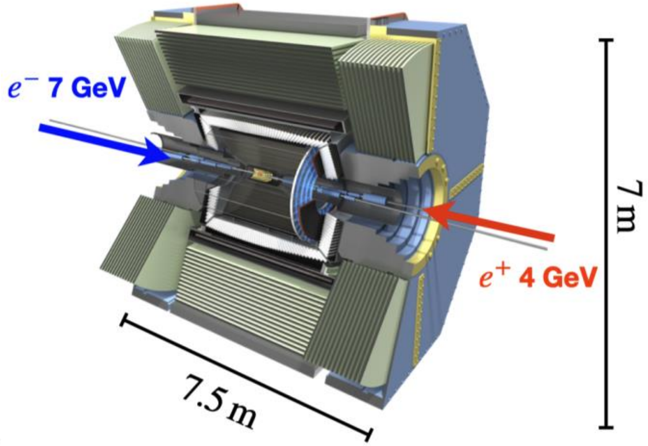


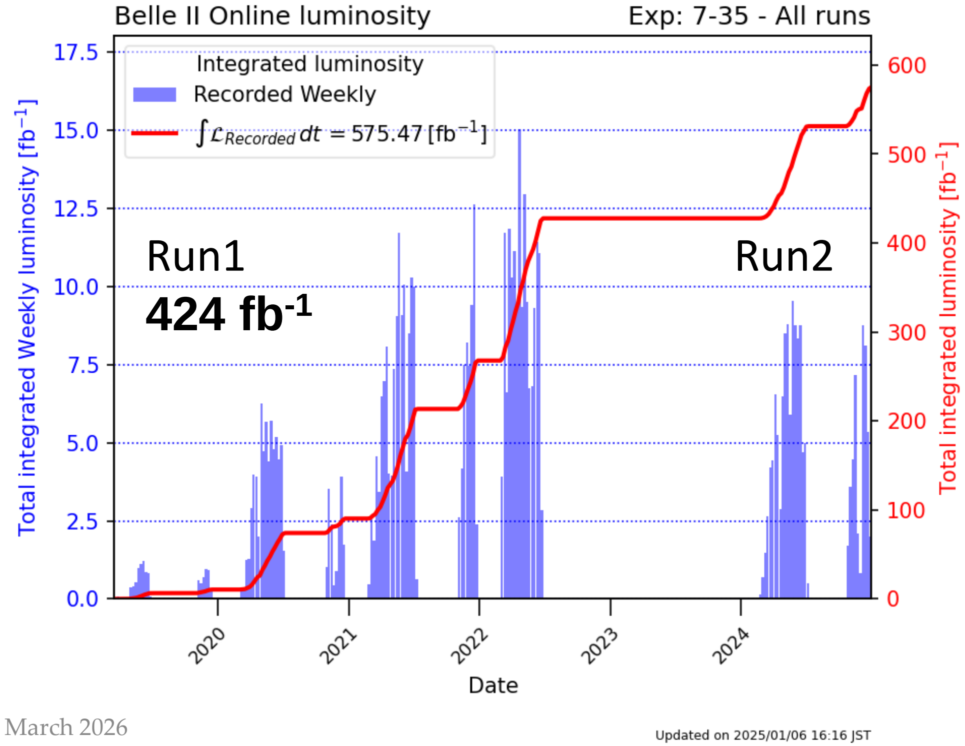




Belle II Experiment at SuperKEKB

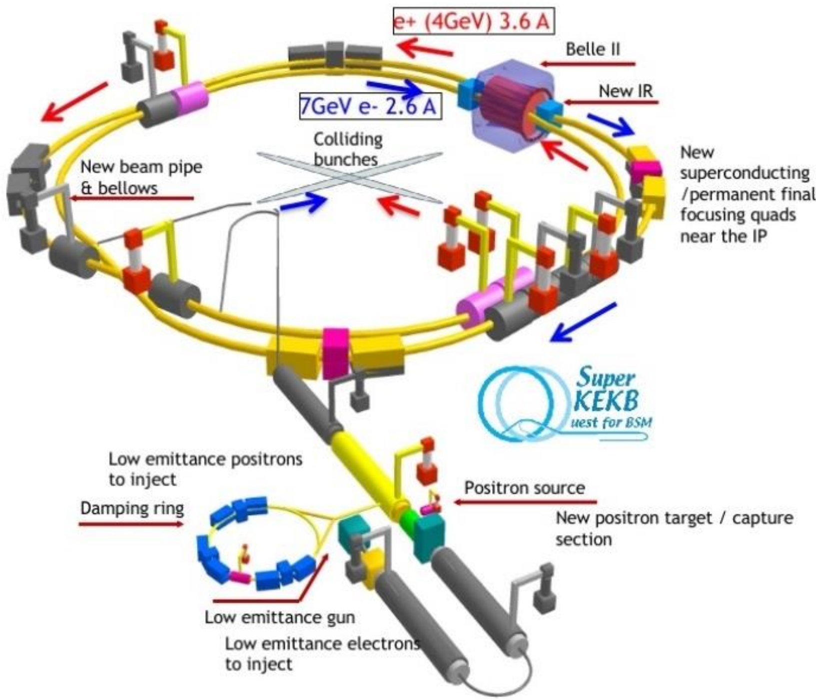
- Belle II searches for new physics beyond standard model at luminosity frontier
- SuperKEKB collider:
  - Asymmetric e^+e^- collisions at Υ (4S) resonance at 10.58 GeV
  - Long shutdown 2022/23, Run2 since 2024
  - Achieved luminosity 575 fb^{-1} with 4.7E34 $cm^{-2}s^{-1}$ (**target: 50 ab^{-1} , 6E35 $cm^{-2}s^{-1}$**)





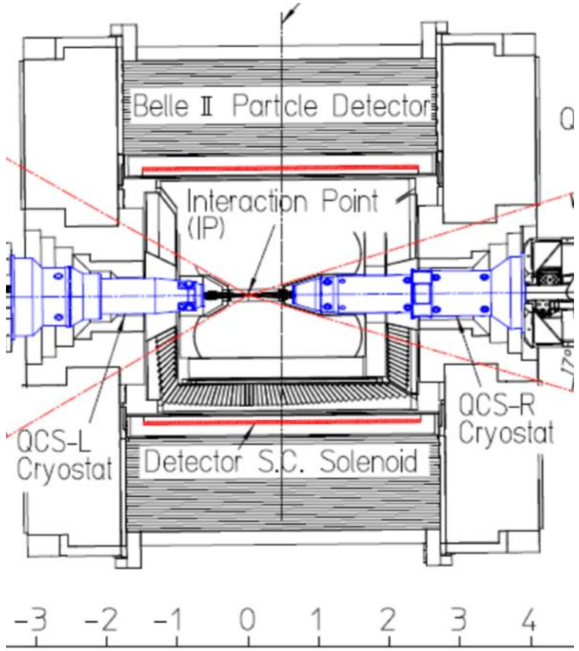
Belle II: FWD - BWD asymmetric onion-shaped detector

- K_L and Muon Detector
- EM Calorimeter
- Particle ID Detector
- Central Drift chamber
- Vertex Detector

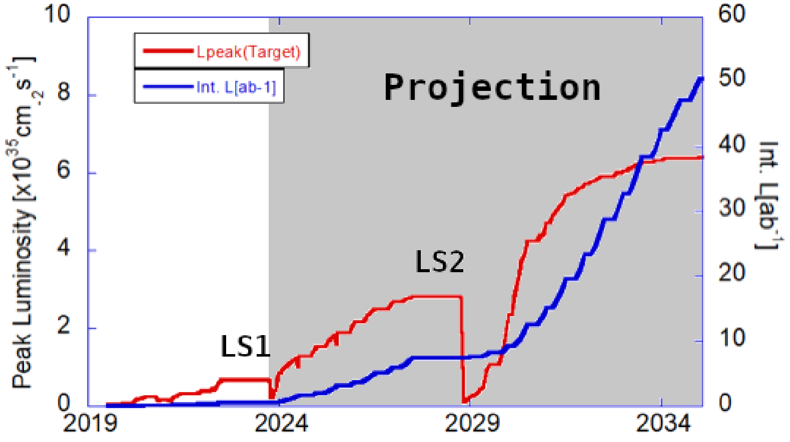


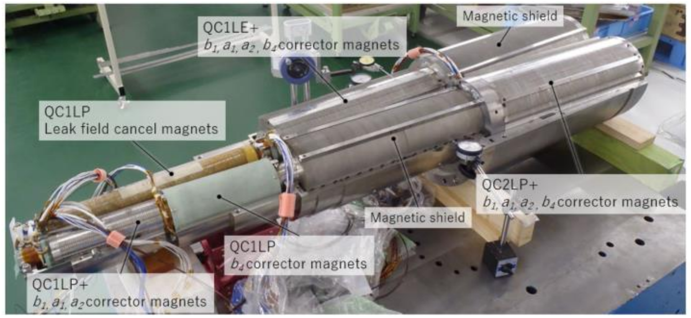
Motivation for Upgrade (1)

- Large uncertainty on background extrapolation at target luminosity and with a possible upgrade of the IR:
  - MDI design: Final focusing quadrupole QCS inside detector, actually consisting of several magnets (correctors, field cancel magnet,..)
  - Possible background mitigation scenarios [ref. CDR]
- Limited safety margin and performance degradation in high background scenario
  - PXD layer 1: up to 2% occupancy (32 MHz/cm^2)
  - SVD layer 3 up to 9% occupancy (9 MHz/cm^2)



- At target luminosity we may reach the limits of current detector
  ⇒ need higher granularity and time resolution in all layers



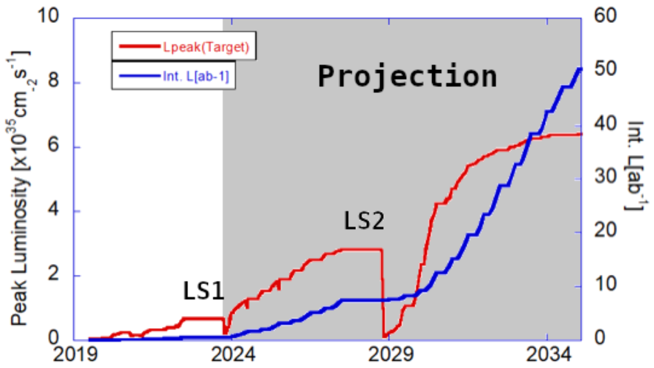


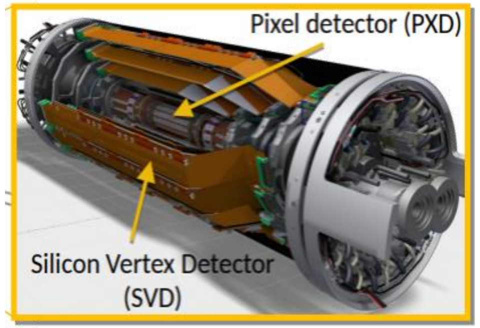
QCS superconducting final focussing magnet
https://doi.org/10.1016/j.nima.2021.165930

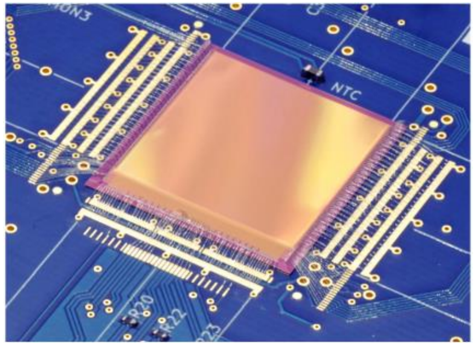
Belle II VTX Upgrade

Replace SVD+PXD with full MAPS detector

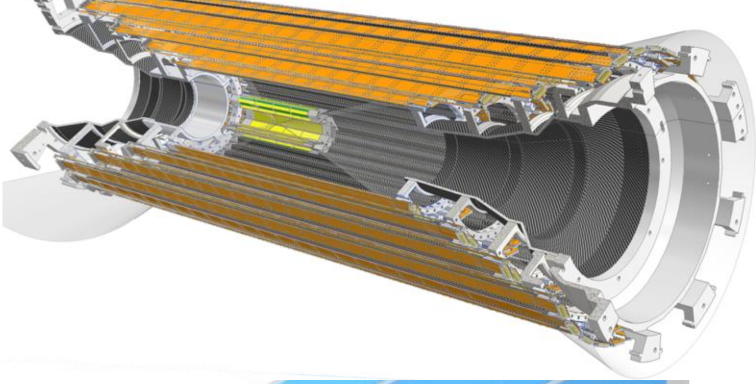
- Six straight layers with DMAPS CMOS pixel sensors, separated in two regions
  - iVTX (2 layers) + oVTX (4 layers)
- Reduce occupancy to improve tracking in high background using:
  - Spatial resolution <15μm results in 30 - 40 μm pixel pitch
  - 25 - 100 ns timestamp resolution
  - 120 MHz/cm² hit rate

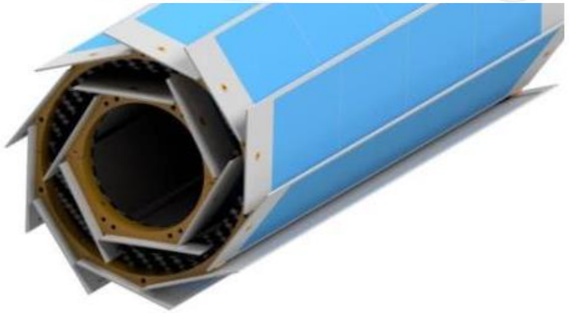


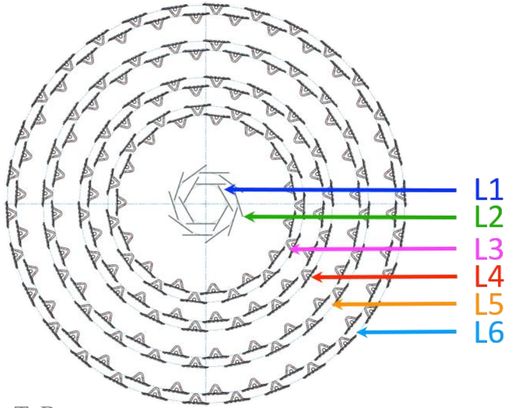




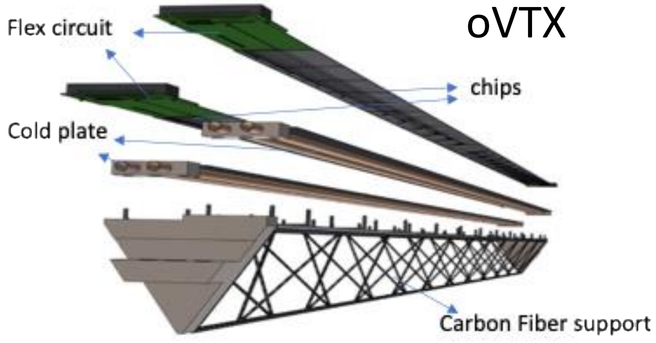
Possible VTX design







oVTX

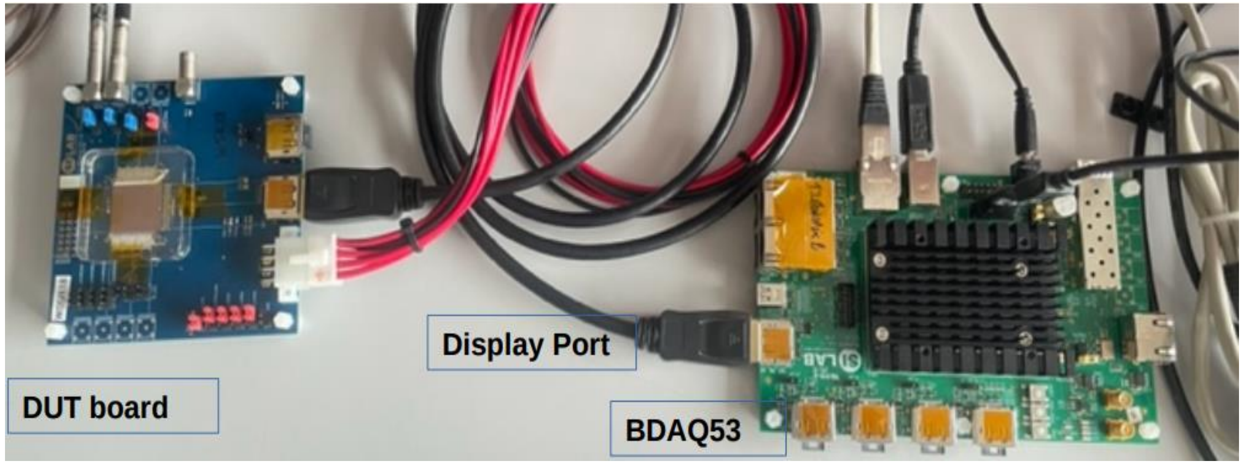


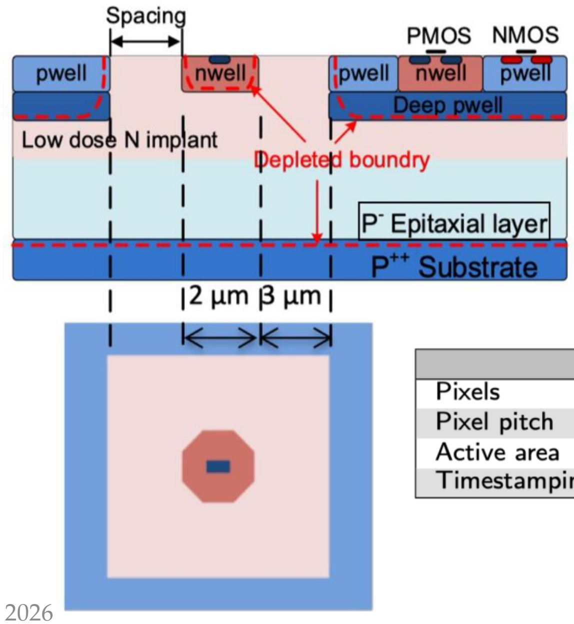
TJ-Monopix2 characterization

M. Babeluk, J. Habala, C. Irmler [NIMA (2025), M Babeluk PhD thesis]

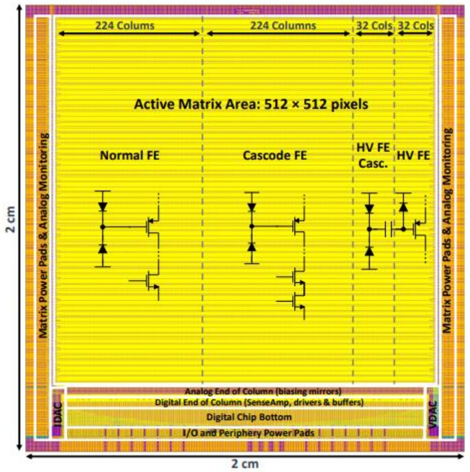
TJ-Monopix2 as starting point of Belle II VTX Upgrade MAPS chip

- R&D chip, designed initially for ATLAS ITK outer layers
- TowerJazz 180 nm process
  - Small collection electrode design, modified process with deep n-implant

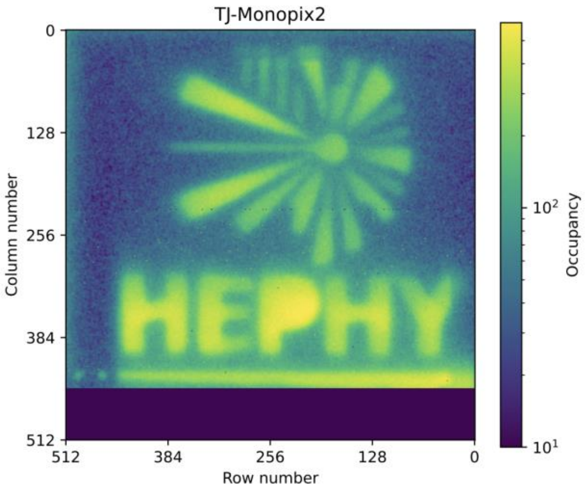




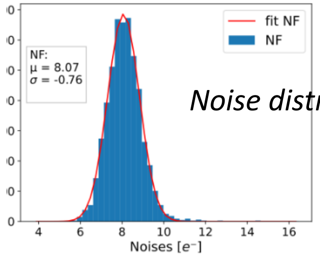
	TJ-Monopix2
Pixels	512 × 512
Pixel pitch	33.04 × 33.04 µm^2
Active area	16.92 × 16.92 mm^2
Timestamping	25 ns



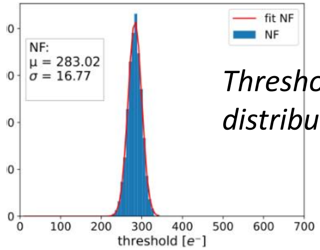
Layout of TJMP2 sensor: divided in 4 regions with different FE



Exposure with ^{90}Sr Source above 15 mm PLA Mask.



