Hybrid Semiconductor Detectors

C. Gemme *(INFN Genova)* ,
A. Macchiolo *(University of Zurich),*
G. Pellegrini *(IMB-CNM-CSIC)*

AIDA++ Open Meeting
4 September 2019, CERN

Hybrid Silicon Detectors- Timing with 3D sensors

TIMING with 3D sensors		**Participating Institutes**	**EC contribution (kE)**
G. Pellegrini	3D optimized for timing	CSIC, IFAE, JSI	160
G. Dalla Betta	3D sensors for Tracking with Timing at High Fluence	INFN, FBK, Manchester	350
C. Da Via’	3D for precision tracking in future Vertex Detector	Manchester, INFN, Prague. FBK	60
S. Pospisil	3D in silicon and compound material for precise particle tracking	CTU Prague, Manchester, INFN, FBK	90

Total 660 kEuro

Simulation		**Participating Institutes**	**EC contribution (kE)**
D. Passeri	TCAD Radiation Damage characterization and modelling	INFN, HEPHY	100
G. SImi	Radiation damage in 3D silicon sensors and electronics	INFN	50

Total 150 kEuro

Hybrid Silicon Detectors – Timing with LGAD sensors

TIMING with LGADs		**Participating Institutes**	**EC contribution (kE)**
Macchiolo/ Cartiglia	Small pitch LGAD sensors	INFN/UZH/Uni-HH/To/Piemonte Orientale/FBK	300
A. Tricoli	4D silicon detector for future collider experiments	BNL	/
L. Serin	Timing for large pad sensors after irradiation	LAL, Bonn, CNM, JSI, IFAE, Omega,	250
P. Allport	Proton irradiation and characterization of fine pitch LGADs	FBK, Birmingham	80
M. Williams	LGADs at MICRON	Manchester, Glasgow, Krakow, MICRON, CNM	195
I. Vila	Inverse L-GAD sensors	CSIC, CERN, NIKHEF, USC	190

Total 1015 kEuro

Hybrid Silicon Detectors – Planar and Tools for R&D

Planar Pixel Sensors		**Participating Institutes**	**EC contribution (kE)**
G. Calderini	Thin planar sensors with small pitch and advanced trench layout	LPNHE, FBK, LAL, INFN, CERN, IZM	210
D. Münstermann	Passive CMOS sensors	Lancaster, Bonn, UZH, ETH, INFN, LFoundry	280

Total 490 kEuro

Radiation Hardness and Tools for generic R&D		**Participating Institutes**	**EC contribution (kE)**
M. Mikuz	Silicon Detectors at Fluences above 1e17 n_{eq}/cm^2	JSI, CERN, INFN, Cantabria, CSIC,	300
M. Moll	Radiation Hardening of p-type detectors	CERN, Hamburg, Bucharest, CIS	170
M. Moll	Two Photon Absorption TCT	CERN, CSIC, Fyla	200
O. Brandt	Systematic studies of radiation hardness	Cambridge, Birmingham CSIC	230

Total 900 kEuro

Hybrid Silicon Detectors – Alternative semiconductor material and Mixed Proposals

Alternative Semiconductor Materials		**Participating Institutes**	**EC contribution (kE)**
A. Oh	3D Diamond detectors	Manchester, CERN, Florence, INFN, CNR	196
G. Pellegrini	3D SiC detectors	CSIC, IFAE, PSI, ETH, DECTRIS	200
M. Menichelli	3D detectors on amorphous a:Si-H	INFN, EPFL	100

