4D tracking detector development in DRD3

Alessandro Tricoli
(Brookhaven National Laboratory)

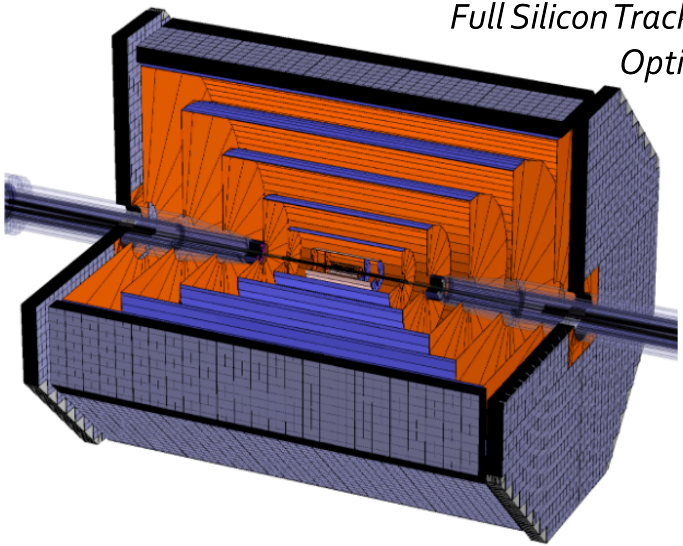
The 2024 International Workshop on
the High Energy Circular Electron Positron Collider
Oct 22 – 27, 2024
Hangzhou Platinum Hanjue Hotel

CEPC Tracker Specifications

CEPC Tracking Requirements:

- Single-point resolution of 1st layer < 3 µm
- Material budget < 0.15% Xo per layer (incl. support structures)
- 1st layer close to the beam pipe at r= 16 mm
- Detector occupancy ≤ 1%.
- Power consumption of the sensors and readout electronics < 50 mW/cm² , if the detector is air cooled.

Full Silicon Tracker Option



❖ **Options:**

1. **Silicon Vertex** + TPC + **Silicon Tracker** (pixel and strips)
2. **Full Silicon Tracker**

➢ Sensor technologies which achieve **fine pitch**, **low power, low mass** and **fast readout** must be selected

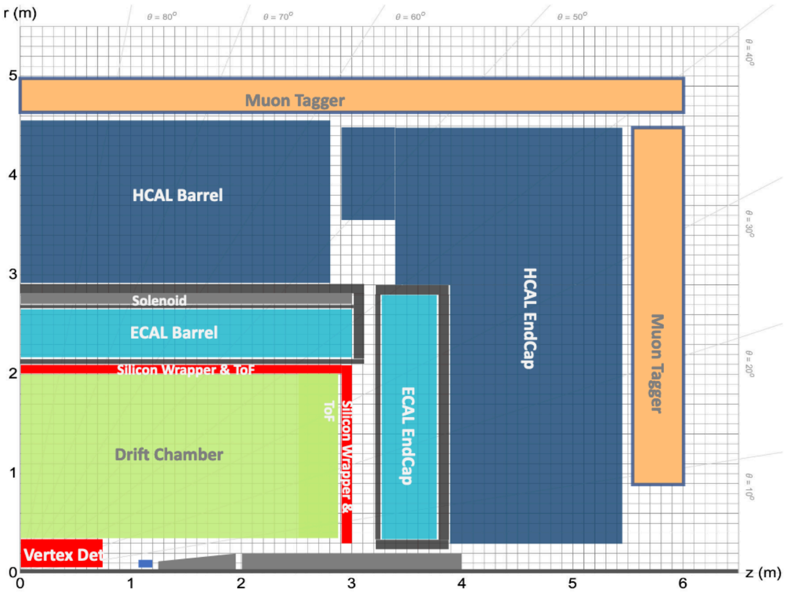
- **MAPS are prime candidates for silicon tracker**
- **What about Timing ? 4D tracker?**

The need for 4D Detectors

❖ **As 4D detector Technologies are becoming more advanced, we realize their benefit in collider experiments**
- Timing useful input to **Particle Flow** algorithms
- Timing as additional information from the **Calorimeters**: identification of slow from prompt shower components
- **PID capabilities** across a wide momentum range is essential: flavor physics, H→ss…
  - **Time-Of-Flight**: ~10 ps resolution over 2m

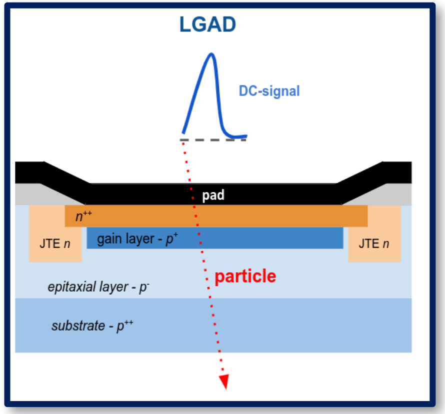
❖ **ALLEGRO Detector concept at FCC-ee as an example**
- Vertex Detector: **MAPS or DMAPS**- Possibly ALICE 3 like?
- Silicon Wrapper + ToF: **MAPS or DMAPS possibly with timing layer (LGAD)**

***ALLEGRO** Detector Concept for FCC-ee*

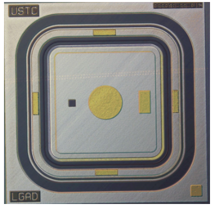


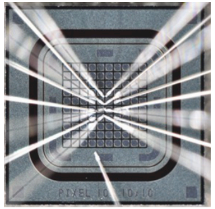
➢ Silicon technologies can meet the need for 4D detectors at Future Lepton Collider experiments

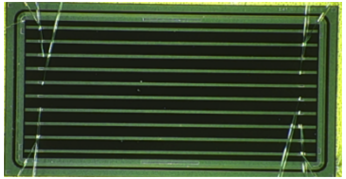
LGAD Technologies



- **Low Gain Avalanche Diode (LGAD) is advanced technology for precision timing**
  - Used in ATLAS and CMS for HL-LHC timing detectors
  - Several foundries in China, Europe, US and Japan
- **Thriving field of research for 4D detectors: pixels or strips with various processes**

