Semiconductor sensors development and applications

WG-5.2.3 meeting

FAPESP Thematic 2020/04867-2

October 18th 2022

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

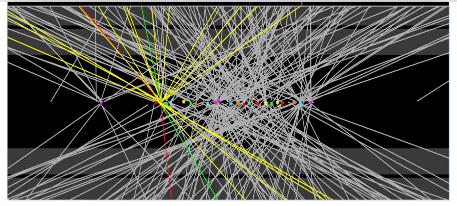
ATLAS EXPERIMENT
HEPIC IFUSP
LSI
centro universitário FEI
ipen

WG-5.2 Organization

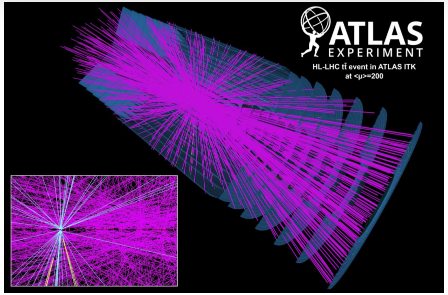
- WG-5.2.1 : ATLAS High Granularity Timing Detector (HGTD)
- WG-5.2.2 : Low Gain Avalanche Detectors (LGADs) for low energy applications
- WG-5.2.3 : Device Fabrication and Characterization

Please refer to August FAPESP Thematic Kick-off meeting for details :
https://indico.cern.ch/event/1183963/

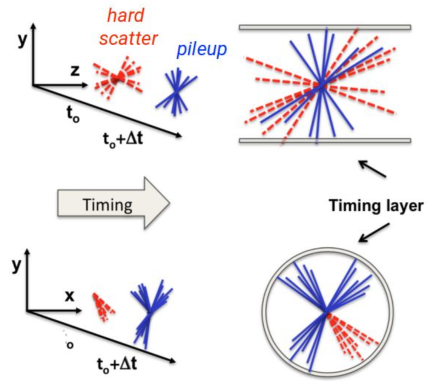
WG 5.2.1 : ATLAS HGTD



- ➔ most of LHC data are expected to come from HL-LHC phase (~4ab^{-1})
- ➔ unprecedented 200 simultaneous p+p collisions at every 25 nanoseconds
- ➔ pile-up dominated environment
- ➔ very challenging track-vertex association during event reconstruction
- ➔ impossible for the central semiconductor tracker to achieve the necessary spatial resolution in forward region crucial for the precision measurements in the Higgs sector (e.g.VBF)

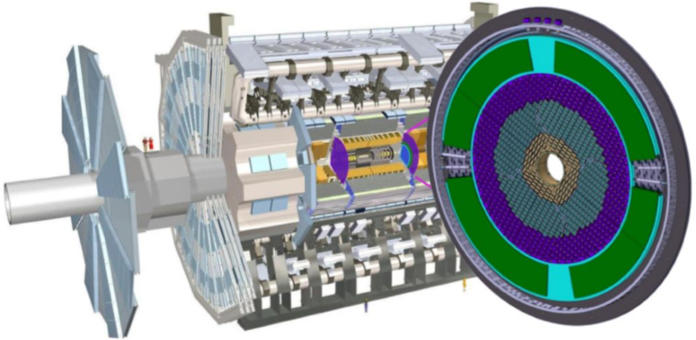


- ➔ introduce a 4th dimension (time) in the spatial track reconstruction
- ➔ must be capable of < 30 picosecond timing resolution
- ➔ high segmentation for track association

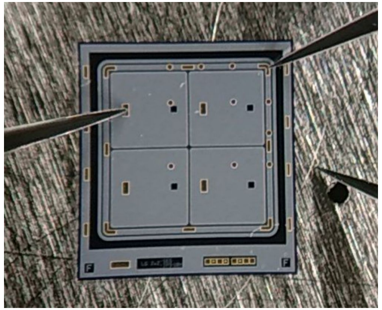


The High Granularity Timing Detector (HGTD)

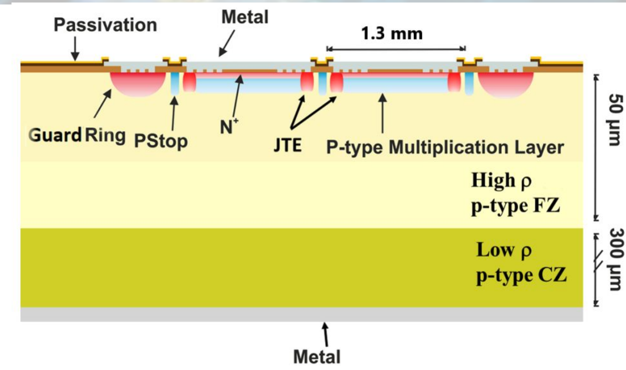
- ➔ 8 layers of ultrafast semiconductor sensors
- ➔ 16000 15x15 sensor arrays in 3 rings (3.4M channels)
- ➔ Total thickness ~ 12cm
- ➔ Total radius ~ 1.1m
- ➔ very radiation hard
- ➔ Needs very thin, very high timing resolution sensors !!



WG 5.2.1 : ATLAS HGTD

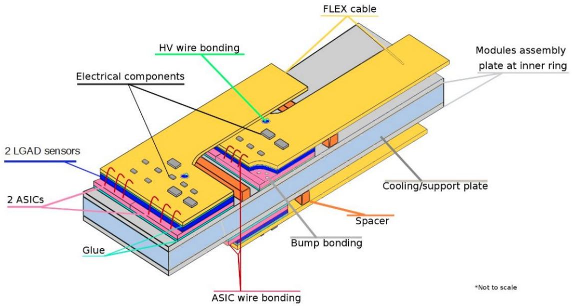


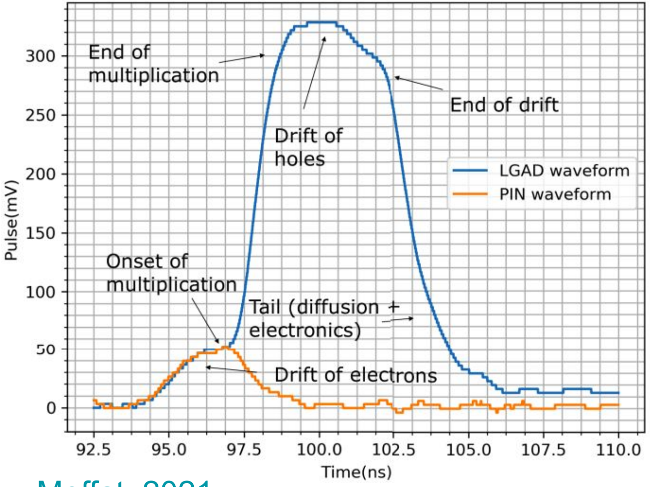
- ➔ Low Gain Avalanche Detector (LGAD)
- ➔ state-of-the-art in ultra-fast timing (20-30 ps)
- ➔ n-on-p silicon , highly doped p-layer under junction
- ➔ intrinsic charge multiplication, independent of thickness
- ➔ "simple" design
- ➔ 1.3x1.3mm2 (ATLAS HGTD), 1x3 mm2 (CMS MIP Timing Detector), 15x15 array
- ➔ can be fabricated very hadiation hard
- ➔ Prototypes by CNM (Spain), Hamamatsu (Japan), FBK (Italy), Micron (UK), Brookhaven (US), IHEP (China)



