Latest developments in Ultra Fast Silicon Detectors for synchrotron radiation detection

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Projeto Especial FAPESP
"Física e Instrumentação de Altas Energias com o LHC-CERN"

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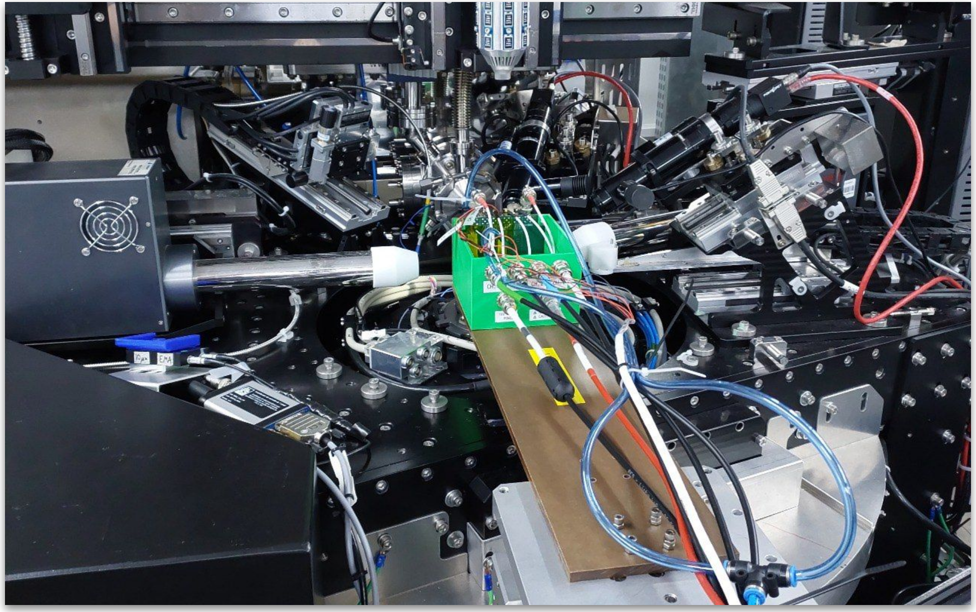
On this presentation

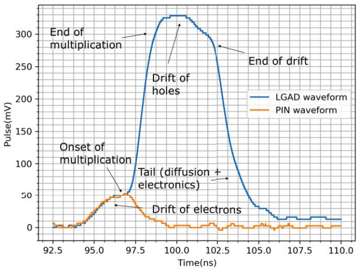
- ➔ Introduction:
  - ◆ Ultra Fast Silicon Detectors
- ➔ Setup assembly at SIRIUS
- ➔ Analysis and results
- ➔ Outlook and Remarks



2x2 DC-LGAD setup at Carnaúba beam Line (2024)

Low Gain Avalanche Detectors (LGAD)

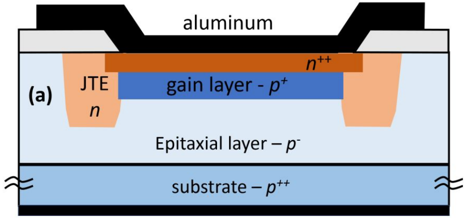
- Proposal made within the RD50 collaboration (Sadrozinski et al) ~ 2013 aiming at very radiation hard devices for LHC etc.
- LGADs are PiN Si diodes + an intrinsic gain layer for charge multiplication
  - Moderate gain (10 ~ 50)
  - Very fast response (< 30 ps for MIP)
  - DC LGADs can be segmented (area >> gain layer thickness) for position sensing
  - Devices can be fabricated from ~30 μm to ~300 μm active thickness
  - Operates at reverse bias (tens to hundreds of Volts)



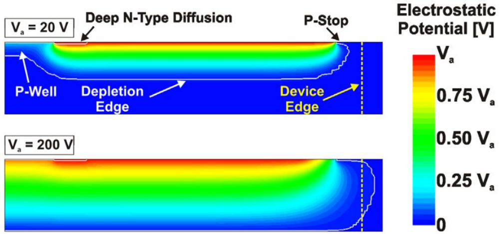
LGAD response to ^{90}Sr electrons

LGAD structure

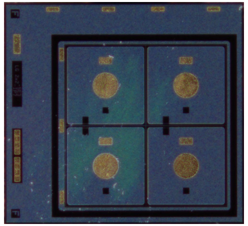
1906.11542v2

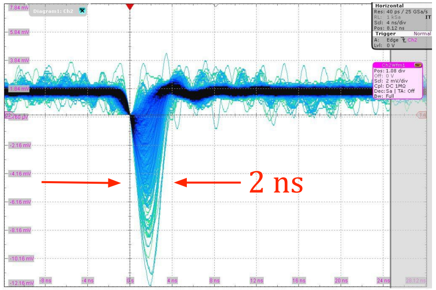


LGAD Internal Electrical Field

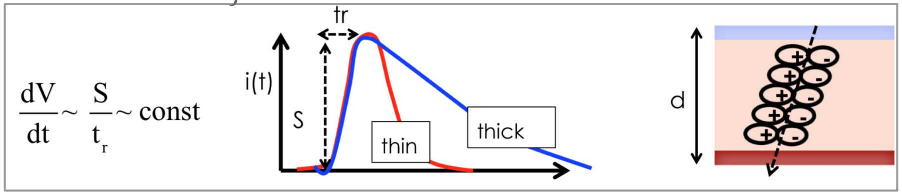


2x2 LGAD (HPK)

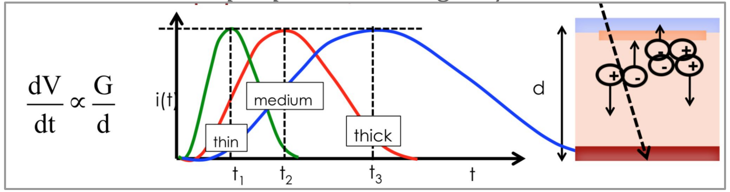




Planar detector: fixed rise time



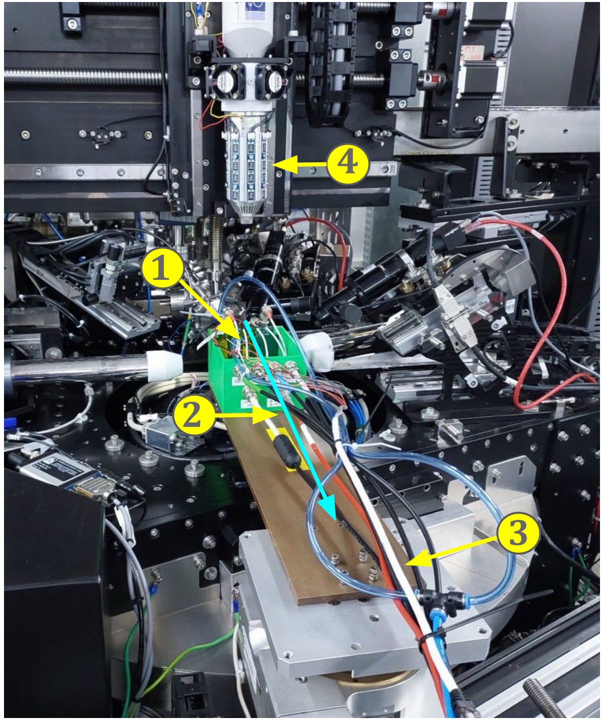
LGAD: rise time proportional to gain/thickness

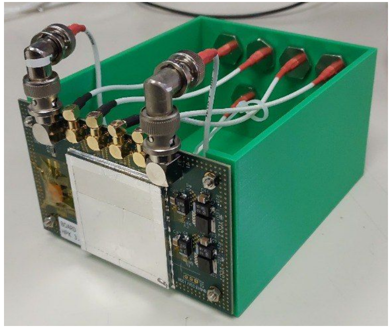


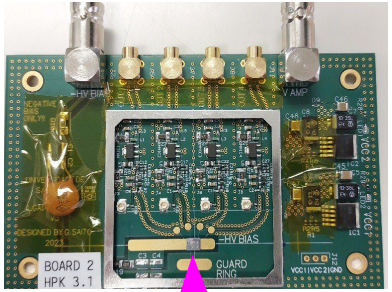
2x2 LGADs (HPK 3.1) tests @ Sirius Carnaúba BL

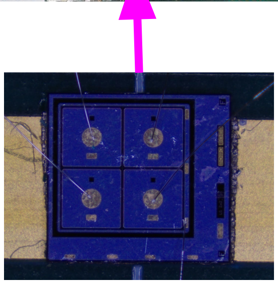
- ATLAS HPK 3.1 2x2 array prototype
- Beam size **350 μm** or **150 nm**
- Detector can move and rotate wrt to the beam
- LN2 nozzle can be used to **change temperature**
- **Energy/timing** resolution wrt
  - X-ray energy, bias and temperature
- EPIC by Sirius to control/store conditions
- Readout similar to SSRL
  - St. Cruz 1st stage amplifier + broadband amplifier (now on-board)
  - Oscilloscope 2 GHz/50 GS/s
  - Jitter from electronics < 1 ps

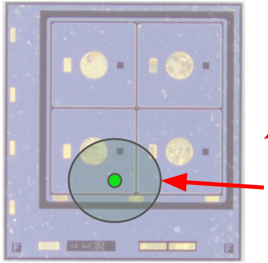
1. **LGAD**
2. **Beam direction**
3. **Linear stage**
4. **Cooling nozzle**