Total 496 kEuro

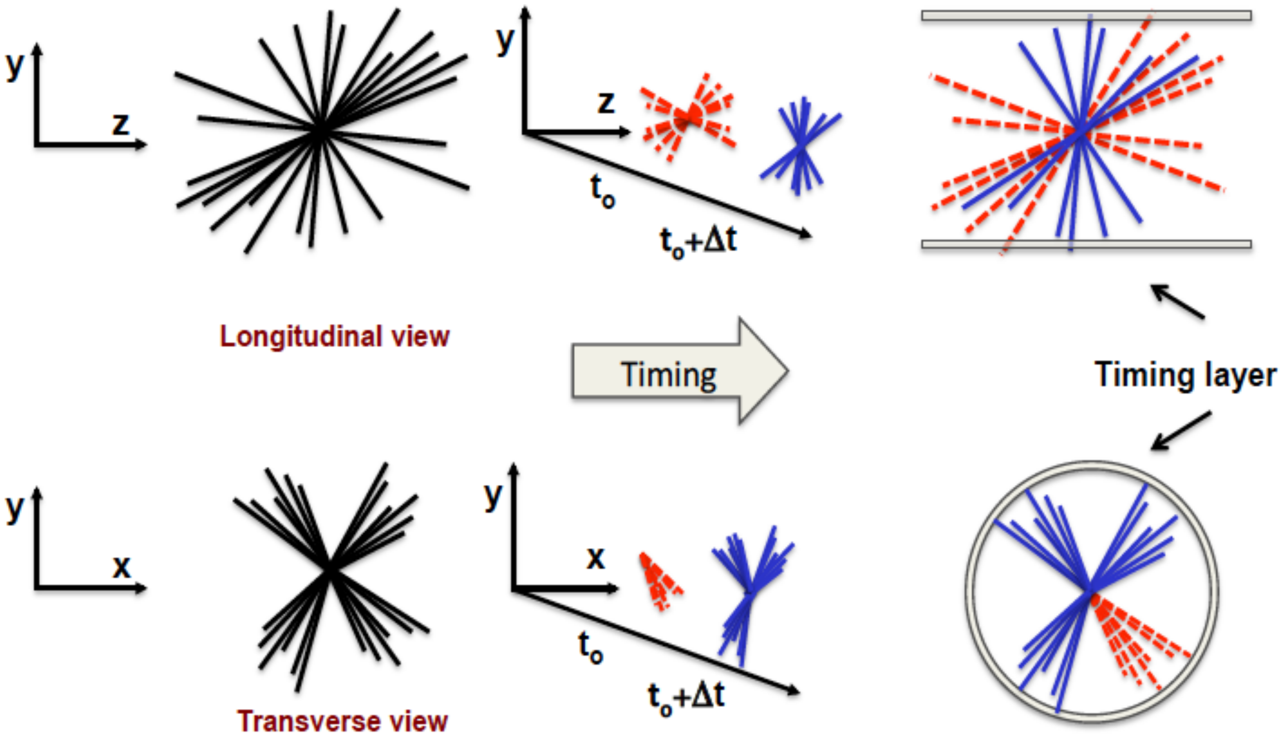
Proposals across multiple WPs		**Participating Institutes**	**EC contribution (kE)**
I. Gregor	Development of ultra-thin pixel assemblies	DESY, Bonn, IZM	348
M. Van Beuzekom	PICOTRACK: telescope with ps precision	NIKHEF, CERN, Oxford, CSIC, USC, ASI	280
K. Akiba	Lumiscope: a high precision beam imaging device	NICKHEF, CERN, ASI, Dortmund	116

Total 744 kEuro

Total EC contributions requested for hybrid sensors: 3.7 MEuro + Mixed EoI

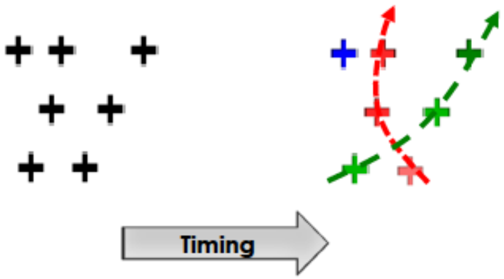
Timing for tracking- 3D and LGAD sensors

Timing layers as separate sub-detectors with coarser granularity → timing at ~30 ps level to disentangle spatially overlapping events

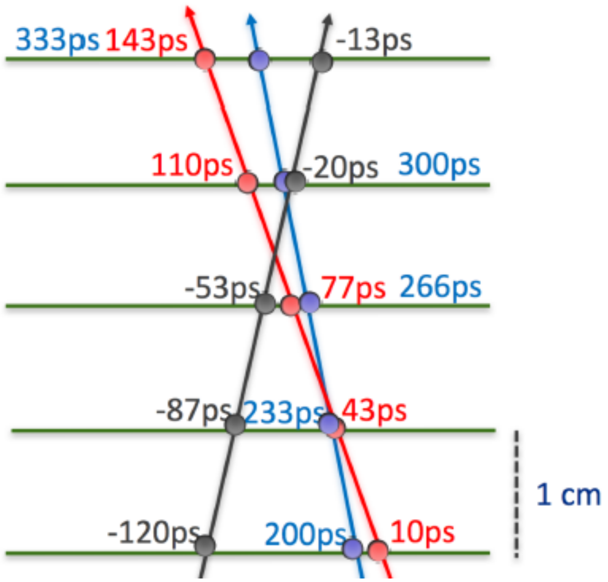


Timing info within pixel layers

→ timing info for pattern recognition: use only time compatible points



N. Cartiglia



4-D tracking for future detectors: 3D and LGAD sensors

- 3D sensors: Optimize pixel cell design to improve timing performance and achieve extreme radiation hardness
- LGADs: Reduce the minimum distance between pads (dead area) to cope with high density tracking environment