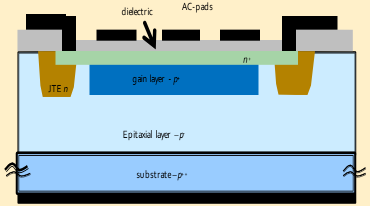






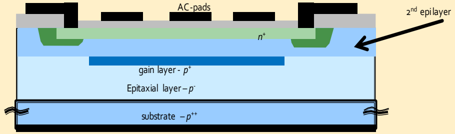
AC-LGAD

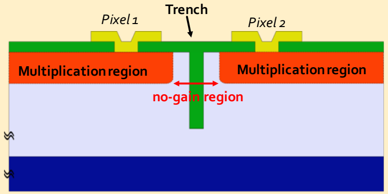
100% fill factor, excellent spatial resolution with signal sharing, for low interaction rates



Deep-Layer AC-LGAD

an AC-LGAD with higher rad-hardness



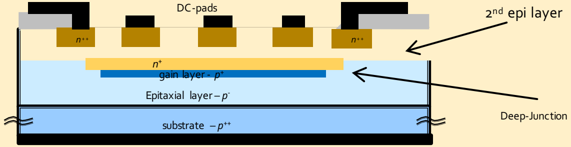


Trench-Isolation LGAD

~100% fill factor, signal in single pixel (no share)

Deep-Junction LGAD

Position resolution given by pitch, as in std pixels/strips

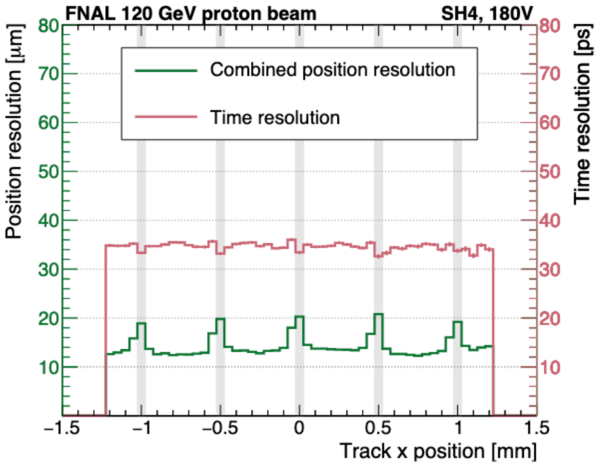


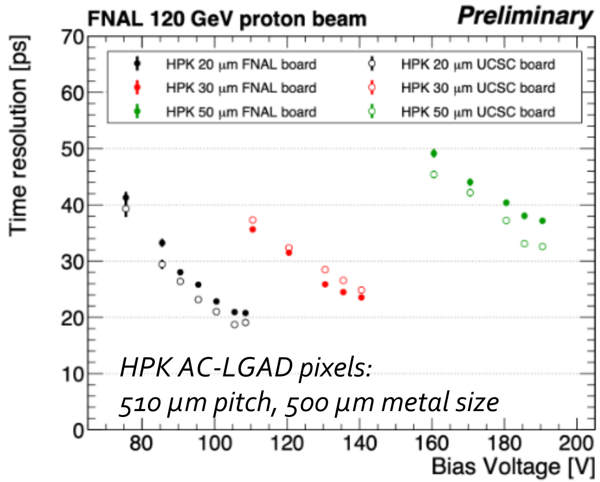
LGAD Performance

<u>AC-LGAD</u> demonstration in test-beams of simultaneous O(10 µm) & O(30 ps) resolution with large pixel or strip pitches
➔ technology for 4D-trackers!

Signal shared between neighboring electrodes in AC-LGADs:
Measure position based on signal ratios

- **100% detection efficiency** across sensor surface
- **Position: 15-20 µm** resolution in *1 cm strips, 500 µm pitch*
- **Timing: 30-35 ps** resolution for 1 cm strips

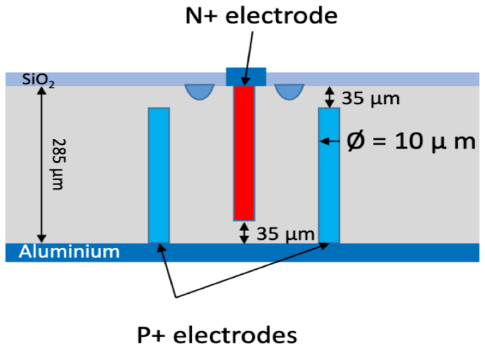




➢ **Better the timing with smaller the thickness (20 µm): ≤ 20 ps resolution**

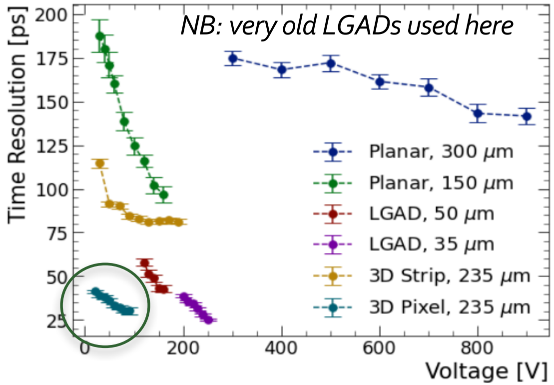
arXiv:2407.09928

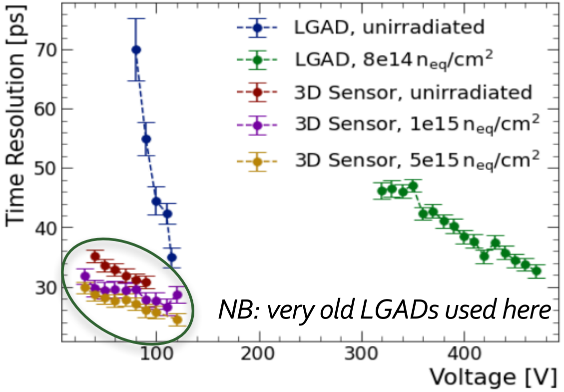
3D sensors



- **3D sensors: charge collection distance decoupled from sensor thickness**
- **3D sensors proven more radiation hard than planar silicon**
  - Less affected by signal trapping
  - Partial depletion possible

- 3D double-sided technology:
  - Hexagonal and Quadratic geometries,
    285 µm active thickness, 10 µm column diameter





- Before irradiation, 3D sensors **reach time resolutions of 30-35 ps**, comparable to 50 µm -thick LGADs
- 3D pixel sensors improve resolution after irradiation with constant bias voltage
- **3D pixels withstand 5×10^{15} n_{eq}/cm^2** while keeping their timing performance