Noise distribution



Threshold distribution

ÖAW AUSTRIAN ACADEMY OF SCIENCES

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

Optimized BELle II pIXel sensor

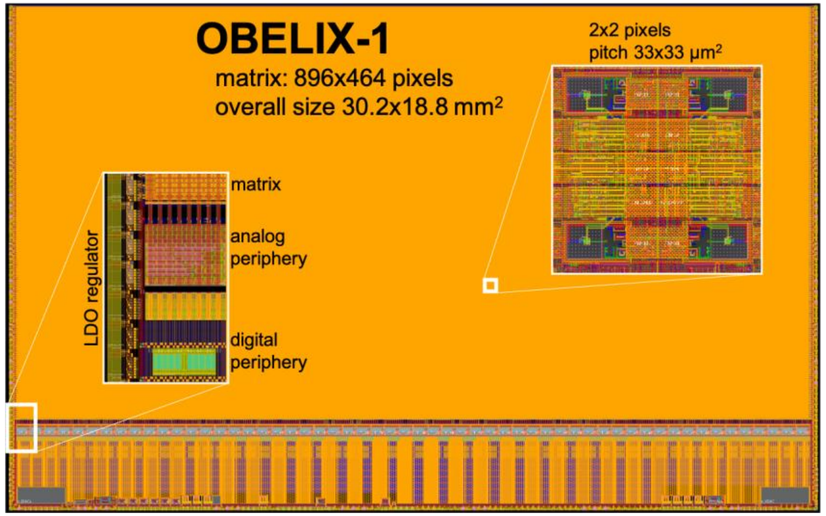
M. Babeluk, J. Habala, C. Irmler [NIMA (2025), M Babeluk PhD thesis]

Analog matrix inherit from TJ-Monopix2 with Belle-II-specific adaptions like:

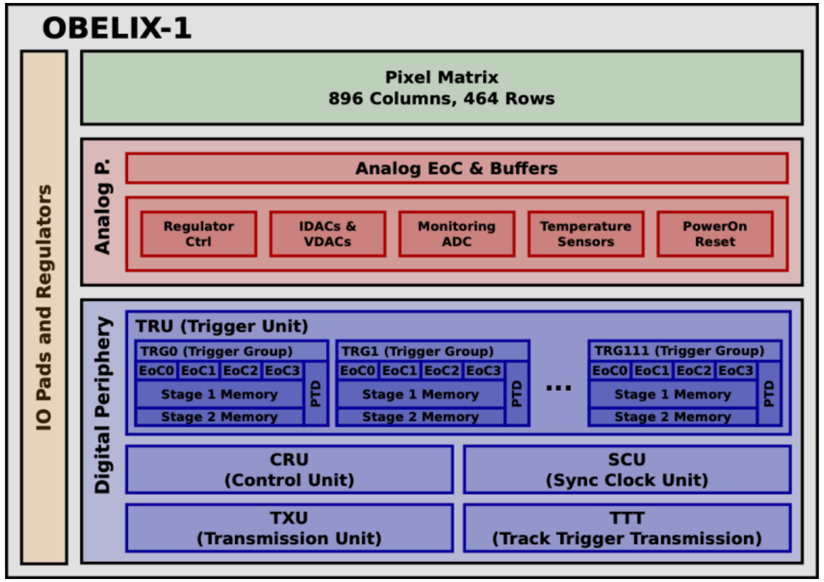
- Geometry
- Trigger logic and buffer memory
  - Allows ~10 μs trigger latency at 30kHz
  - TTT: Trigger output ~10 ns resolution
- Powering (on-chip LDO voltage regulators)
- Time stamping: 50 to 100 ns
  - PTD: Fine time stamping ~5ns

Optional features to be enabled on outer layers

	TJ-Monopix2	OBELIX
Pixels	512 × 512	896 × 464
Pixel pitch	33.04 × 33.04 μm^2	33.04 × 33.04 μm^2
Active area	16.92 × 16.92 mm^2	29.60 × 15.33 mm^2
Die area	20.20 × 20.60 mm^2	30.17 × 19.36 mm^2



Floorplan

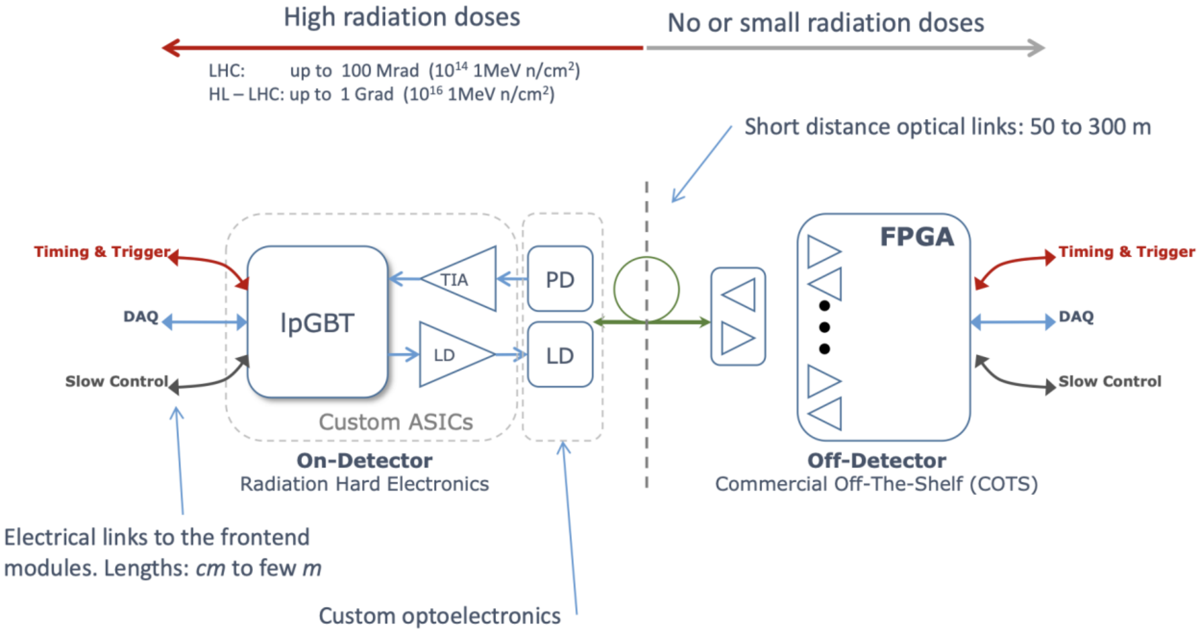


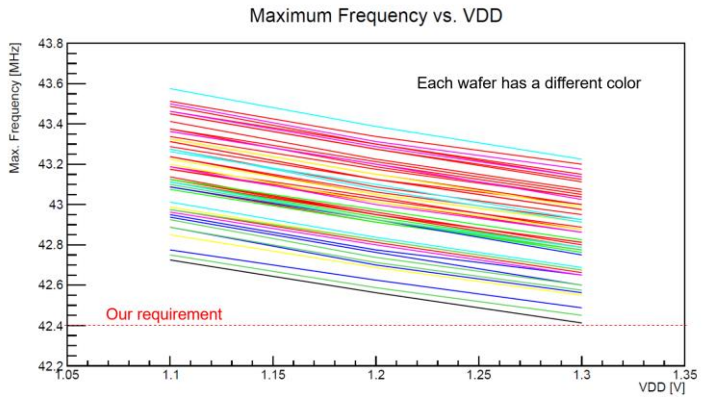
Logical Structure

M. Friedl, H. Steininger

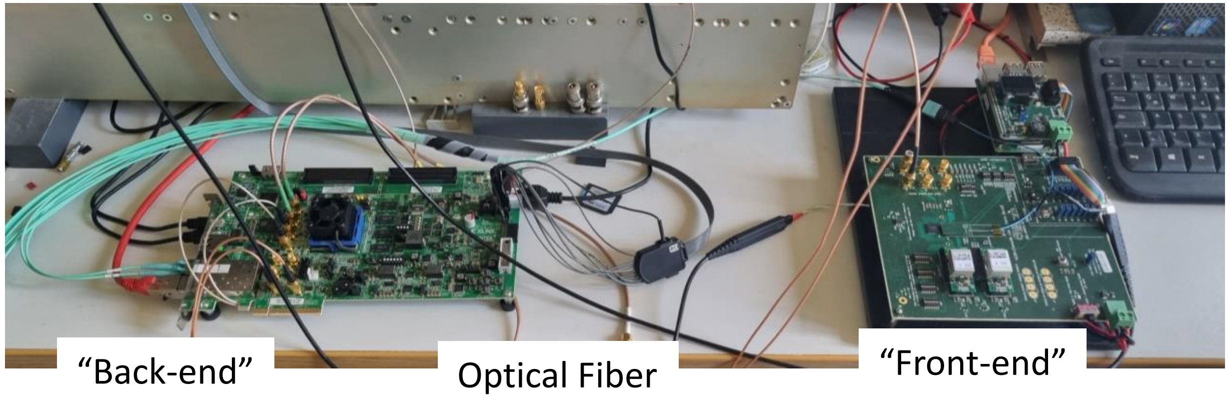
OBELIX DAQ Chain

- CERN lpGPT is considered as transceiver for transmission of DAQ, Trigger and slow control (including VTRX+ optical transceiver)
  - Data with 5.12 or 10.24 Gbps (for uplinks), 2.56 Gbps (for downlinks)
  - I2C, GPIO, 10bit ADC, different DACs
  - Designed for 200Mrad TID
- Will be used at a different clock at Belle-II rather intended (LHC)
  - We want to operate at SuperKEKB RF clock / 12 = 508.887 MHz / 12 = **42.40725 MHz**
  - Outside specs from CERN developers (40 +/- 1 MHz)





Test setup at HEPHY:



DRD3 OCTOPUS Project

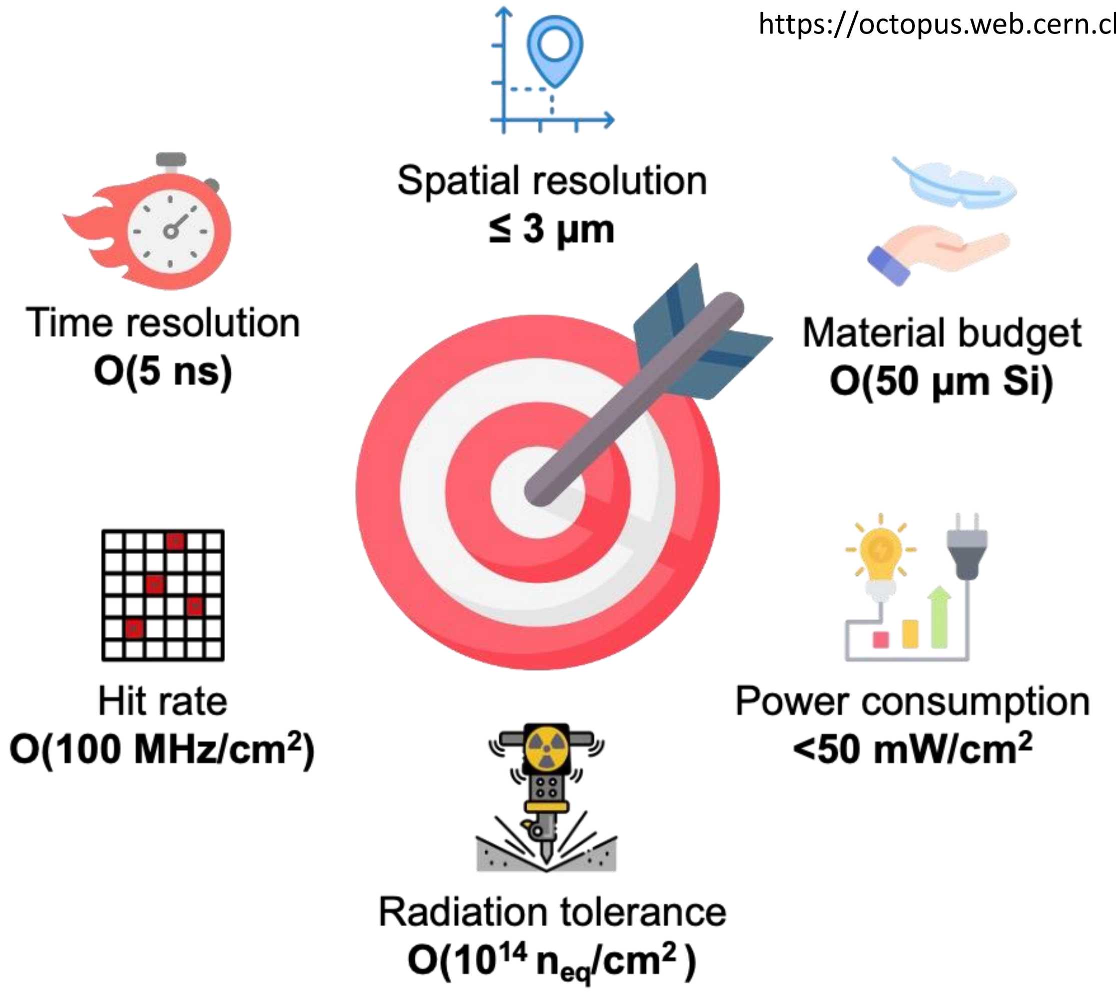
C. Irmler, R. Russo, J. Habala, H. Steininger,..

Optimised **C**MOS **T**echnology f**o**r **P**recision in **U**ltra-thin **S**ilicon (TPSCo 65 nm)

https://octopus.web.cern.ch

Main aim: Develop full-size MAPS for FCC-ee vertex detector on the long term

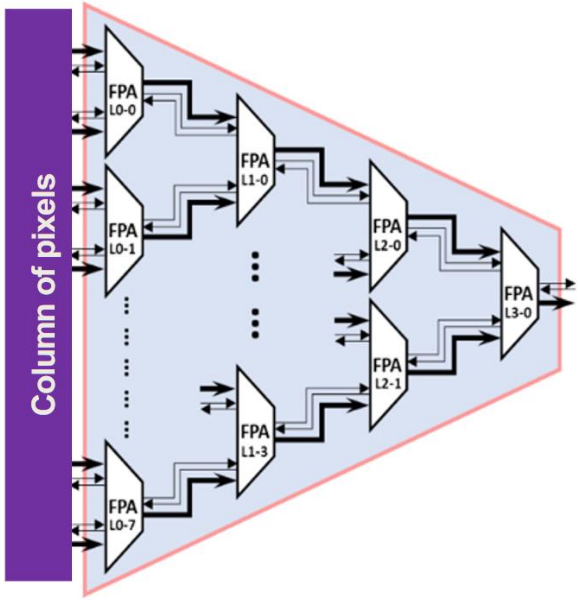
- **Staged approach**: 1st submission to provide sensors called “WOLFI”, suitable e.g. for a beam telescope
  - Full column height, small number of columns
  - Pixel pitch of <=20x20μm^2
  - FE based on MOSAIX (ALICE ITS3)
  - APA (Asynchronous Priority Arbiter) readout of matrix with pixel grouping → proof-of-concept prototype SPARC
  - Submission planning for ER3 and MPR2 (2026)

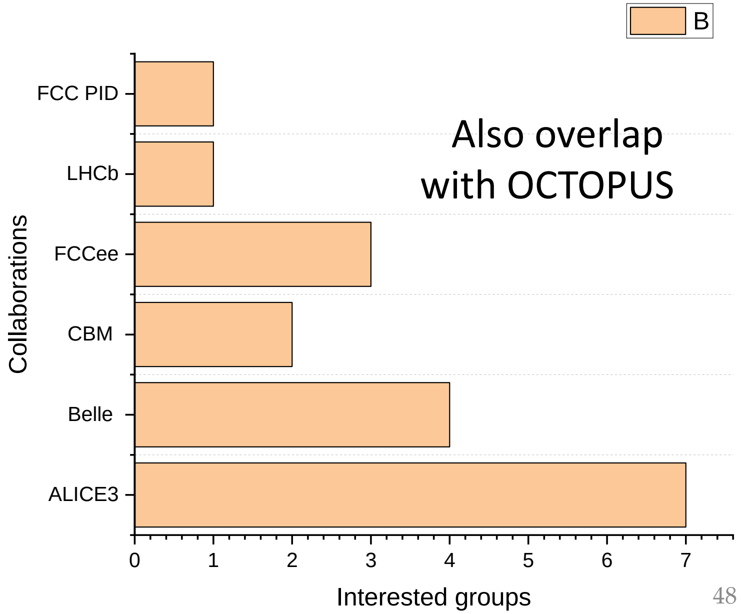


DRD3 MANTA Project

C. Irmler, R. Russo, J. Habala

- Aims to develop "Versatile MAPS" sensor for multiple tracking applications in TPSCo 65nm
  - MAPS have mostly been used for "small" vertex detectors, but how about scaling up to trackers? (ALICE3 OT: 65 m^2 silicon)
- Approach: Configure MAPS chip to **combine pixels to reduce power consumption and bandwidth**
  - based on position in the detector or even dynamically based on occupancy (an idea TB already had years ago)
  - Where to combine? Connect multiple diodes/pixel before/after first pre-amplifier stage or after ADC, at arbiter level





Also overlap with OCTOPUS

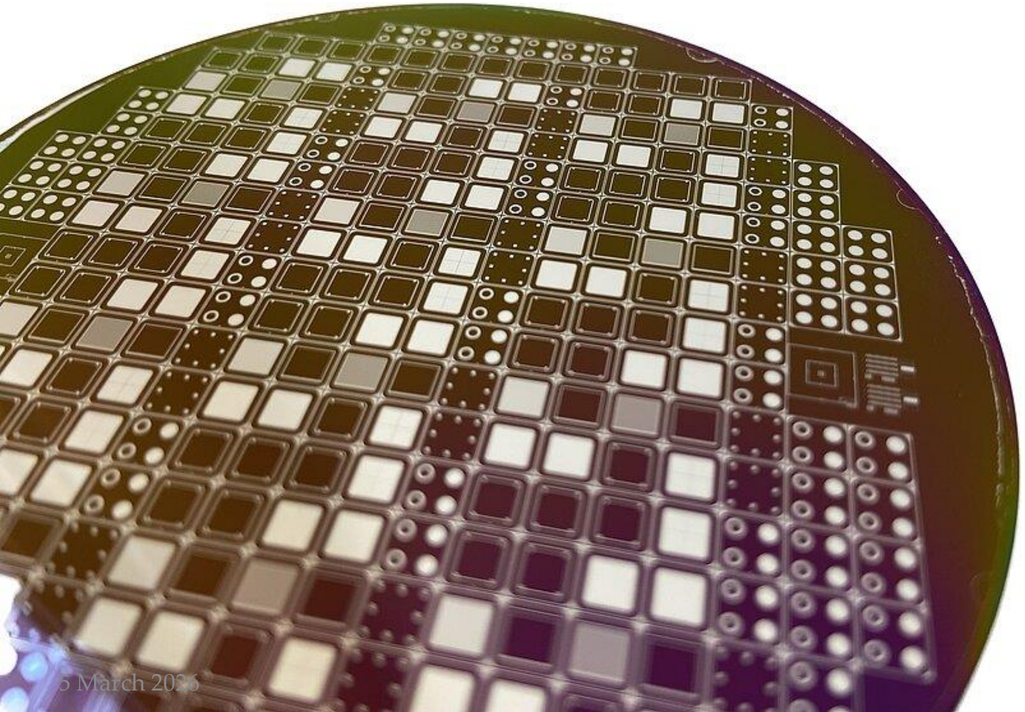
Silicon Carbide Detectors and Medical Applications

Why 4H Silicon Carbide?

- Insensitive to visible light (E_g = 3.26 eV)
- Can work at high temperatures (> 600 °C)
- No need for cooling, even after irradiation
- Middle of the road between silicon and diamond

However:

- Lower signal yield than Si
- Thickness limitations of epi
- Radiation hardness t.b.c.



Why SiC for Detectors?