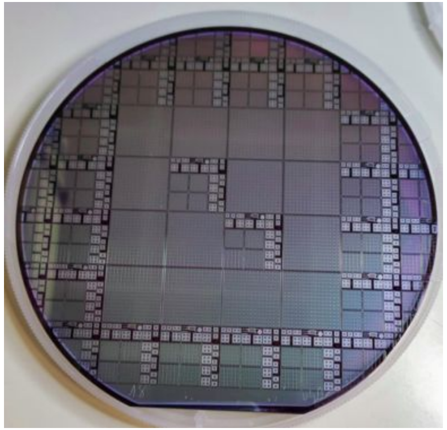
- ➔ custom ASIC readout
- ➔ ToA, ToT, hit counting

RD50





Moffat, 2021



FBK 6" wafer for ATLAS HGTD

WG 5.2.1: Activities at CERN and USP

ATLAS COLLABORATION – Final DRAFT-v0.5 CERN-MoU-2021-005

ANNEX 3: List of Upgrade Project Sub-units and Deliverables to be Provided by the Upgrade Institutes and Funding Agencies

Work Breakdown Structure

WBS	MoU Item
8.1	**Sensors**
8.1.1	LGAD Sensors
8.2	**Electronics**
8.2.1	ASIC
8.2.2	Peripheral Electronics Board
8.2.3	High-Voltage System
8.2.4	Low-Voltage system
8.3	**Luminosity, DAQ and Control**
8.3.1	Luminosity boards
8.3.2	DCS
8.3.3	Interlocks and Protection System
8.3.4	DAQ Software
8.4	**Modules and Detector Units**
8.4.1	Bare module hybridization
8.4.2	Module Flex
8.4.3	Modules assemblies
8.4.4	Detector units
8.4.5	Flex cable tails
8.5	**Mechanics, Services and Infrastructure**
8.5.1	HGTD hermetic vessel
8.5.2	On detector cooling system
8.5.3	CO_2 cooling system
8.5.4	Water-cooling system
8.5.5	Nitrogen system
8.5.6	Cables and connectors
8.5.7	Fibers and optical connectors
8.6	**Detector Assembly and QA on surface**
8.6.1	System for detector certification
8.6.2	Tools for surface assembly
8.6.3	Assembly of components on cooling plates
8.6.4	Final integration inside vessels
8.7	**Installation and Commissioning**
8.7.1	Tool for transport and cavern installation
8.7.2	Services, patch panels and cooling installation
8.7.3	Back-end electronics installation in USA15
8.7.4	Detector installation and connectivity
8.7.5	Global commissioning in LS3
8.8	**Demonstrator activities**

WG 5.2.1: Activities at CERN and USP

MoU Item 8.1.1: LGAD Sensors

Description: Design and procurement of n-in-p Low-Gain Avalanche detectors (LGAD) silicon sensors. Reception quality control (QC) of full-size sensors, including visual inspection and a set of specific tests for all device and full characterization of a fraction of devices with a probe station. Irradiation qualification of sensor batches utilizing miniature sensors and test structures.

MoU Item 8.2.2: Peripheral Electronics Board

Description: The Peripheral Electronics Board (PEB) receives the data from the modules, encodes and aggregates them before transmitting them via optical links at 10.24 Gbps to the off-detector electronics. In the down link direction, at 2.56 Gbps, this board transmits the trigger commands and clock to the ASIC. In addition, this board distributes the DC voltage to all ASICs using DC-DC regulators and the High Voltage to the sensors. The board also handles voltage and temperature monitoring and parameter setting in the ASICs for the detector control system. The data from a readout row will enter the peripheral electronics via independent or integrated flex cables. The PEB includes all components, PCB production, assembly and reliability tests.

WG 5.2.1: Activities at CERN

MoU Item 8.6.3: Assembly of components on cooling plates

Description: The assembly of the HGTD components (detector units, peripheral electronics, flex tails, pigtails) on the cooling plates will be done at CERN in building 180 using ~110 m^2 of the clean room presently used by the ATLAS NSW. In total 8 half disks will be instrumented with the components mentioned above, that will be shipped to CERN from the Institutes responsible for each deliverable. This WBS includes all the activities related to the instrumentation and certification of the half-disks and will use dedicated assembly tools (PBS 8.6.2) to allow the disks assembly in the optimal position and the certification test bench (PBS 8.6.1).

MoU Item 8.7.2: Services, patch panels and cooling installation

Description: The installation of HGTD services (cables, fibres), patch panels and infrastructure (CO_2, pressurized Water and Nitrogen) connectivity will be done in close collaboration with Technical Coordination. The delivery of CO_2 plant, water cooling stations and the N_2 gas plant is the responsibility of Technical Coordination and the CERN support cooling and gas teams. To decouple the installation of cables, patch panels from the final HGTD vessels, arriving later in the cavern, patch panels and vessel outer ring mockups will be put in place. This will allow to identify the exact position of the final vessel feedthroughs/connectors and indicate the cable connection points.

MoU Item 8.7.4: Detector installation and connectivity

Description: This work package covers the integration and insertion of the HGTD detector in the ATLAS pit. This activity is done in tight coordination with ATLAS Technical Coordination. The two complete HGTD detectors, with a weight of ~300 Kg, 1100 mm radius and 105 mm thickness each will be transported inside the vessels, from surface building 180 to the surface of the ATLAS cavern by truck, using a dedicated tool (PBS 8.7.1). They will be lowered in the cavern by crane and will be mounted on the LAr end-cap calorimeter faces, in the space presently occupied by the MBTS counters. Those counters and the moderator disk presently located in this place will be dismounted before this operation by the ATLAS Technical coordination. The installation of the new external moderator, to be provided by ITK, will be the first step. After the installation of each HGTD vessel, all the services (cables, fibres, cooling lines), already installed will be connected to the vessel outer ring feedthroughs. This operation will take approximately one month for each end-cap.

MoU Item 8.7.5: Global commissioning in LS3

Description: The commissioning will start after the installation and connectivity of each HGTD end-cap is accomplished, good access is insured and will take several weeks. It includes the commissioning of the different items in standalone and integration with ATLAS (cooling, DCS, HV, LV, DAQ, Luminosity, ...). The first step will be the verification that all services are well connected up to the back-end electronics racks, sitting in USA15 and the cooling plant is providing the required temperature inside the vessel down to -30°C. The integration of HGTD with the ATLAS DAQ, DCS, Interlocks and Protection System will follow. Full charge injection calibrations and tuning of the approximately 3.6 Million ASICs/channels should be done, before HGTD is ready for stable beams.

Will require highly trained, experienced people for installation @CERN
(MK, RM for ATLAS TC NSW)

ATLAS NSW B180 - 2018

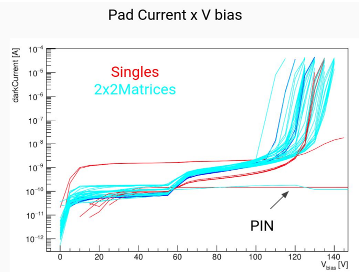
ATLAS NSW B180 - 2019

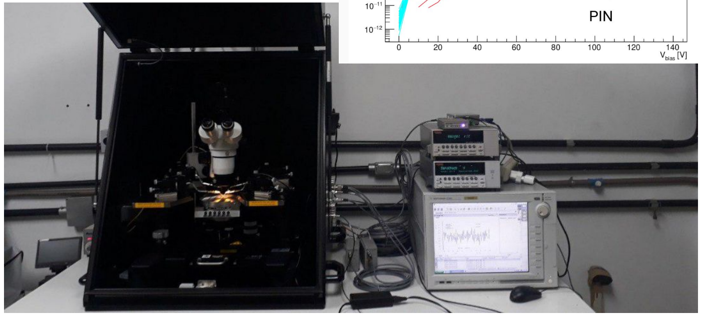
MoU Item 8.8: Demonstrator activities

Description: Provision of final size components for demonstrator tests at CERN/building 180, in order to validate the detector layout and its performance, in particular modules, flex tails, peripheral electronics boards, cooling plate, Felix board. These components will be delivered by the Institutes involved in the PBS associated to the mentioned components. Provision of the infrastructure and organisation of unirradiated and irradiated LGAD sensors, Altiroc and modules for the testbeam periods (~2-3 per year at CERN/SPS). Parts used in the testbeams are provided by the Institutes involved in the relevant activity and have no additional CORE value