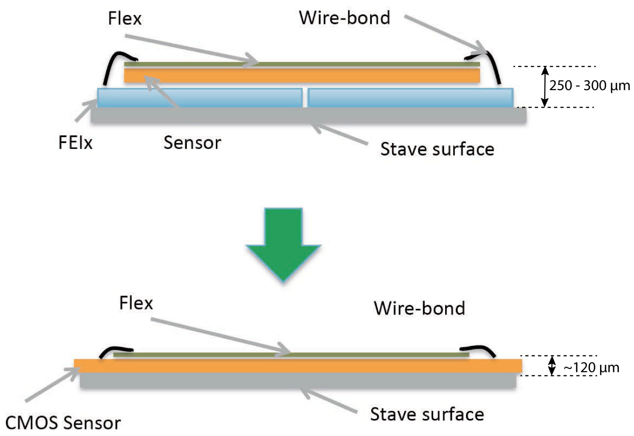
Ulrich Parzefall talk
(https://indico.cern.ch/event/1434481/)

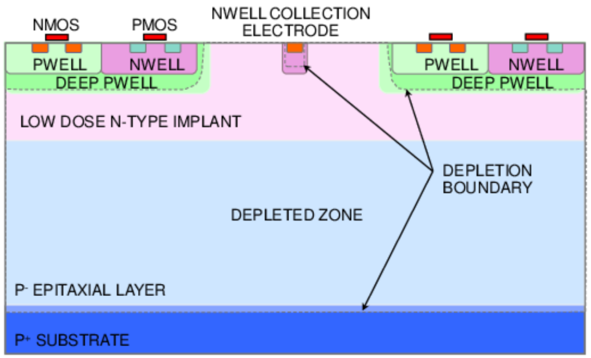
Monolithic Detectors

- **Material budget and cost** for large volume trackers are a concern for future collider experiments
- **Monolithic Active Pixel Sensor (MAPS)** established technology
  - ➢ **Silicon sensor and front-end electronics in a single device**
- **4D tracking is possible with MAPS**

Advantages

- **Low mass:** combine readout circuitry and sensing elements in a single and compact device
- **Commercial foundries** can be used
- **Cost savings**, i.e. in bump-bonding, cooling
- New MAPS process technology



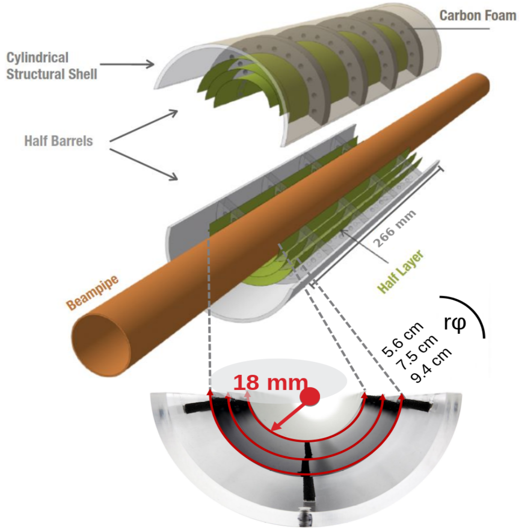


arXiv:1909.11987

Mini-Malta (DMAPS)

- TJ 180 nm CMOS
- Pixel 36.4 x 36.4 µm^2
- High resistivity epitaxial p-type substrate
- originally proposed for ATLAS ITk outer pixel layer

Monolithic Detectors for Tracking and Timing



❖ **ALICE ITS3 for Tracking**

- Reduce **material thickness**
- Remove **electrical substrate, mechanical support, and active cooling** circuit in detector acceptance
- First detection layer **closer to interaction point**

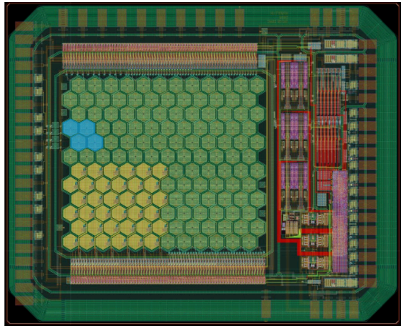
ITS3: ultra-light, truly cylindrical layer

- **65 nm MAPS**, 300 mm wafer-scale stitched sensors, ~50 μm thickness
- **Bent to the target radii** (Layer-0 from 23 mm to 19 mm)
- Mechanically in place by carbon foam ribs
- **Air cooling between the layers**
- **Low material budget** (0.05% X0)

❖ **SiGe BiCMOS MAPS (without Internal Gain)**

- 130 nm by IHP
- 50 μm- thick epilayer with 350 Ωcm (fully depleted)

- **Time Resolution:**
  - 45 ps for 1200 e^- (0.4 x MIP)
  - 3 ps for 11k e^- (3.5 x MIP)

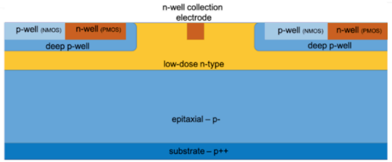


144 hexagonal pixels of 65 μm side

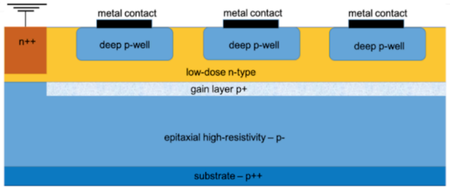
https://arxiv.org/abs/2401.01229

Towards 4D Monolithic Detectors with Gain

- **MAPS sensors in a commercial process (e.g. CMOS) can provide fast timing (~10 ps) and precise spatial resolution (~5 μm)**
  - 4D tracking detectors for colliders of the future
    ➔ e+e– Higgs factories and multi-TeV colliders
  - Electronics for signal processing are placed in dedicated p–and n-wells contained within a deep p-type well
  - *<u>Intrinsic gain</u>* will allow MAPS detectors to perform precise time measurements in addition to spatial measurements