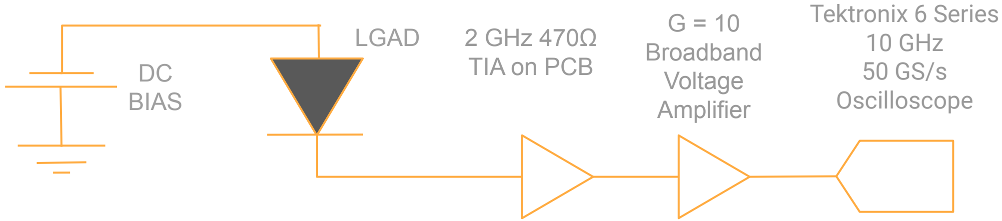




2x2 HPK 3.1 LGAD array

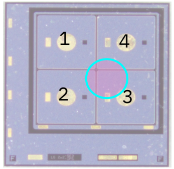
150 nm or 350 μm X-ray beam

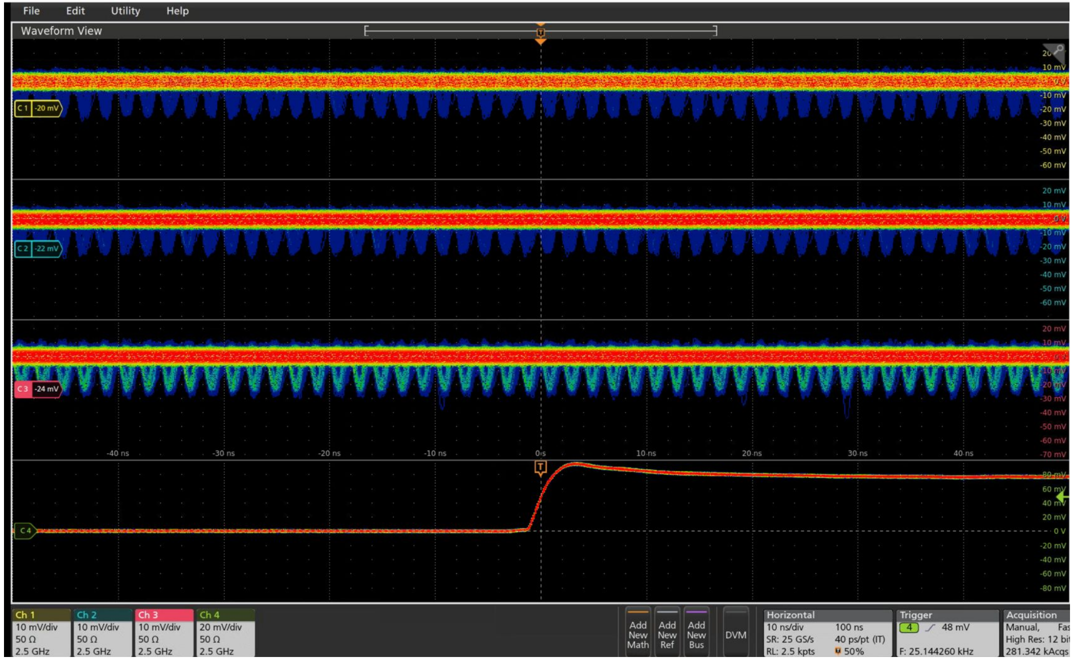
Simple Measurement Setup

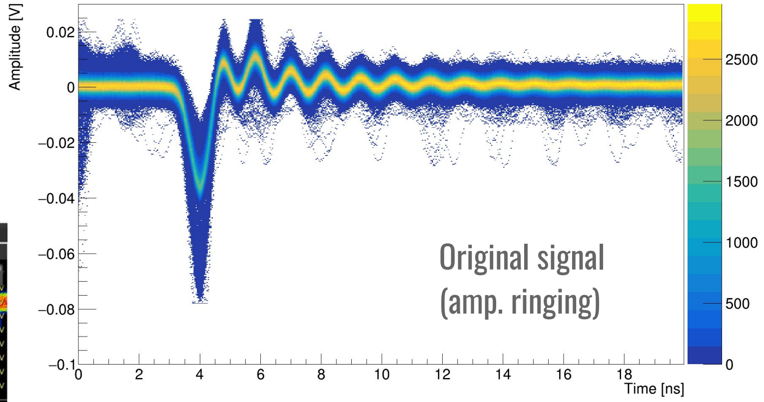


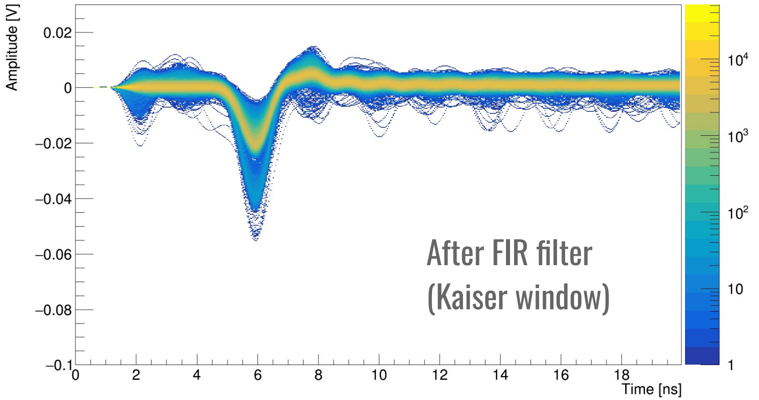
Data Analysis

- Beam size $\mathbf{350\,\mu m}$
- Different X-ray energies, bias
- Trigger signal from machine





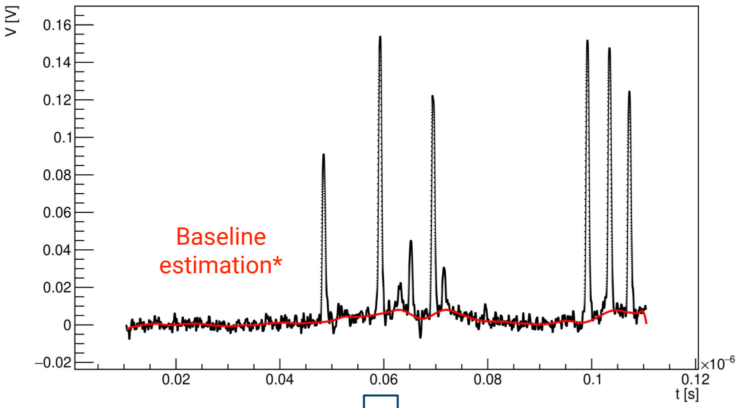


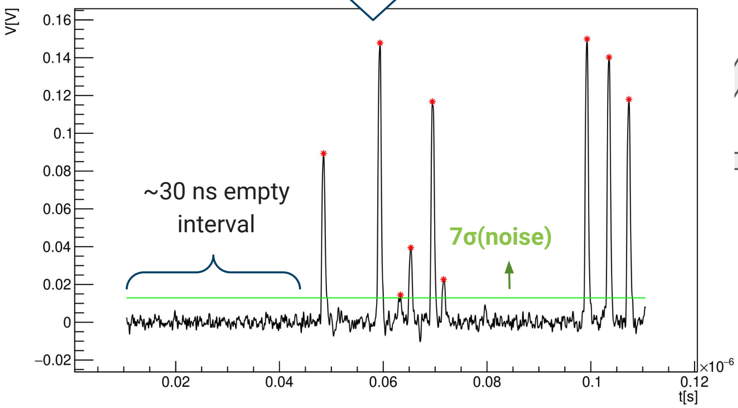


Single pad LGAD data processing

https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006

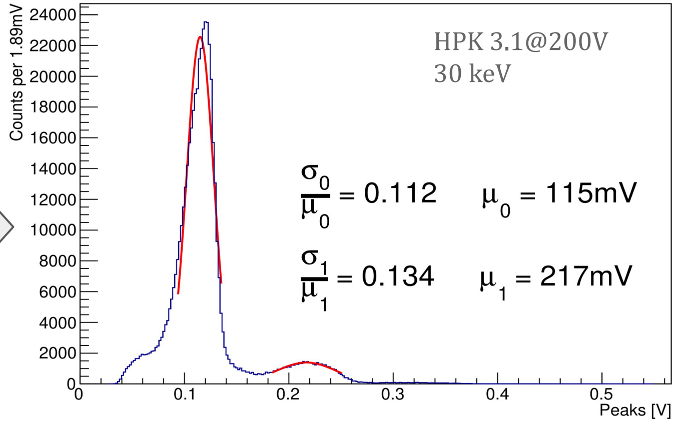
- All data from oscilloscope digitized waveforms





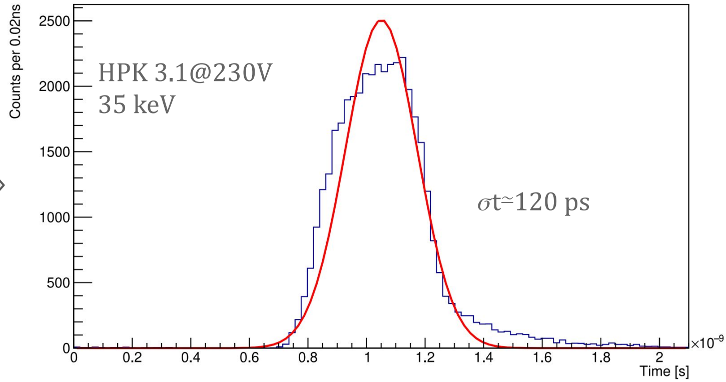
Energy

σE/E from Amplitude distribution



Timing

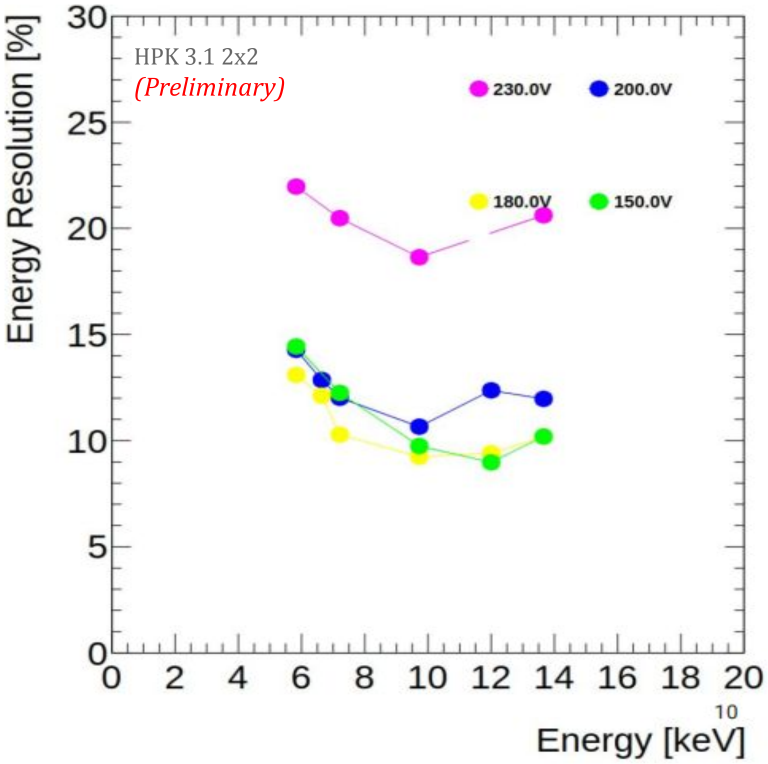
σt based on 2.1 ns interval (20% CFD)