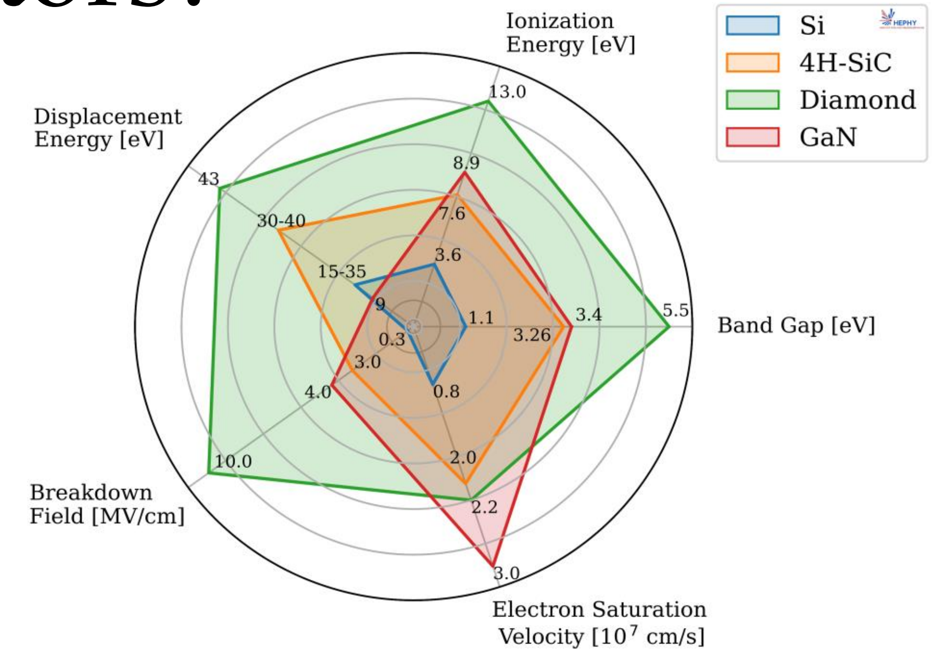
- SiC has a wide bandgap :
  → no cooling / pA currents even after irradiation, allows more lightweight detector design, insensitive to visible light

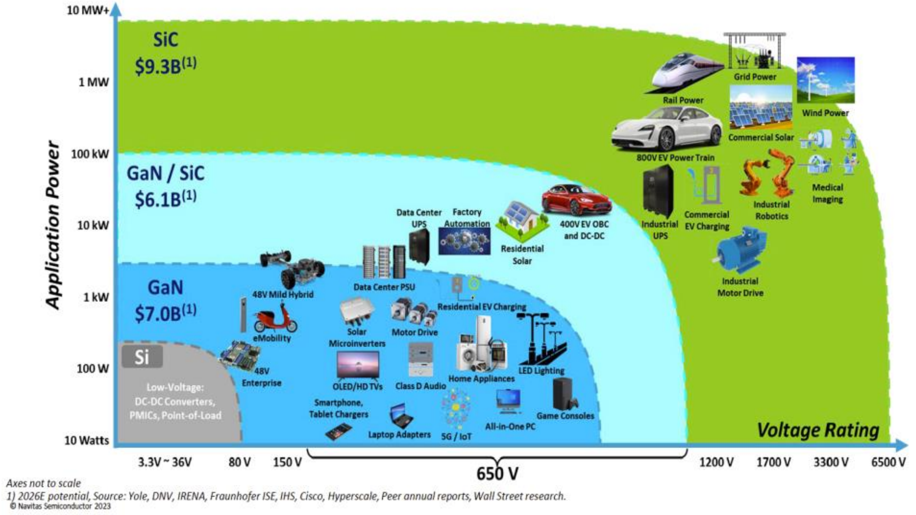
- High V_{BD}, high v_{sat} :
  → high voltages, fast signals → good for timing

- Best industrial availability of wide-bandgap materials (due to compatibility with silicon processing)

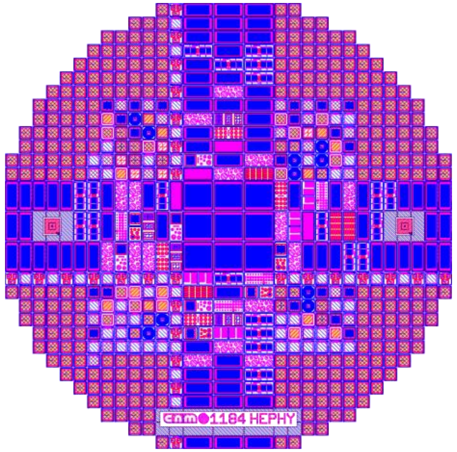
- High ionization energy, low epi thicknesses available
  → small signals
  → Improve SNR with **SiC-LGADs** (sensor with internal gain)

- SiC less known in literature
  → mix-up of different polytypes, many parameters only based on single measurements



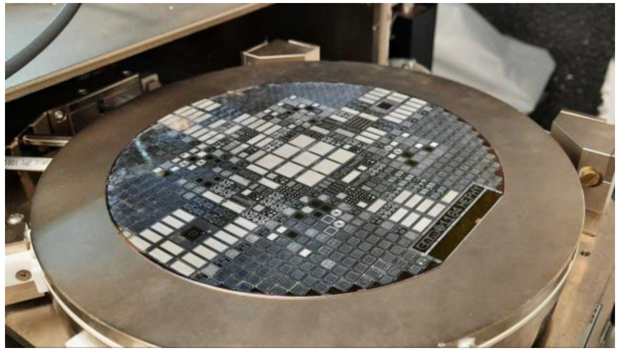


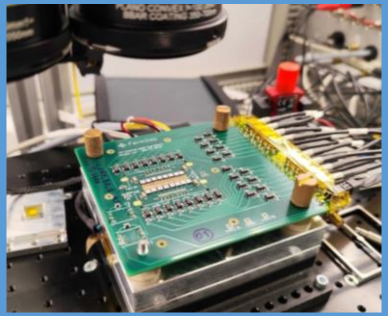
SiC Productions @ CNM

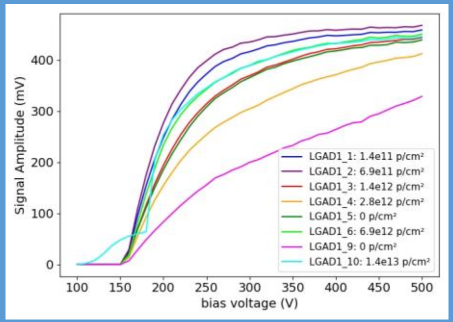


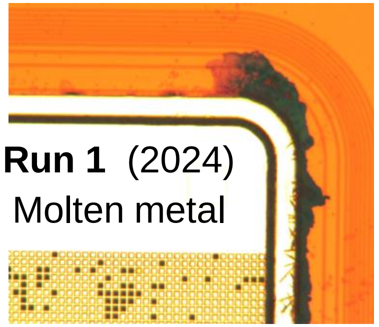
- HEPHY-CNM Collaboration to **develop SiC-LGAD sensor** (2022ff)
  - RD50 common project
  - Planar run 1: March 2024, Run 2: May 2025 (necessary due to production problems, now has its own issues)
  - SiC-LGADs still pending (Run3)

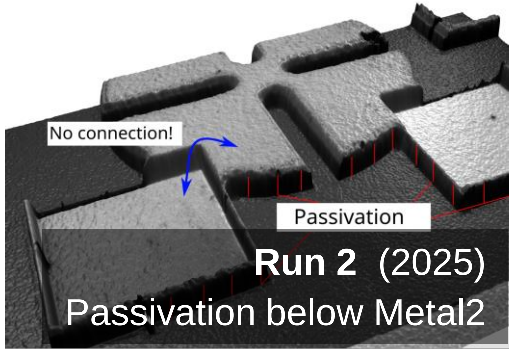
- Meanwhile, first SiC-LGADs demonstrated ~1 year ago:
  - **OnSemi and Czech Universities** arXiv:2503.07490
  - **LBNL / NCSU / BNL** 10.1109/LED.2025.3548509
  - **IHEP / Jilin Univ.** 10.1109/TNS.2024.3471863
- Large community interest – united in DRD3
  - We study e.g. OnSemi SiC-LGAD samples

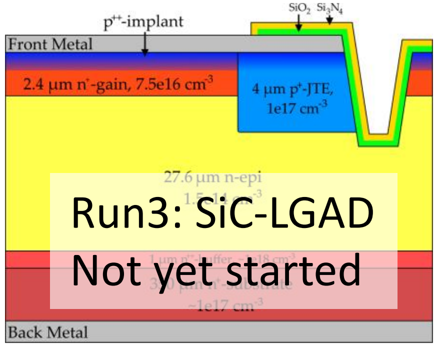




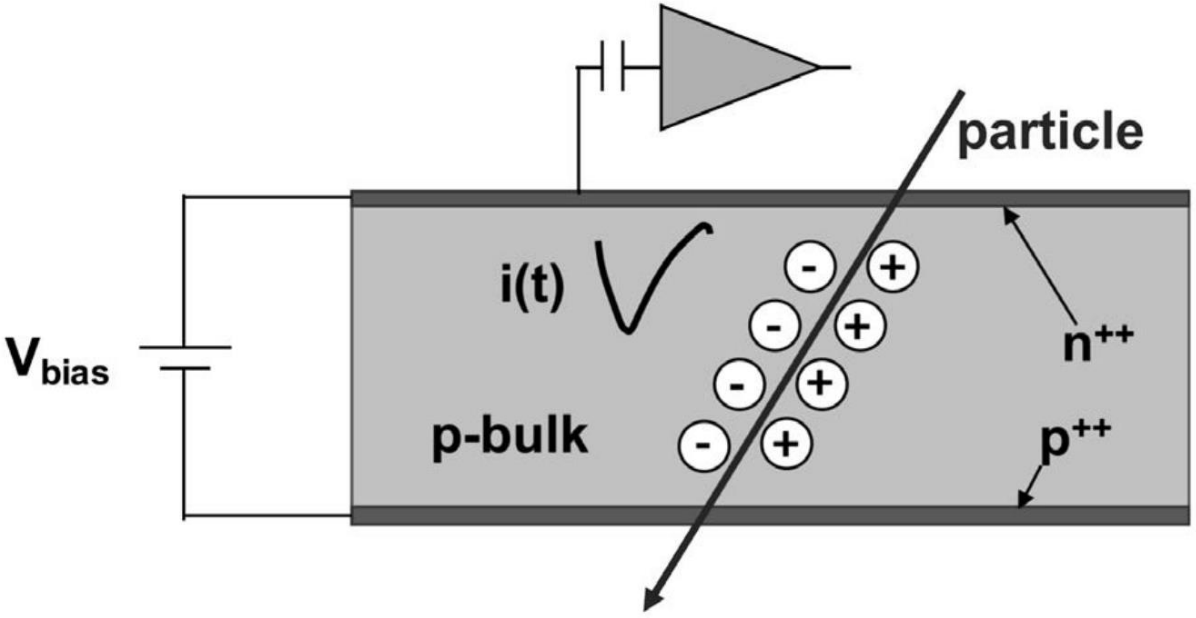


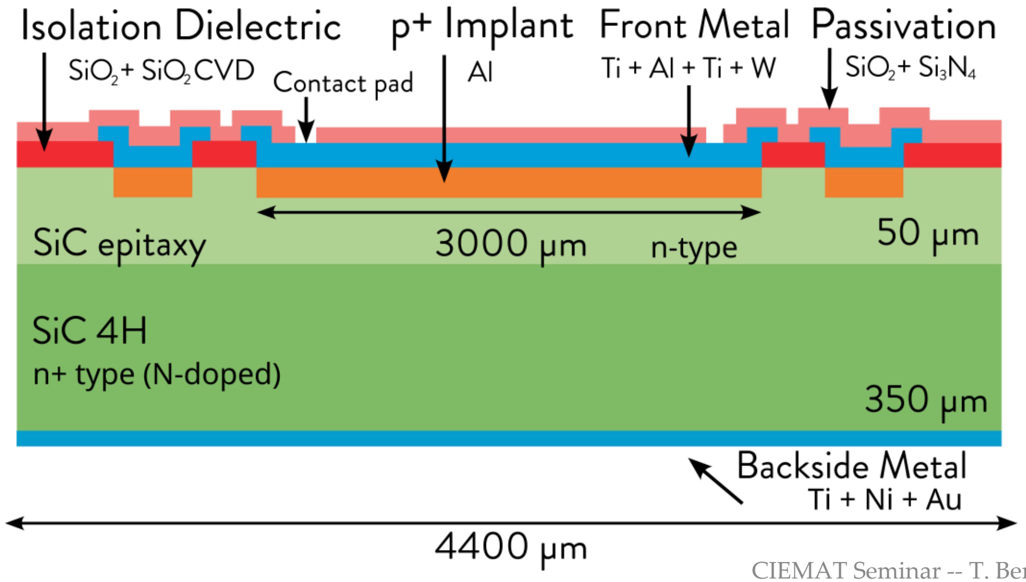


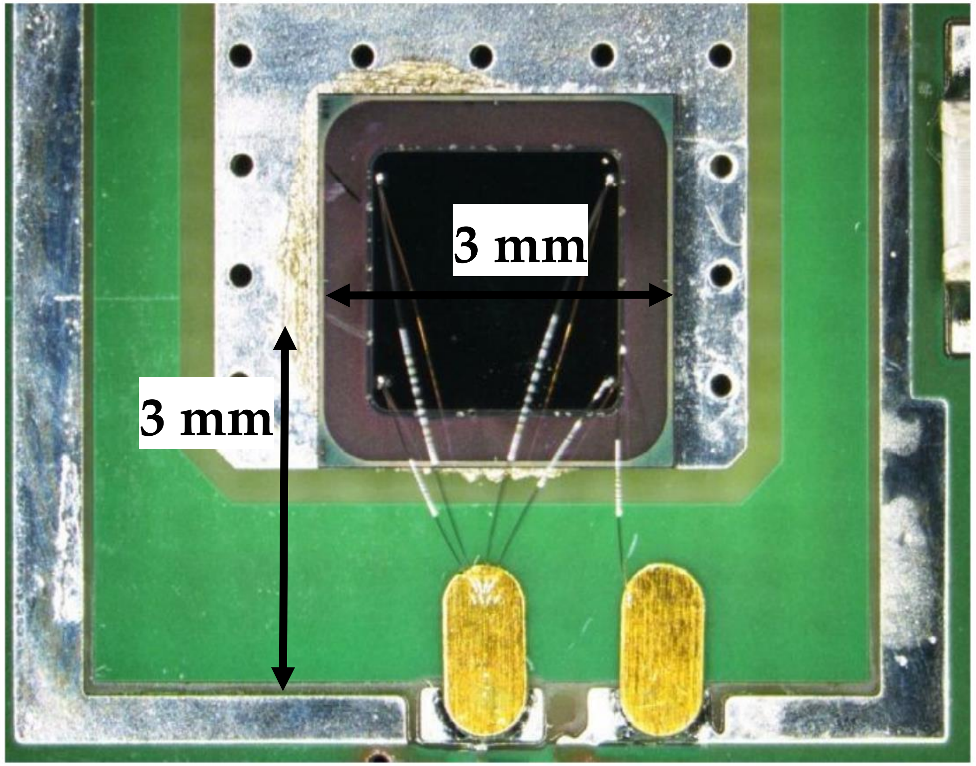




4H-SiC PiN diodes

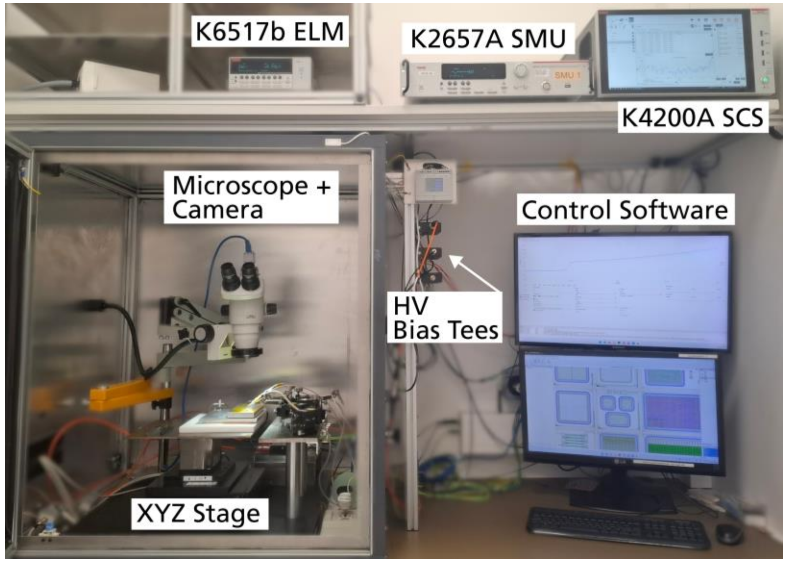




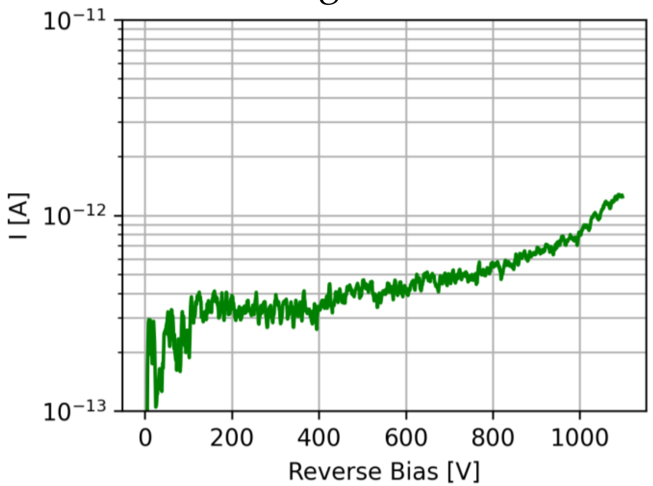


Electrical Characterization

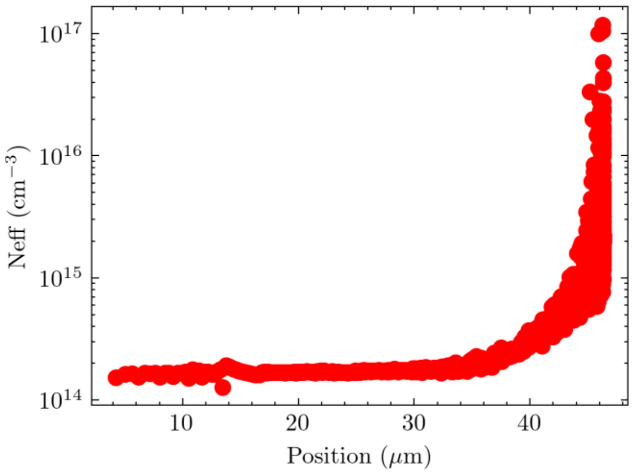
- Quantify yield, measure process parameters
- Input to TCAD simulations
- SiC presents special challenges:
  - Very low currents (< 100fA/ mm²)
  - and very high voltages 3 kV) at the same time
- Use of Semiconductor analyzer (ÖAW Innovation Fund)

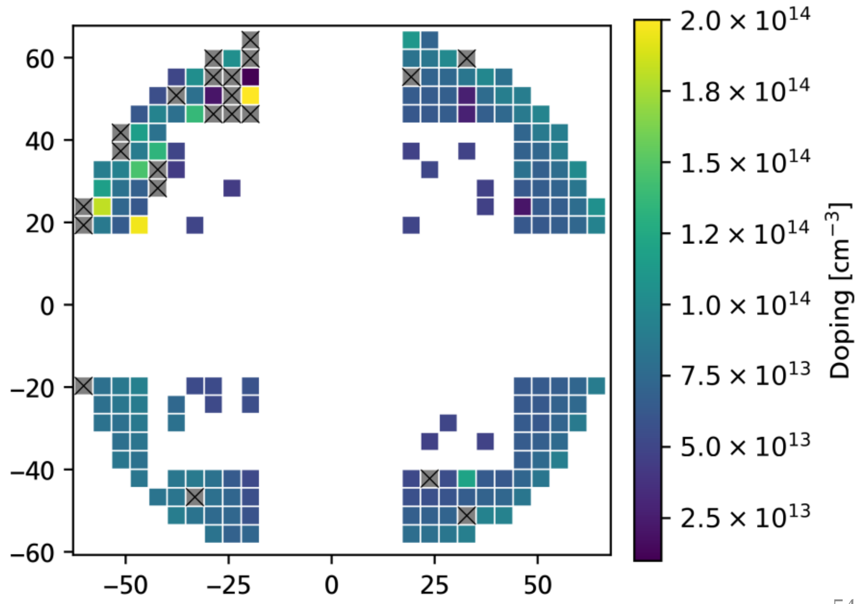


Leakage Current



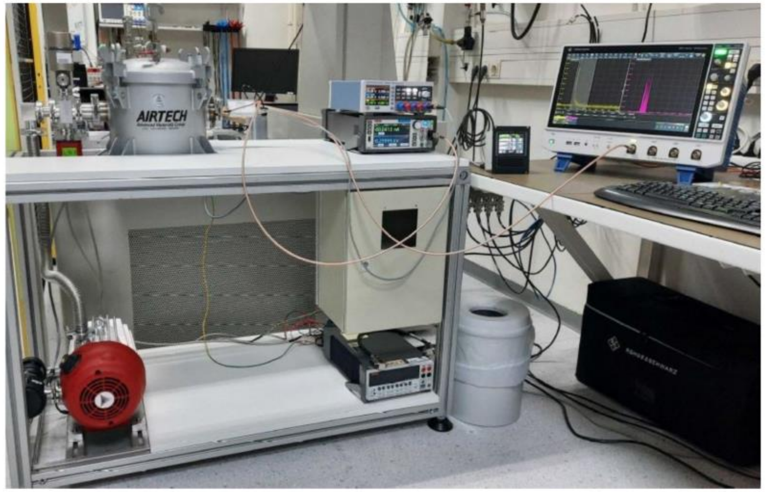
Extracted Doping Profile



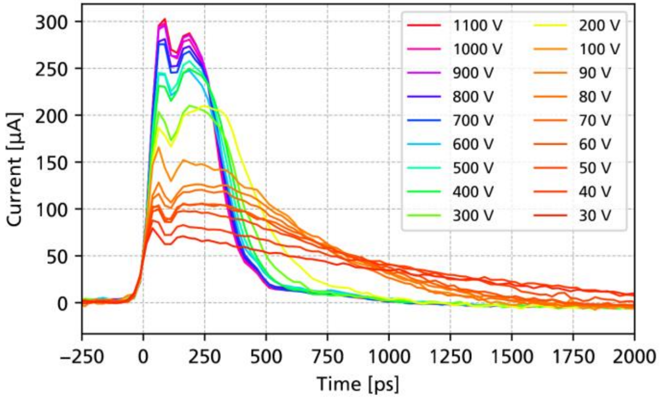


Setups using Ionizing Radiation at MBI

Alpha spectroscopy in vacuum

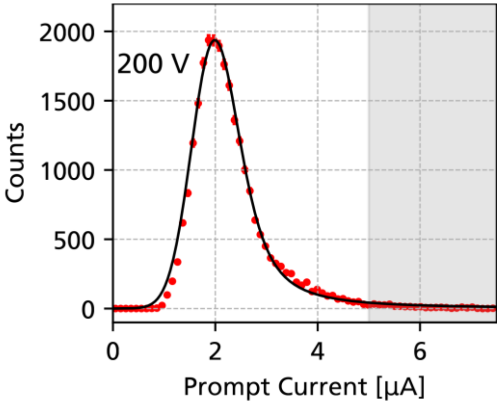


Jinst 10.1088/1748-0221/18/01/C01042

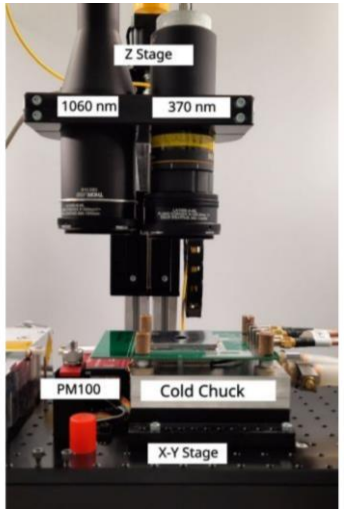


High-Energy **Protons** (MedAustron)

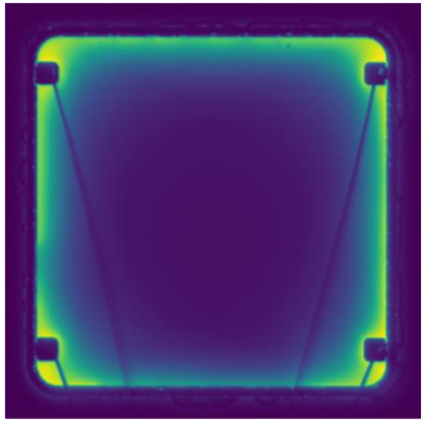
NIM A 10.1016/j.nima.2022.167218



Picosecond pulsed **UV laser**



PoS 10.22323/1.468.0103



4H-SiC Material Properties

4H-SiC material parameters vary significantly in literature and between different manufacturers

- **Extensive literature review** to understand origin of commonly used values of TCAD parameters (231 pages, 939 references) within FFG RadHardDetSim project

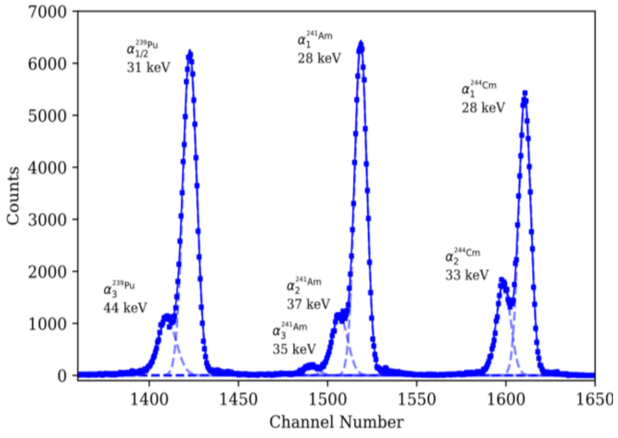
Additionally, measure material parameters for existing samples (for ex. ε_i)

$$\epsilon_{\mathrm{i,SiC}} = (7.83 \pm 0.02)\,\mathrm{eV}$$

Previously published values of $\epsilon_{\mathrm{i,SiC}}$ for 4H-SiC. For measurements that compare to silicon, the value of $\epsilon_{\mathrm{i,Si}}$ is indicated. The reference labeled "*" refers to the results obtained in this work.