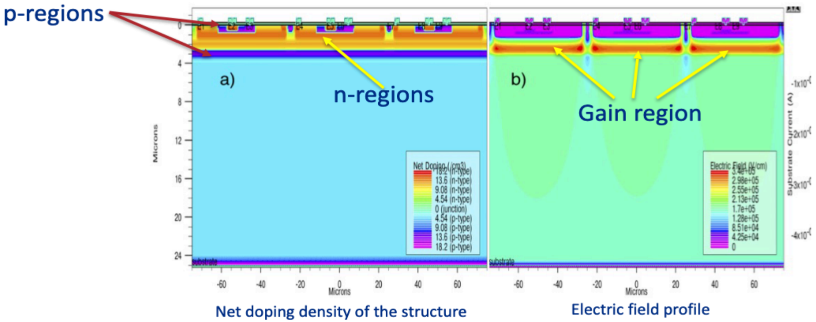


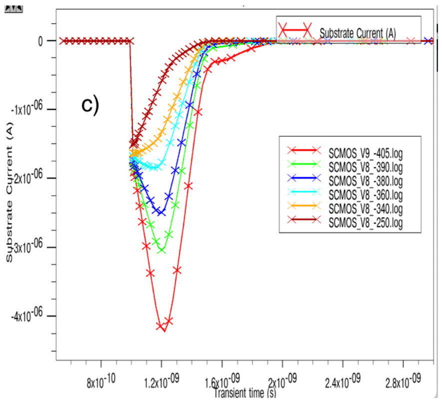
CMOS sensor



Monolithic AC-LGAD

TCAD Simulation



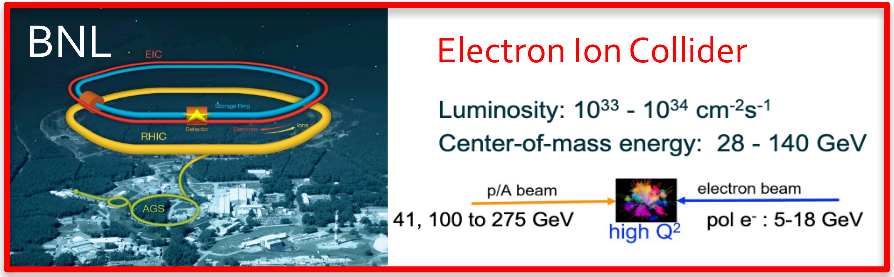


- Substrate current pulses for bias voltages from 250 (brown) to 405 (red) Volts showing the onset of gain.
- Rise time of the top electrodes will be determined by the details of the CMOS well capacitance

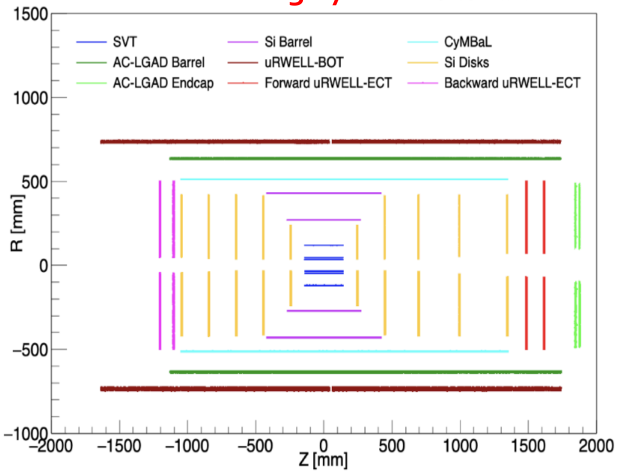
Cross Fertilization – Example from ePIC at EIC

ECFA R&D Roadmap:
- Tracking and Timing specifications for next generation **lepton colliders** and **EIC** are identical

Central Tracker Requirements:
- High pattern recognition efficiency
- High spatial resolution
- Low material budget
- Good time resolution
- https://eic.jlab.org/Requirements/index.html



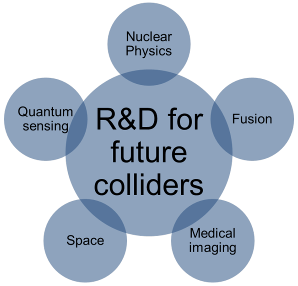
ePIC Det. Tracking System ePIC 24.2.1



❖ **Silicon Vertex Tracker (SVT):**
- **Monolithic Active Pixel Sensor (MAPS):** ~20x20 µm
- 3 vertex barrels: **ITS3** curved wafer-scale sensor, 0.05% X/Xo
- 2 outer barrels: **ITS3** based Large Area Sensors (EIC-LAS), 0.55%X/Xo
- 5 disks (forward/backward), EIC-LAS, 0.24% X/Xo

❖ **AC-LGAD:**
- **PID Time of Flight** detectors to cover PID at low pT
  - Also provide time and spatial info for tracking
  - Resolution: ~30 ps, 30 um (with charge sharing)
- **Barrel (BTOF):** 0.05 x 1 cm strip, 1% X/Xo
- **Forward disk (FTOF)** : 0.05 x 0.05 cm pixel, 2.5% X/Xo
- **Far-Forward Detectors:** Luminosity Monitor (strips), Bo (pixels), Roman Pots (pixels)

CERN's DRD Collaborations



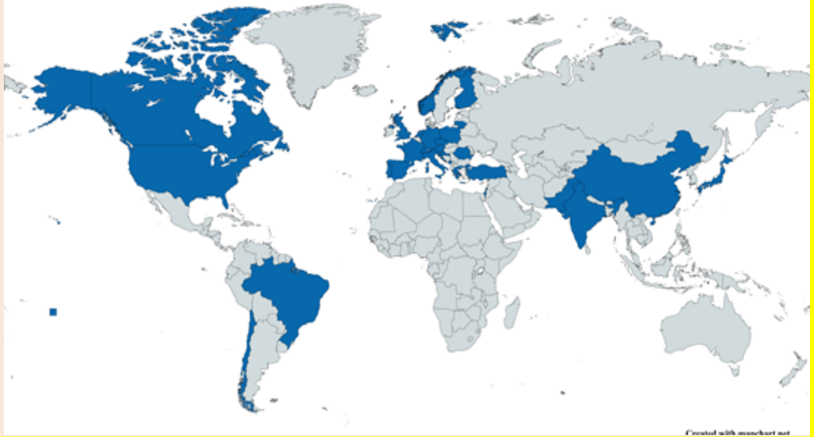
ECFA Detector R&D Roadmap

Detector R&D (DRD)