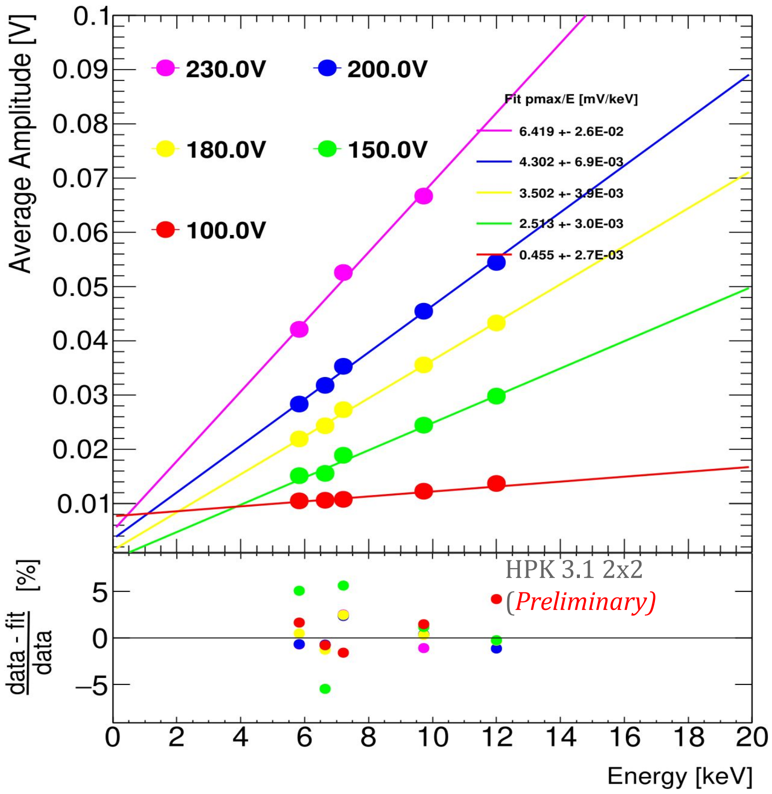


**asymmetric reweighted penalized least squares smoothing*

2x2 LGAD Energy response

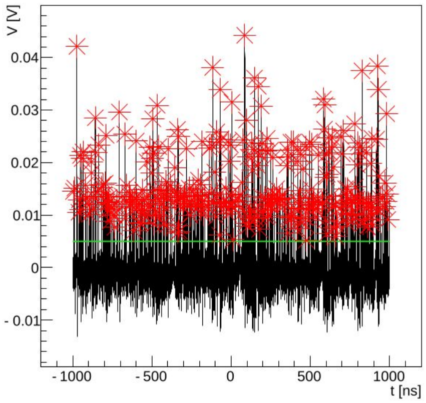
- Energy resolution (σE/E) measured as a function of X-ray energy and bias voltage
- Linearity ~ ±5 %



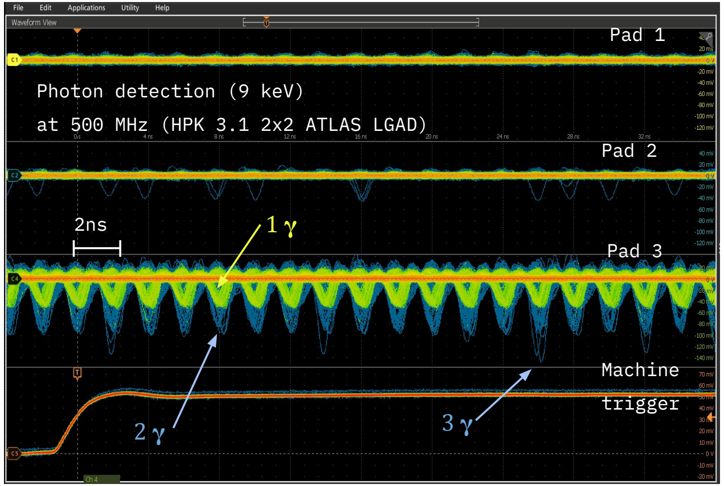


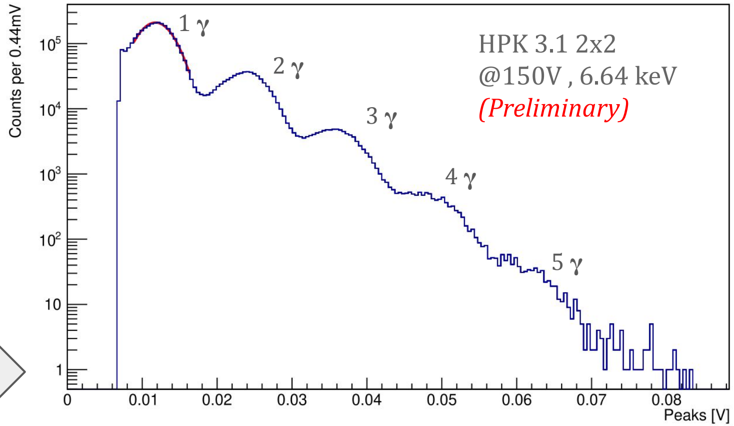
2x2 LGAD Energy response

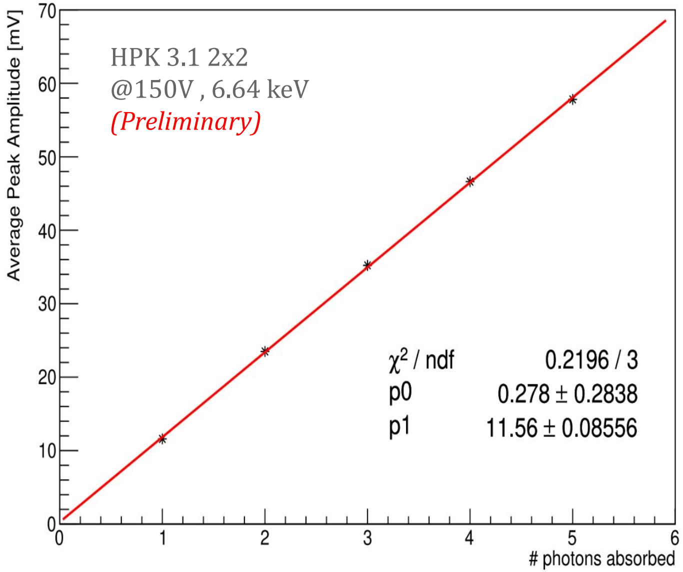
Multiple photon conversions observed (up to 5)

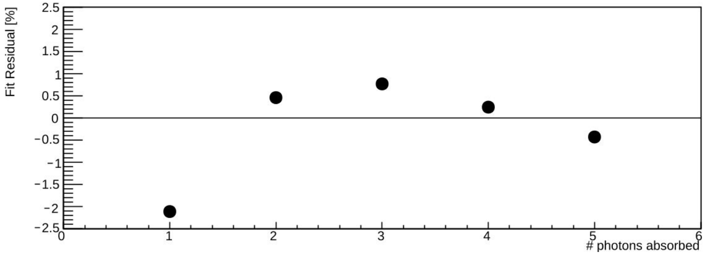


After many wfm. segments



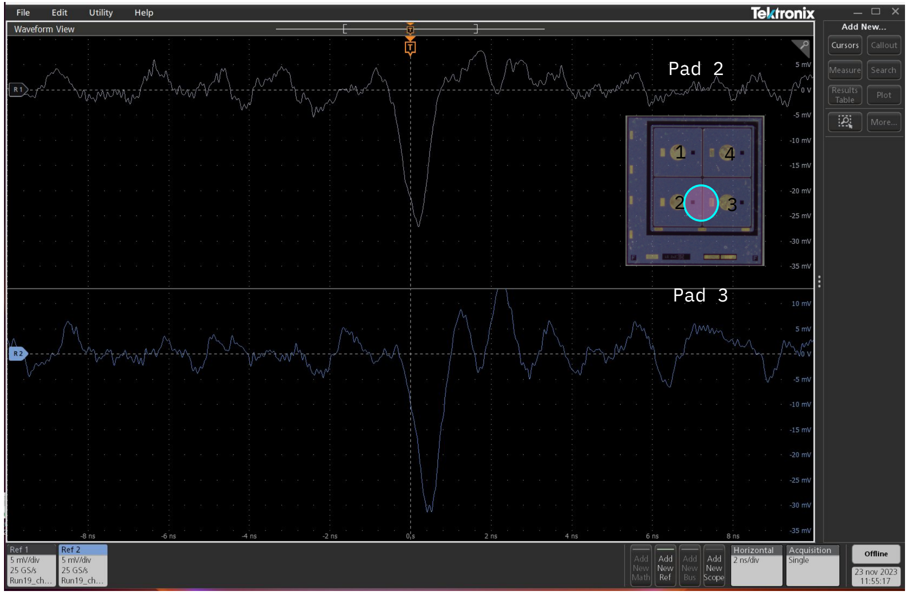


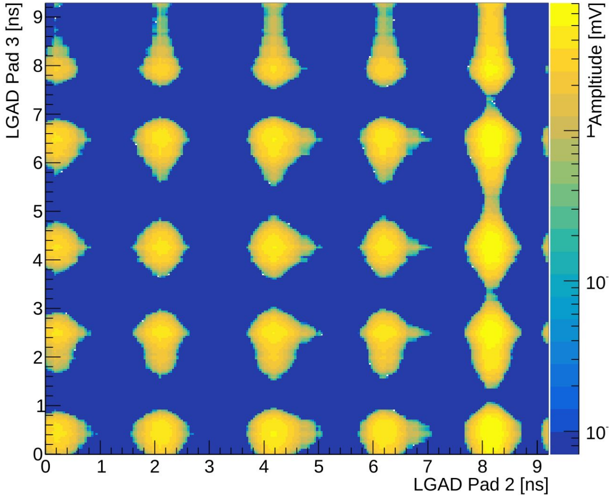


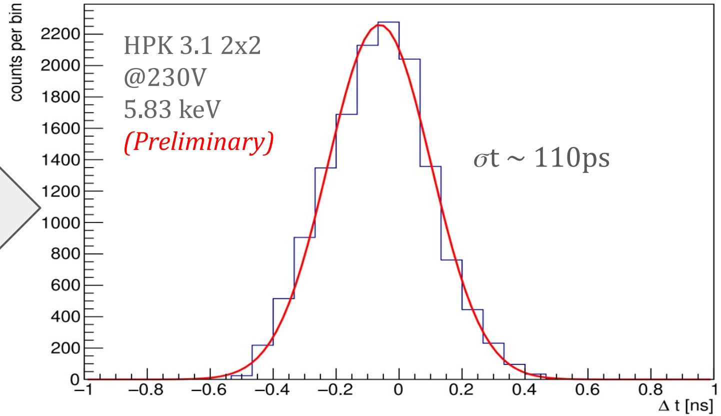


2x2 LGAD Timing response

- Multiple photon conversions can be used to measure the intrinsic timing resolution
  - $\sigma(t_2 - t_3)$
- Data was taken with **AND** between two pads signals