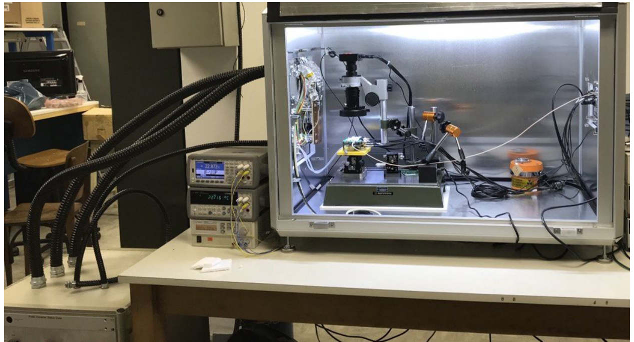
WG 5.2.1: Activities at CERN and USP

Electrical characterization

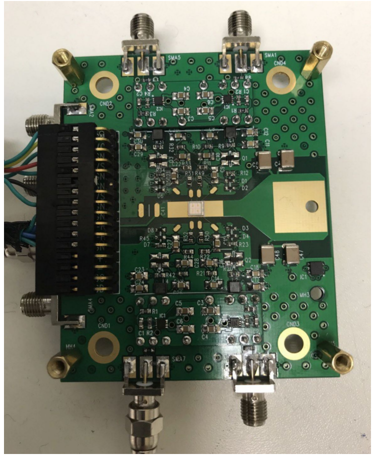


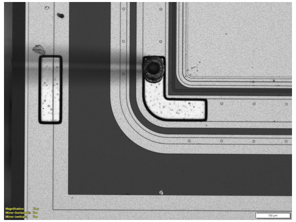


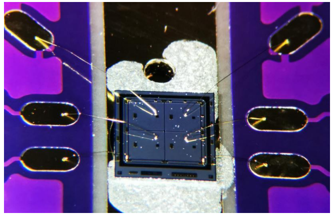
Box with thermal link cooling (-45C) for testing irradiated sensors

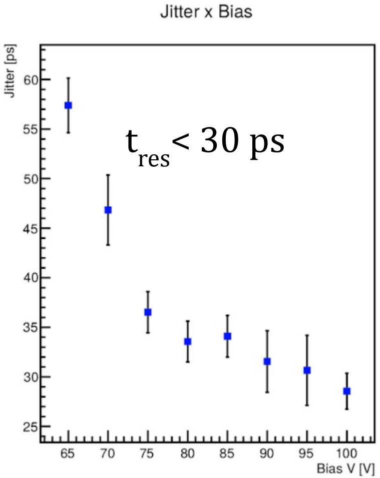


Fast Timing board designed @ IFUSP (4 channels)

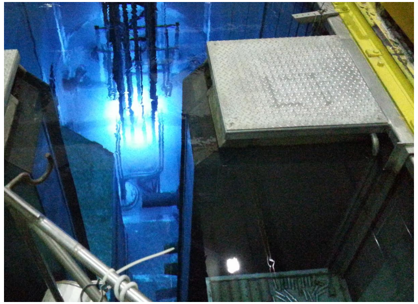


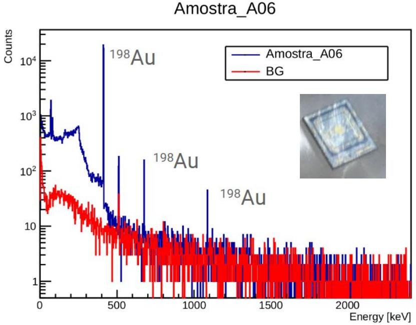






LGAD Sensors already irradiated @IPEN reactor

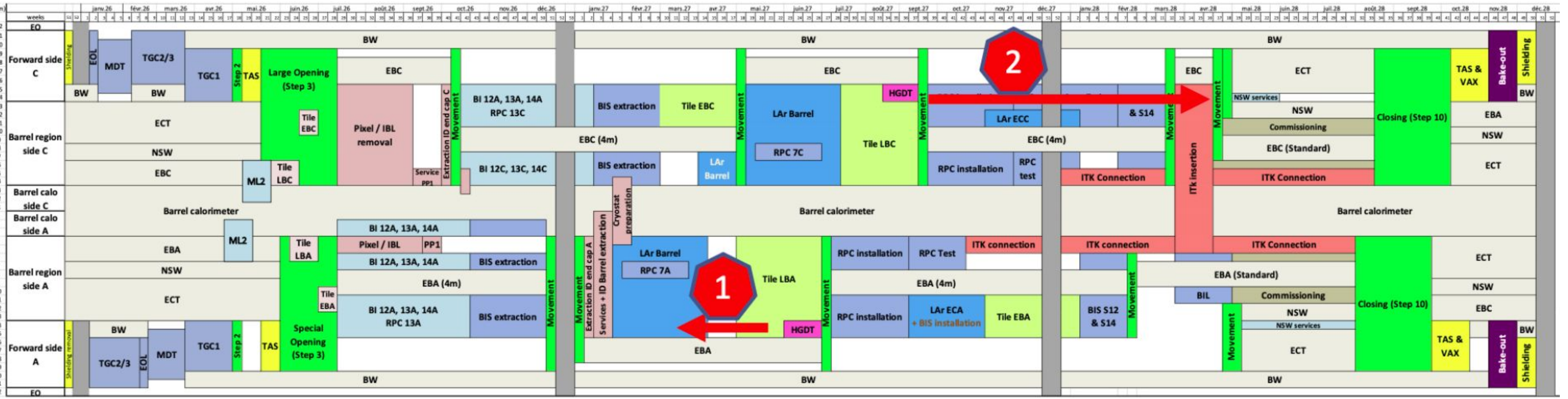




HEPIC-IFUSP will be one of the 4 ATLAS sites for QA/QC of HGTD LGAD sensors (FBK/CNM) (FAPESP Funding)

WG 5.2.1: Schedule

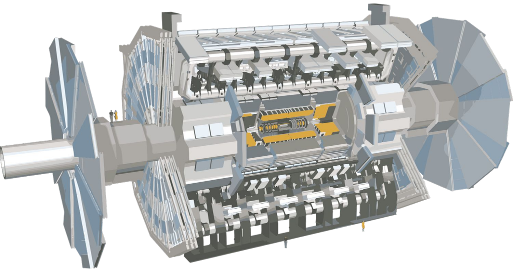
- Schedule is driven by HGTD installation in ATLAS (high priority)
  - Side A : May 2027
  - Side C : November 2027
- Detailed schedule is controlled/enforced by HGTD and ATLAS Upgrade Steering Group
- Periodic report on HGTD internal meetings (sensor, sensor related)
- **Very aggressive schedule, intense work starting next year**