Possible applications in Future Detectors

Upgrades of Pixel systems at HL-LHC with timing sensors (~2030)

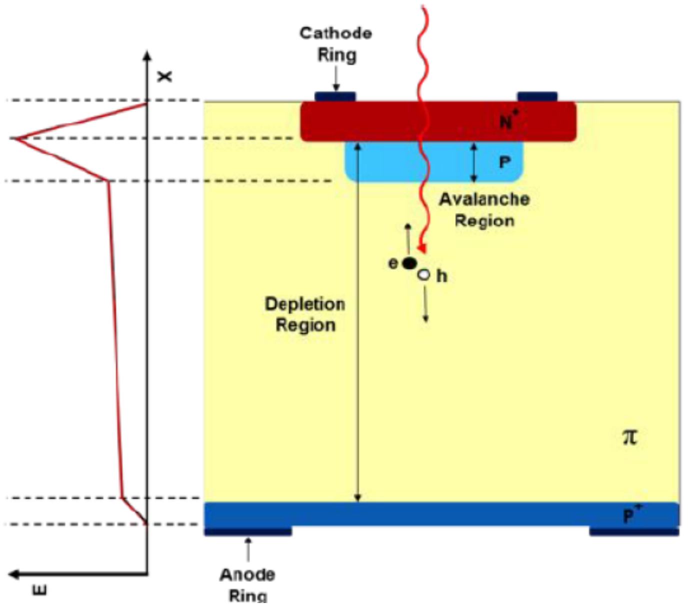
Application at future hadron collider to disentangle overlapping collisions

Time of flight particle identification at e^+e^- colliders

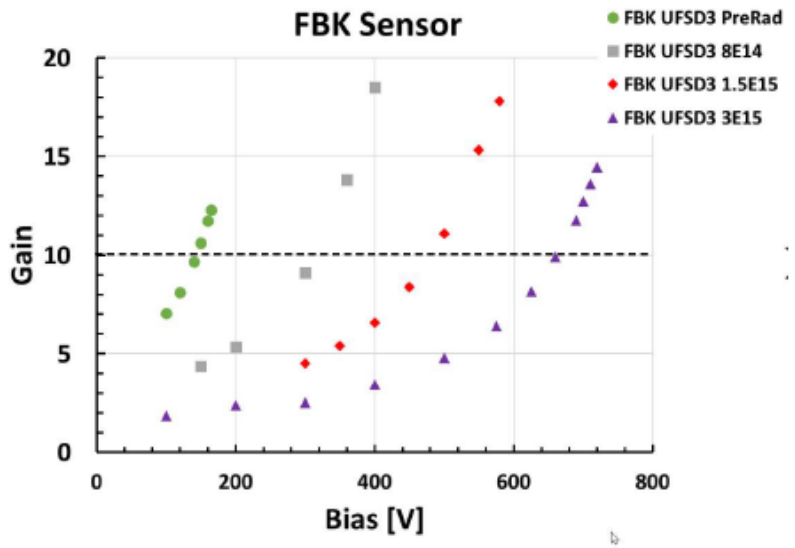
First application to beam telescopes as tools for the R&D on timing

Present status of LGADs developments

- Low Gain Avalanche Diodes:
  - Highly Doped p$^+$ region below the n$^+$ implant
  - Moderated internal gain from 10 to 30
  - Low thickness (35-50 μm) to maximize slew rate: dV/dt



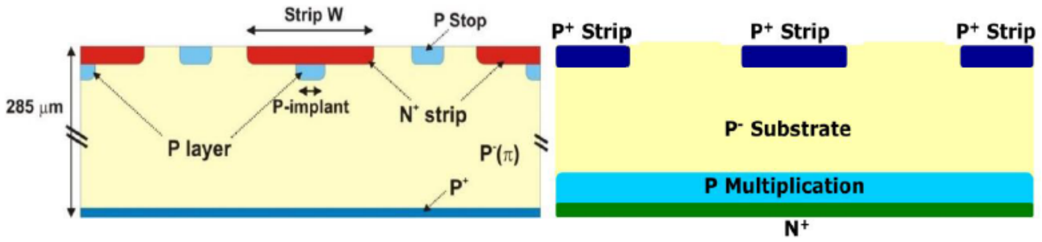
- Problem:
  - Gain decreases as function of irradiation (limited mitigation with higher bias) → de-activation of the gain layer
  - Different solutions are being explored (as Carbon co-implantation)



Technologies path towards small pitch LGADs

- Different technologies to be explored to achieve small pitch LGADs necessary for 4D tracking