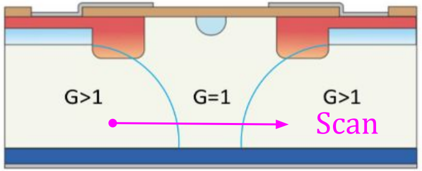




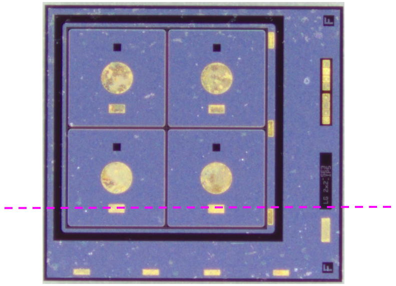


2x2 LGAD Interpad measurements

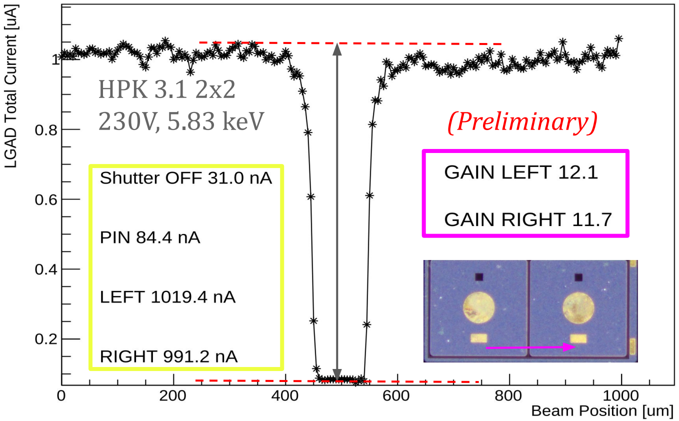
- **Important do assess the Fill Factor**
- **150 nm beam**
- 5μm step beam lateral scan

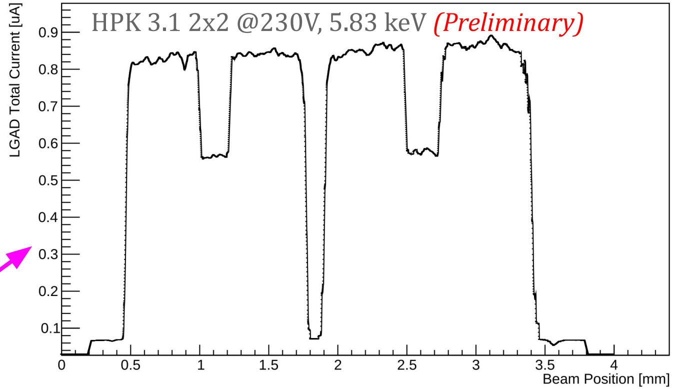


- Extract device gain from ratio (G=1) region (Skomina et al)

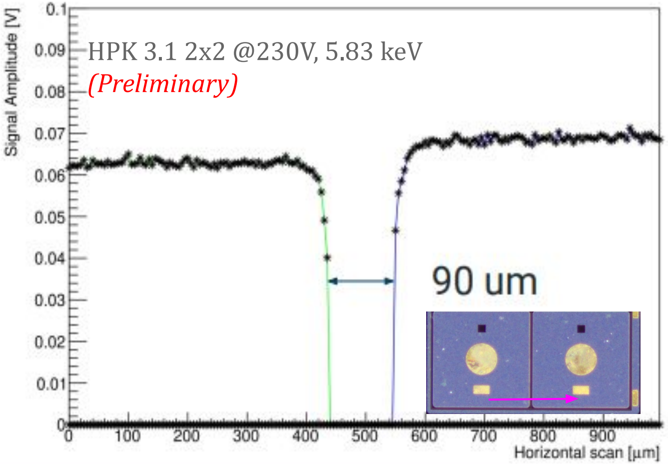


LGAD **CURRENT** profile





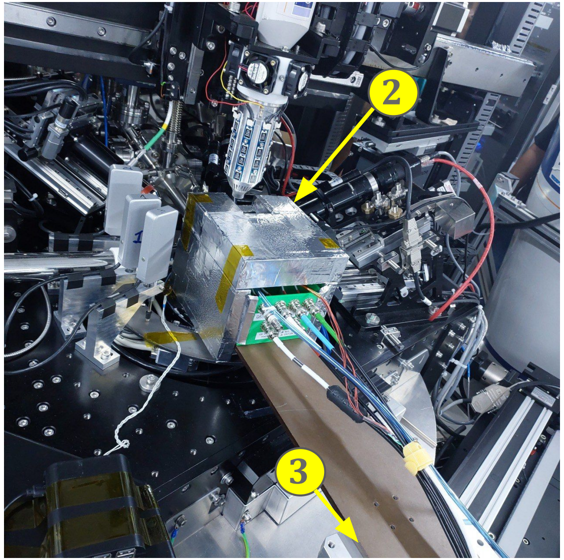
LGAD **PULSE AMPLITUDE** profile

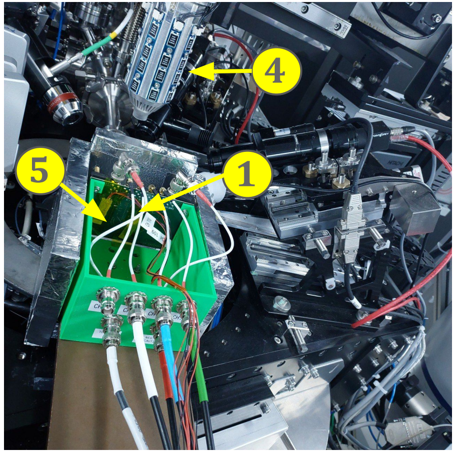


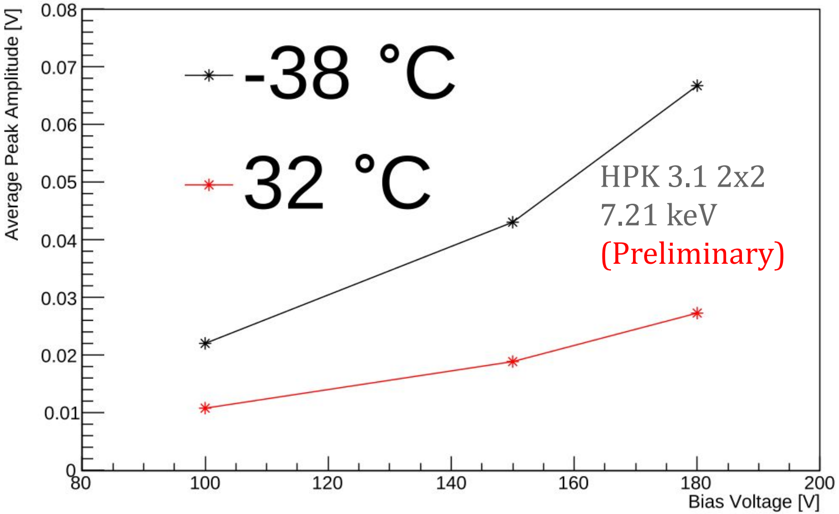
2x2 LGAD temperature response

- HPK 3.1 2x2 array
- N2 cooling nozzle and detector position remotely controlled
- Temperature recorded by 2 PT100 on the PCB

- Beam line using a focused beam at 7.21 keV
- Bias and temperature scan
- Increase in signal amplitude (due to increased gain) as expected







1 LGAD 2 Insulator box 3 Linear stage 4 N2 Nozzle 5 PT100

Where we stand

- New applications can profit from a robust R&D for LGAD sensors done for HL-LHC
- Comprehensive measurement campaign of LGADs X-Ray performance is underway
- **Two facilities** (SLAC and Sirius) providing similar test conditions
- Devices are very robust, **survived several days** of high intensity, highly focused X-rays
- X-ray applications will need **highly segmented devices** (μm resolution)
  - **However, even the millimeter size devices can be used at beam lines for diagnostics and beam studies**
- Continue the tests, focusing on alternative segmented LGAD designs, **optimized electronics and signal processing**

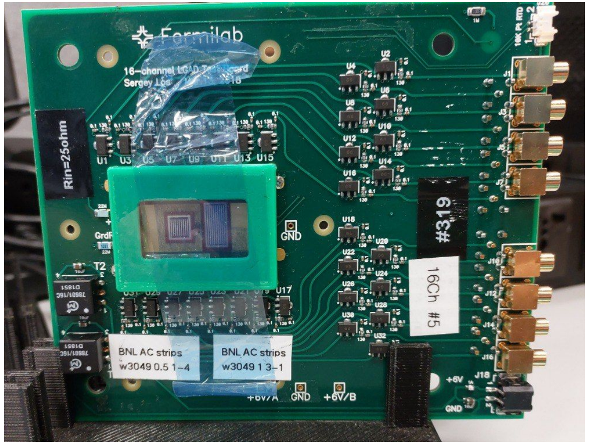
*Excellent support from Sirius people and management ⇨ **very efficient (and very intense)** campaigns !!!*

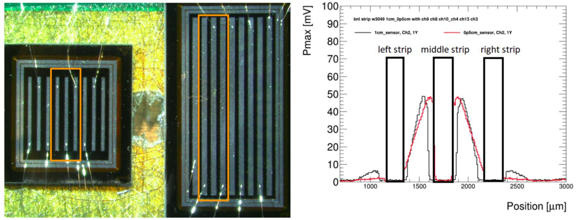
BACKUP

AC LGAD Tests

- AC LGAD limited tests at SSRL (wide beam)
- BNL strip design (not very useful for X_rays)

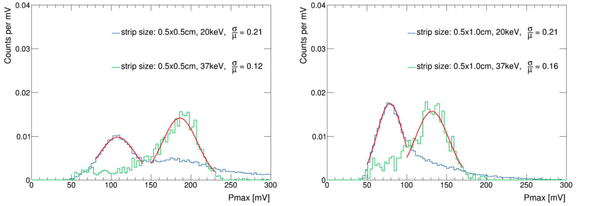
https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006





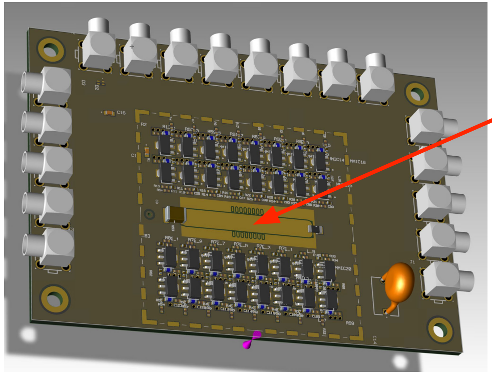
(a) (b)

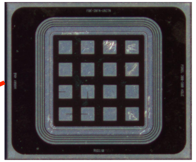
Figure 17: (a) Picture of AC-LGAD with strip length 5 mm and 10 mm. The strips used on the analysis are highlighted by the orange box. The sum of p_{max} from the three signal strips are used to measure the energy resolution. (b) Response of the middle strip as a function of position perpendicular to the strip, AC-LGAD with strip length 5 mm (red) and 10 mm (black), data taken with an IR laser TCT setup.