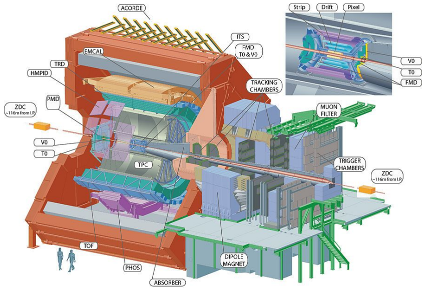
2027

WG 5.2.1: LGADs Beyond ATLAS

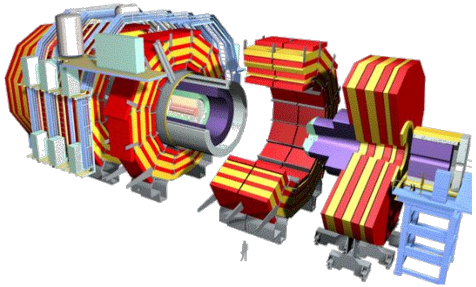
ATLAS



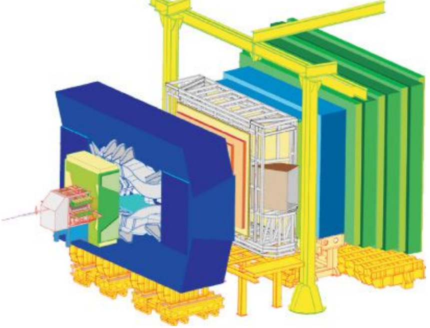
ALICE

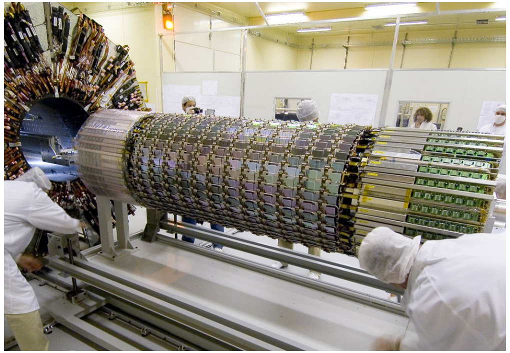


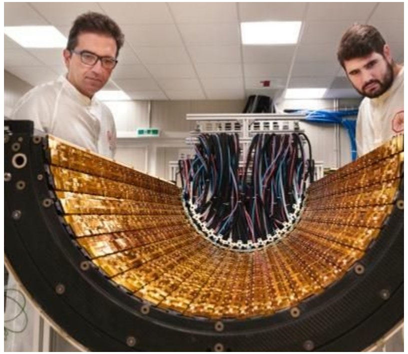
CMS

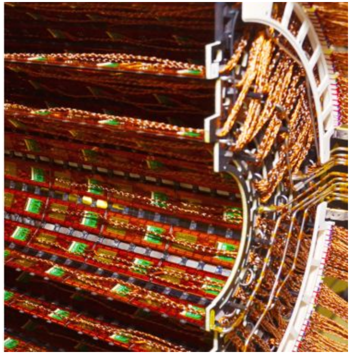


LHCb







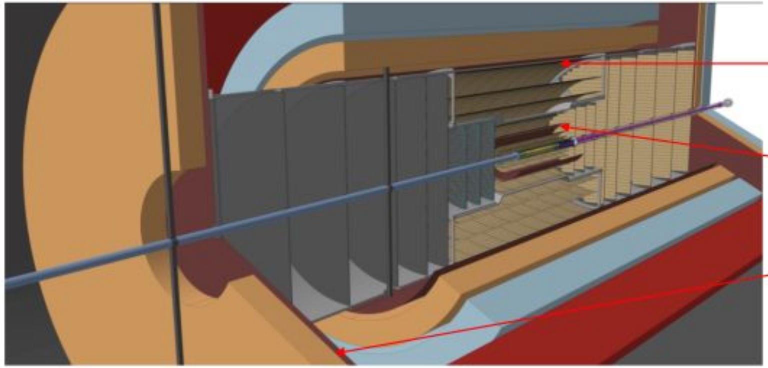


- ➔ Proton-proton collisions @ 13 TeV (also ion-ion at lower CM energy)
- ➔ **Semiconductor detectors (100'sq. m) across all experiments for tracking, beam diagnostics and calorimetry**
- ➔ **Fast readout, radiation hard, billions of channels**, DAQ integration with other detector systems for reconstruction

Time of Flight for Particle Identification

Sub-system of ALICE3

➔ Construction starting ~2028, data-taking ~2035



Barrel TOF ($|\eta| < 1.75$)

- Outer TOF radius = 85cm
  surface: 30m^2, pitch: 5 mm
- Inner TOF, radius = 19 cm
  surface: 1.5m^2, pitch: 1 mm

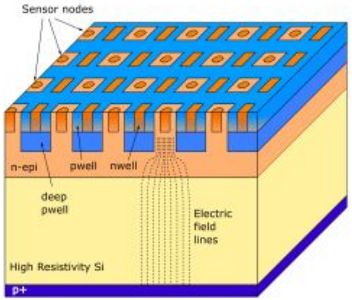
$\sigma_{TOF} \lesssim 20$ps

Forward TOF ($1.75 < |\eta| < 4$)

- Inner radius = 15 cm, Outer radius = 150 cm
  surface = 14m^2, pitch = 1mm to 5mm

Two R&D lines

- **CMOS sensors with gain (baseline):** main R&D line in ALICE
- **LGADs (fallback):** R&D line in ALICE with very thin sensors



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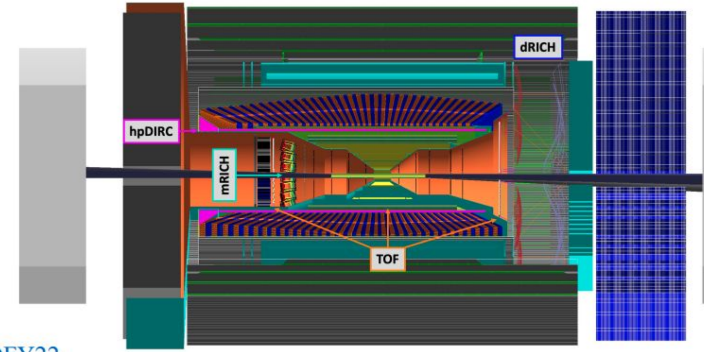
[Electron Ion Collider Detector R&D](#)

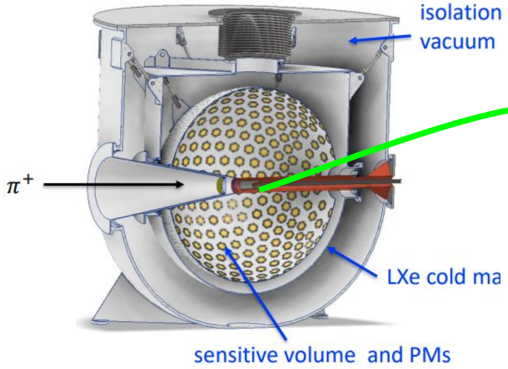
eRD112: AC-LGAD for EIC [1]

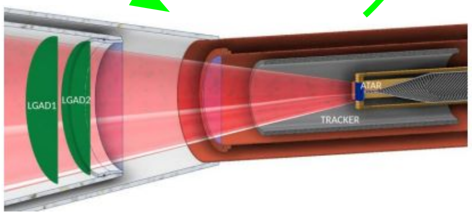
- AC LGAD detectors proposed for EIC
  - Roman Pots and B0
  - TOF for PID (and tracking)
- Have common designs in sensor, ASIC etc. when possible, combine R&D efforts

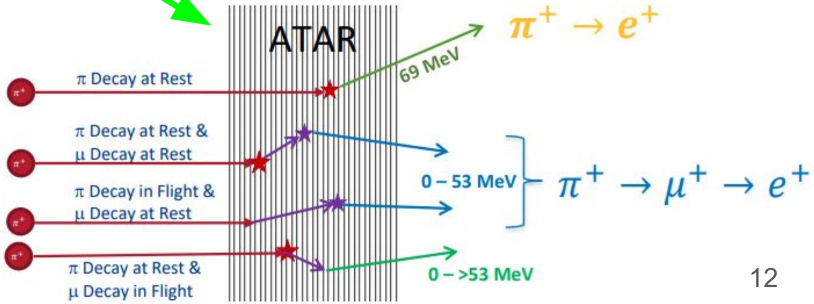


[1] https://wiki.bnl.gov/conferences/index.php/ProjectRandDFY22

PIONeer Experiment (PSI)