Ref.	Year	$\epsilon_{\mathrm{i,SiC}}$ [eV]	Radiation	Method	Device type	$\epsilon_{\mathrm{i,\,Si}}$ [eV]
*	2023	7.83 ± 0.02	α	Comp. to Si	Diode	3.62
[9]	2013	7.82 ± 0.02	α	Charge inj.	Schottky	-
[8]	2013	7.28	α	Charge inj.	Schottky	–
[10]	2006	5.05	e^-	DC Current	Diode	–
[11]	2005	7.78 ± 0.05	α	Comp. to Si	Schottky	3.62
[11]	2005	7.79 ± 0.09	protons	Comp. to Si	Schottky	3.64
[12]	2005	7.6	X-rays (^{241}Am)	Comp. to Si	Diode	3.60
[13]	2004	8.6	α	Comp. to Si	Diode	3.62
[14]	2004	7.71	α	Comp. to Si	Schottky	3.62
[15]	2003	7.8	X-rays (SEM)	Comp. to Si	Diode	3.67

A Gsponer, M. Knopf et al.: [NIMA (2024)]



Tri-Alpha spectrum

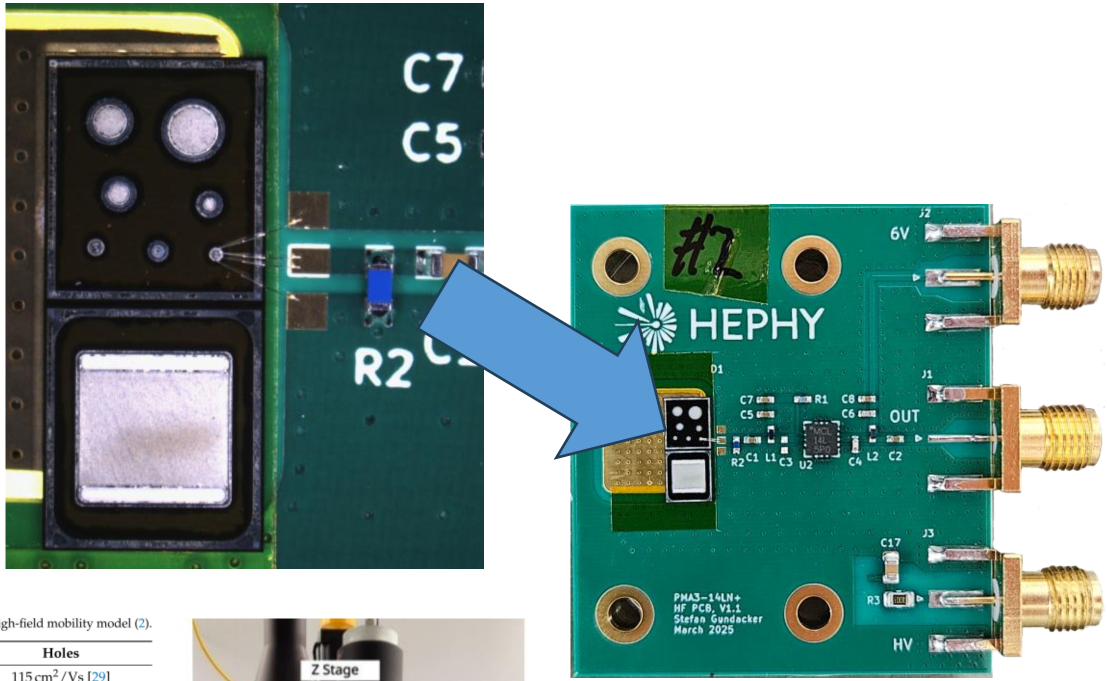
TABLE IX. Parameters for fundamental fittings of the Okuto-Crowell model found in literature. If only a single value spanning across two columns is presented the crystal direction was not specified.

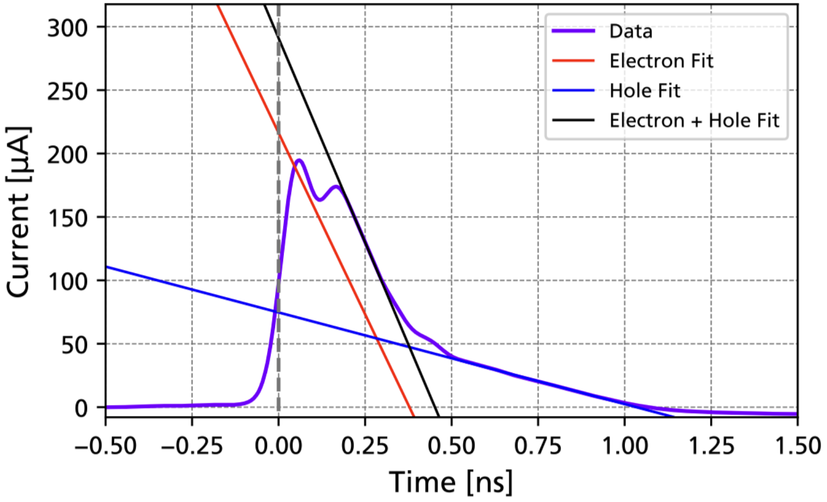
ref.	electron $a_\parallel$ [10^6/cm]	electron $a_\perp$	electron $b_\parallel$ [MV/cm]	electron $b_\perp$	electron c [10^{-3}]	electron d [10^{-3}]	electron m [1]	hole $a_\parallel$ [10^6/cm]	hole $a_\perp$	hole $b_\parallel$ [MV/cm]	hole $b_\perp$	hole c [10^{-3}]	hole d [10^{-3}]	hole m [1]	F region [MV/cm]
[Ragh99][448]	-	-	-	-	0	0	1	3.09		17.9 ± 0.4		−3.46	0	1	2.5–3.2
[Bert00][465][j]	0.4	48	15		0	0	1.15	1.8	45	15		0	0	1	-
[Sher00][464][d][l]	-	-	-	-	0	0	1	5.18	-	14	-	0	0	1	-
[Mori01][344][d]	-	-	-	-	0	0	1	-	-	-	-	0	0	1	-
[Ng03][451]	1.98		9.46		−2.02[a]	0	1.42	4.38		11.4		−0.913[a]	0	1.06	1.8–4
[Zhao03][163][d]	7.26		23.4		0	0	1	6.85		14.1		0	0	1	-
[Hata04][466]	176	21	33	17	0	0	1	341	29.6	25	16	0	0	1	2–5
[Choi05][73][d]	16.5		25.8		0	0	1	5.5		13.5		0	0	1	1.5–5
[Loh08][450]	2.78		10.5		0	0	1.37	3.51		10.3		0	0	1.09	1–5
[Loh09][467]	-	-	-	-	0	0	1	3.321		10.385		−2.78	0.48[k]	1.09	1.33–2
[Nguy11][452]	0.46		17.8		0	0	1	15.6		17.2		0	0	1	1.5–2.7
[Gree12][457][h]	0.019		2.888		0	0	4.828	0.06		1.387		0	0	0.96	1.6–4
[Nguy12][453]	3.36		22.6		0	0	1	8.5		15.97		0	0	1	1.5–4.8
[Sun12][431]	1.803		13.52		0	0	1.2	1.861		9.986		0	0	1.11	1.5–5
[Niwa14][444]	8190		39.4		0	0	1	4.513		12.82		0[f]	0	1	1.4–2.7
[Hama15][445]	0.99		12.9		0	0	1	1.61		11.5		0	0	1	2.5–7
[Niwa15][462]	0.143	-	4.93	-	0[c]	0[c]	2.37	3.14	-	11.8	-	6.3[c]	1.23[c]	1.02	1–2.8
[Shar15][468]	186	-	28	-	0	0	1	301	-	20.5	-	0	0	1	-
[Kyur16][456][i]	38.6 ± 15.0		25.6 ± 0.1		0	0	1	5.31 ± 0.30		13.10 ± 0.01		0	0	1	1–5
[Zhan18][469]	1.31		13		−1.47	0	1	2.98		13		−1.56	0	1	-
[Bali19][112][d]	313		34.5		0	0	1	8.07		15		0	0	1	1.1–5
[Zhao19][455]	0.339	-	5.15	-	0	0	2.37	3.56	-	11.7	-	6.19	1.15	1.02	1–3.2
[Stef20][454]	-	6.4	-	12.5	0	0	1	-	6	-	13.3	0	0	1	1.3–2
[Bane21][94][d]	100		40.268		0	0	1	41.915		46.428		0	0	1	0.1–1
[Chea21][458][g]	0.932		7.19		0	0	1.95	1.75		6.56		0	0	1.45	1.6–10
[Stef21][460][e]	2.8	-	20.7	-	−1[b]	−0.29[b]	1	2.5	-	12.1	-	1.74[b]	0.59[b]	1	-

Literature Review of 4H-SiC model parameters
https://arxiv.org/abs/2410.06798

HF-Readout and Charge Carrier mobility

- High-frequency readout board developed (10GHz)
  - Tiny sensor for low capacitance and ultra-short bond wire required
  - Take advantage of all the high-level equipment we have: TCT/Laser setup, HF Oscilloscope, electronics workshop, wire bonding
- Directly measure **electron and hole mobility** in thin 4H-SiC PIN detectors by carrier drift time
  - Parameters not well known in literature
  - Input to TCAD and Allpix2 models





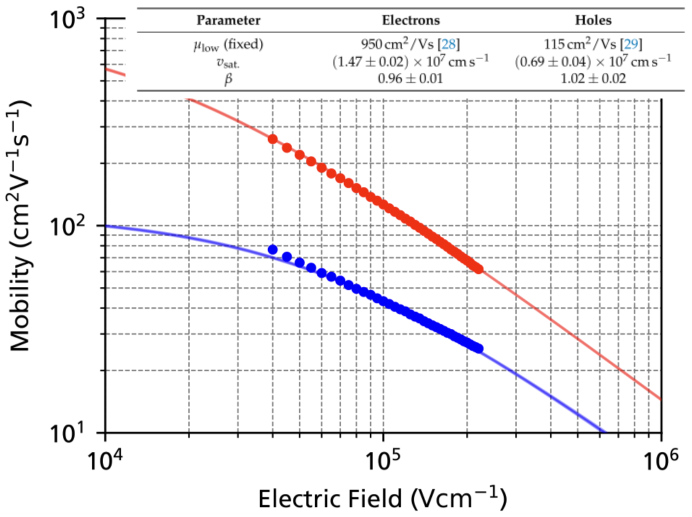
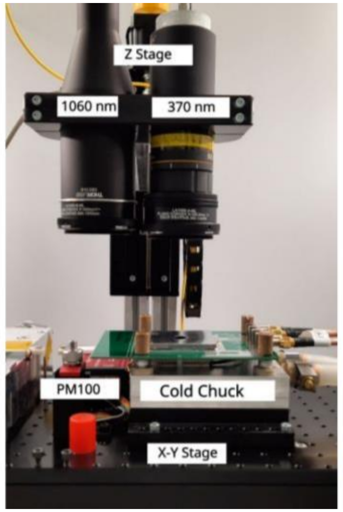
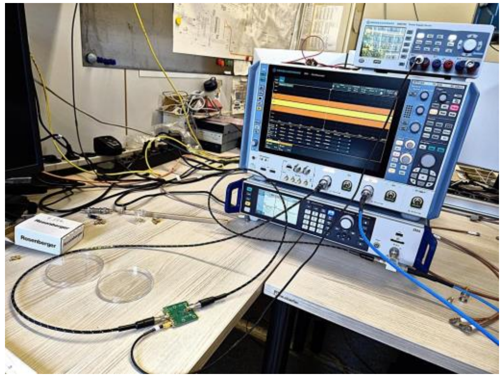


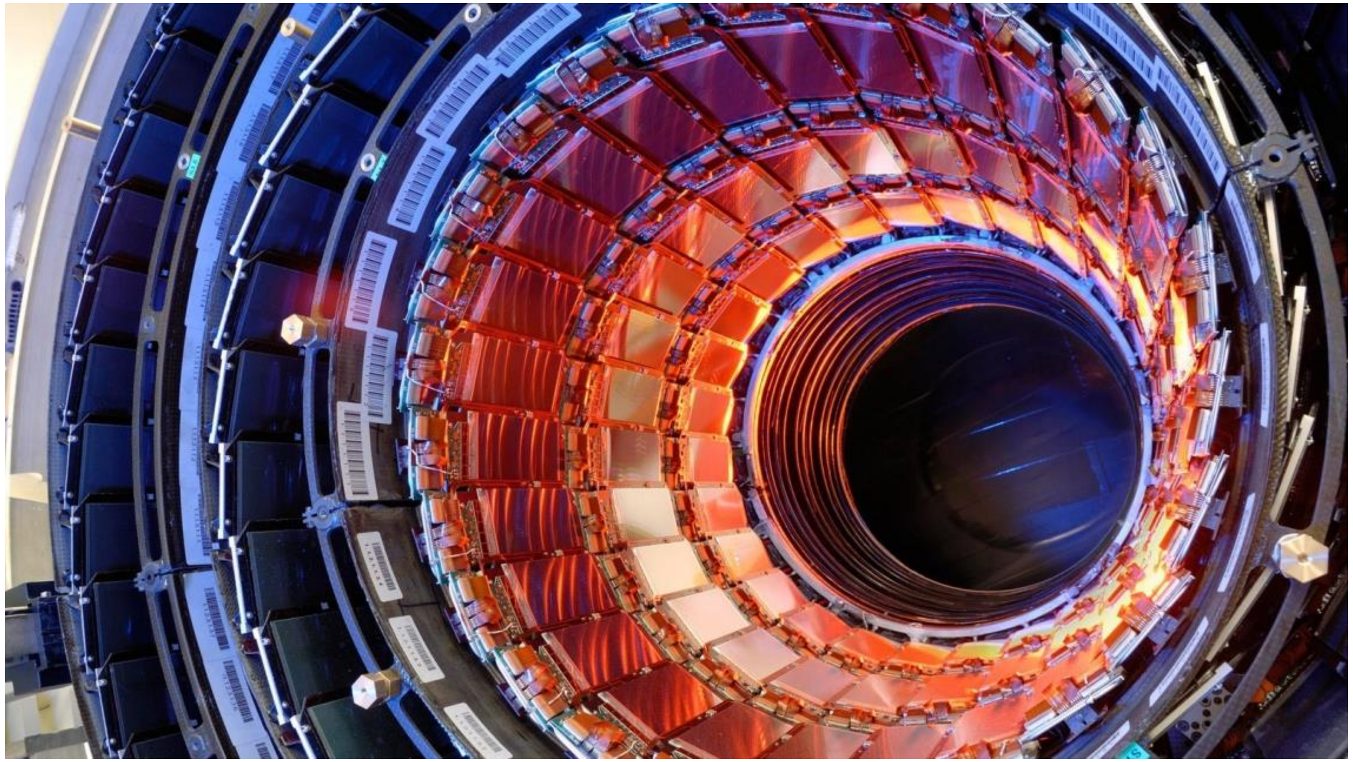
Table 1. Fit results for electrons and holes using the Caughey-Thomas high-field mobility model (2).

Parameter	Electrons	Holes
μ_{low} (fixed)	$950\,cm^2/Vs$ [28]	$115\,cm^2/Vs$ [29]
$v_{sat.}$	$(1.47 \pm 0.02) \times 10^7\,cm\,s^{-1}$	$(0.69 \pm 0.04) \times 10^7\,cm\,s^{-1}$
β	0.96 ± 0.01	1.02 ± 0.02





High Energy Physics: Radiation Hardness & Timing Resolution

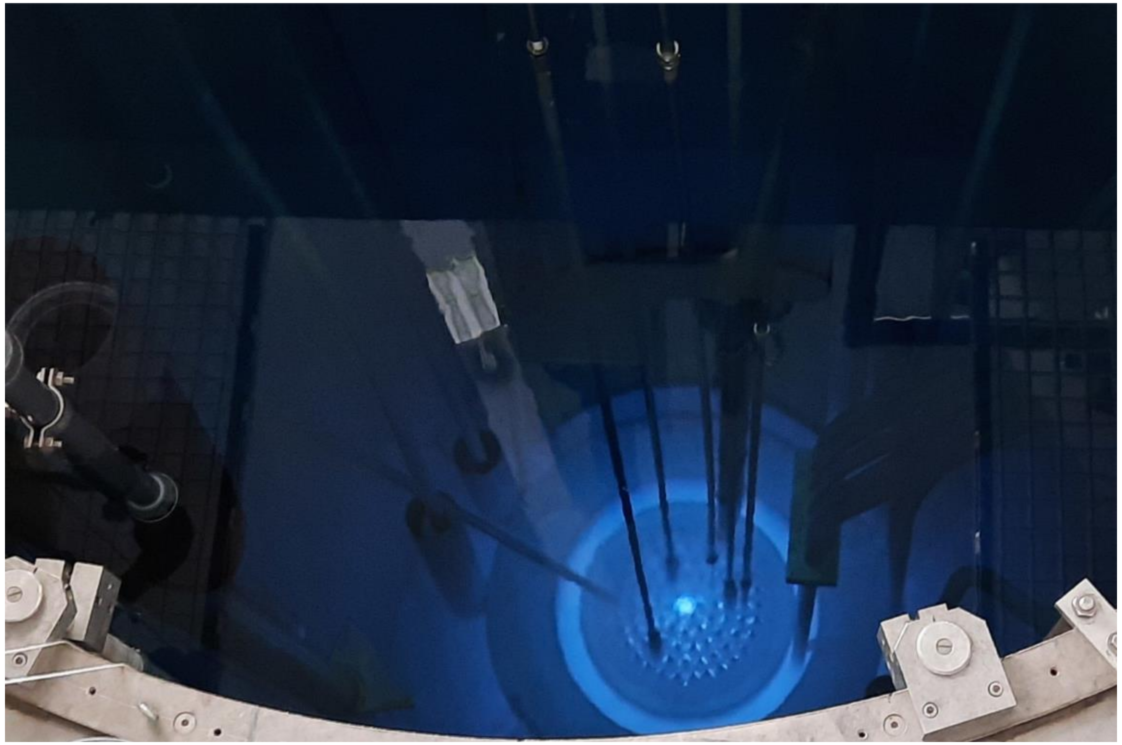


Irradiation Campaigns

Neutron Irradiation

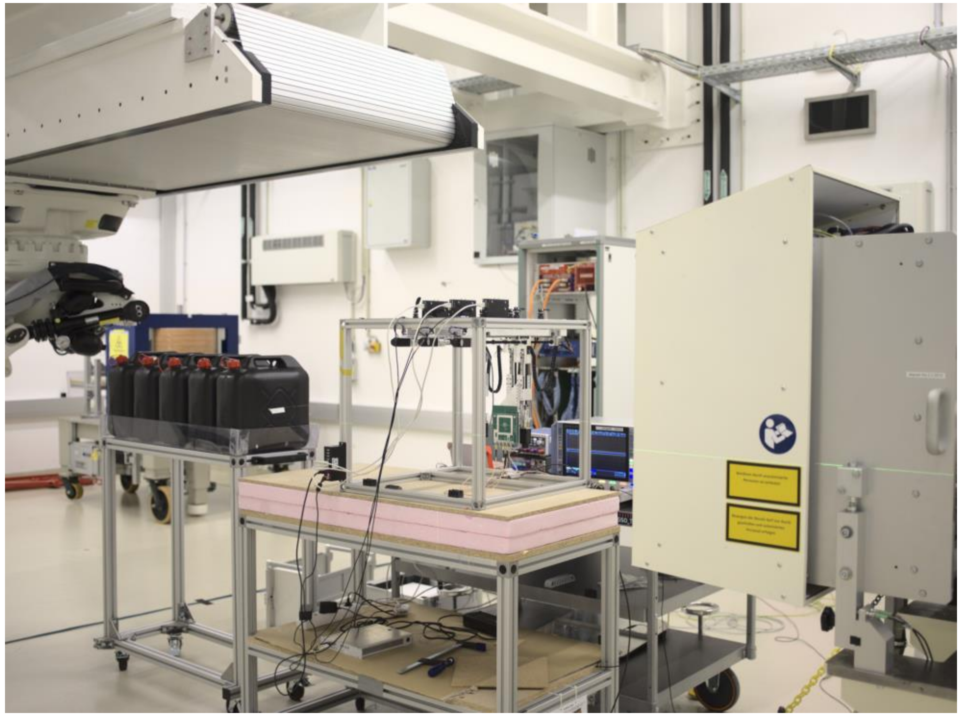
ATI 2021 : $5 \cdot 10^{14} – 1 \cdot 10^{16}\ n_{eq}/cm^2$