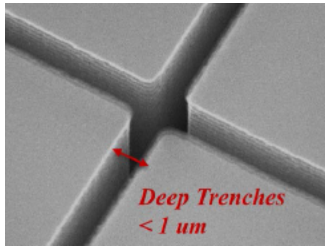
EoI 131, *I. Vila*

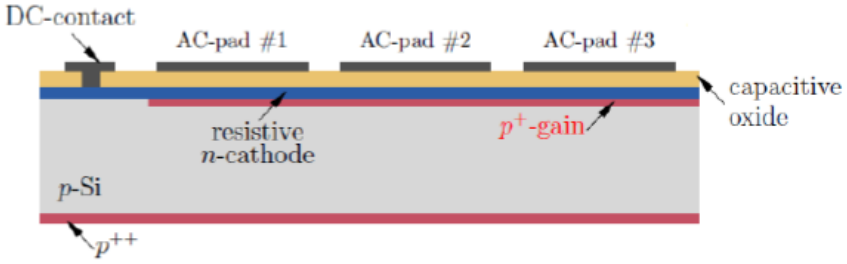


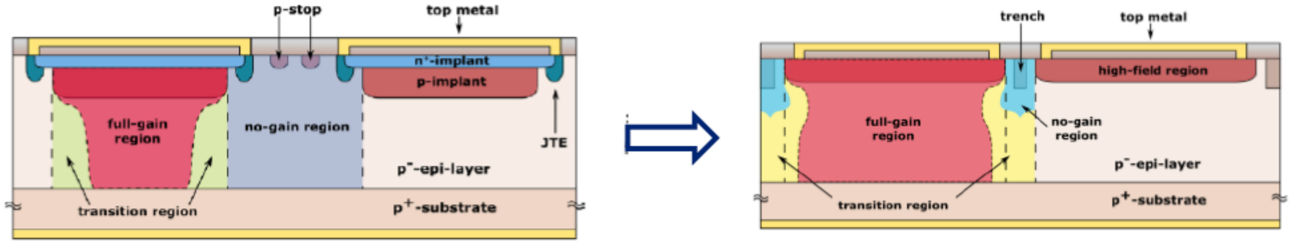
I-LGAD at CNM

EoI 31 and 44, *A. Tricoli*

EoI 31 A. *Macchiolo - N. Cartiglia*,
EoI 107 *P. Allport*, EoI 109 *A. Oh*







AC-coupled LGADs, FBK and BNL

LGADs with trench isolation, FBK and MICRON

Timing for HL-LHC and FCC (sensors and read-out electronics)

Improved time resolution for large pad sensors after irradiation (**EoI 72, *L. Serin***) :

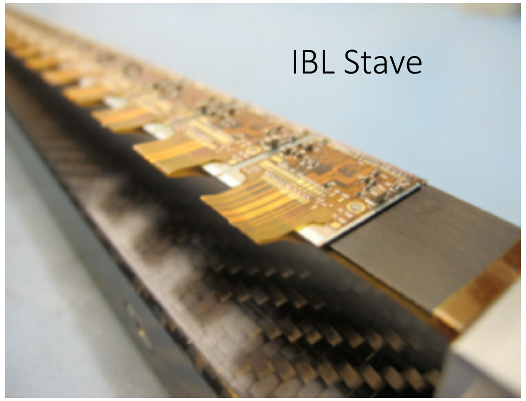
- Investigation of **finer segmentation** of the present pads (4 amplifier feeding the same TDC) to reduce jitter
- Study **3D sensors** for better radiation hardness instead of LGADs
- **Read-out ASIC in 65 or 130 nm CMOS** optimized for timing (possible application also for 3D diamond detectors)

Development of a 4D silicon detectors for future collider experiments (**EoI 44, *A. Tricoli, BNL***)

Collaborative efforts with European partners to:

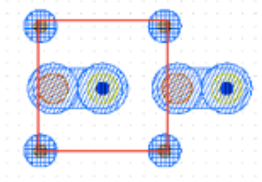
- Develop 4D timing detectors as AC-coupled LGADs
- Investigate the combination of monolithic HV-CMOS sensors with LGAD sensors

Present status of 3D developments

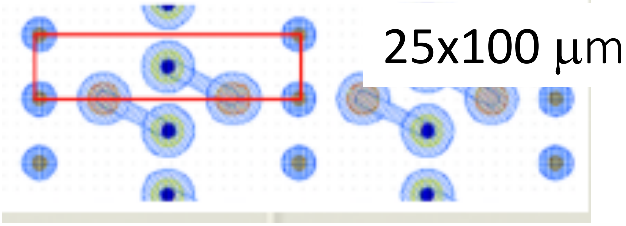


- 3D sensors have been used for the first time in a HEP experiment in the IBL detector, installed in ATLAS in 2014, taking data in Run2