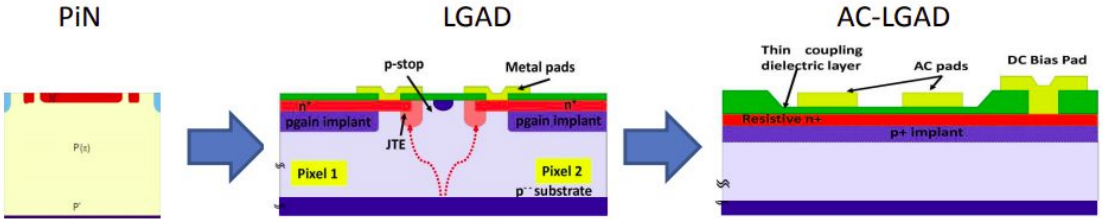
WG 5.2.2
Low Gain Avalanche Detectors
for
Low Energy Applications

WG 5.2.2 : Description

- ➔ Intrinsic gain (10~20x), thin sensors ✅
- ➔ Good efficiency for soft X-Rays ✅
- ➔ Very fast signal (ps resolution) ✅
- ➔ "Simple" geometry ✅
- ➔ Radiation hard ✅
- ➔ Intense activity in HEP now (HL-LHC) ✅
- ➔ Designs optimized for MIP ❌
- ➔ Large pixels (mm) ❌
- ➔ If you try to reduce pixel size … ❌

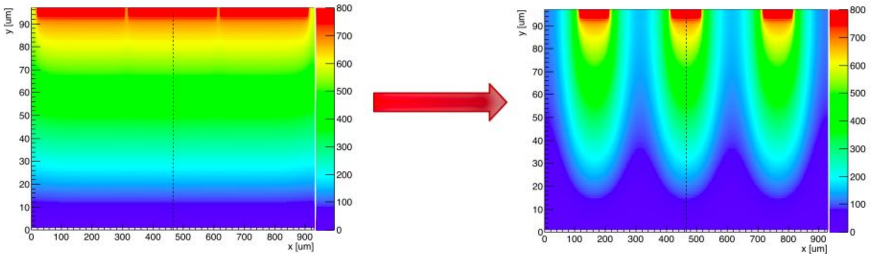
The AC-LGAD

[Resistive AC-Coupled Silicon Detectors: principles of operation and first results from a combined analysis of beam test and laser data]



H. Sadrozinski (2021)

Electrode segmentation makes the E field very non uniform, and therefore ruins the gain and timing properties of the sensor

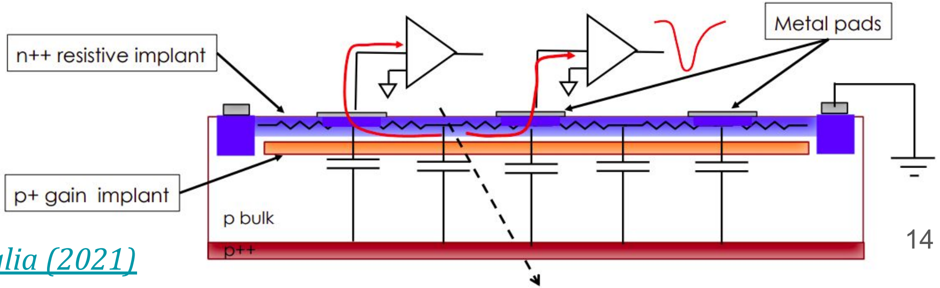


Cartiglia (2015)

Non uniform E field and Weighting field

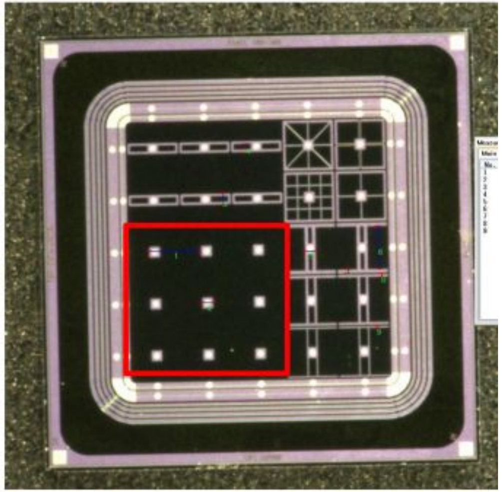
N.Cartiglia (2021)

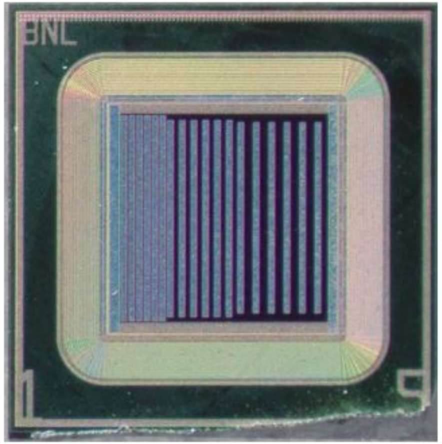
- ➔ Add a resistive layer for charge sharing
- ➔ Readout AC coupled
- ➔ ~few um spatial resolution
- ➔ 100% fill factor

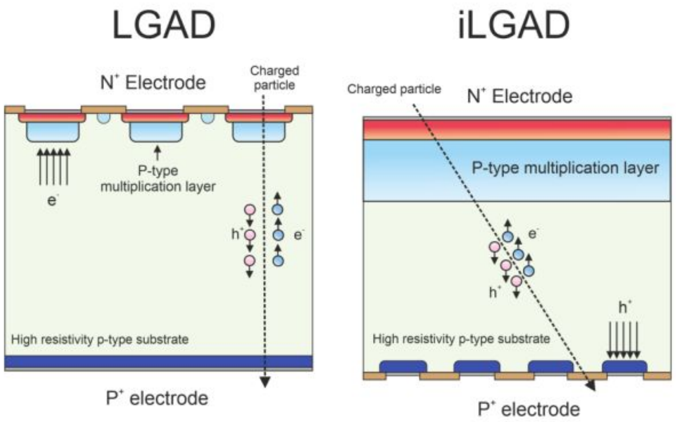


WG 5.2.2 : Description

AC-LGAD	AC-LGAD	Inverted-LGAD







UCSC (FBK) - S.. Mazza, 2022

➔ 20~35ps
➔ 5~7um
➔ 100% FF

BNL Giacomini (2021)

➔ ~35ps
➔ < 15 um
➔ 100% FF

CNM (2021)

➔ ~20ps
➔ 100% FF

Simulation of detectors with resistive elements, AC LGADS - (Wiegler 2021)

WG 5.2.2 : WBS and Deliverables

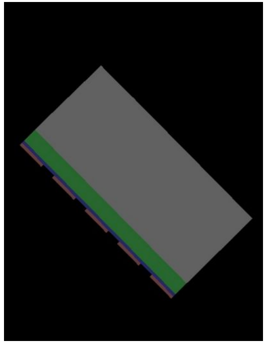
WBS (Tentative)