JSI 2024 : $1 \cdot 10^{18}\ n_{eq}/cm^2$



Proton Irradiation

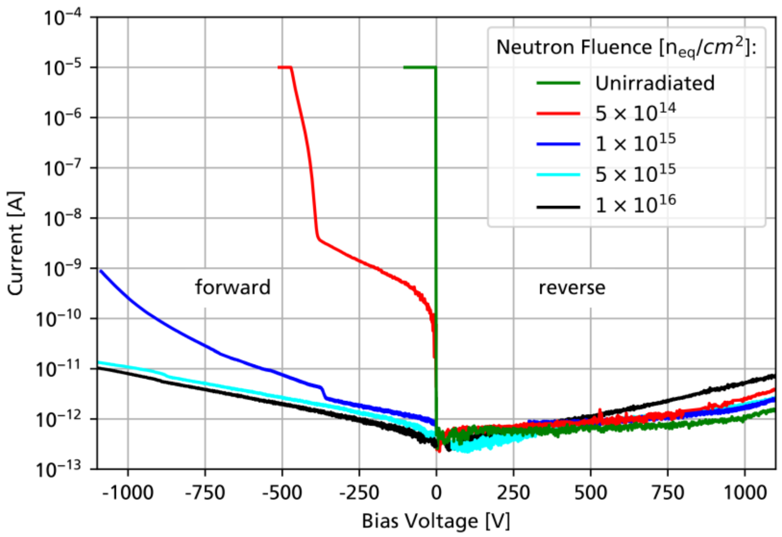
MedAustron 2025: $5 \cdot 10^{10} – 3 \cdot 10^{13}\ p/cm^2$

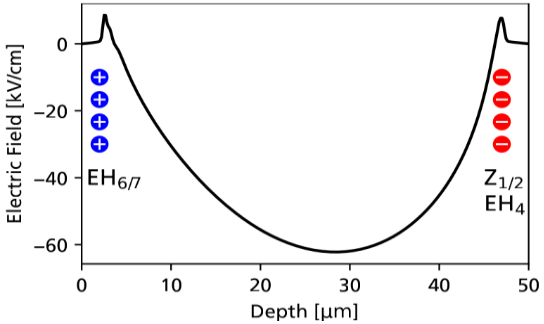


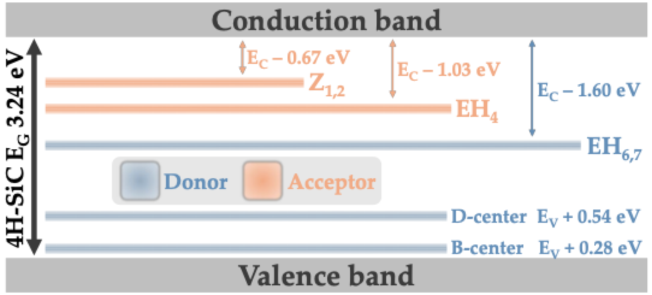
Study of SiC Radiation Hardness

P. Gaggl, J. Burin, A. Gsponer, S. Onder, D. Radmanovac, M. Knopf [arxiv (2025), NIMA (2025), JINST (2024),..]

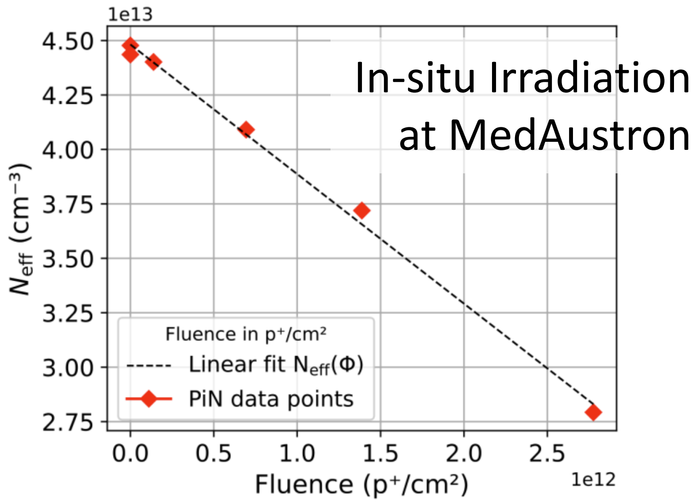
- Several irradiation campaigns with Neutrons (ATI, Ljubljana) and protons (MedAustron) performed
- CCE drops, but still growing with $\sqrt{V}$; not saturated up to 1.1kV → higher voltages needed to study
- Interesting effects observed: loss of rectifying function of pn-junction, material becomes intrinsic
- Developed TCAD irradiation model with 5 trap levels and studied donor removal rate

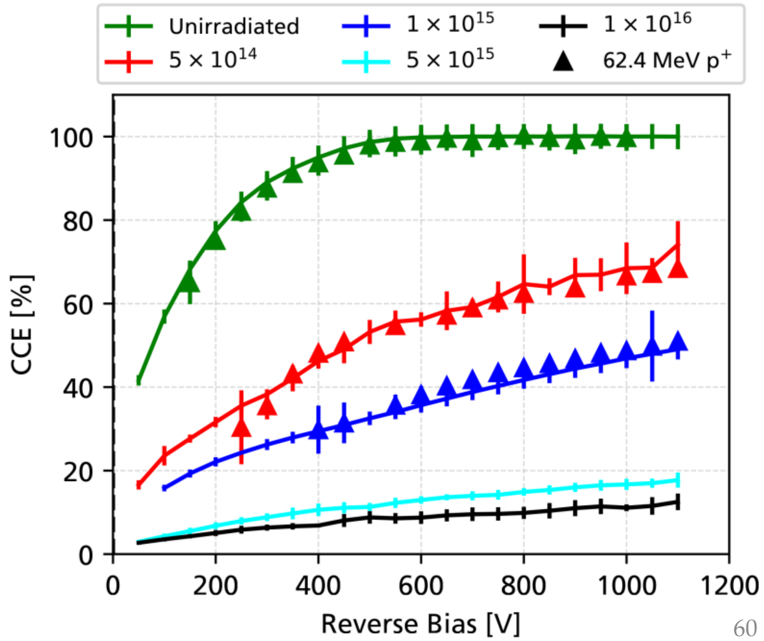






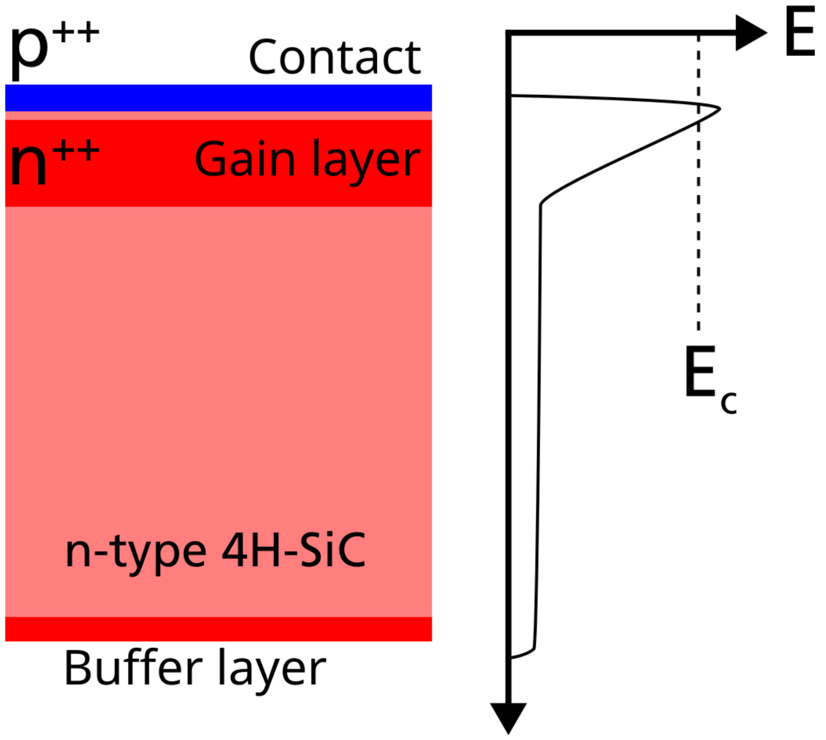
Donor removal rates derived between 4.2 – 6.4 cm⁻¹.



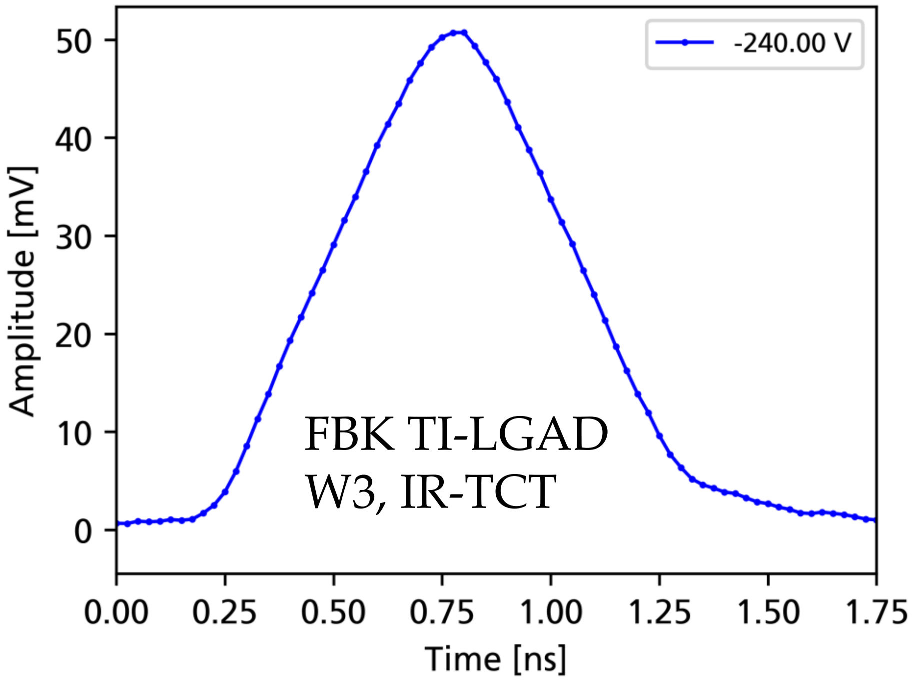


4H-SiC Low Gain Avalanche Diodes

- SNR is limited by ε_i and low epi thickness. Signal $57e^-/\mu m * 50\mu m \sim 3000e^-$
- SiC-LGADs are a key technology for future 4H-SiC detectors to internally amplify signal by factor 5-30



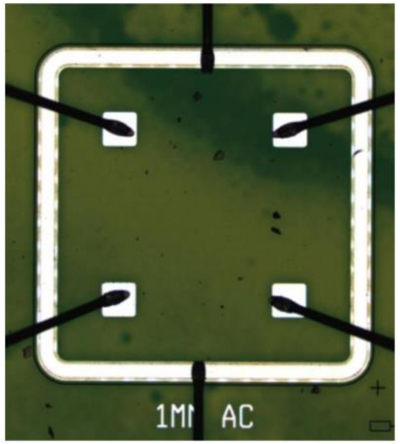
Silicon LGAD



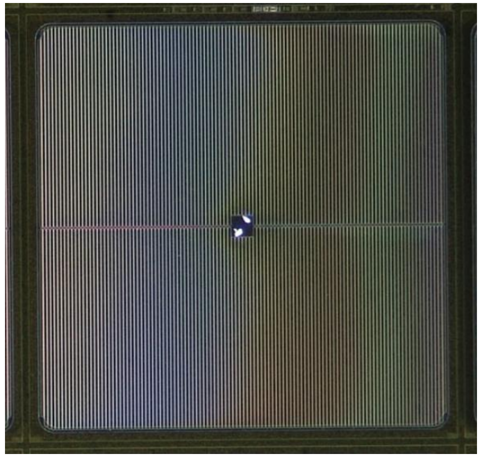
Towards SiC-LGADs

- First SiC-LGADs have been demonstrated ~1 year ago
- Very large community interest

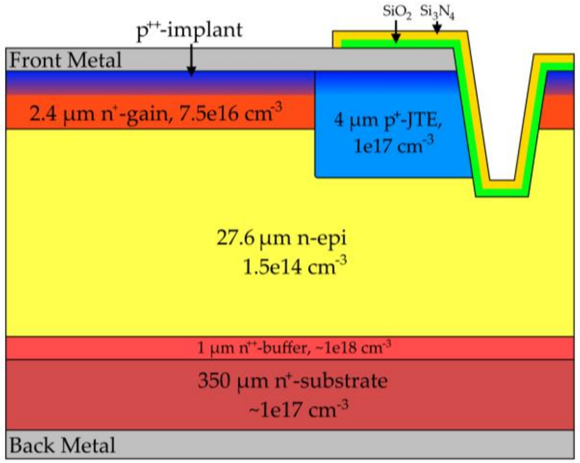
LBNL / NCSU / BNL
10.1109/LED.2025.3548509



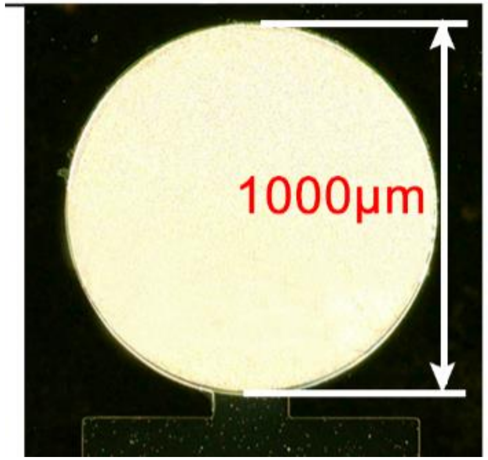
OnSemi and Czech Universities
PIXEL 2024
arXiv:2503.07490



RD50-SiC-LGAD HEPHY, CNM
DRD3 Talk



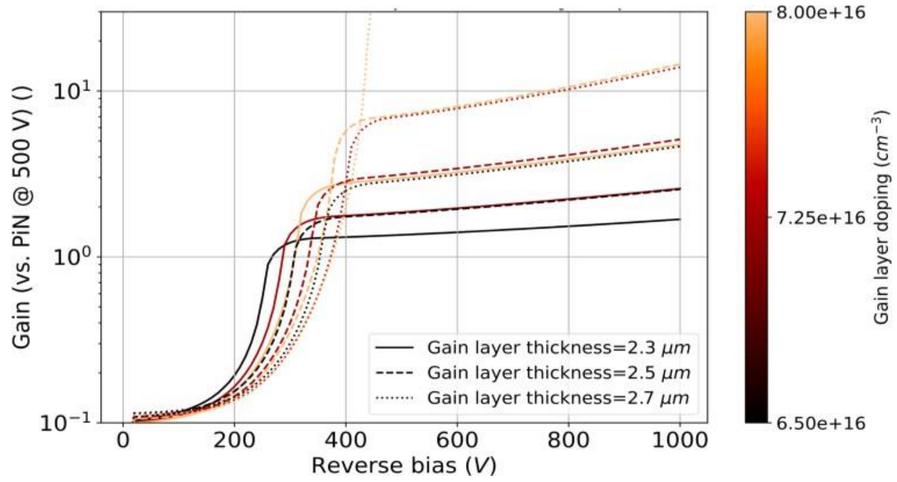
IHEP / Jilin Univ.
10.1109/TNS.2024.3471863



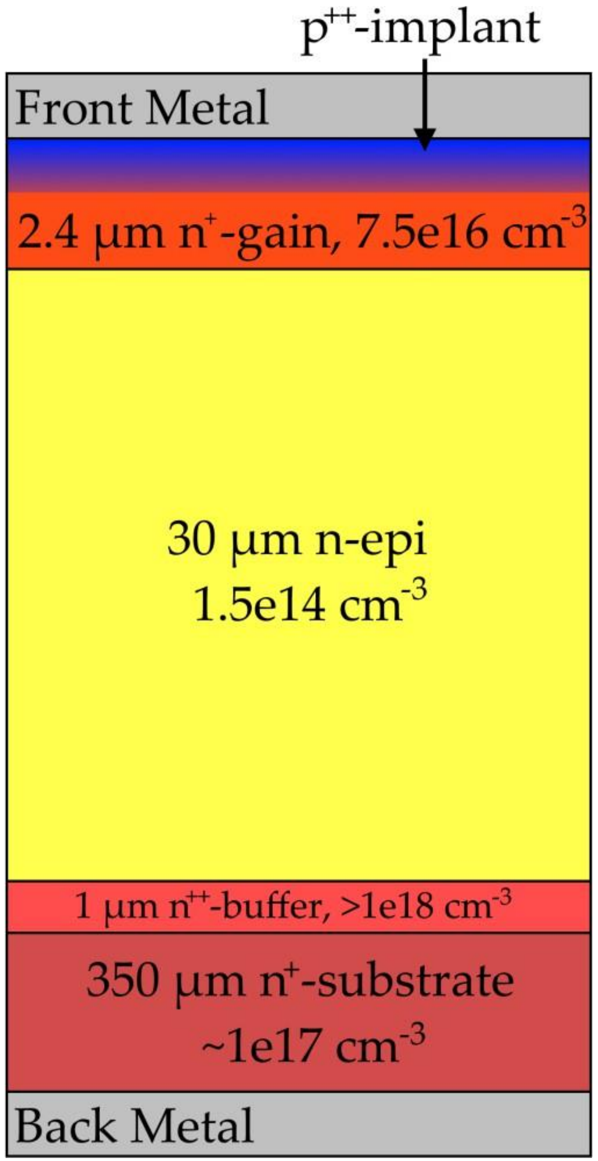
SiC-LGAD Gain Layer TCAD

- RD50 SiC LGAD Common Project* (+ planar run → back up)
- Designed by HEPHY, produced by CNM
- Gain layer is non-trivial to manufacture:
  - Dopant diffusion is extremely low in SiC
  - Deep implants (> 1 µm) need high energies (> 1 MeV)
- ⇒ Epitaxially grown gain layer on 30 µm epi, $V_{FD} < 600V$
- Gain of 1-10 within error margin of gain layer thickness / doping, $V_{FD} < V_{BD}$

*Contributing institutes: HEPHY, CNM, CERN, INFN Perugia, ICFA Santander, NIKHEF

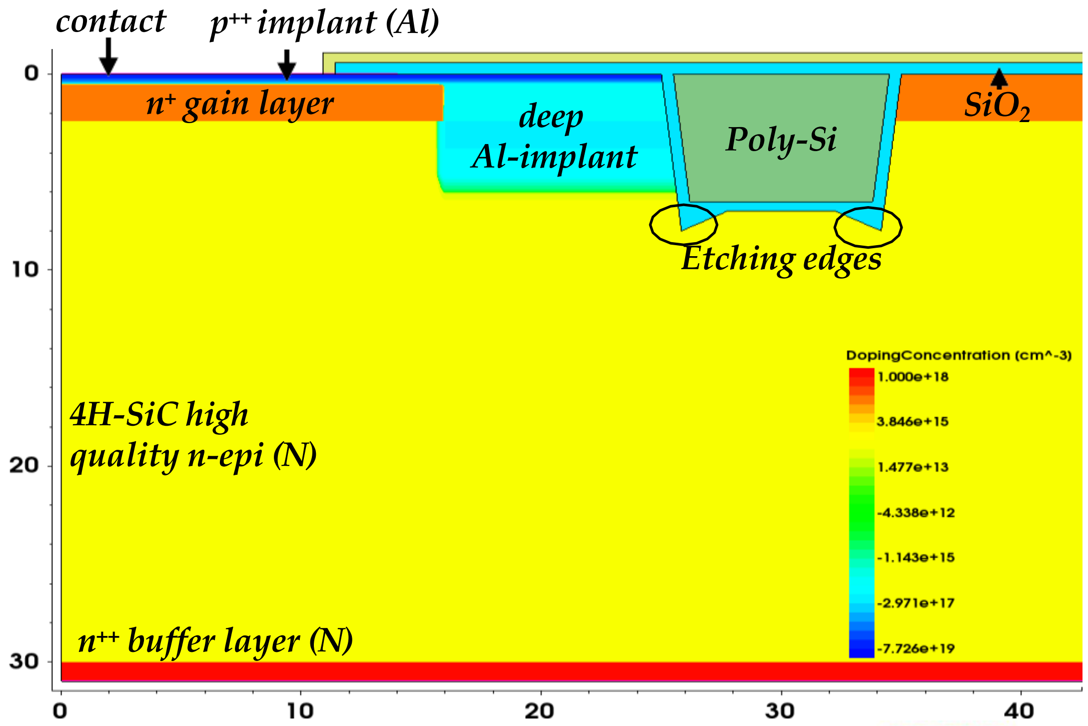


Design parameter	Target	Error
Sensor thickness	30 µm	-
Gain layer thickness	2.4 µm	0.2 µm
Gain layer doping	$7.5 \cdot 10^{16}$ cm^{-3}	10 %