- Since then a lot of R&D has been done by few vendors and new sensors compatible with HL-LHC are currently under evaluation:
    - Pitch compatible with 50x50 μm^2 electronics
    - Rad hardness up to 10^{16} n_{eq}/cm^2 for RD53A modules

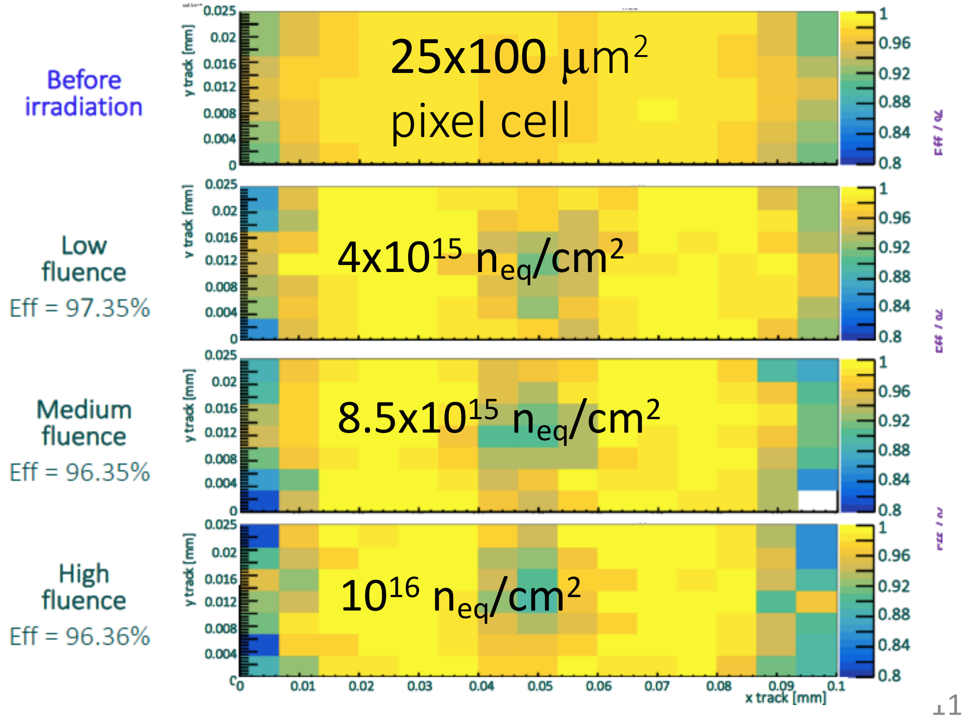


50x50 μm^2



25x100 μm^2

A. G. Alonso et al., IWORID 2019, Irradiated 3D RD53A modules

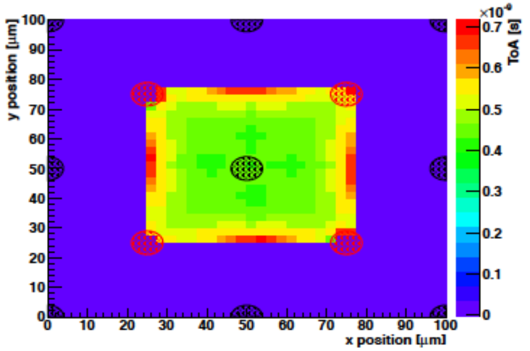


New proposal for 3D technologies – I

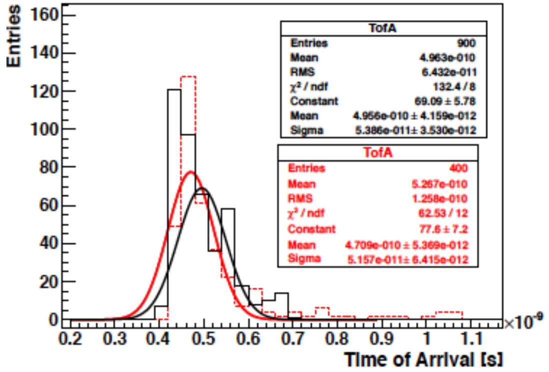
Optimized 3D detectors for timing applications at high fluences **(EoI 3, *G. Pellegrini*)**

- Improve current measured timing resolution of 75 ps in 3D 50x50 μm^2 , 300 μm thick
- 3D sensors may overcome LGAD limitation such as loss of gain with irradiation and fill factor.
- Deliverables: Simulation, Production of sensors coupled to RD53 FEs, test of irradiated devices.