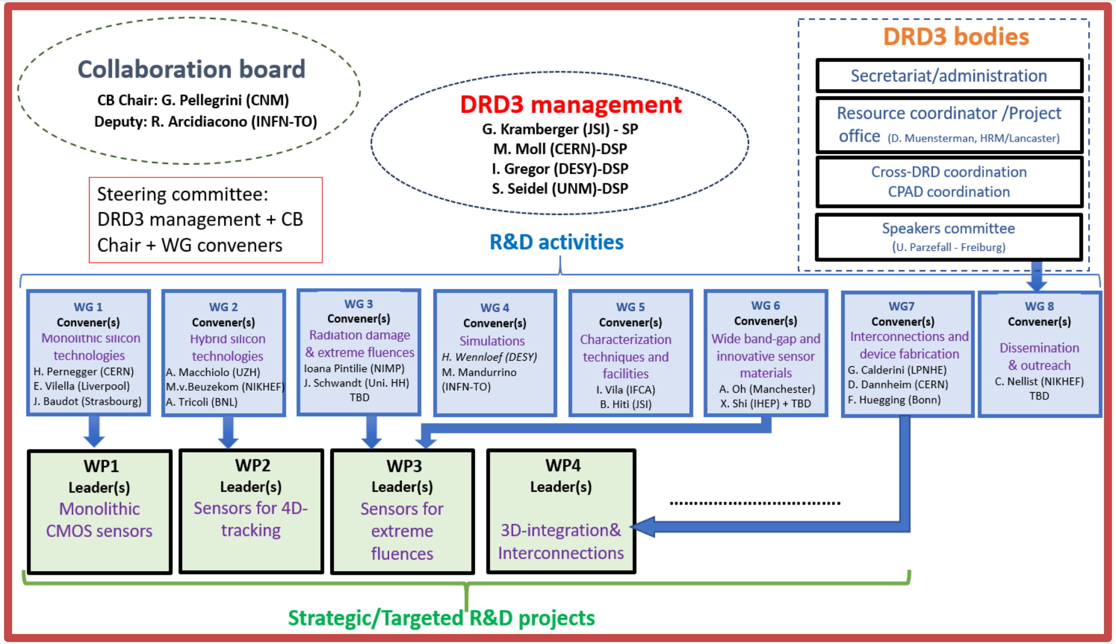
DRD1 Gaseous Det.	**DRD3** Semicond. Det.	**DRD5** Quantum Det.	**DRD7** Electronics
DRD2 Liquid Det.	**DRD4** Photo-Det./PID	**DRD6** Calorimetry	

DRD3
Semiconductor Det.
https://drd3.web.cern.ch/

- **143+ institutions**
- **600++ people**



DRD3 Organisation



- **Working Group (WG) = organizational structure of the work with a long term horizon, aiming to fulfil research goals.**
  - R&D can be also outside DRD Tasks, but related to semiconductor detectors:
    - R&D outside particle physics application with benefits for HEP
    - Novel semiconductor materials
    - Technology not yet listed in the Work Package guidelines (Silicon Electron Multiplier Sensors…).

- **Work Package (WP) = strategic R&D activity and is linked to DRD Tasks. It should pursue the goals listed there.**
  - WPs gather a subset of DRD3 institutions, are resource loaded with clear milestones and deliverables and funded
  - WPs reviewed/approved by DRD3 and appended to MoU annex
  - WPs will be shaped and optimized (synergies with similar projects, sharing runs…)

DRD3 Working Group 2 (4D Hybrid Detectors)

❖ Broad scope:

- Sensors with *4D capabilities* foreseen in many systems, from *Time-of-Flight* systems with only 1-2 layers of sensors with the best possible timing resolution to large *4D trackers* with many layers.
- Two main technologies assumed in WG2: *3D and LGAD sensors* (in all their flavors)
- *Additional technologies* can be explored in the future if new ideas will come forward

❖ Challenges:

- **Hadron colliders:** high radiation levels and high occupancies
- **Lepton colliders:** requirement of low material budget and low power dissipation

Webpage (under development): https://drd3.web.cern.ch/wg2

WG2 – Research Goals

WG2 research goals <2027	
	Description
RG 2.1	Reduction of pixel cell size for 3D sensors
RG 2.2	3D sensors for timing ($\leq 55 \times 55$ μm, < 50 ps)
RG 2.3	LGAD for 4D tracking < 10 μm, < 30 ps, wafer 6" and 8"
RG 2.4	LGAD for ToF (Large area, < 30 μm, < 30 ps)

DRD3 scientific proposal:
https://drd3.web.cern.ch/documents

- **RG 2.1 Reduction of pixel cell size for 3D sensors.**
  - 2024-2025: 3D sensors test structures with pixel size smaller than the current 50×50 μm^2 or 25×100 μm^2
  - 2026-2028: Large size 3D sensors with reduced pixel size.
  - $\geq$ 2028: Expand the number of foundries capable of producing 3D sensors for HEP applications.
- **RG 2.2: 3D sensors with a temporal resolution better than 50 ps.**
  - 2024-2025: Production of a small matrix with pitch equal to or less than 55×55 μm^2 to be connected with existing read-out ASICS
  - 2026-2028: Production of large-size sensors (using the selected geometry from the R&D runs) and interconnection with custom-made read-out ASIC
- **RG 2.3: LGAD Sensors with very high fill factor, and an excellent spatial and temporal resolution.**
  - 2024-2025: LGAD test structures of different technologies (TI-LGAD, iL-GAD, AC-LGAD/RSD, DJ-LGAD), matching existing read-out ASICs.
  - 2026-2028: Large LGAD sensors based on the best-performing technology.
  - 2025-2028: Investigation of radiation hardness of LGAD technology beyond $\sim 2.5 \cdot 10^{15}$ n_{eq}/cm^2.
- **RG 2.4: LGAD sensors for Time-of-Flight applications**
  - 2024-2026: Production of LGAD sensors with large size for Tracking/Time-of-Flight applications to demonstrate yield and doping homogeneity. Study of spatial and temporal resolutions as a function of the pixel size.
  - 2026-2028: LGAD structures with 4D capabilities produced with vendors capable of large-area productions to demonstrate the industrialization of the process.