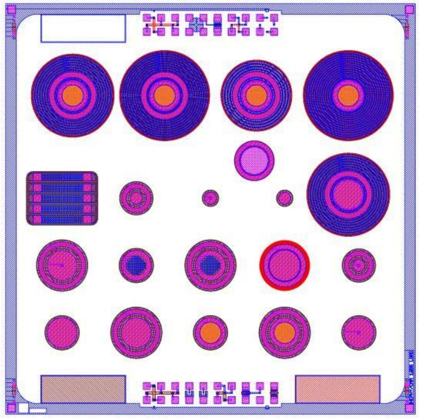


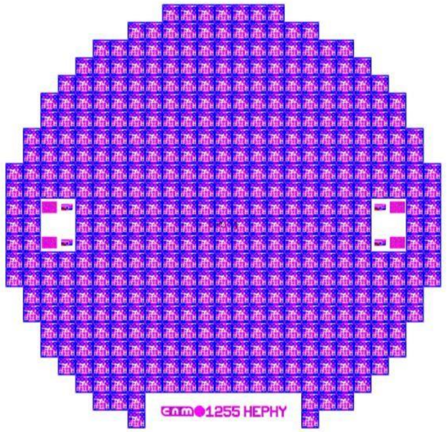
SiC-LGAD JTE TCAD Simulations

- Gain layer epitaxially grown homogeneously across whole wafer
  ⇒ no guarding with shallow implants
- 3 guard structure variants utilizing combinations of
  - etched trenches
  - deep JTE implants (4 μm)
  - floating metal field plates (FMFPS)
- TCAD simulations suggest V_{BD} > 2kV for all combinations
- Mask design is finalized and submitted for production



Mask Layout of
SiC LGAD design





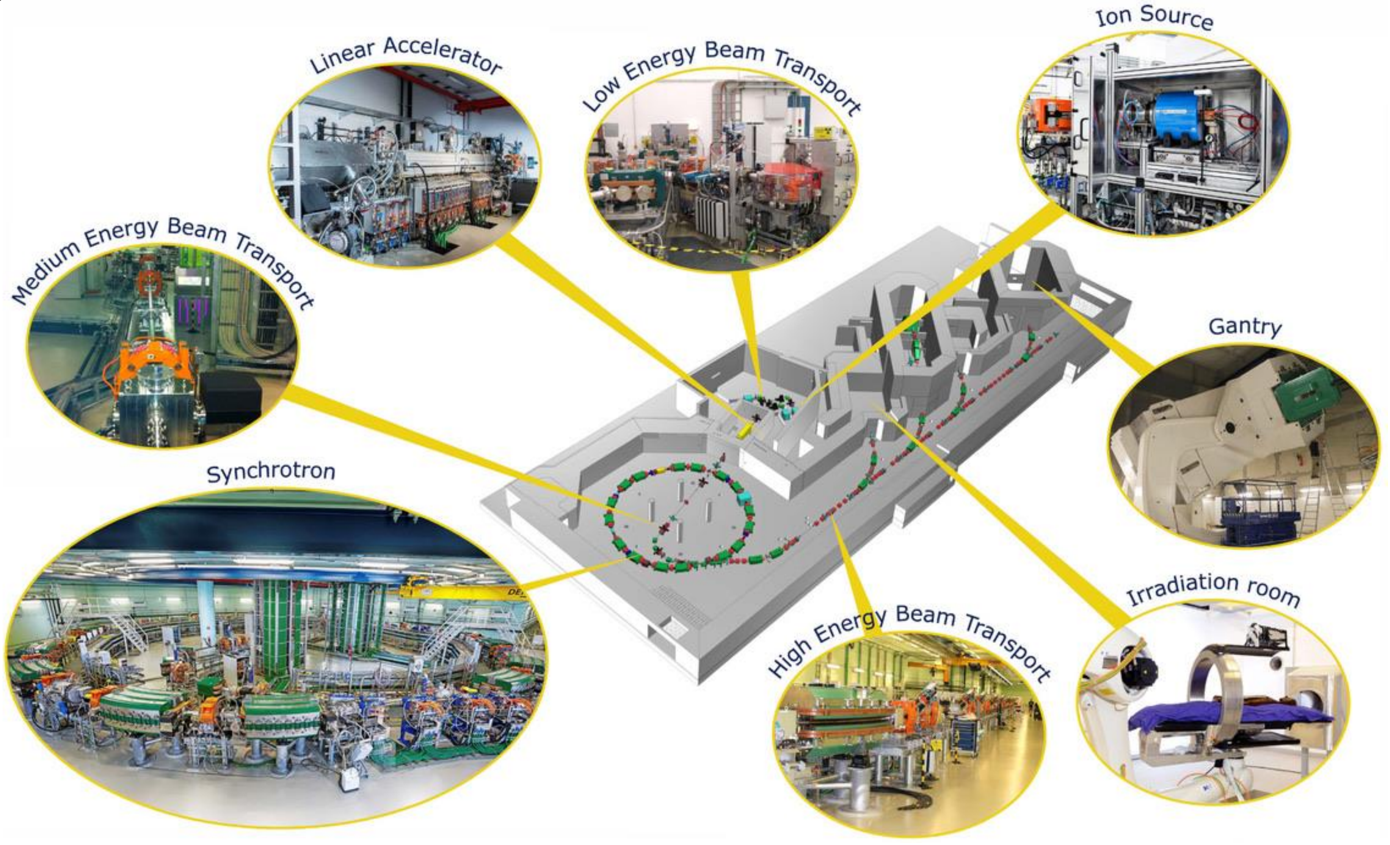
Medical Applications at MBI

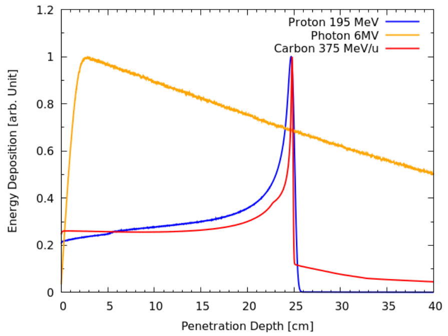
(where single MIP sensitity might not be necessary)

Ion Therapy at MedAustron

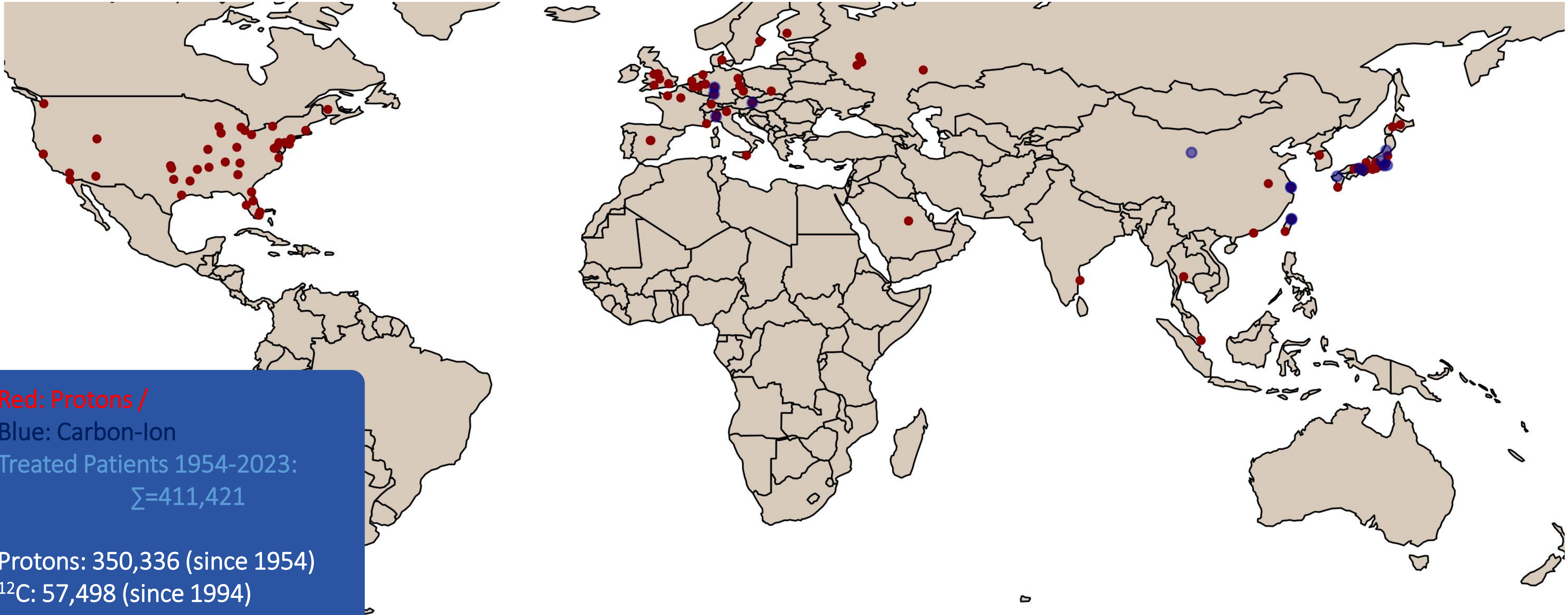
MedAustron: cancer therapy center

- Located in Wr. Neustadt (50km south of Vienna)
- Became operational end of 2016
- Based on CERN PIMMS study
  - Identical facility: CNAO Italy
- Patient treatment using proton and carbon beams utilizing Bragg peak
  - Protons: 60 MeV to 800 MeV, Clinical energies ≤ 250 MeV (equals WET ~ 37cm)
  - Carbon ions: 120 MeV/u to 400 MeV/u
  - Helium ions





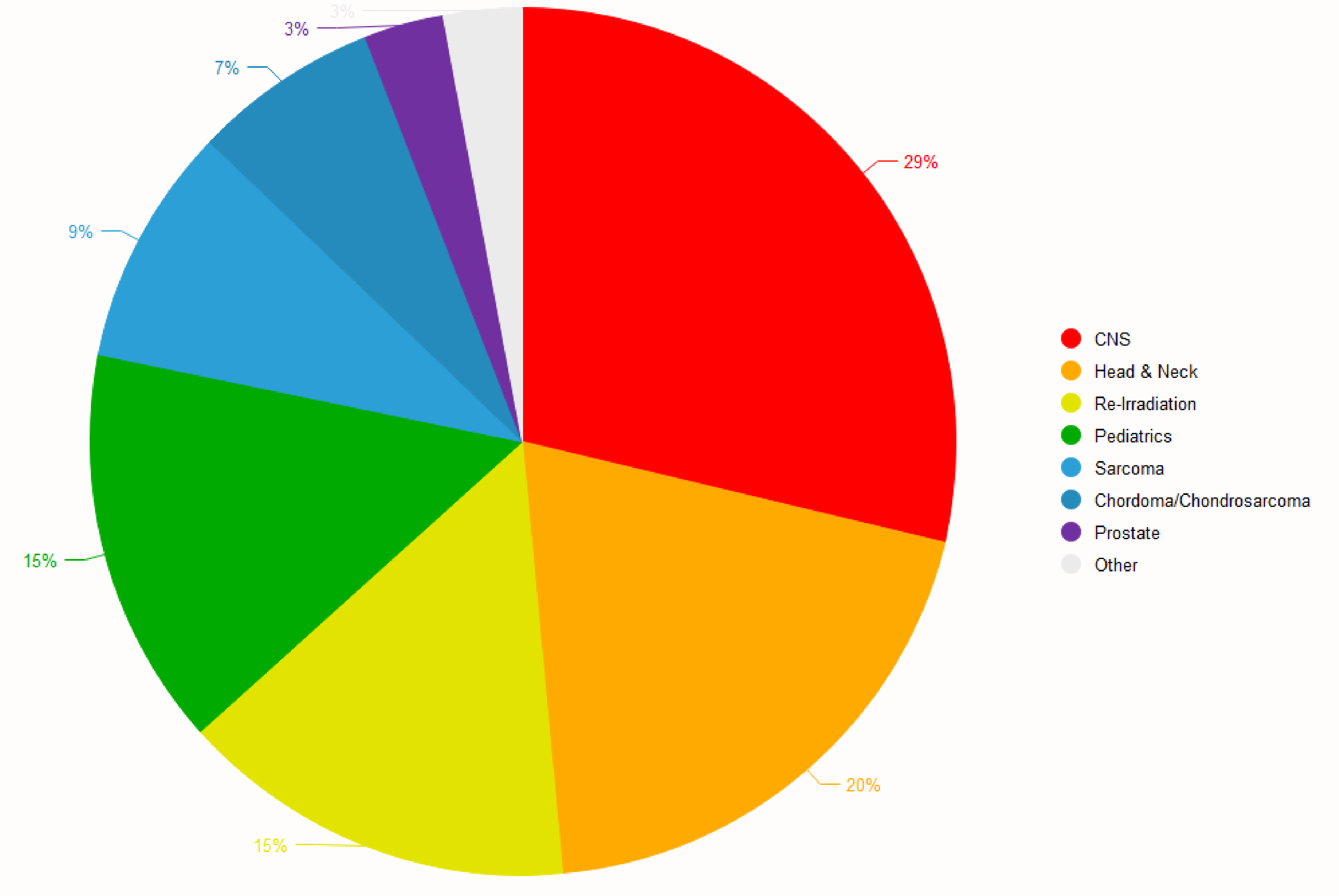
Particles Therapy Centers Worldwide



Red: Protons /
Blue: Carbon-Ion
Treated Patients 1954-2023:
∑=411,421

Protons: 350,336 (since 1954)
^{12}C: 57,498 (since 1994)
Others: 3,587

Patient Statistics

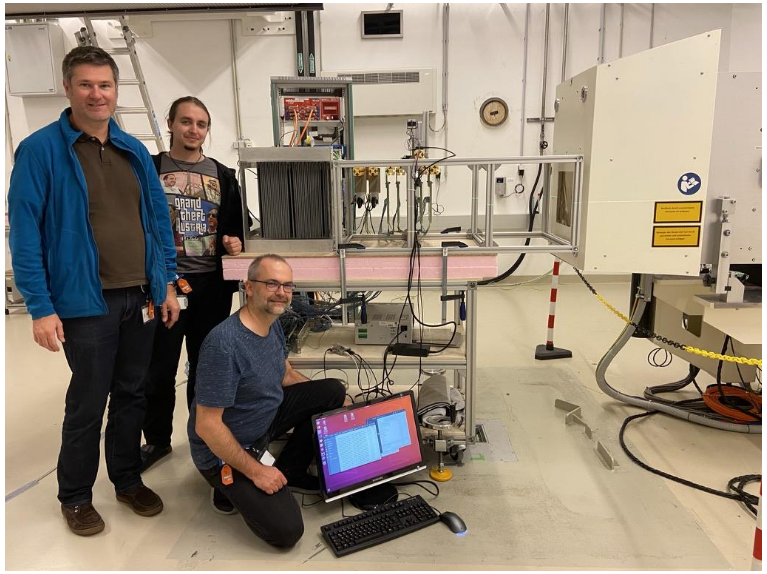


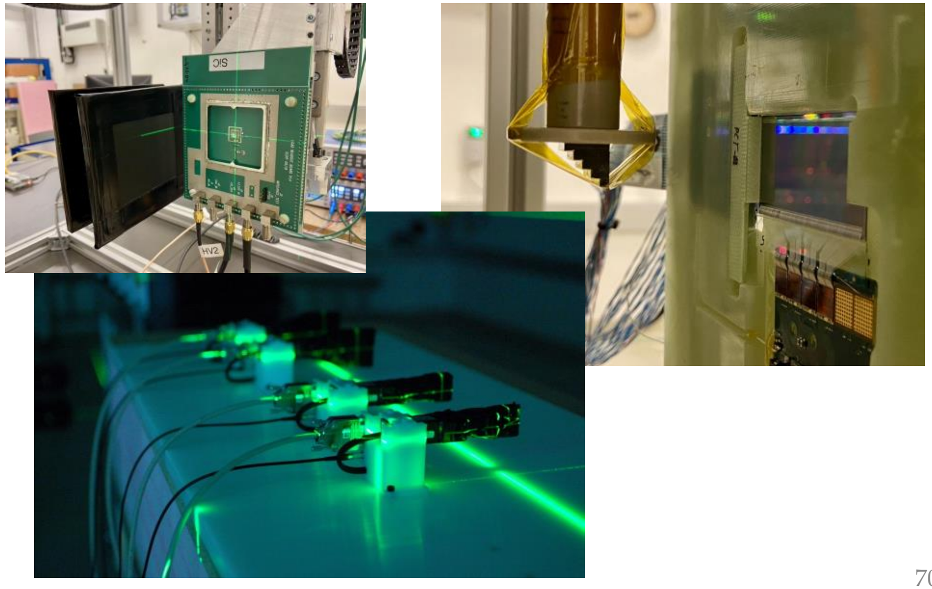
- >2500 patients treated at MedAustron between 12/2016-10/2024
- Annual rate, increasing, now at ~400 patients per year
- Main Indications:
  - Central nervous system
  - Head and Neck
  - Pediatrics
  - Re-Irradiation

Non-clinical research

- One irradiation room (out of four) devoted to non-clinical research
  - Allows proton and carbon ion beams (p up to 800MeV)
  - Beam time on weekends only

- Currently shared between several groups:
  - Radiation Oncology @ MedUni Wien (D. Georg, P. Kuess)
  - Accelerator Physics @ TU Wien (E. Renner, M. Benedikt)
  - Medical Radiation Physics with Specialization in Ion Imaging @ TU Wien (A. Hirtl, T. Bergauer)
  - Universities of Applied Science (Wr. Neustadt)





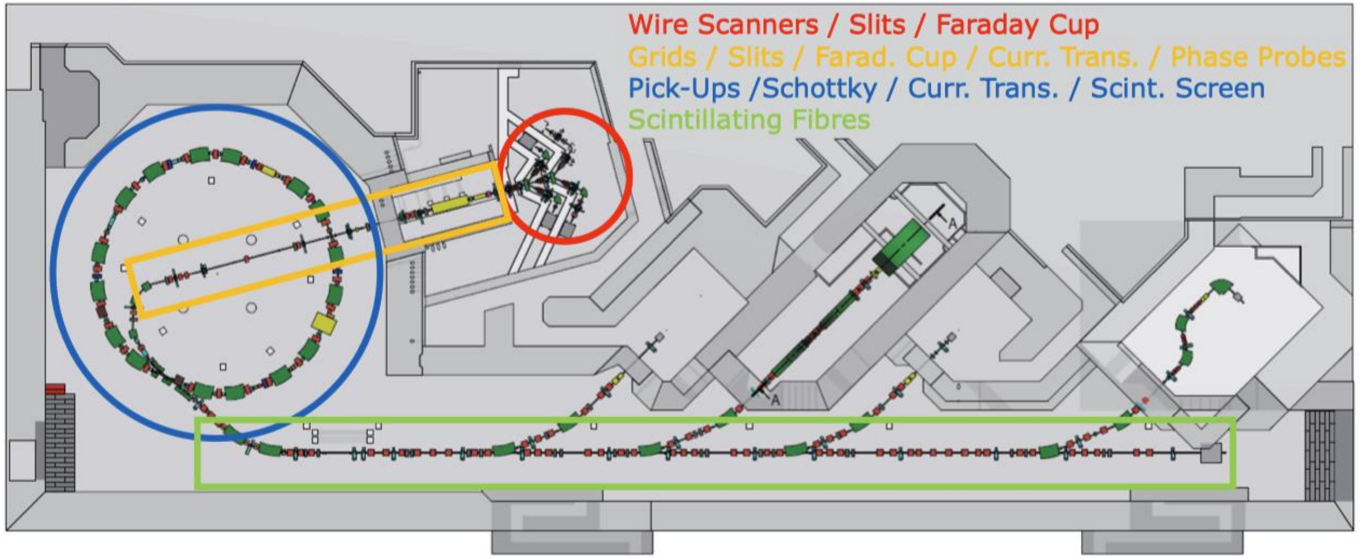
ÖAW AUSTRIAN ACADEMY OF SCIENCES
S. Waid, R. Thalmeier