G. Kramberger et al.



(a)



3D sensors for tracking with timing at high fluences **(EoI 69, *G. Dalla Betta)***

- New family of 3D to provide a position resolution of ~10 µm and a timing resolution of ~20 ps, and to extend the well-established radiation tolerance of 3D pixels up to at a maximum fluence of ~10^{17} n_{eq}/cm^2 to cope with future accelerator-based HEP projects
- Goals will be pursued by **optimizing the pixel layout and electrode geometry,** in order to minimize the drift distance and electric/weighting field non-uniformities in the charge deposition volume
- Deliverables: sensor simulation, fabrication of at least two batches of sensor prototypes, post-processing activities and thorough characterization in laboratories and beam test of non-irradiated and irradiated sensors.

New proposal for 3D technologies - II

3D for precision tracking in future vertex detector **(EoI 128, *C. Da Via)***

- Achieve goals to fulfill **extreme radiation tolerance** and high spatial and timing resolutions by further reducing the inter electrodes spacing (IeS), currently 35 um.
- Small IeS also leads to **fast responses**, in particular if associated with tailored geometries and **moderate charge multiplication**
- Application to FCC and LHC forward detectors as AFP
- Deliverables: design, fabrication and simulation of ultra-small pitch diodes, before and after irradiation in the lab and at beam lines; validating the tracking performance of new layouts after hybridisation with existing readout electronics like Timepix3 and shortly coming Timepix4

3D in silicon and compound material for precision particle tracking **(EoI 129, *S. Pospisil)***

- Fabrication and testing of a compact and transportable detection systems based on Timepix3 and Timepix4 detectors with fast readout interface allowing remote control of the systems
- 3D, SiC, GaAs, CdTe, CdZnTe, LiInSe2 sensors with different readout configurations
- Applications to luminosity measurements in MoEDAL (LHCb) and ATLAS AFP forward tracker.

Simulation

TCAD Radiation Damage characterization and modeling for detectors at e+/e- and hadronic accelerators **(EoI 53, *D. Passeri)***

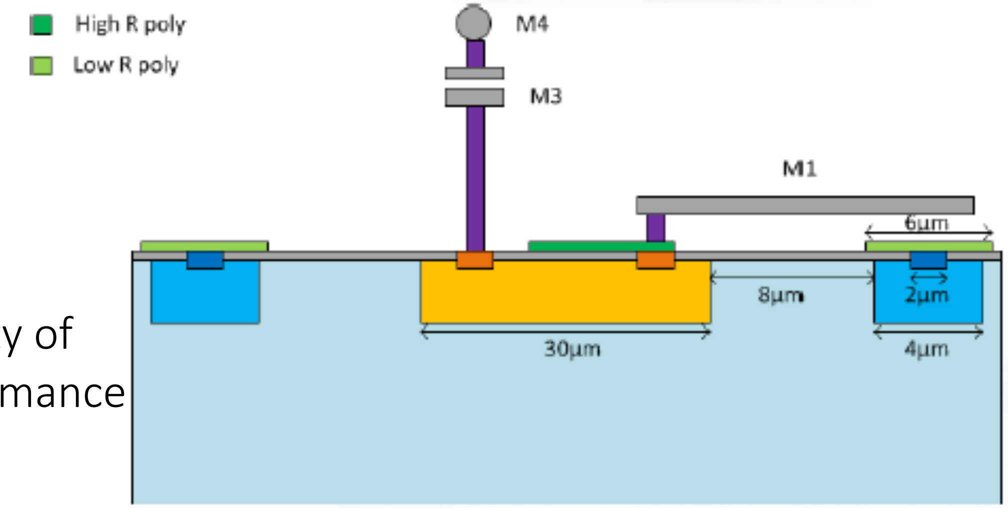
- Test results will be used as input for TCAD simulations to develop and refine a radiation damage model, aiming at disentangling the effects of **bulk** and **surface** damages, different at e+/e- and hadronic accelerators and sensor technologies.
    - Electrical characterization and irradiation of small samples (e.g. diodes) of different detector types (planar, 3D, LGAD, HV-CMOS) and different vendors.
    - Spreading Resistance Profiling (SRP) technique is used to determine doping profiles of physical samples.
- Calibration/extension of the previously developed models ("Perugia model" and its recent upgrade) and Physical model interface (PMI) input tool for model introduction in commercial TCAD will be delivered.

Radiation damage in 3D silicon sensors and electronics **(EoI 163, *G. Simi)***

- Study and simulate the radiation hardness of 3D and electronics In particular the **uniformity of the timing response of the active** elements depends on the geometry of the electrodes and needs to be studied and simulated in detail in order to understand and optimize the design.