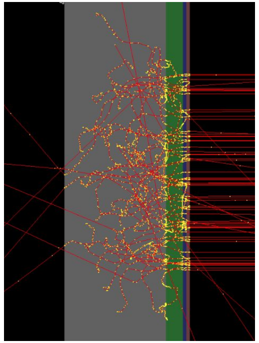
1. **Simulation**
   1.1. Geant4 Simulation (LGAD, AC-LGAD)
   1.2. TCAD Simulation (LGAD, AC-LGAD)
   1.3. Multiplication Mechanism Simulation (Weightfield-2, Garfield++, KDetSim)
   1.4. Radiation damage processes
   1.5. Charge Sharing and position determination (Custom Code)
   1.6. Circuit and Layout simulation (ELDO, Spice, Hyperlinx)
   1.7. Integration framework
2. **Characterization of *available* LGAD, AC-LGAD**
   2.1. Sensors electrical characterization
   2.2. Aux. structures electrical characterization
3. **Readout electronics for *availabl*e LGAD, AC-LGAD**
   3.1. Fast amplifier and calibration board
   3.2. Prototype readout system (ATLAS-FELIX based)
4. **Radiation testing of *available* LGAD, AC-LGAD**
   4.1. X-Ray testing
   4.2. Charged particle testing (electrons, protons, ions)
   4.3. Picosecond X-Ray testing
5. **Irradiation of *available* LGAD, AC-LGAD**
   5.1. Photons
   5.2. Neutrons

Deliverables

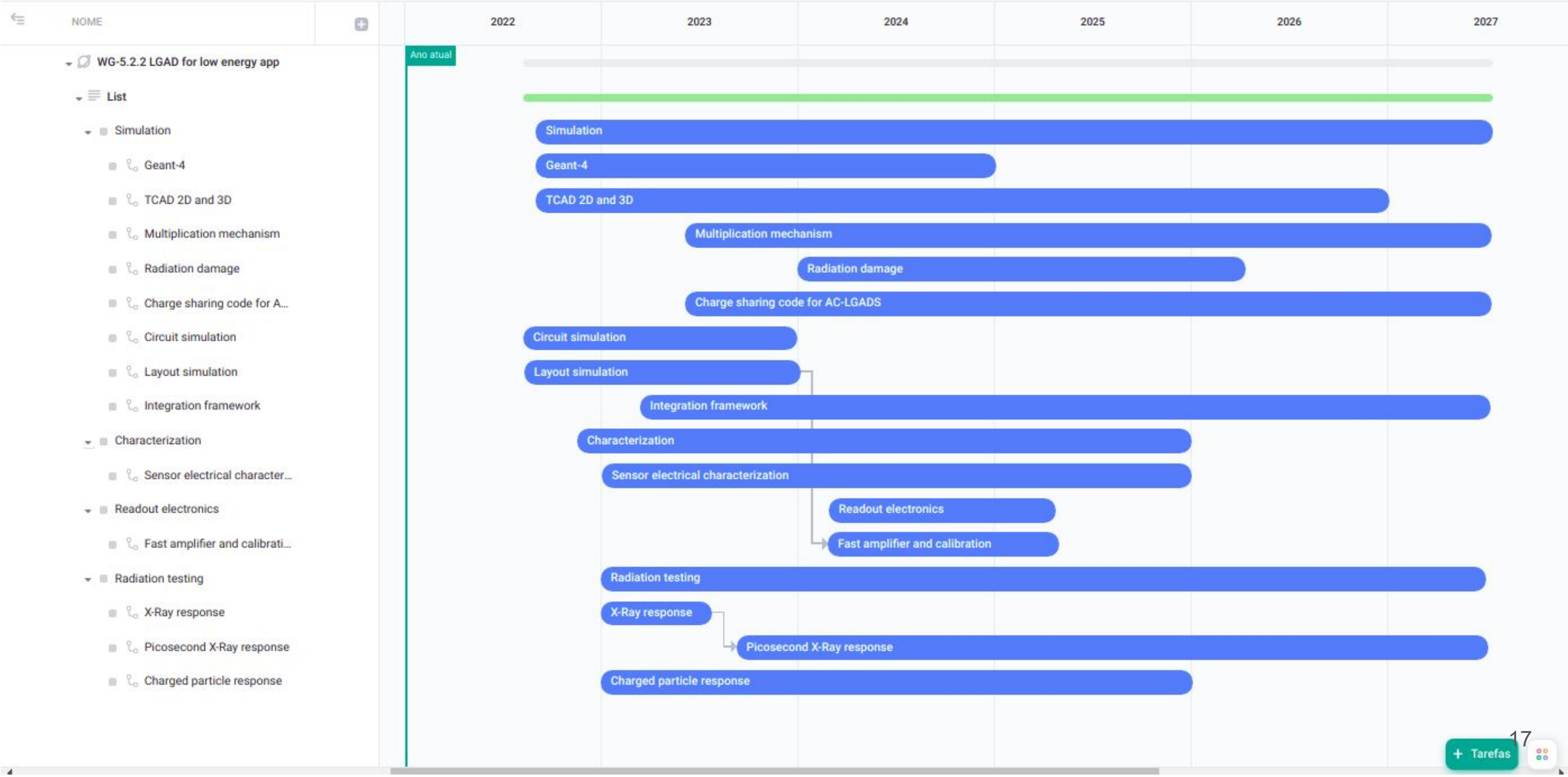
1. Analysis and interpretation of simulation results (G4)
2. Analysis and interpretation of simulation results (TCAD)
3. Readout board simulation, design, assembly and test
4. Analysis of *available* LGAD and AC-LGAD X-Ray testing
5. Analysis of *available* LGAD and AC-LGAD picosecond X-Ray testing
6. Analysis of LGAD charged particle testing
7. Validation of framework integration for simulation/beam test
8. Electrical testing of irradiated/non-irradiated sensors

AC-LGAD Geant4 Simulation (e^- 300keV)





WG 5.2.2 : Schedule (tentative)



WG 5.2.2 Organization

1. Current participants
    1.1. Document “Team Members Organization and Responsibilities” (See SAGE)
    1.2. Institutions with people on WG5.2 :
        1.2.1. EPUSP
        1.2.2. IFUSP
        1.2.3. IPEN
        1.2.4. FEI
2. General organization :
    2.1. Each member of the project will have to assign him/herself to a WBS item
    2.2. If you don’t have a CERN account, register in Indico as external user
    2.3. Bi-weekly meetings of the activities will be registered in the Indico system of WG 5.2.2 to present a short status report (few slides)
    2.4. Monthly plenary meeting with all activities of WG-5.2
    2.5. All developed and reported activities must be strictly related to the project.
    2.6. We are open to new developments and ideas, but this must be discussed beforehand with the project coordination
    2.7. These contributions and Indico links to the presented material will be used to compile the FAPESP annual report

- Very high intersection/feedback/cross-feed with HGTD activities (5.2.1) and fabrication (5.2.3)
- Ongoing discussions with U. California Santa Cruz and CNPEM (X-Rays)
- Ongoing discussion with RENAFAE and CNPEM (ALICE, ATLAS, LHCB, CMS) for UFSD collaboration
- Ongoing discussion with Instituto Eldorado (advanced packing, assembly, testing)

WG 5.2.3

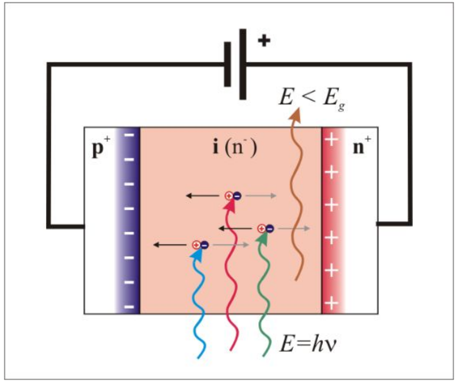
Sensor Fabrication and Characterization

The following devices structures will be developed and tested for the detection of X-rays and other ionizing particles.