(a) (b)

Figure 18: p_{max} distributions for the sum of three selected strips for 5 mm long (a) and 10 mm long (b) strip sensors with superimposed energy resolution fit. A selection of 40 mV is applied to the middle strip in both cases to remove events not centered in the three strips. The beam was illuminating more than the 5 mm sensor; this explains the higher tail due to the increased number of double photon events.





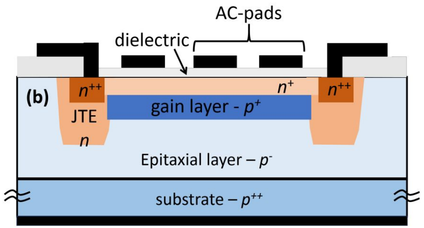
We are designing a 16ch two-stage amplifier board for testing pixel and strip devices at Sirius

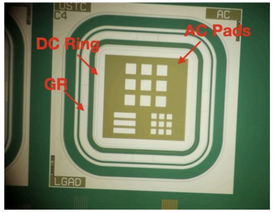
LGAD Design Variations

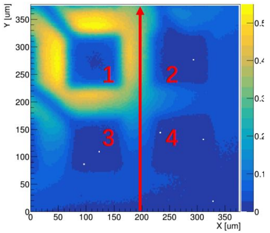
Fact: DC-LGADs have a coarse spatial resolution and large inter pad (inactive) region (~50 μm) and electrodes facing the beam

Challenge: How to fabricate devices with optimal (μm) spatial resolution and few μm interpad region and zero front dead-region?

AC-LGAD (*link*, *link*)

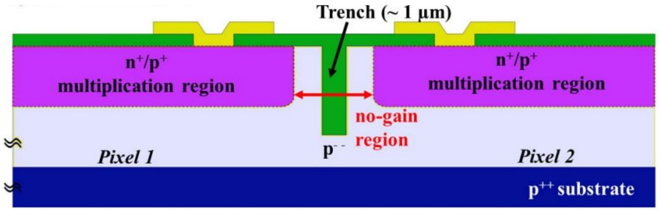


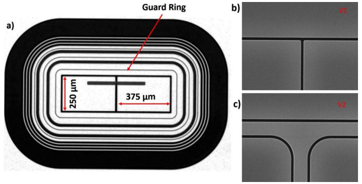


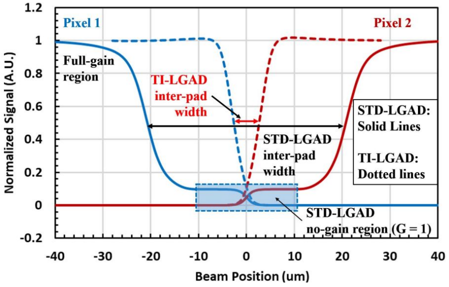


TCT measurement:
σ_x = 1.7 μm
σ_t = 25 ps

Trench Isolated (TI-LGAD) (*link*)

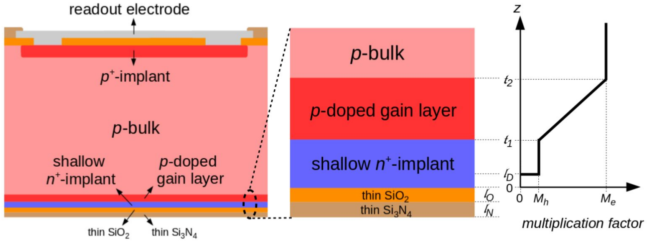


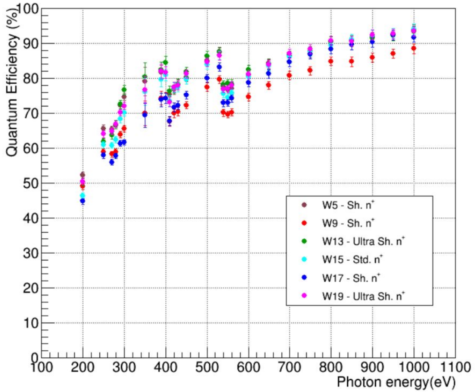


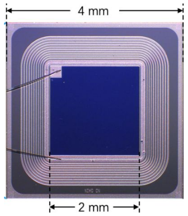


TCAD simulation: IP~5 μm

Inverted LGAD (*link*)





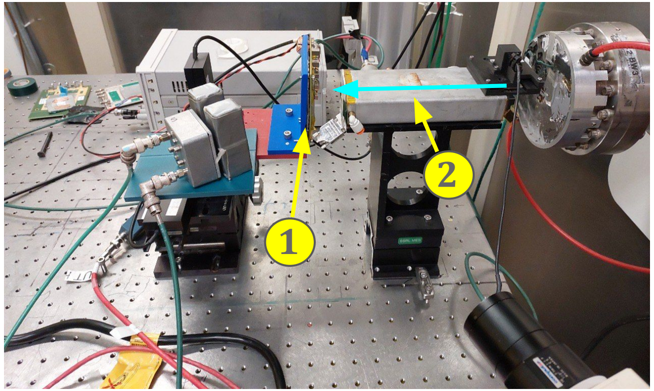


X-rays down to 200eV

Intro : The light source facilities

SSRL (SLAC) at Stanford (USA)

Beam Line 11-2 @ SSRL



Beam Line Specifications

Source

26-pole, 2.0-Tesla Wiggler, ≤1.5 mrad variable acceptance

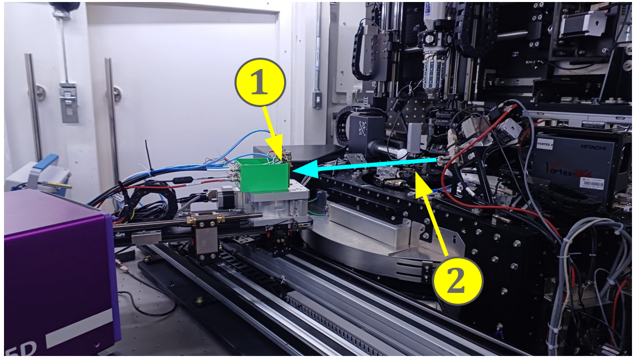
	Energy Range	Resolution ΔE/E	Spot Size
Focused	5000-20000 eV	1 x 10^{-4}	0.5 x 1 mm^2
Unfocused	5000-37000 eV	1 x 10^{-4}	3 x 30 mm^2
Collimated	5000-23000 eV	1 x 10^{-4}	2 x 30 mm^2

1 LGAD setup

2 Beam direction

Sirius at LNLS-CNPEM in São Paulo (Brazil)

Carnaúba beam line @ Sirius



PARAMETERS

Parameter	Value	Condition
Energy Range *	2.05 – 15 keV	Si(111)
Energy Resolution (ΔE/E)	10^{-4} – 10^{-5}	
Harmonic Content	< 10^{-5}	Above 5 keV
Energy Scan	Yes	
Beamsize at sample [μm] @Tarumã	0.15 x 0.15 (0.55 x 0.55)	8 keV (2 keV)
Beam Divergence at sample [mrad] @Tarumã	(1 x 1)	All energy range
Estimated flux [ph/s/100 mA] @Tarumã	10^{11}	–

** BL being commissioned, available now : 5.8 to 13.8 keV.*

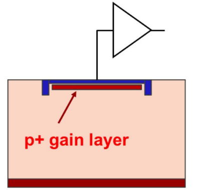
Both sites provide high intensity, quasi-monochromatic pulsed X-ray beams (10 ps wide pulses, 2 ns appart) with several geometries

I - Single Pad LGADs tests @ SSRL BL 11-2

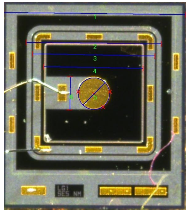
https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006

- "Flat" beam : 25mm x 1 mm (nominal)
- Energy scan from 5 to 37 keV (70 keV with harmonics)
- Bias Scan
- **Single pad** (1.3 x 1.3 mm^2) LGADs

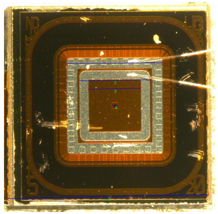
Ferrero et al.



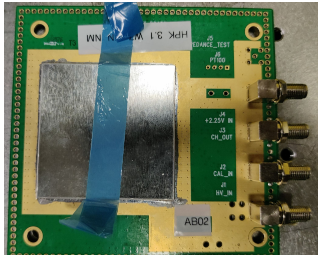
Low Gain Avalanche Diode



HPK
DC LGAD



BNL
DC LGAD

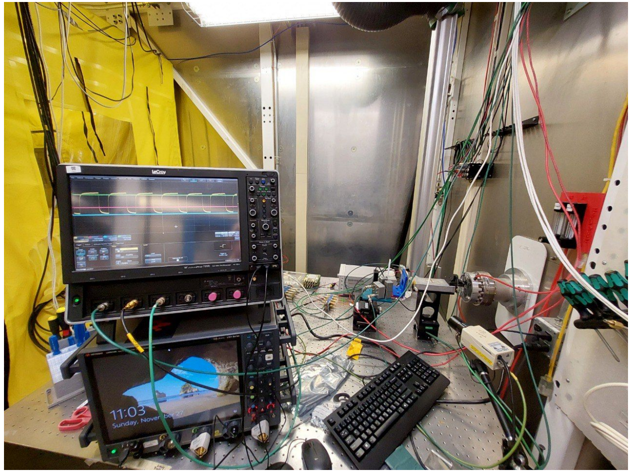


Santa Cruz board with
LGAD and 1-ch. amplifier

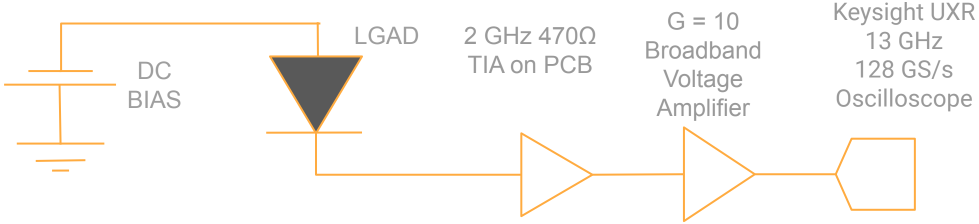
Devices Tested

Device	Active Thick.	Gain Layer	Breakdown
HPK LGAD type 3.1	50 μm	shallow (1μm)	~230 V
HPK LGAD type 3.2	50 μm	deep (2μm)	~130 V
HPK PIN	50 μm	no gain layer	~400 V
BNL LGAD 20um	20 μm	shallow (1μm)	~100 V