Planar pixel sensors

Passive CMOS sensors **(EoI 89, *D. Muenstermann*)** :



- CMOS foundries can provide **high through-put at low cost**
- **Process optimization** with multi-layer routing
- R&D proposed:
  - Optimization of stitching
  - Introduction of **multiplication layer** using the CMOS capability of having implants at different depths to improve timing performance

Planar Pixel sensors with small pitch and active edges **(EoI 47, *G. Calderini*)** :

- Active edges for very thin sensors **(30 —100 µm thickness)** –
  - Reduce material for electron colliders and improve radiation hardness for hadron colliders
- **Small pitch** (from 50x50 to 25x25 µm^2)
  - Improve the position resolution for high density environments
- **Different interconnection technologies** explored (SnAg bumps, Cu pillars, anisotropic conductive films)

Sensors and read-out electronics

Development of Ultra-thin pixel assemblies **(EoI 108, I. Gregor)**:

- **Wafer-to-wafer bonding** : sensor and read-out chips processed on thick 8” wafers
- **Thinning after bonding**: 50-100 μm for sensors and 10 μm for electronics
- Sensor backside processing after interconnection

↓

Ultra-low mass hybrid pixel detectors with pixel cell sizes well below 25-50 μm

Shared with Electronics-Interconnection WP

PICOTRACK: tracking telescope with micro-meter and picosecond precision **(EoI 152, Martin van Beuzekom)**

- Target of **30 ps timing resolution** and pointing resolution below 2 μm
- 8 planes of silicon sensors read-out by the **Timepix4 chip**
- Timestamping of tracks with a combination of 2 planes of Cherenkov radiation detectors with Timepix4 sensor planes
- Implement **3D and LGAD sensors** developed in other EoIs (3D and LGADs for timing)
- Fast data acquisition system and user friendly DUT integration

Shared with Test-beam facilities and DAQ WP

Sensors and read-out electronics

LUMISCOPE:
A high precision beam imaging device based on beam-gas vertexing and time tagged track reconstruction **(EoI 140 K. Akiba)**

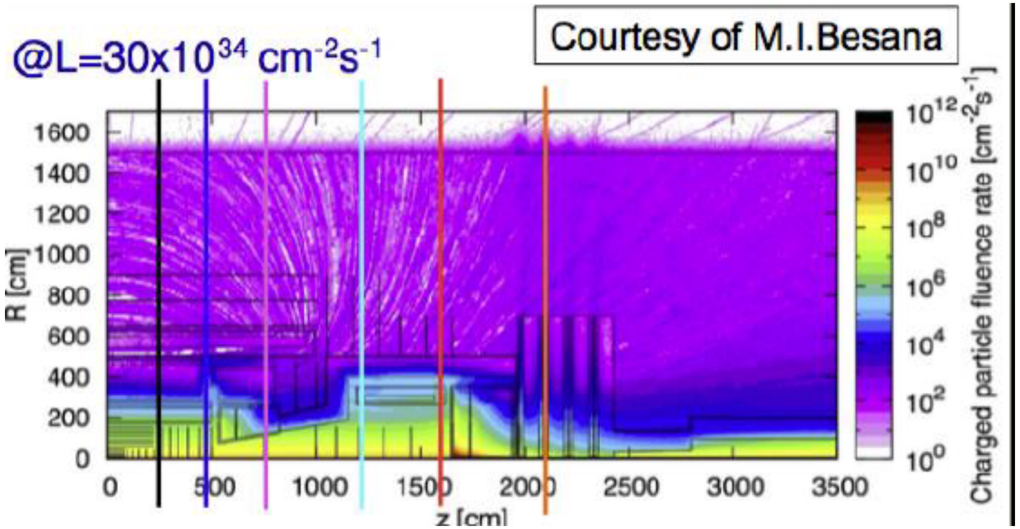
- perform real-time beam imaging of the main and satellite LHC bunches using tracks reconstructed from the interactions of beams with gas in the interaction region of LHCb
- A beam imaging system with 20 μrad angular pointing resolution and timing resolution of 500 ps or better built with the Timepix3 (and later Timepix4) ASIC
- fast and radiation hard DAQ systems for Timepix3

Shared with DAQ WP

R&D on radiation hardness

Extreme radiation hardness (**EoI 38, *M. Mikuz***) :

- Study of basic properties of silicon devices to the **fluence range 10^{17} n_{eq}/cm^2** and above, foreseen for future hadron colliders
- Extend the present encouraging studies performed after neutron irradiation to proton irradiations



Fluence rate at FCC-hh

Radiation hardness studies for LGADs and HV-CMOS (**EoI 65, *M.Moll***) :