(a) **LGAD (Low Gain Avalanche Detectors)**
(b) **PIN Diode**
(c) **HV-MOS Detector**

PIN Diode

- This device is composed of three layers, one of the P type, one of the N type and between them a layer of intrinsic silicon (non-doped), the biggest advantage in the manufacture of this structure are the thick layers and the smaller number of process steps. This device is conventionally used in light intensity detectors, for the detection of RX, it is necessary to increase the thickness of the intrinsic layer.



PIN Diode

In this development we working in three fronts;

- (a) Modification and/or optimization of comercial PIN diodes
- (a) Development and fabrication of structure for PIN diodes
- (c) Development of electronic transduction and signal adjustes.

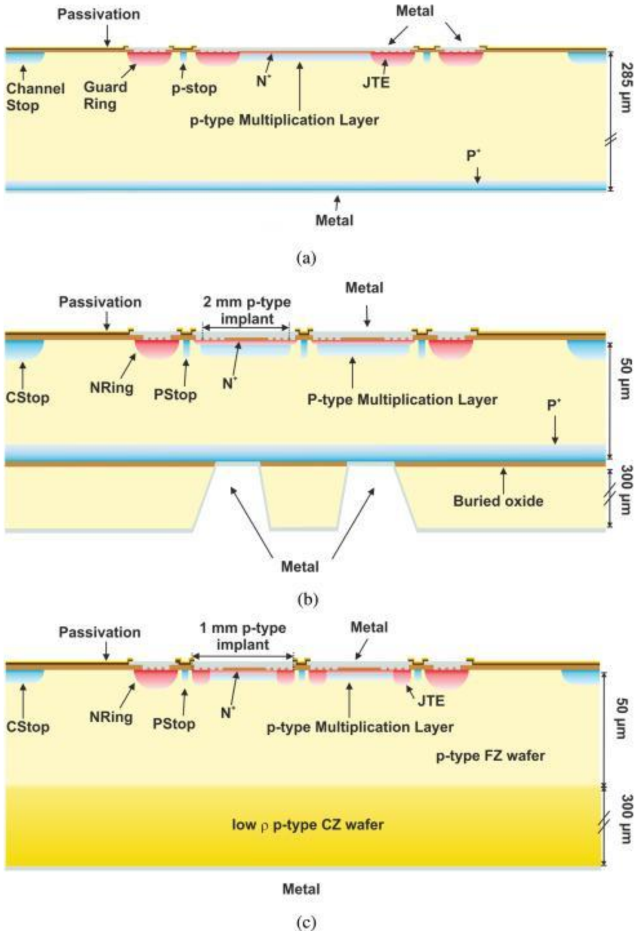
PIN Diode

For the study of these devices, the following steps will be carried out

1. Acquisition of commercial PIN-type sensors
2. Development and deposition of layers of radiation sensitive material on commercial pin diodes.
3. Acquisition of N-type silicon substrates
4. Acquisition of intrinsic silicon substrates
5. Study of amorphous silicon deposition and crystallization in a neutral environment
6. Study of P-type and N-type silicon deposition by sputtering
7. P and N-type doping of intrinsic substrate by ion implantation and thermal diffusion.
8. Manufacture of PIN type sensors
9. Testing the sensors with X-rays
10. Project of the Pre-Amplifier and the signal conditioning circuit.

Low Gain Avalanche Detectors

Low Gain Avalanche Detectors or LGAD are silicon sensors with built-in signal amplification. The amplification is due to the high field region realized by an additional doping layer below the charge carrier collection electrode. For example, in a PIN-type sensor, an additional P-doping is used as the multiplication layer. This creates signal amplification with similar noise levels as standard PIN diodes, but the multiplication needs to be small enough not to saturate the front-end readout.



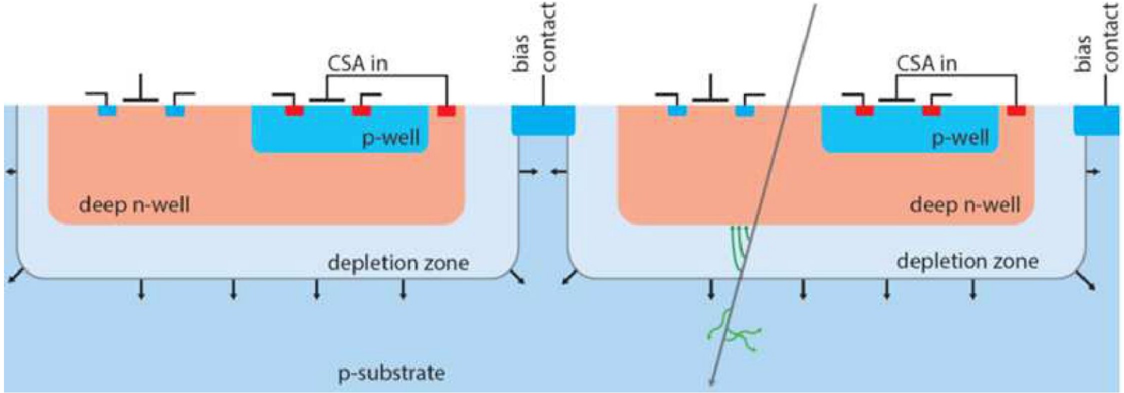
Low Gain Avalanche Detectors

With the experience and the results acquired in the manufacture of the PIN diode, a new structure will be proposed for the manufacture of the LGADs, for which the lithographic masks will be designed and manufactured, then the doping of the amplifying layer will be studied and finally the preamplifier will be designed. , which will act as a front-end circuit for the developed detector. For the development of LGAD type detectors, the following steps will be carried out:

1. Acquisition of silicon substrates
2. Design of lithographic masks
3. Study and simulation of doping by diffusion and ion implantation
4. Study and simulation of the detector device steps
5. Integration of oxidation and diffusion steps to obtain LGAD structures
6. Tests of standard structures

HV CMOS Detector

A new way of producing particle detectors is the commercially available HV-CMOS technology. The main application here is sensors that benefit from local amplification. It is also possible to include processing electronics in the pixel cell, creating a fully monolithic detector that does not need a front-end readout chip. CMOS fabrication technology allows detectors to be produced with a size of 50 × 50 μm2 or smaller



HV CMOS Detector

For the development of the HV-CMOS type detector, the following steps will be carried out:

1. Design and simulation of the structure with buried wells
2. Acquisition of silicon substrates
3. Design and manufacture of lithographic masks
4. Developments of the doping, oxidation and diffusion steps
5. Developments in the metallization and contact fabrication steps
6. Device tests
7. Design, manufacture and testing of signal conditioning circuits.

There is the possibility of using commercial devices like CCD or CMOS image sensors at this stage, we are choosing the most suitable devices for this stage. The commercial devices purchased will be post-processed at the LSI with the addition of radiation sensitive layers, covering with residual radiation absorbing layers and protective metallic grids.