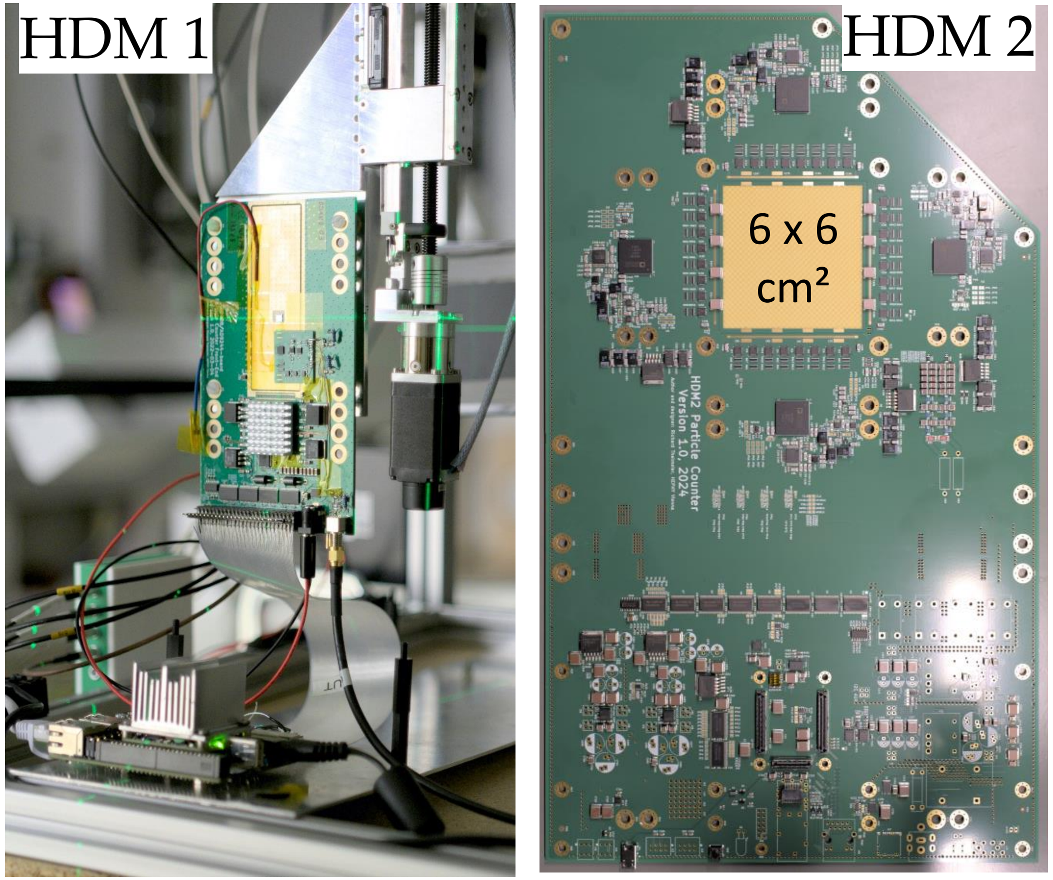
The HiBPM Project at MedAustron

«Hi-Precision Beam Position and Intensity Monitor for Accurate Cancer Treatment with Ions»

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS
FFG
Simon Waid, Richard Thalmeier

- Improve over scintillating-fiber-based beam monitor currently deployed at MedAustron
- Wide dynamic range: from single particles to GHz ("integrating mode")
  - At high rate DC-coupled SiC sensors are used
  - Possible due to very low leakage current, which is not increasing with radiation damage





SiC-based beam monitor

ÖAW AUSTRIAN ACADEMY OF SCIENCES

A Gsponer PhD thesis

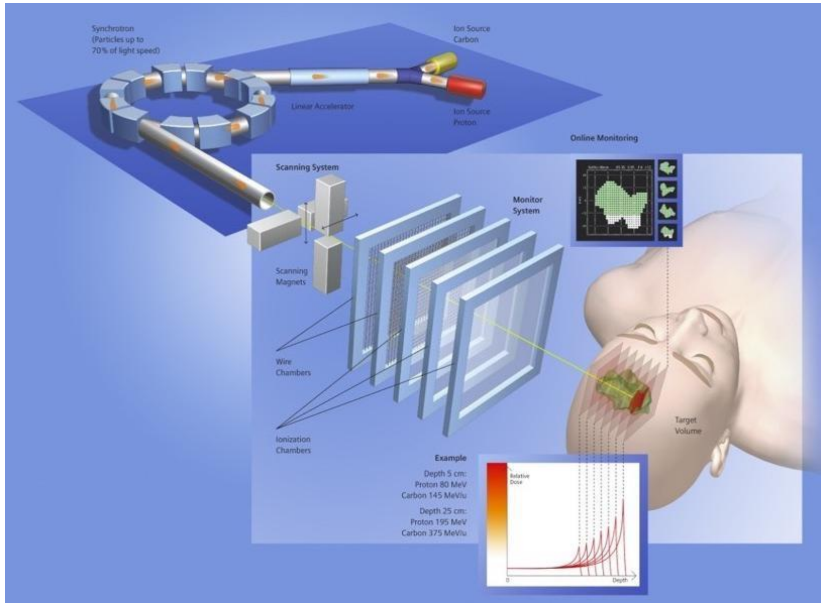
FLASH Radiotherapy

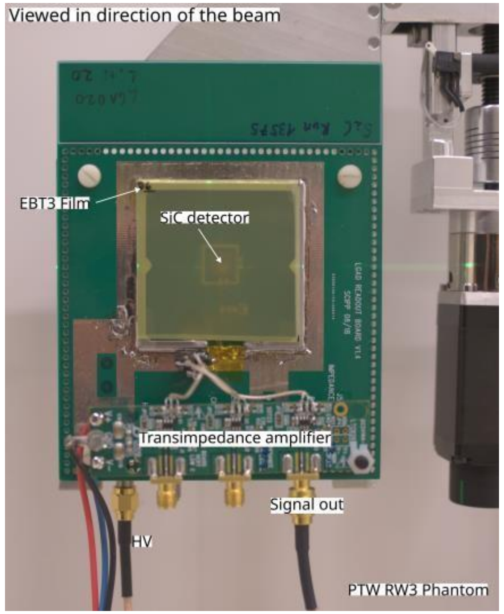
MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

MedAustron

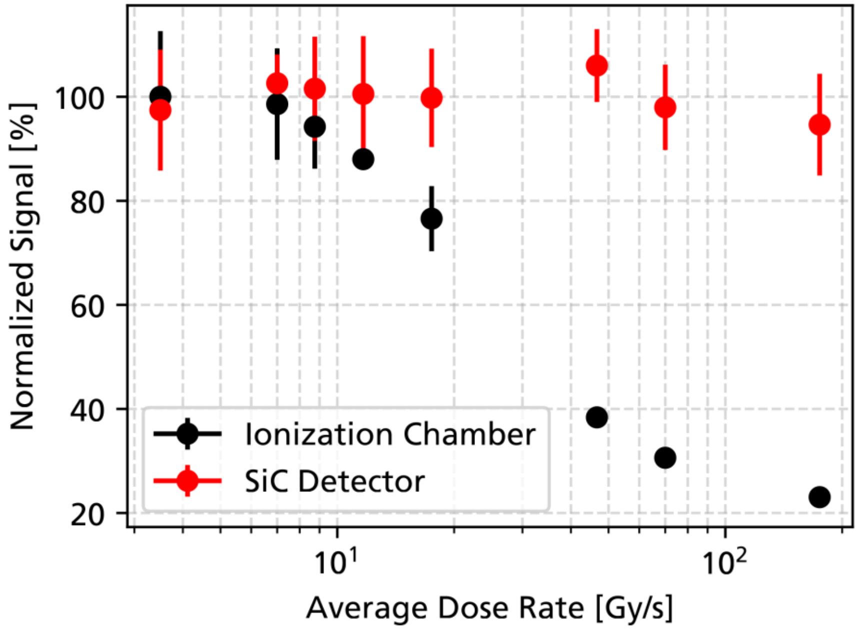
TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

- FLASH effect increases therapeutic window by sparing healthy tissue
    - requirements : **> 40 Gy/s, > 8 Gy / fraction**
- Ionisation chambers currently deployed at MedAustron get saturated at high dose rates
    - We demonstrated that SiC is linear up to 400 Gy/s





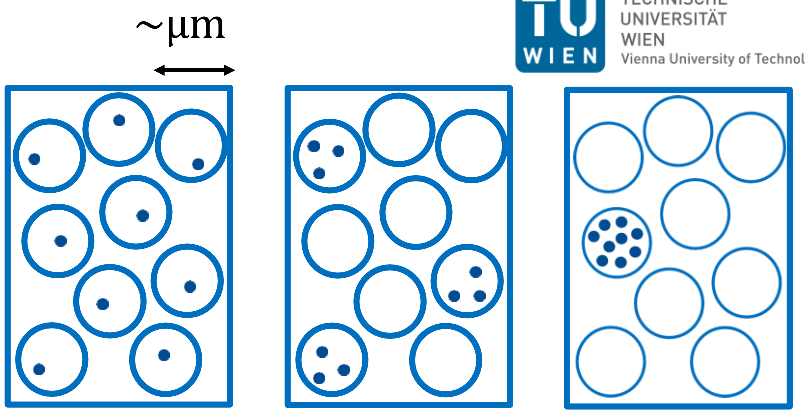
Dose-rate independent dosimeters required



Micro-Dosimetry

M. Knopf et al,.. [NIMA (2026), PMB (2025),..]

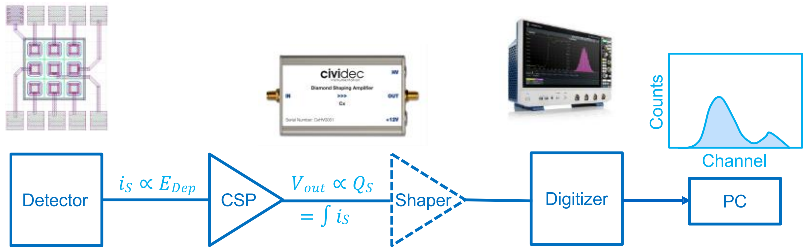
- Micro-dosimetry investigates the stochastic nature of energy loss in matter
  - Same dose [J/kg] → different effects [keV/µm]
- Solid State Micro-dosimeters similar to thin pad or pixel detectors
- Large overlap with MBI detector development
  - Small sensitive volume (µm) → Small signal per particle
  - Low noise electronics -> CSA amplifiers
  - SiC with low leakage current offers low noise
- Biggest challenge: Pile-up identification and un-folding pile-up signals into individual pulses, even for small and thin sensors
  - Software algorithm
  - Fast hardware (high noise ☹)

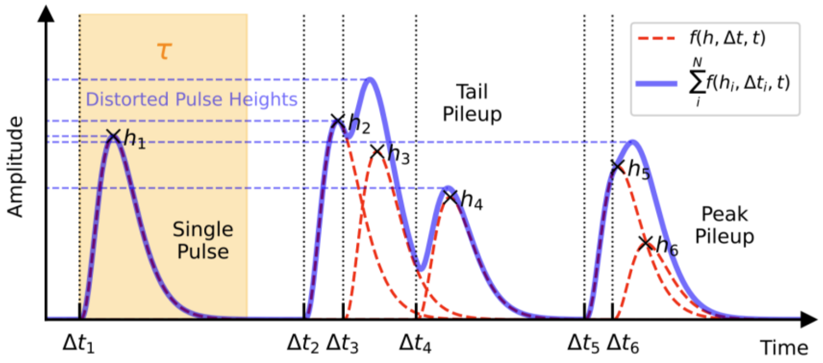


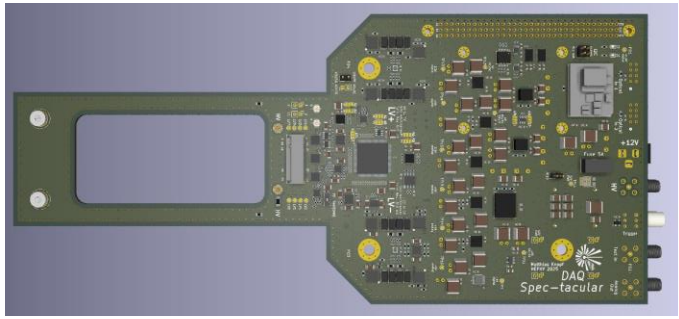
1Gy - Photons

1Gy – Protons 60 MeV [100 keV/µm]

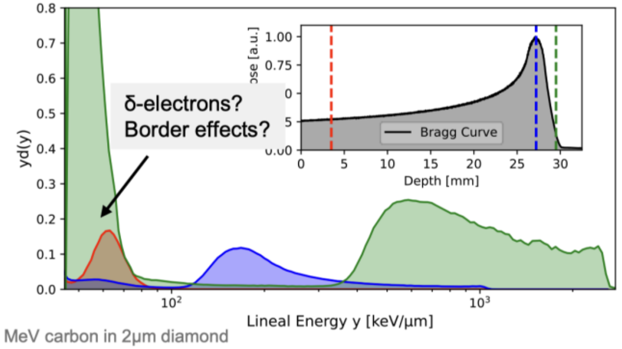
1Gy – 50 MeV C-12 [300 keV/µm]







Modular Readout system supporting exchangeable front-ends (CSAs,..) currently under development

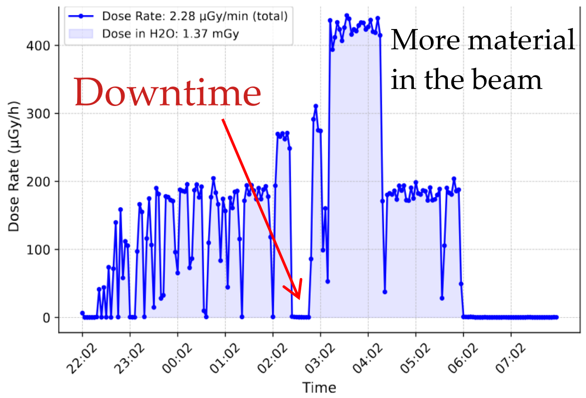


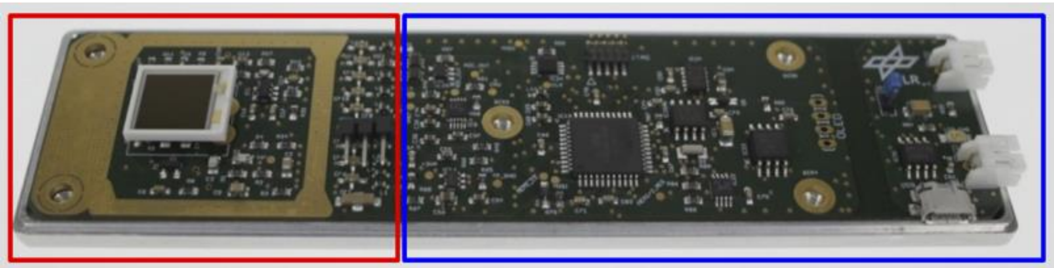
120 MeV carbon in 2µm diamond

SpaceSiC: Dosimetry with SiC

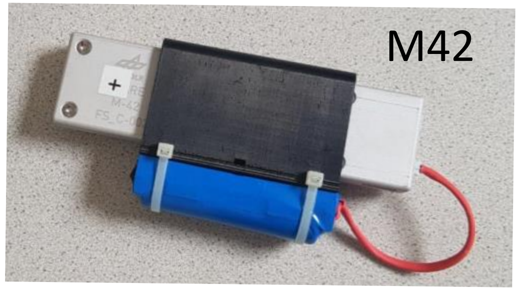
Daniel Radmanovac et al.

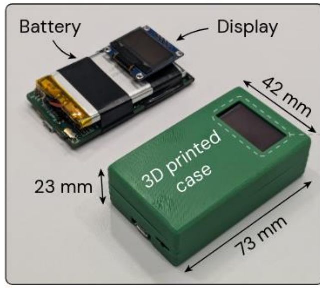
- Development of active dosimeters using Silicon Carbide as detector
  - Collaboration with Deutsche Gesellschaft für Luft- und Raumfahrt DLR
- Topics:
  - Develop an active dosimeter based on Silicon carbide (due to temperature stability in space)
  - Study of Galactic cosmic radiation at ESA's *Galactic Cosmic Ray Simulator* (beamline at GSI delivering spectrum of heavy ions up to iron [arxiv]) and MedAustron
  - Launch as payload of DLR MAPHEUS rocket (launch site: Kiruna, Sweden)
- Evaluated DLRs "M42" autonomous dosimeter (HPK Si Diode) from NASA ARTEMIS-1 mission
- Built own autonomous dosimeter based on Lyso scintillator and SiPM, based on OpenDosimeter project (summer internship)



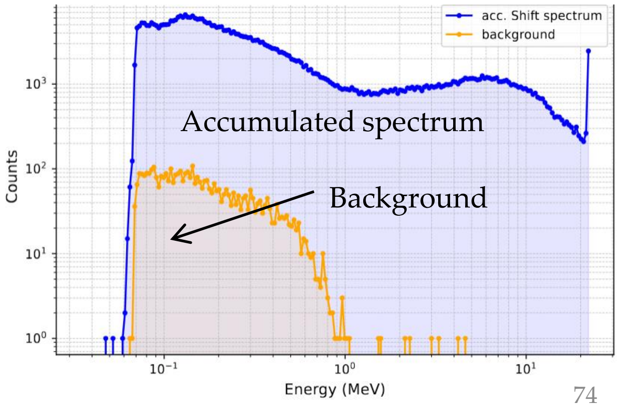


Analog circuit (red) with Si-diode, digital-circuit and I/O (blue)





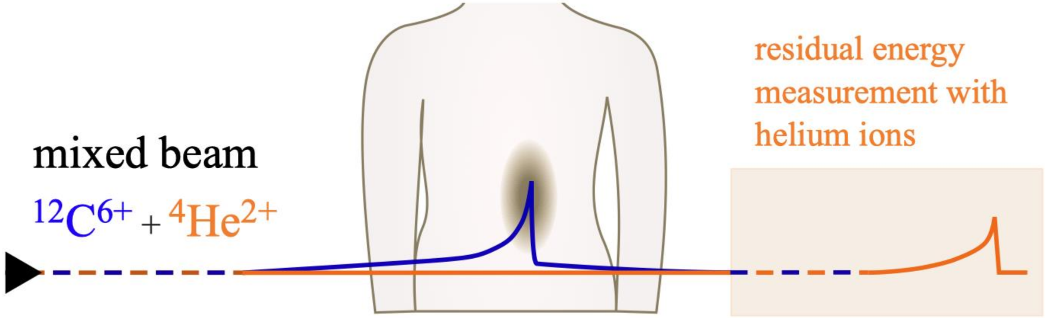
OpenDosimeter

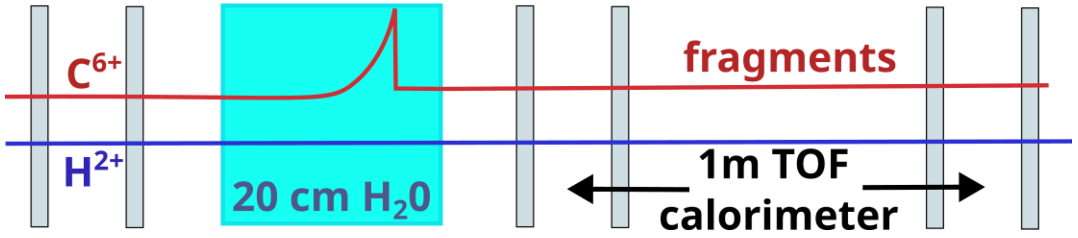


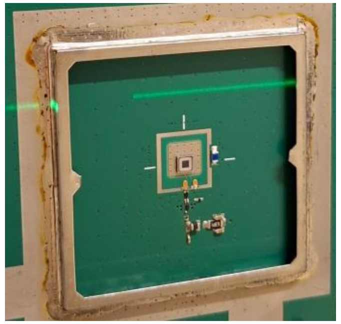
Mixed ion beam instrumentation

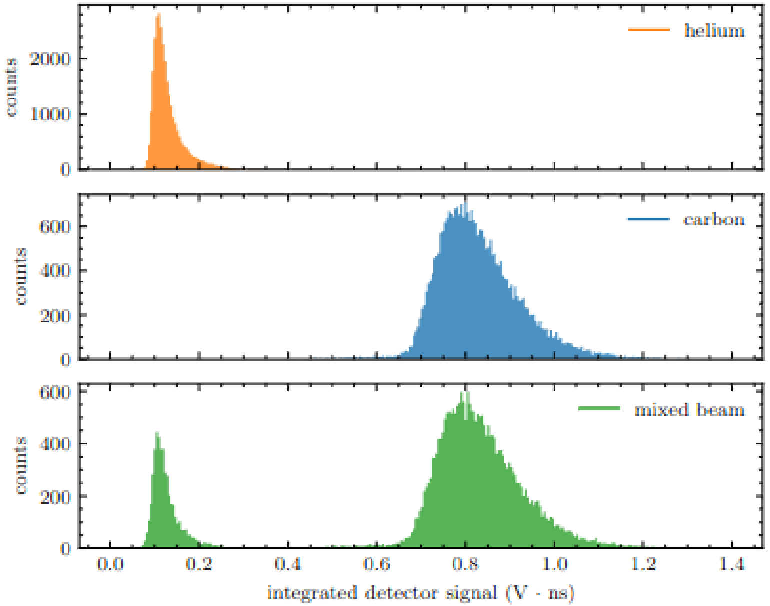
A. Gsponer, M. Kausel et al [arxiv]

- Mixed ion beams of C-12 and He allow simultaneous treatment and range verification
  - Work of accelerator physicists of TU Wien and MedAustron to generate 262.3 MeV/u mixed beam
- Confirmation of both ion species by by Si LGAD detector
  - Later on, residual energy verification by ToF