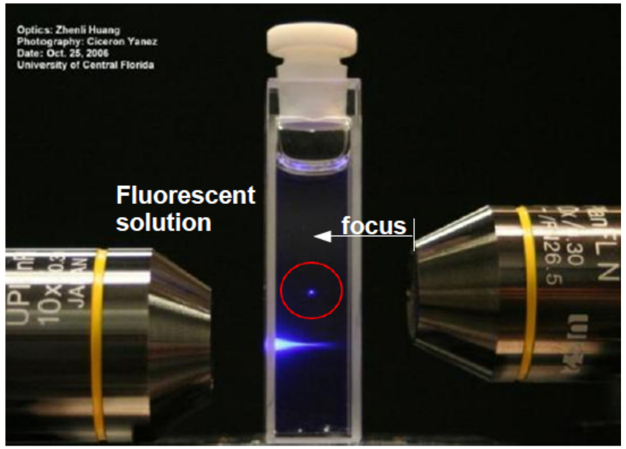
- Provide a comprehensive knowledge of **radiation induced defects** and their generation mechanism focused on p-type substrate and to the case of **LGAD and HV-CMOS devices**
- Apply the gained knowledge to **improve the radiation hardness** in these devices
- Produce **theoretical models** describing the generation and evolution of the defects in the presence of **different types of impurities**.

Tools for investigation of silicon devices

Two Photon Absorption TCT **(EoI 66, *M. Moll*)** :

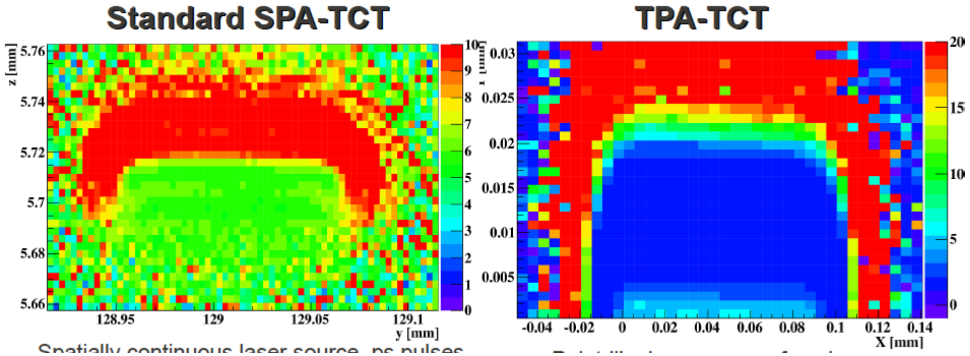
TPA-TCT creates charges only in a tiny voxel in the focal point of the laser beam → true **three dimensional TCT characterization** possible

- Complete the development from the proof-of-concept installation towards a user-friendly TCT system to offer a sensor **characterization service to the full community**



“RadHardSi” Systematic studies of radiation damage in silicon sensors **(EoI 159, *O. Brandt*)** :

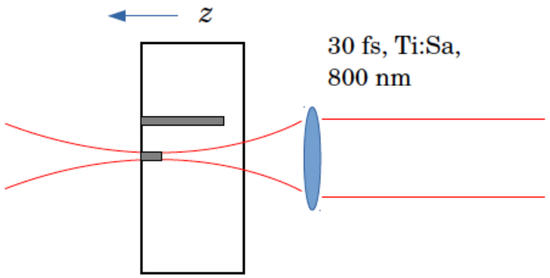
- Studies of radiation damage up to the fluences foreseen at FCC-hh with high statistics systematic studies of process variations →**automated test** set-up tailored to carry out standardized measurements on **dedicated new test-structures** in a controlled environment
- Target of improving the radiation hardness of commercially (??) produced silicon detectors



Other semiconductor materials

Development of **3D diamond detectors (EoI 108, A. Oh)** :

Femto-second laser micro-machining techniques to form electrically conductive nano-graphite wires →
optimise the design and properties of 3D diamond devices for applications that require high radiation tolerance and excellent timing resolution



3D SiC detectors for harsh environment **(EoI 4, G. Pellegrini)** :

Optimize 3D sensor processing through a doping-selective electrochemical-etching method able to
create deep holes in SiC.

- Renewed interest due to progress in wafer fabrication (high quality material in 6" wafers)
- Fabrication and full characterisation of 3D SiC detectors as small chips

3D detectors based on **a-Si:H for particle tracking (EoI 94, M. Menichelli)** :

- Moderate leakage current levels also after irradiation
- Use 3D detectors to overcome high depletion voltages

Conclusions

- 24 different proposals in the field of hybrid semiconductor detectors
  - 37 institutes and 4 companies
  - ~4 M Euro EU funds requested in total

- Very diversified proposals in terms of technologies and scope, with a substantial shift of interests with respect to the detectors currently employed or in constructions for the running experiments:
  - mainly timing + extreme radiation hardness

- Several EoIs have large overlaps and could be merged for the final proposal towards common deliverables

Very strong interest of the HEP community in this detector field!