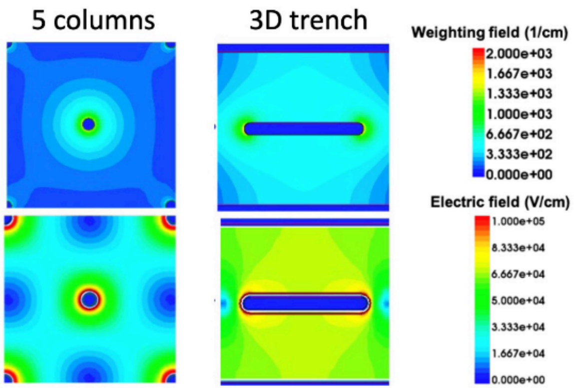
WG2 – Activities (3D detectors)

RG 2.1

- **3D Applications at high radiation environment, e.g. hadron colliders:**
    - Short-term application for the replacement of the innermost pixel layer of *ATLAS/CMS pixel dets.*
    - HL-LHC geometries: 50x50 μm^2 or 25x100 μm^2.
    - Phase-3 replacement: 28 nm CMOS technology for the ASICs could allow for finer pixel sizes to improve hard scattering track reconstruction and pile-up rejection
    - 3D sensors still the most promising candidate due to radiation resistance and low power dissipation
    - ASIC pixel size possibly down to 30x30 μm^2 (No timing functionality included)

RG 2.2

- **3D with advanced timing capabilities:**
    - Possible short or medium term application for replacing the present *LHCb's VELO vertex det. (Upgrade-II)*
    - Compare the performance in terms of timing properties and radiation hardness of columnar and trench 3D detectors



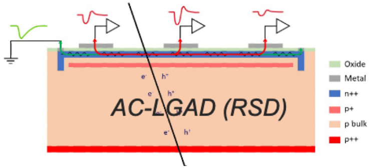
WG2 – Activities (LGAD detectors)

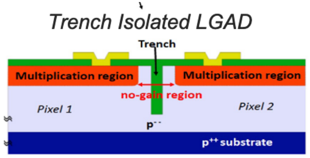
RG 2.3

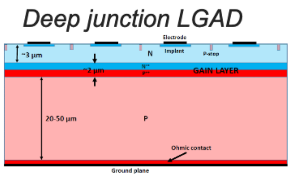
- **Full scale detector with pixelated LGAD sensors to achieve a position resolution <10 μm, with a timing resolution <30 ps before irradiation, also in high occupancy environments.**
  - Possible application for the replacement of outer pixel layers or disks in the CMS/ATLAS pixel dets. in Phase-III. Requested radiation tolerance for HL-LHC can be in the range of 1-5x10^{15} n_{eq}/cm^2

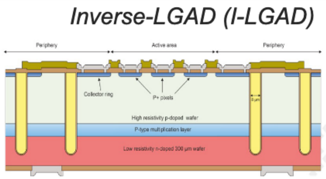
RG 2.4

- **LGADs for particle identification (Time of Flight)**
  - Possible applications: *ALICE 3 (Run5), Belle2, Electron Ion collider (Tracking+TOF@ePIC) >2031) and Future Lepton colliders (>2040)*.
  - Larger surfaces (several m^2) have to be covered
  - Yield and reproducibility of the process have to be demonstrated while radiation hardness is less of a problem
  - *Electron Ion Collider*: a spatial resolution ~30 μm and timing resolution <30 ps are required. An area up to 13 m^2 has to be instrumented. Proposal: pad size of 0.5 mm with a spatial resolution ~ 10 μm
  - *Future lepton colliders*: a ToF could be placed as the most external tracking layer, with a surface of around 100 m^2, < 30 ps, and spatial resolution ~10 (90) μm (r-ϕ, z).









WG2 – Readout Challenges

- **ASICs for HL-LHC Timing detector (pitch of 1.3 mm x 1.3 mm):**
  - **ATLAS HGTD *ALTIROC*** chip in 130 nm CMOS
  - **CMS ETL *ETROC*** chip in 65 nm CMOS

- **From the ECFA Roadmap: Technology Choice**
  - The selection and adoption of the *28 nm CMOS* technology as a "mainstream" process will "fuel" the developments of "near-future" experiments
  - A few chips are being developed at the moment for *4D tracking*:
    - *Ignite* and *PicoPix*, focused on LHCb VELO upgrade in 28 nm CMOS
    - *EICROC* for ePIC detector at EIC in 130 nm CMOS
    - Fermilab's *FCFD* for 4D trackers in 65 nm CMOS Etc.
  - but nothing readily available at the moment

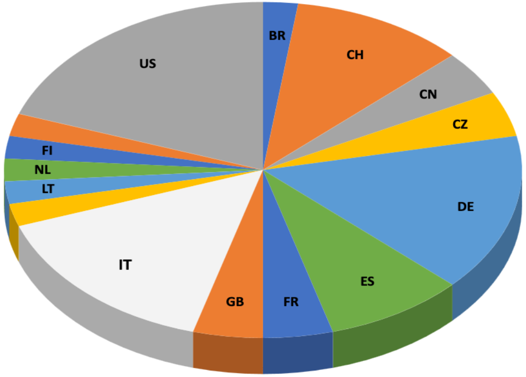
❖ WG2 will help to collect requirements for future ASICs and unify efforts

DRD3 WG2 - Institutes

- UZH
- JSI
- LPNHE-Paris
- MPP
- INFN Milano
- Oak Ridge
- PSI
- SLAC
- Uni Trento + TIFPA INFN
- Uni Chicago
- Uni Sao Paulo USP
- Uni Sci & Tech China
- Vilnus
- Nikhef
- FZU Prague
- Birmingham
- Gottingen
- GSI
- INFN Torino
- ETHZ
- KEK
- KIT
- LANL
- Hamburg
- HEPHY
- HIP (Helsinki Institute of Physics)
- ANL
- UNM
- IFCA (CSIC-UC)
- Charles University, Prague
- BNL
- CERN
- IMB-CNM-CSIS
- FBK
- FNAL
- Freiburg
- IMECAS
- INFN-Firenze
- INFN-Perugia
- IFAE
- IFGAE (Santiago)
- Oxford
- Santa Cruz
- INFN Genova
- IJCLAB