For details,
See *Ref.*

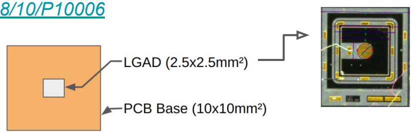


Simple
Measurement
Setup

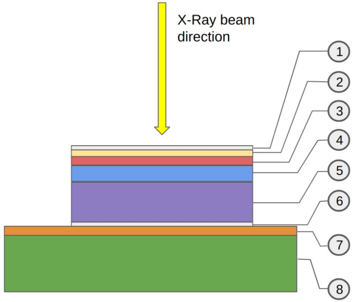


I - Simulations - Single Pad LGAD

https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006

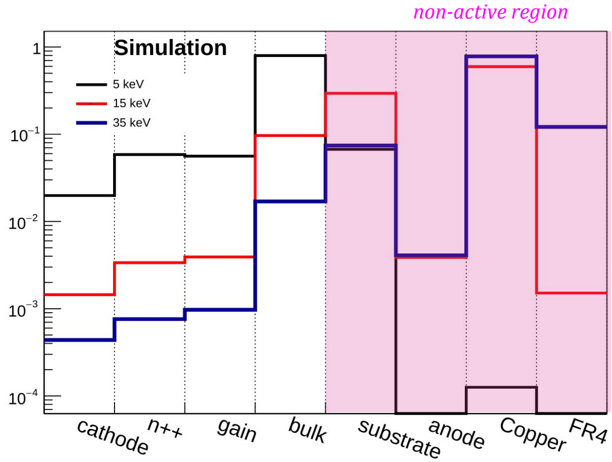


GEANT-4 simulation of absorbed photon fraction per LGAD layer for 5, 15 and 35 keV (*50 μm active*)

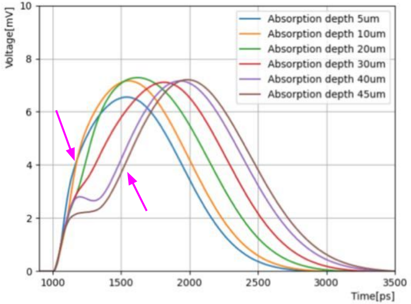


	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

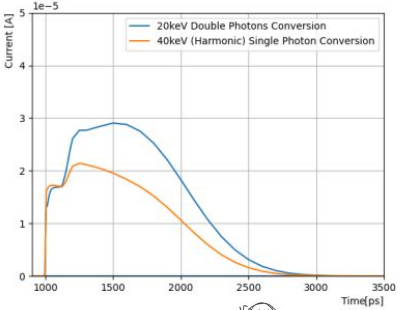
	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600



TCAD simulation of 50 μm LGAD signal response to a single 20 keV photon at different absorption depth.



(b) Convoluted voltage signal with TIA.



20+20 ≠ 40

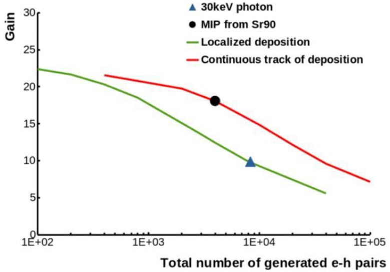


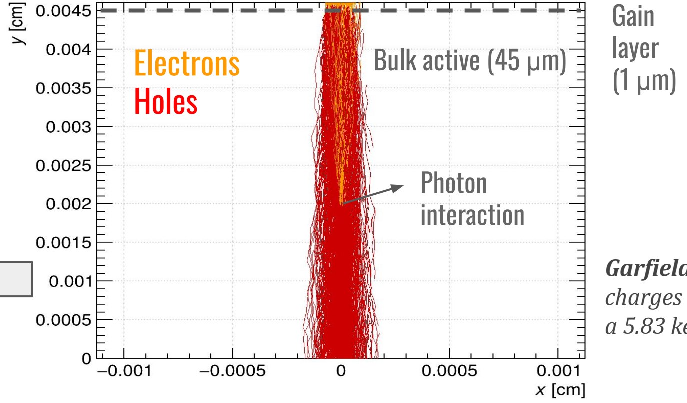
Figure 9: TCAD simulated gain for continuous track of energy deposition (MIP) and localized energy deposition (X-ray). The gain corresponding to a MIP from ^{90}Sr and a 30 keV X-ray are highlighted in the plot.

I - Simulations - Single Pad LGAD

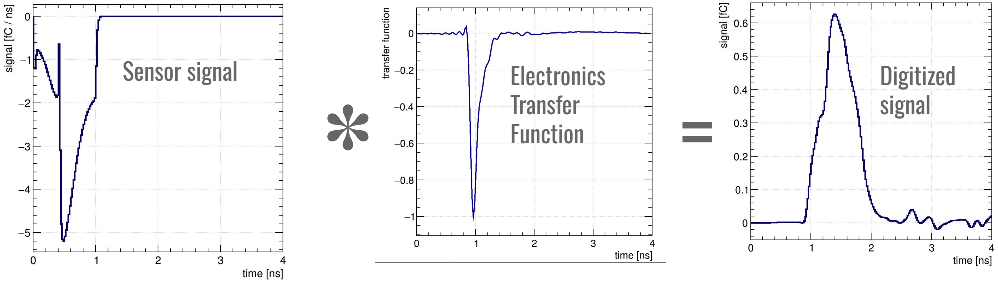
- Garfield++ (link) framework can simulate the impact ionization process
- Predicts the transient response of the signal
- Simple field calculation, but can import data from = TCAD
- Can also import the hits from Geant 4

→

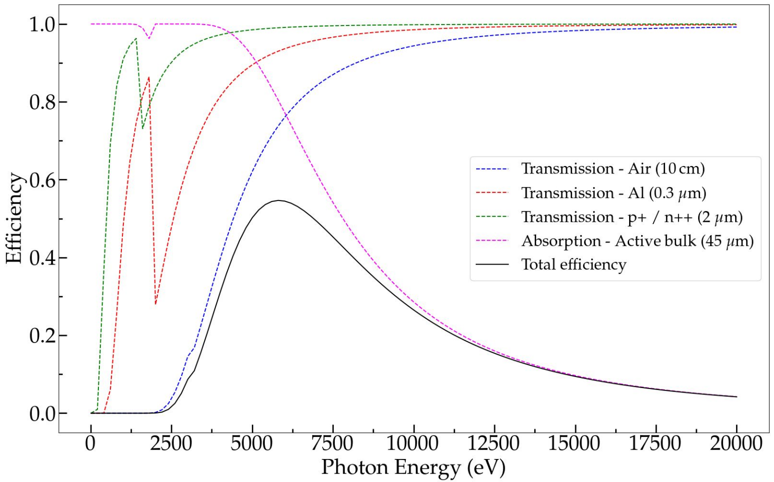
- R. Van Overstraeten and H. de Man
- Grant
- Okuto and Crowell
- Massey.



Garfield++: *charges produced by a 5.83 keV photon*

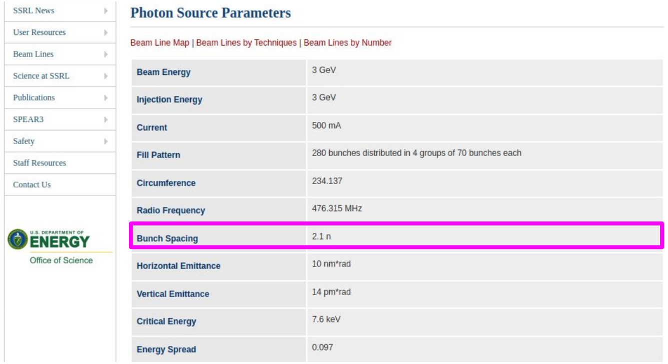


Detection efficiency for 50μm LGAD for several photon energies



I – Autocorrelation of Digitized Signals

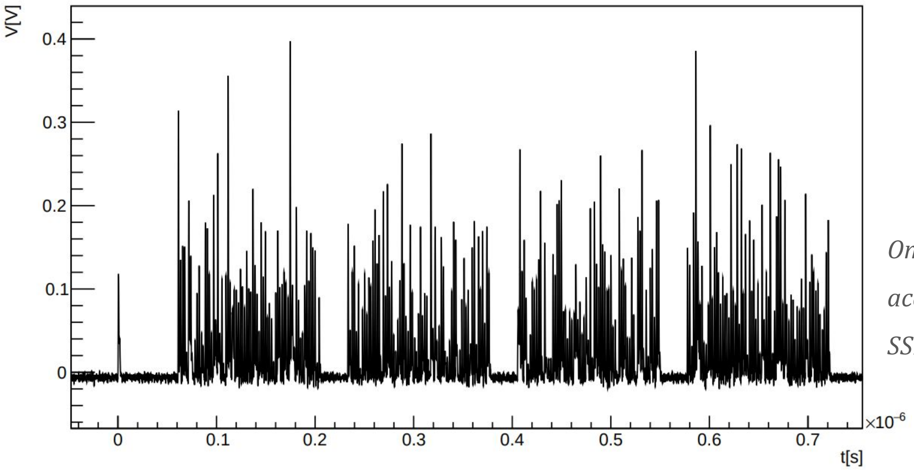
- For MIP, we use a telescope for timing measurement (Δt) ; for X-rays we have to resort to something else
- Acquisition is synchronized by a machine trigger signal, but not good enough for timing
- We can rely on the very uniform bunch separation of 2.1ns
- This can be measured using the LGAD !
- The SSRL fill structure is : …1–0–fill–0–fill–0–fill–0–fill–0…


SSRL News
User Resources
Beam Lines
Science at SSRL
Publications
SPEAR3
Safety
Staff Resources
Contact Us
U.S. DEPARTMENT OF ENERGY
Office of Science