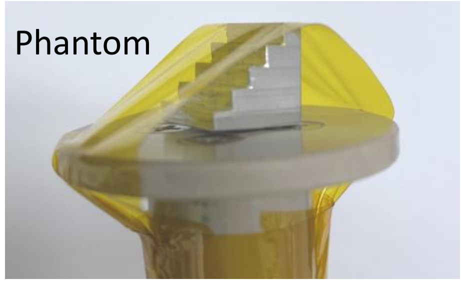


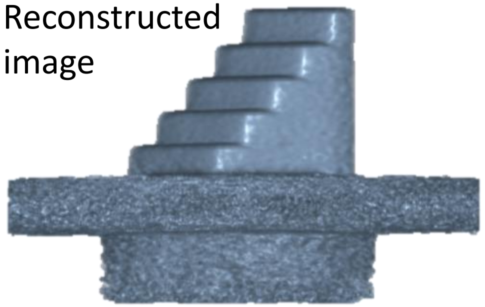


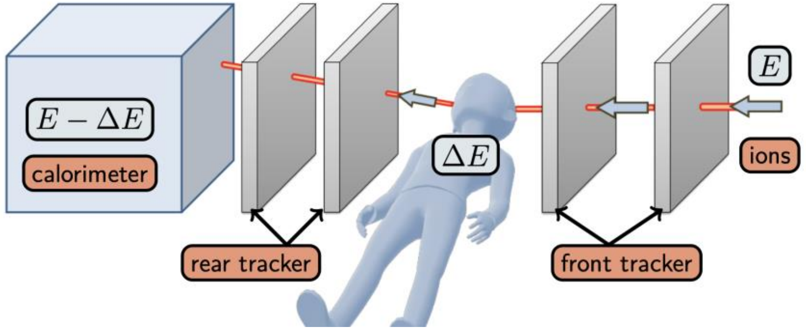


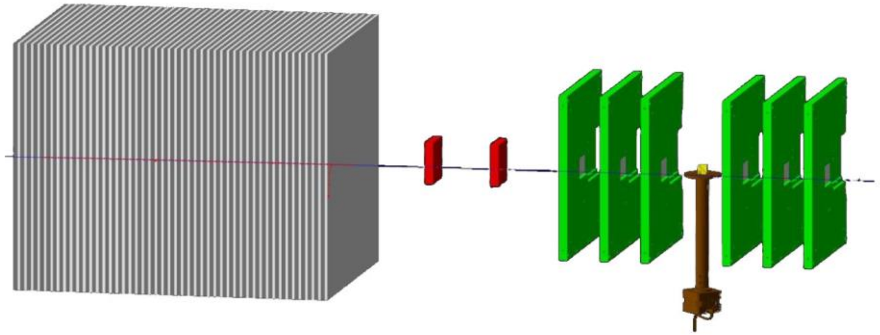
Ion Imaging: Phase I

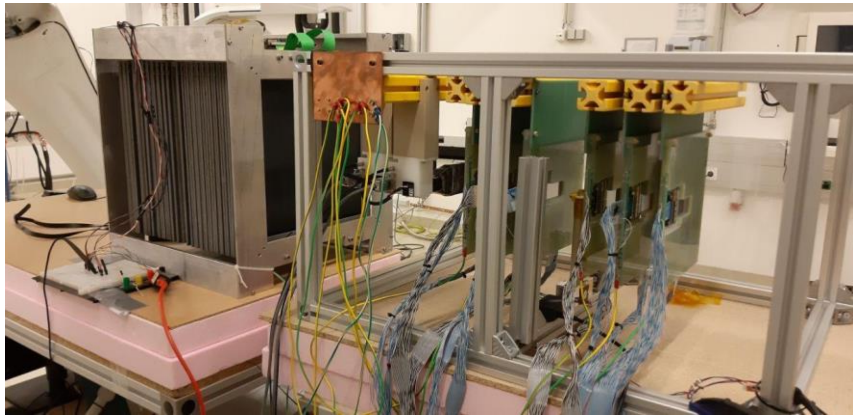
- Treatment planning based on x-ray CT
  - Conversion errors from Hounsfield units (HU) to relative stopping power (RSP) lead to range errors
- Ion computed tomography allows determining RSP directly
  - Several prototypes have been developed, but meeting all clinical requirements at once is challenging:
  - RSP accuracy < 1%, Energy resolution < 1%
  - DAQ rate > 10^6-10^7 Hz to keep imaging time low
- Our Hardware approach:
  - Tracker: Double sided silicon sensors
  - Calorimeter to measure residual energy: Sandwich calo using scintillator planes and SiPM readout (TERA PRR30)











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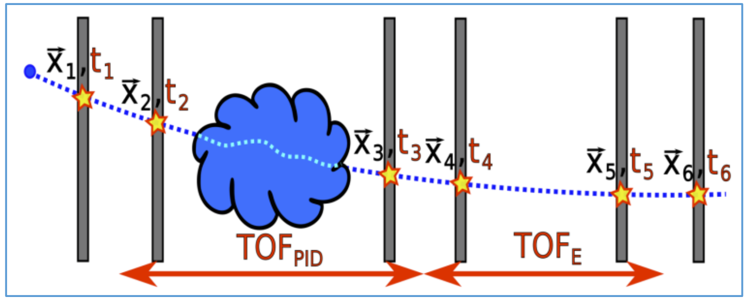
Ion Imaging: Phase-II

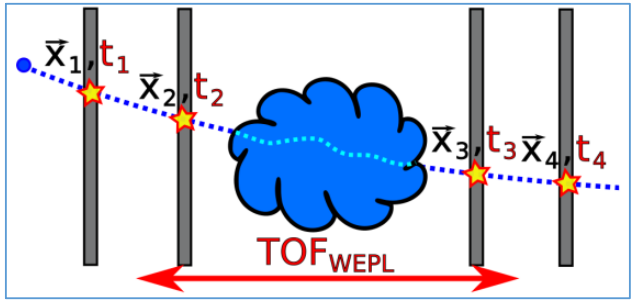
MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

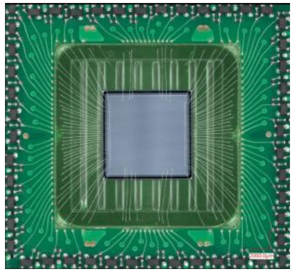
F. Ulrich-Pur et al [DPG meeting, PMB]

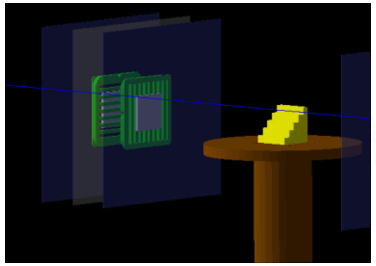
- We started to replace calorimeter with ToF system using LGADs:
  - "Feasibility study of a proton CT system based on 4D-tracking and residual energy determination via time-of-flight". In: Physics in Medicine & Biology. DOI: 10.1088/1361-6560/ac628b.

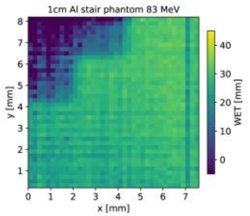


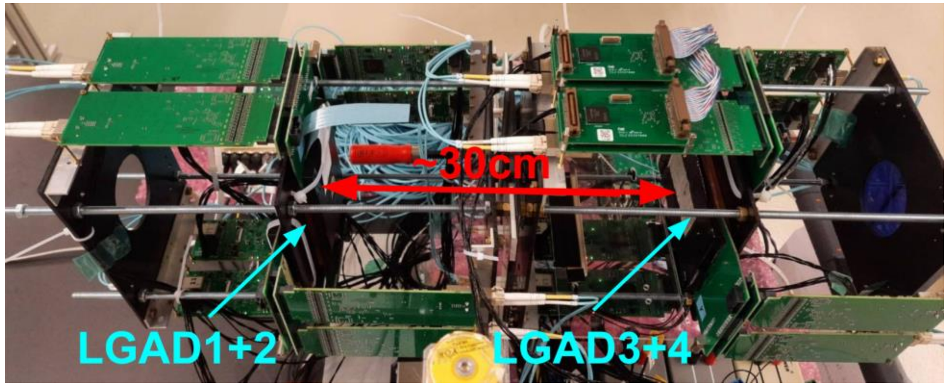
- Later, it turned out tracking and ToF stations can be combined:





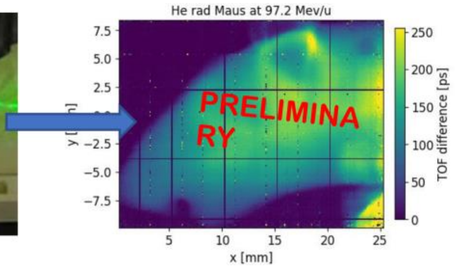




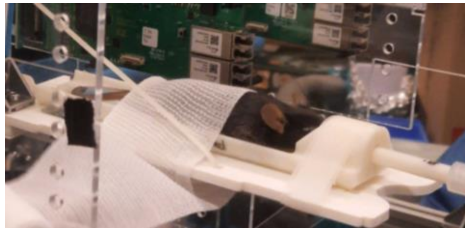


mouse phantom

TU Hamburg (Wegner et al. 2023=



Real mice:



Summary & Outlook

- FCC is favored by Europe as next flagship project at CERN
  - Stepping stone projects until then: Belle-II, ePIC, ALICE3
- Comprehensive detector R&D program developed after the last update of European Strategy 2020, confirmed and strengthened in 2026 update:
  - ECFA Detector Roadmap
  - Eight DRD Collaborations, review committee at CERN
- MBI research pillars well aligned:
  - MAPS sensors for Belle-II, ALICE3 OT, FCC-ee vertex detectors
  - Wide-bandgap semiconductor Silicon Carbide as most promising for radiation hardness
- (Medical) Applications and contacts with/to industry and new communities become essential and rewarding

Thank you very much for your attention

Status in US and Asia

US HEP community has been broadly engaging in the process on defining and shaping the DRD

- In addition, US Snowmass process recommended creating **Detector R&D collaborations (DRCs)**, organized by CPAD (annual workshop, last Oct 2025@UPenn)
    - P5 recommends to increase the budget for generic and targeted Detector R&D (#93 (CPAD) and #230 (P5 recommendations)
- Higgs Factory Circular Committee proposes organizational structure for the pre-project detector R&D scope

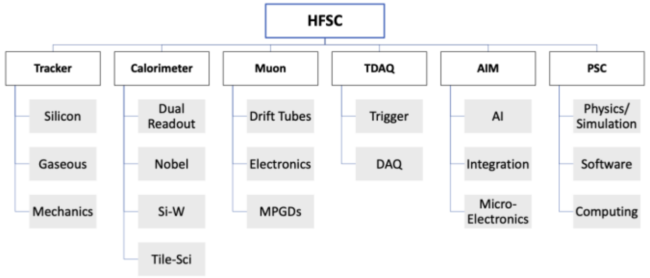
#229

Japan: some involvement in DRDs, but also man national developments, e.g. *Instrumentation Technology Development Center* (ITDC) established at KEK in 2023 (input proposal #99)

China: Many Chinese groups joined DRD collaborations and see them as way to continue R&D after CEPC decision

US RDC collaborations:

RDC#	TOPIC
1	Noble Element Detectors
2	Photodetectors
3	Solid State Tracking
4	Readout and ASICs
5	Trigger and DAQ
6	Gaseous Detectors
7	Low-Background Detectors
8	Quantum and Superconducting Sensors
9	Calorimetry
10	Detector Mechanics
11	Fast Timing

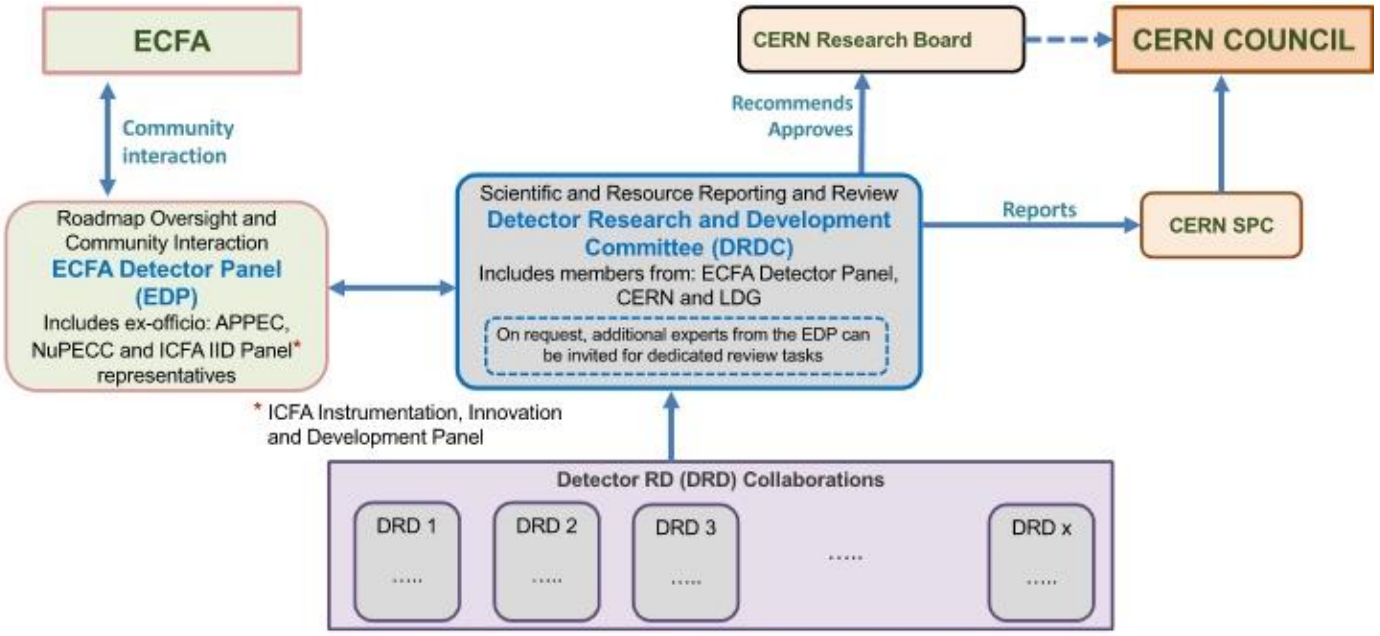


Roadmap Implementation Plan

- 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
    - Organizes "DRD managers forum" (six meetings so far)

- **Each DRD collaboration is treated like a "small experiment"**
  - Needs management structure beyond spokesperson and WP/WG leaders: MoUs as legal basis, collaboration board, resources board, regular review,…

Seen as too administrative by many



Memoranda of Understandings

- MoUs are required for collaborations at CERN – Template follows example for “small experiments” at CERN
  - Initial idea was to **distribute MoU including funding requests** to institutions and funding agencies. Did not work out as resources were not agreed or committed by FAs
  - DRD1 proposed a “**light MoU**” using a **staged concept**: omitting resources as a viable approach to moving forward and initiating the signature process
  - Resource-loaded Work Packages require separate internal approvals by CB, RB, and Funding Agencies (2nd stage of MoU approval)
- Open problems:
  - CERN very slow in getting MoUs ready to initate signatures
  - The **Common Fund** remains problematic and currently blocks signatures from several institutions, e.g. INFN, but is seen by DRD1 and DRD3 as ”base” funding, independent of resource-loaded projects
  - **Negotiations with DOE/NSF** to sign agreements to secure US participation need to continued

Collaboration	Topic	CF requested	amount / comment
DRD1	gas detectors	yes	3 kCHF cash
DRD3	semiconductors	yes	2 kCHF cash (possibly in-kind)
DRD4	photodet. PID	not now	1 kCHF planned
DRD2	liquid detectors	no	MoU only with existing money
DRD7	electronics	no	MoU only with existing money
DRD5	quantum	no	
DRD6	calorimetry	no	
DRD8	mechanics	no	

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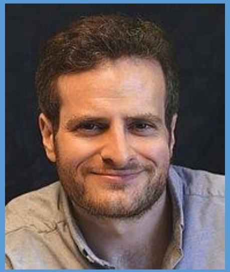
Group Display

- **ÖAW Staff** (mostly third-party funded):
  - **Simon Waid** (Postdoc), **Bernhard Pilsl, Sebastian Onder** (from CMS Tracker Group), **Daniel Radmanovac, Juraj Habala** (just started); **N.N**. to be employed by December
  - Maximilian Babeluk, Andreas Gsponer (both recently finished)
- **Master Students**:
  - J. Müllner, C. Hahn, F. Zivic, D. Muxel, C. Ercher
- Several **BSc/Project students** (~10 in last year)
- **Synergy to other hardware groups**: Belle, former CMS Tracker, most likely also ALICE in the future
  - Postdocs from Belle (**Roberto Russo**) and CMS (**Stefan Gundacker**)
- Close collaboration with TU Wien RadPhys Group
  - **Albert Hirtl**, Felix Ulrich-Pur, Matthias Knopf, Matthias Kausel, Harald Handerkas
- Collaboration with many staff members from the service groups, especially the electronics department


Thomas Bergauer


Simon Waid

From other groups


Stefan Gundacker


Roberto Russo


Sebastian Onder

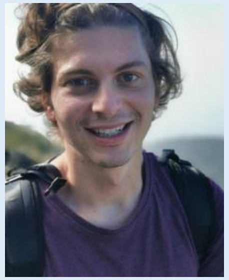

Bernhard Pilsl

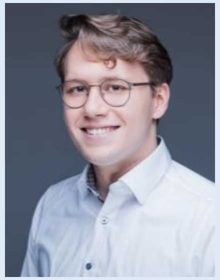

Daniel Radmanovac


Juraj Habala


Albert Hirtl (TU Wien)


Felix Ulrich-Pur (TU Wien)


Matthias Kausel (TU/MedAustron)


Matthias Knopf (TU Wien)


Harald Handerkas (TU Wien)

Third-Party funding

European funding

- **AIDAinnova**: (2021-2025): community-wide large project aiming at networking

Horizon Europe 2021-2027

National funding – here we pioneered access to FFG:

- Call **Industriedissertationen** (2 projects; 1 PhD student /3y each)
- Call **Expedition Zukunft** (1 projects; 1 postdoc /1y each)
- Many **FFG Femtech** students and **FFG Praktika** for school children
- Call **BRIDGE** (2 projects; 1 postdoc + 1-2 PhD students /3y each)
  - **HiBPM** and **Flash-BPM**: *cooperation with MedAustron GmbH*
  - **RadHardDetSim** *in cooperation with "Global TCAD Solutions GmbH"*

HEP Applications benefit for both **Company Interest**

ÖAW Innovationsfond

- for acquiring high-tech equipment (e.g. HF Oscilloscopes, Semiconductor Analyzer, Cold Chuck)

Analog Chip Design Projects

Aim: Front-end and pre-amplifiers to reach higher bandwidths and lower noise

efabless.com

Simon Waid et al. [Austrochip 2024]

Skywater 130nm
"Open Source" PDK

„Fast" TIA Amplifier

- Transimpedance „fast" amplifier
- Google sponsored MPW5 & 7
- Followed by "NIST"-sponsored submission

Fraunhofer SiC-CMOS
via Europractice IC Service

CSA + Pixel Sensor

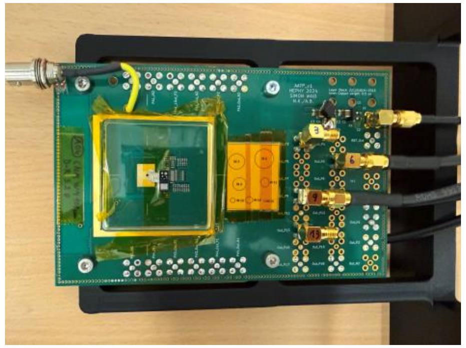
- CSA Amplifier for possible Micro-dosimetry application
- Both sensor and amplifier on SiC substrate

S. Onder et al. [MicEleEng (2026)]

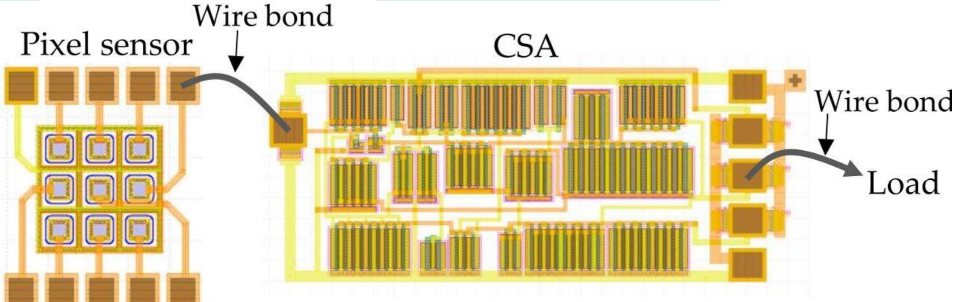
IHP IHP S130G2 PDK
"Open Source" PDK

Micro-dosimetry

- Charge sensitive amplifier
- Application in Micro-dosimetry

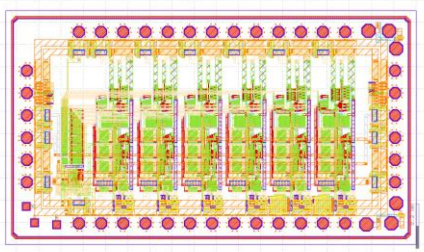


Tested at MedAustron in Sept 2025



Taped out March 24.
Delivery still pending ☹

(not true to scale)



Taped out Sept 25. Delivery expected in Feb. 2026

OBELIX Digital Periphery

M. Babeluk, J. Habala, C. Irmler [NIMA (2025), M Babeluk PhD thesis]

- Triggering system (TRU)
  - Memory buffer to handle 10μs trigger latency with optimized low power consumption in dual-stage memory design
  - Large simulation effort for performance evaluation, including clustering & charge/ToT conversion
- Peripheral Time to Digital (PTD) converter
  - HitOR: all comparator outputs of one column in an OR
  - Allows precision timing of ~5ns; better than Timestamp (47 ns) for low hit rates << 10 MHz/cm²
- Track Trigger Transmission (TTT)
  - Independent Tx for contribution to Belle II trigger