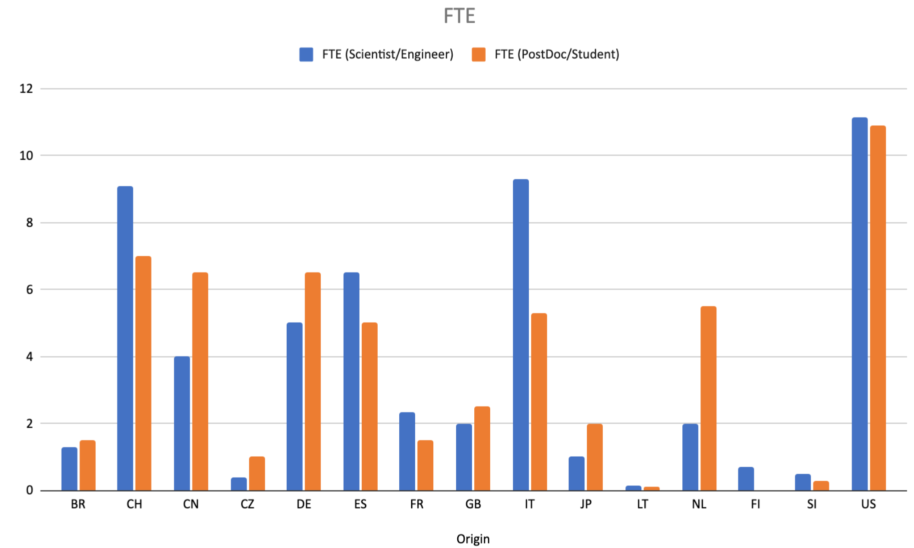
Expressions of Interests (EoIs):
https://drive.google.com/drive/folders/1vQMFIwzgQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing

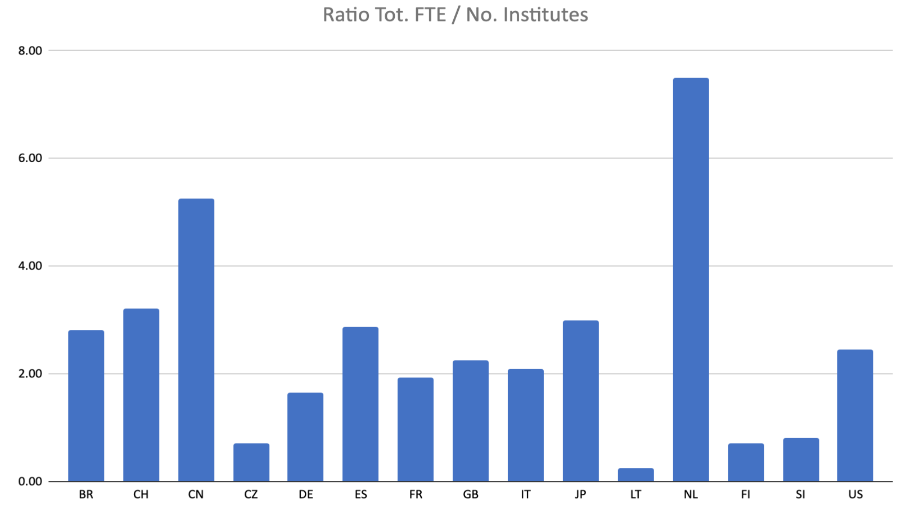
- **46 institutes from 15 countries and 3 continents (Europe, US, Asia and South America)**
  - We welcome more!
  - Contact us to join!



DRD3 WG2 - Commitments

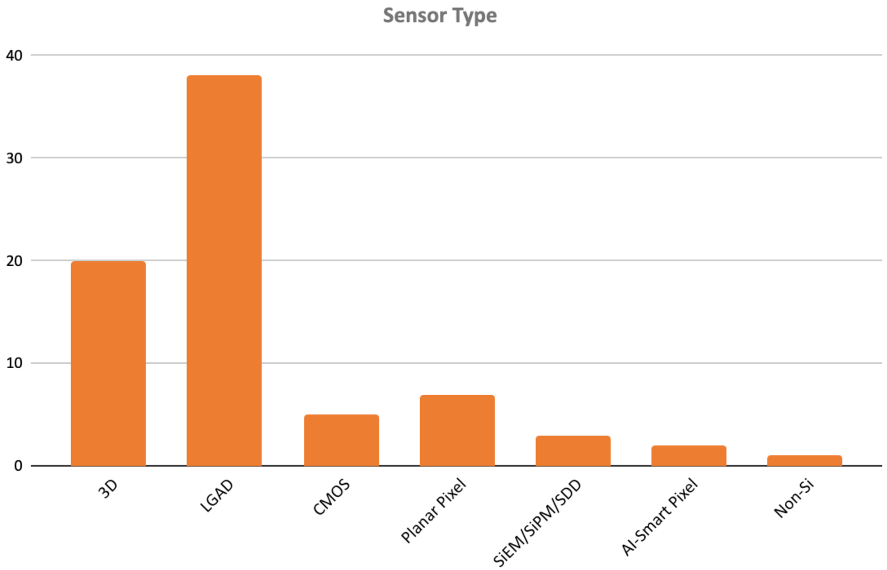
EoIs: https://drive.google.com/drive/folders/1vQMFIwzqQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing





- **110 FTEs evenly distributed between long-term staff and students/postdocs**
  - 55 FTE for Scientists and Engineers
  - 55 FTE for PostDocs and Students
- **Average: 2.4 FTE / Institute**

DRD3 WG2 – Scientific Interests



Most of institutes have extensive experience in silicon tracking or timing detectors in LHC experiments

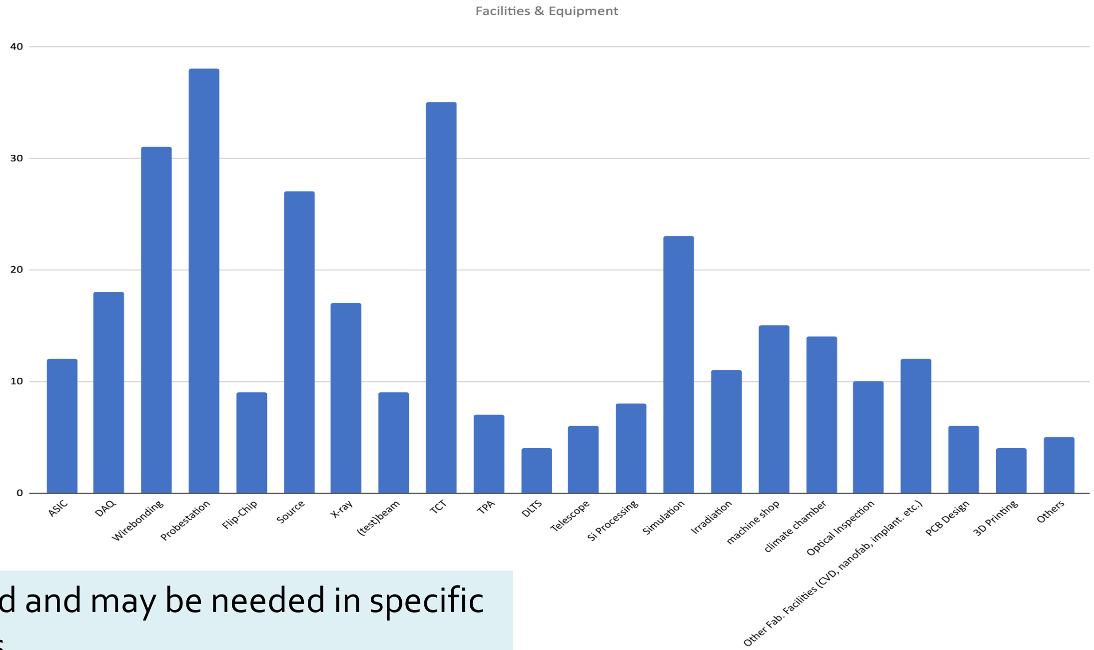
- **LGAD** and **3D** dominates
- Interest also in **Planar Pixel**, **passive/active CMOS** and *other technologies*
- **New and alternative ideas are also welcome**