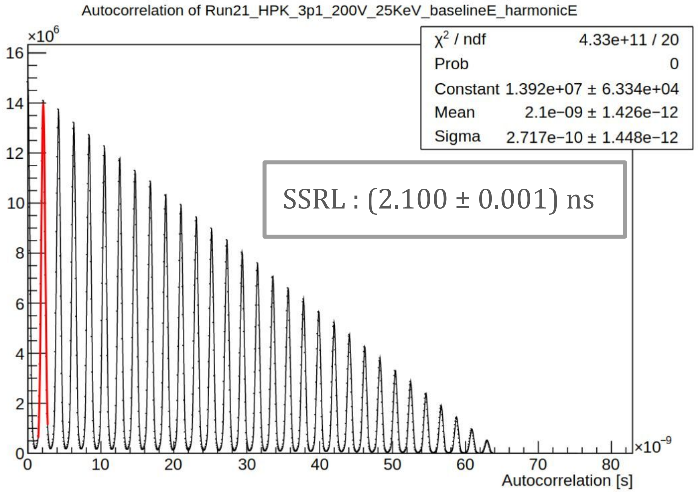
Photon Source Parameters

Beam Line Map | Beam Lines by Techniques | Beam Lines by Number

Beam Energy	3 GeV
Injection Energy	3 GeV
Current	500 mA
Fill Pattern	280 bunches distributed in 4 groups of 70 bunches each
Circumference	234.137
Radio Frequency	476.315 MHz
Bunch Spacing	2.1 n
Horizontal Emittance	10 nm*rad
Vertical Emittance	14 pm*rad
Critical Energy	7.6 keV
Energy Spread	0.097

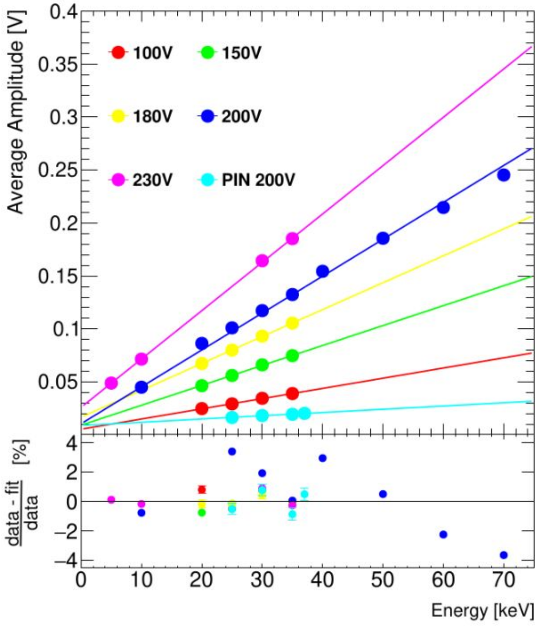


One scope acquisition showing SSRL bunch pattern

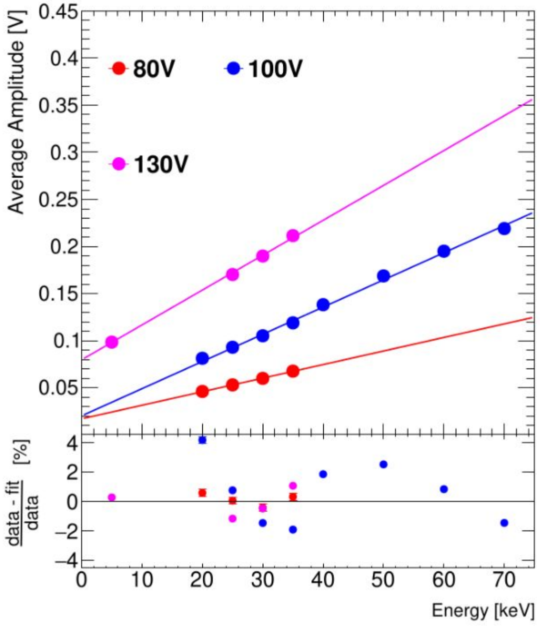


SSRL : (2.100 ± 0.001) ns

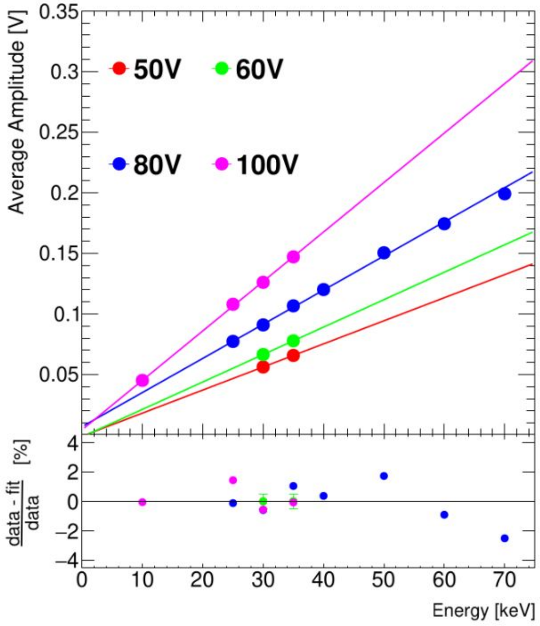
I – Single Pad LGAD X-ray Energy Response



(a) HPK PIN and type 3.1 LGAD

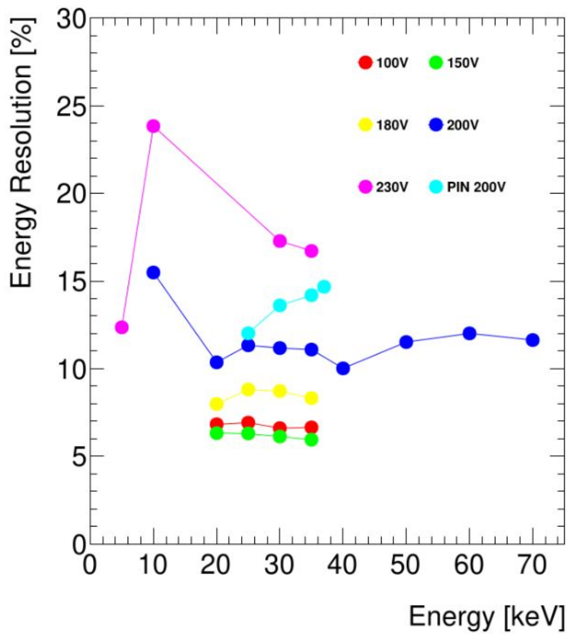


(b) HPK type 3.2 LGAD

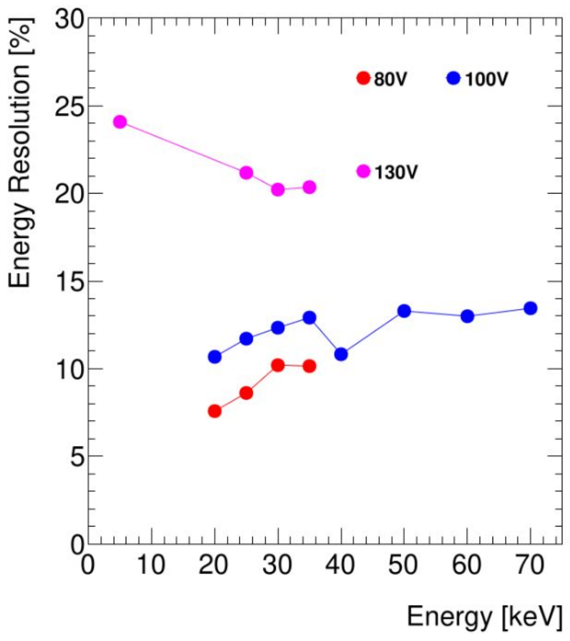


(c) BNL 20um LGAD

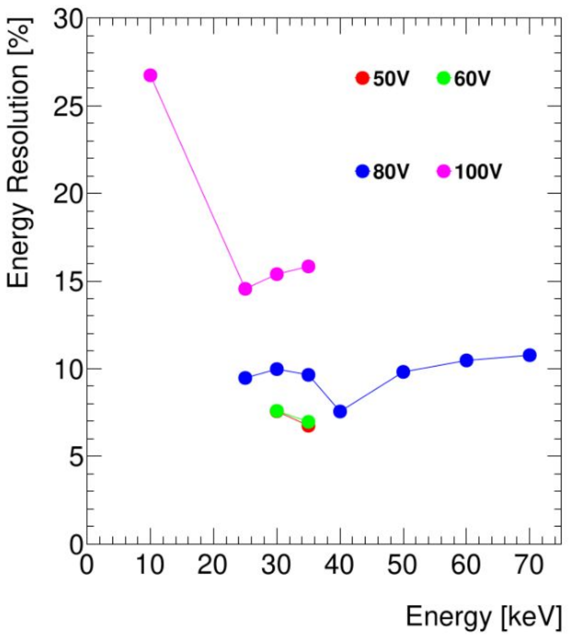
I – Single Pad LGAD X-ray Energy Response



(a) HPK PIN and type 3.1 LGAD

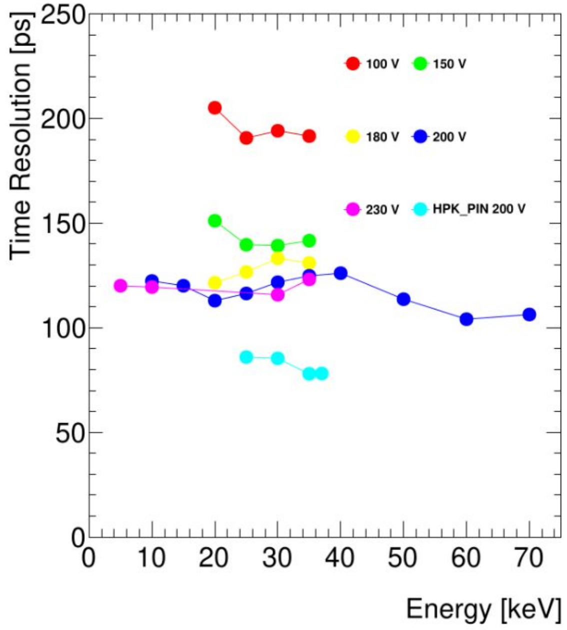


(b) HPK type 3.2 LGAD

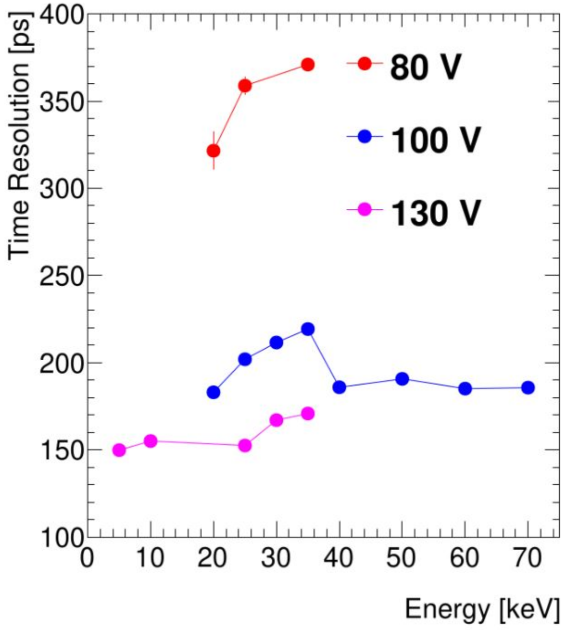


(c) BNL 20um LGAD

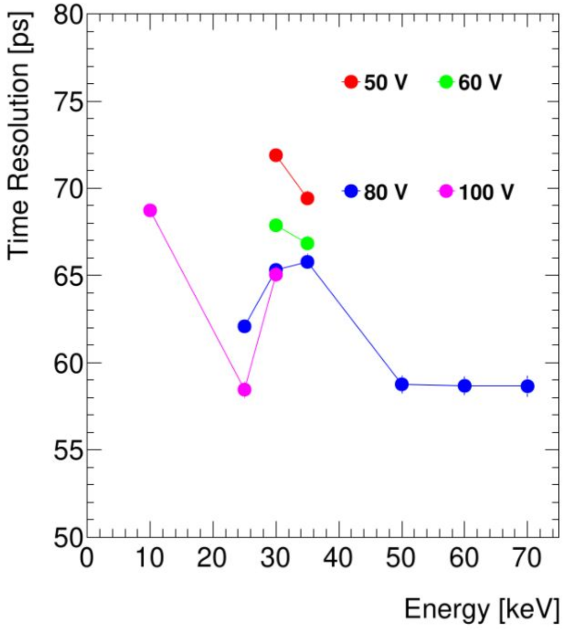
I – Single Pad LGAD X-ray Timing Response