BACKUP

WG 5.2.1: People and Action Items

1. Current Team
   1.1. M. Leite (Physicist)
   1.2. G. Saito (MS,PhD)
   1.3. R. Menegasso (TS)
   1.4. M. Kuriyama (TS)
   1.5. DD (Dedicated)
   1.6. DD (Sharing with PA)
   1.7. PD (Sharing with PA)
   1.8. IC (TT-2 ?)
   1.9. TT-4

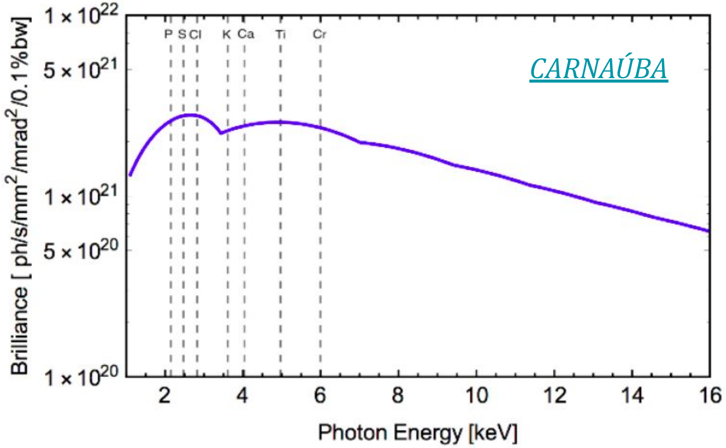
DD–4: *Ultra-fast semiconductor sensors and associated instrumentation for radiation detection*

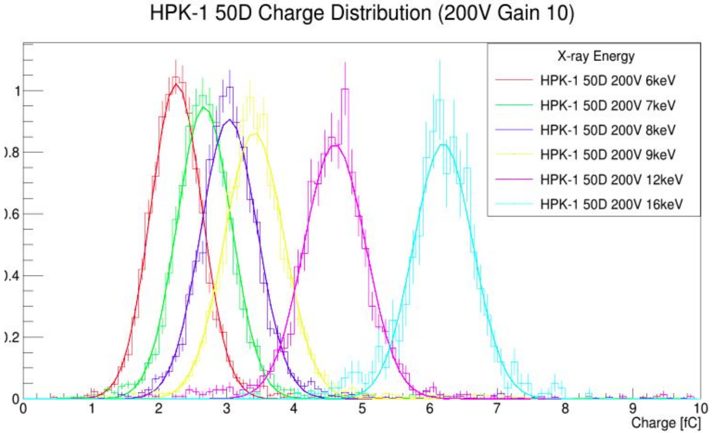
1. Action items
   1.1. Equipment availability (importation)
   1.2. Preparing civil infrastructure for Lab
   1.3. Lab installation
   1.4. PD, DD, TT hiring
   1.5. Start testing sensors
   1.6. Significant work to commission local infrastructure (EMU FAPESP)
   1.7. **Significant commitment of people on @CERN activities**

1. Deliverables
   1.1. LGAD Characterization Lab.
   1.2. Characterization of LGAD sensors (on-going)
   1.3. Performance studies on irradiated arrays (on-going)
   1.4. PEB test stand system
   1.5. Participation in HGTD assembly facility construction @ CERN (on-going)
   1.6. Demonstrator construction @ CERN (on-going)
   1.7. HGTD installation
   1.8. HGTD commissioning

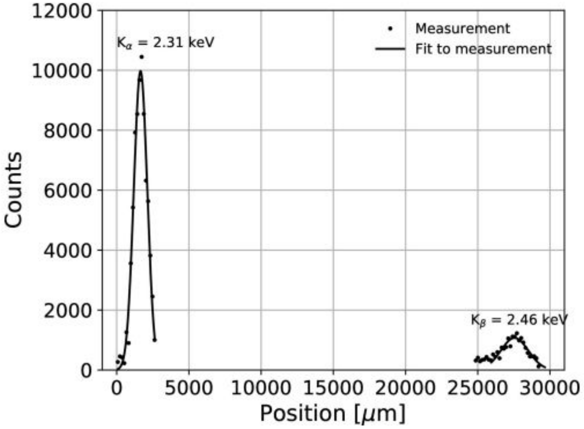
Almost zero float on these items !

LGADs for tender X-Rays applications





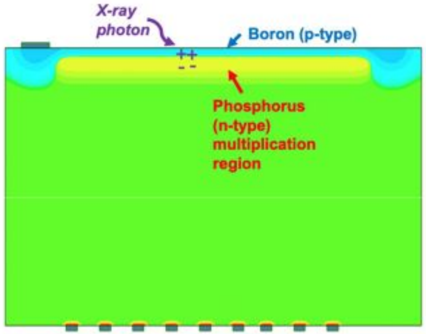
[Use of "LGAD" ultra-fast silicon detectors for time-resolved low-keV X-ray science - ScienceDirect]



→ ~ 2keV

An attempt to lower the limit to ~1 keV…

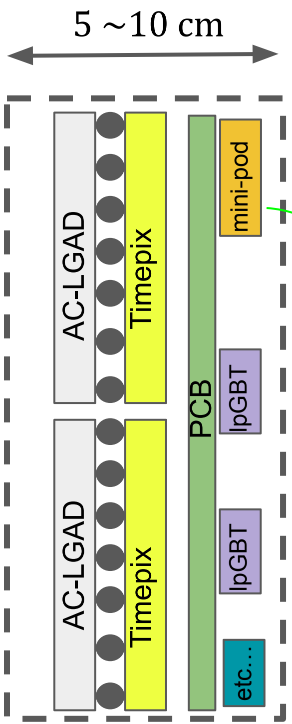
[New Thin-Entrance window LGAD for Soft X-ray Detection at LCLS]



[Development of low-energy X-ray detectors using LGAD sensors]

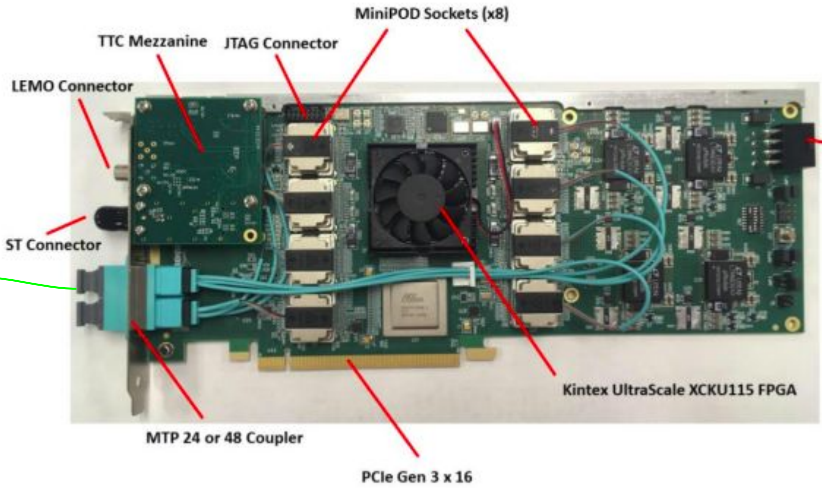
Readout Chain - a *de-facto* approach
(from a HEP physicist perspective …)

[FELIX project]

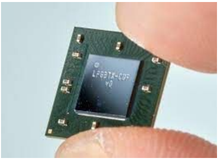


Mini-Pod

48 (24) fibers, 100's meters



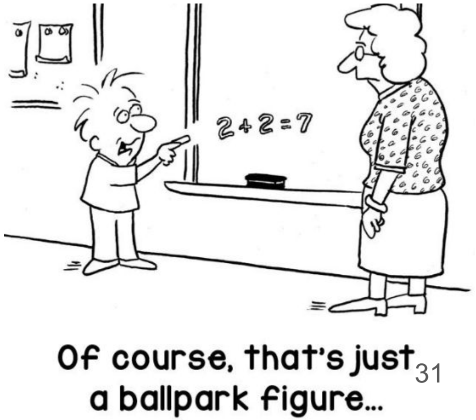
lpGBT (?)



To understand (at least…) :

- ➔ Fast UFSD signal (1 ns width)
- ➔ Timepix amplifier response
- ➔ ToT : depends on the above and Timepix resolution (1.6ns or 200ps)
- ➔ Link aggregation multiplicity (e-links)
- ➔ Cooling the sensor ? (e.g. -30C)

Device	Lanes	Gb/s	Norm
Timepix 3	8	0.640	64
lpGBT	1	10.24	24
Felix	48 (24)	4.8 (9.6)	1
Felix-FLX181	24	25	0.4



LGAD READOUT ASIC FOR ATLAS