EoIs: https://drive.google.com/drive/folders/1vQMFIwzgQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing

DRD3 WG2 – Facilities and Equipment

- **Broad technical capabilities**
  - Most institutes have sensor testing capabilities
- **Widespread testing equipment:**
  - Probe-stations
  - TCT/laser
  - Radioactive sources
  - X-ray
  - Simulation
- **Wire-bonding capabilities are also largely available**
- **Need coordination/sharing:**
  - Test-beams
  - Irradiation
  - Readout development
  - Flip-chip

EoIs: https://drive.google.com/drive/folders/1vQMFlwzgQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing



❖ Sharing of other resources is encouraged and may be needed in specific clusters of institutes for specific projects

DRD3 WG2 – Structure and Liaisons

- **No subgroups (for the time-being)**
  - Discussions open to the whole community, regardless of specific research interests
  - We may have dedicated meetings on specific technologies, specific Research Goals or WP to keep meetings focused
- **Liaisons:**
  - Advice WG2 members on available facilities, techniques, platforms, tools etc.
  - Provide bi-directional communication with other DRD3 Working Groups or DRDx Coll.
  - Provide technical support to community by linking with experts
  - Maintain support web pages

Liaisons

- **Test-beam and Characterisation facilities** → link to WG5
  - **Jordi Duarte-Campderros** (IFCA, Santander), jorge.duarte.campderros@cern.ch
  - **Ryan Heller** (LBL), rheller@lbl.gov
- **Irradiation Coordination** → link to WG3
  - **Leena Diehl** (CERN), leena.diehl@cern.ch
  - **Simone Mazza** (UCSC), simazza@ucsc.edu
  - **Xuan Li** (Los Alamos), xuanli@lanl.gov
- **Interconnections** → link to WG7
  - **Mathieu Benoit** (ORNL), benoitm@ornl.gov
- **Simulation** → link to WG4
  - **Jörn Schwandt** (Uni Hamburg), joern.schwandt@desy.de)
- **Readout Systems** → link to DRD7
  - **Abderrahmane Ghimouz** (PSI), abderrahmane.ghimouz@cern.ch
  - **Manwen Liu** (IMECAS), liumanwen@ime.ac.cn

DRD3 WG2 – Plans

- **In the near future we want to learn about**
  - Main application drivers (e.g. HL-LHC, CEPC, FCC, ILC/CLIC, Muon Collider etc.),
  - Research goals and directions the community wants to pursue,
  - Level of needed vs available effort/person-power for specific developments,
  - Specific interests of various institutes in specific technological areas
  - What proposals for Work Packages are submitted and what effort will be provided
- **We also want to encourage the community to get an overview of all on-going activities before we compartmentalize into focused groups**
  - Cross-fertilization among different R&D areas
  - Boost cooperation spirit
  - Encourage the formation of institute clusters around specific research goals

❖ Next DRD3 WG2 Meeting: Mon. 4th Nov. (remote), https://indico.cern.ch/event/1463712/
❖ DRD3 Collaboration Week: Mon-Fri, 2nd -6th Dec. (CERN), https://indico.cern.ch/event/1439336/

DRD3 WG2 – Keep in Touch

- **Convenors (Anna Macchiolo, Martin van Beuzekom, Alessandro Tricoli):**
  - drd3-wg2-conveners@cern.ch
- **Indico agendas for Meetings and Worshops:**
  - DRD3: https://indico.cern.ch/category/17387/
  - WG2: https://indico.cern.ch/category/18197/
- **Subscribe to WG2 e-group for general communications/announcements:**
  - drd3-wg2-hybrid@cern.ch
  - Follow instructions here how to subscribe: https://drd3.web.cern.ch/egroups
- **Mattermost channels for rapid or extended discussions:**
  - General DRD3: https://mattermost.web.cern.ch/drd3
  - From "Add channels" → "Browse channels" → Select the one to join in the pop-up window, e.g. WG2

Backup

Monolithic Detectors

Chip name	Experiment	Subsystem	Technology	Pixel pitch [μm]	Time resolution [ns]	Power Density [mW/cm²]
ALPIDE	ALICE-ITS2	Vtx, Trk	Tower 180 nm	28	< 2000	5
Mosaic	ALICE-ITS3	Vtx	Tower 65 nm	25x100	100-2000	<40
FastPix	HL-LHC		Tower 180 nm	10 - 20	0.122 – 0.135	>1500
DPTS	ALICE-ITS3		Tower 65 nm	15	6.3	112
NAPA	SiD	Trk, Calo	Tower 65 nm	25x100	<1	< 20
Cactus	FCC/EIC	Timing	LF 150 nm	1000	0.1-0.5	145
MiniCactus	FCC/EIC	Timing	LF 150 nm	1000	0.088	300
Monolith	FCC/Idea	Trk	IHP SiGe 130 nm	100	0.077 – 0.02	40 - 2700
Malta	LHC, ..	Trk	Tower 180 nm	36x40	25	> 100
Arcadia	FCC/Idea	Trk	LF 110 nm	25	-	30

C. Vernieri: https://indico.mit.edu/event/876/contributions/2694/attachments/1039/1721/MIT-workshop-Detector.pdf