(a) HPK PIN and type 3.1 LGAD



(b) HPK type 3.2 LGAD



(c) BNL 20um LGAD

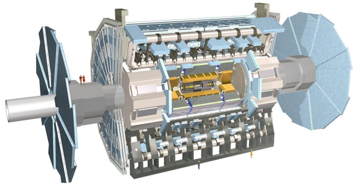
I – Single Pad LGAD Summary Results

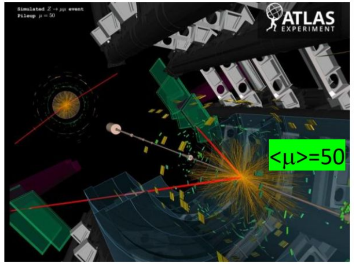
	HPK PIN	HPK3.1		HPK3.2		BNL 20um	
Bias V	200 V	150 V	230 V	80 V	130 V	50 V	100 V
Energy Resolution	14 %	6 %	17 %	10 %	20 %	6 %	16 %
Energy Response	19 mV	75 mV	185 mV	68 mV	211 mV	66 mV	147 mV
σ_t CFD	78 ps	141 ps	123 ps	371 ps	171 ps	69 ps	65 ps

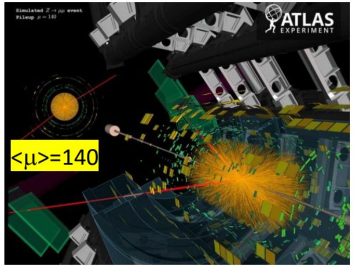
Table 2: Summary of energy and time resolution for the three tested sensors for the different bias voltages that yield the best energy and best time resolution for a 35 keV X-ray beam energy.

The problem

- 200 collisions @ 40MHz
- Irreducible background
- **Challenging for track/vertex reconstruction**
- **New full silicon tracker (ITk) to extend coverage to $|\eta|< 4$**
- **Insufficient spatial resolution in forward region**

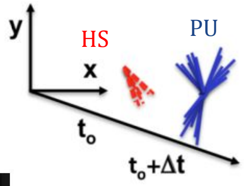


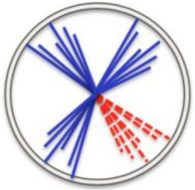


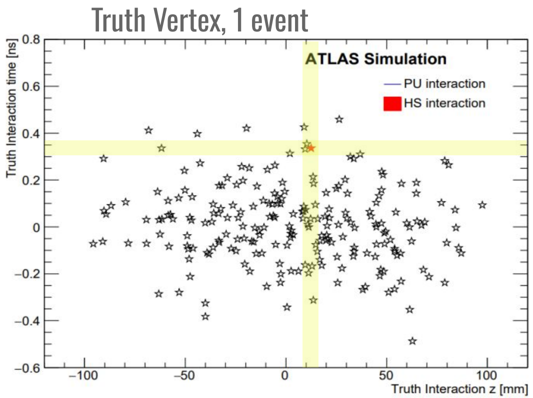


The solution

- Introduce the 4th **dimension** (time)
- **30 ps timing resolution**
- **High segmentation**

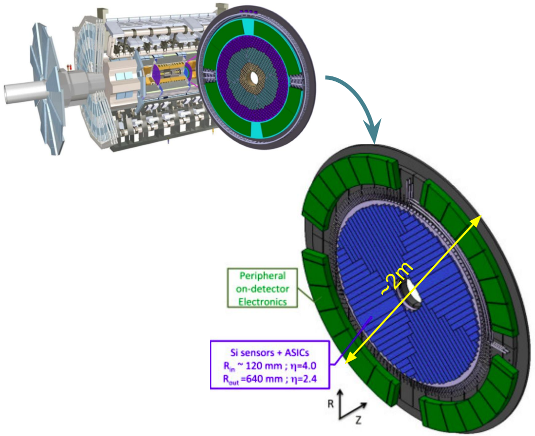






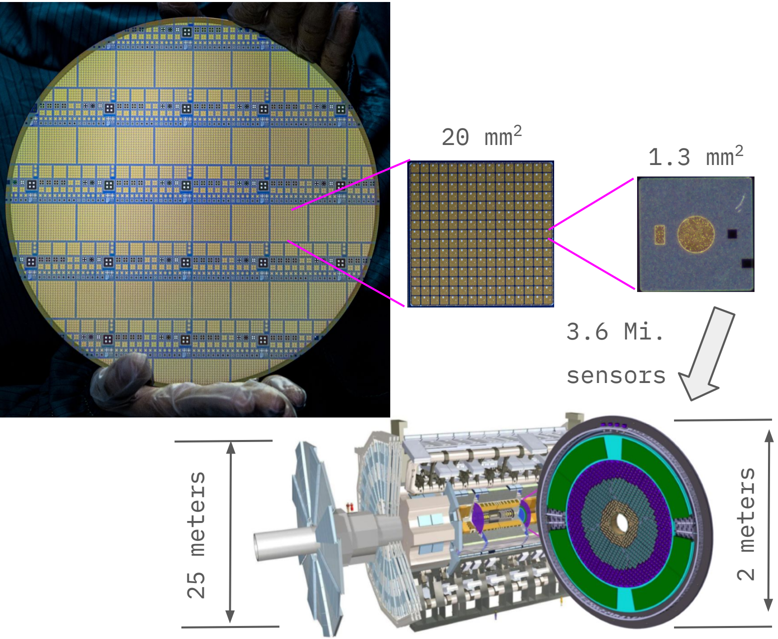
The Implementation

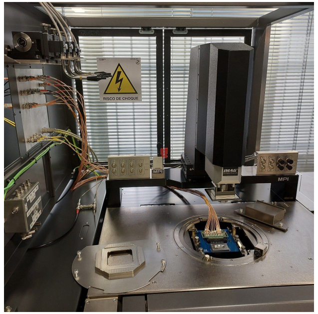
- The ATLAS HGTD
- **New detector**
- 8 layers of state-of-the-art *Ultra Fast Semiconductor Detectors* (LGADs)
- **Two 2m x 12cm disks (2.4 $|\eta|$ 4.0)**
- 3.6 M sensors (1.3mm^2 each)
- Very radiation hard

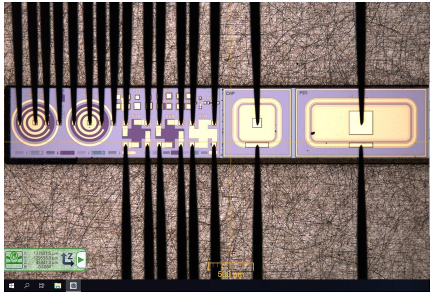


ATLAS High Granularity Timing Detector (HGTD)

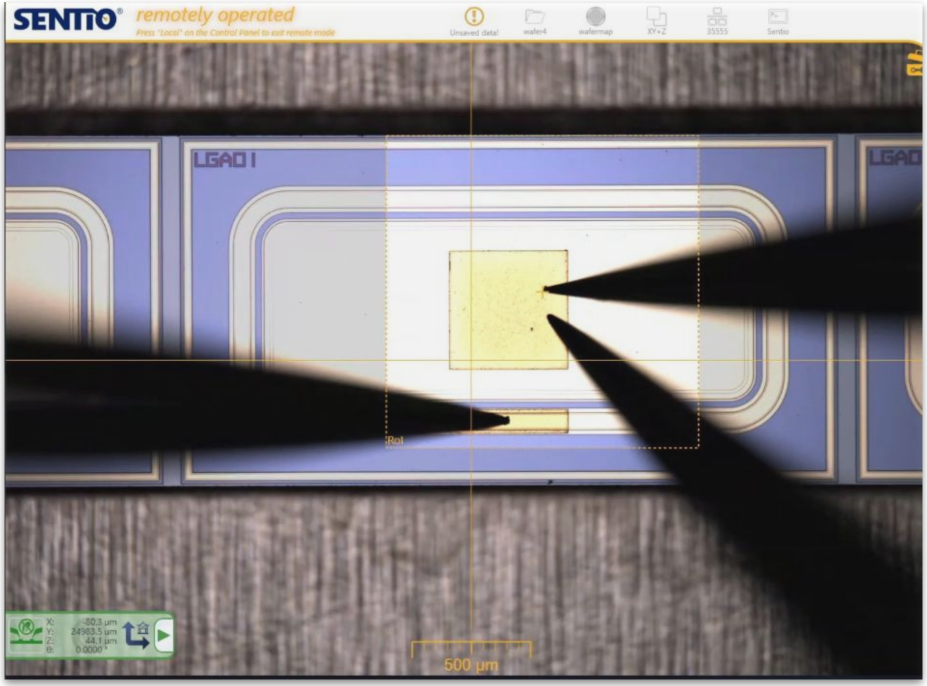
- The HGTD will deploy 3.6 ultra-fast, radiation-hard, state-of-the art silicon sensors (**LGADs**) arranged in 15x15 arrays
- ATLAS Brasil is collaborating with the HGTD since the R&D phase of the sensors and with CERN is part of production QA/QC
- A semiconductor lab was assembled @USP (FAPESP Strategic Project) for this task, and is fully operational
- The Brazilian group will also provide significant contribution to the construction and commissioning of the detector at CERN
- This activity also involves Electronics Readout, DAQ chain and simulation.







What are
Low Gain Avalanche Detectors (LGADS) ?

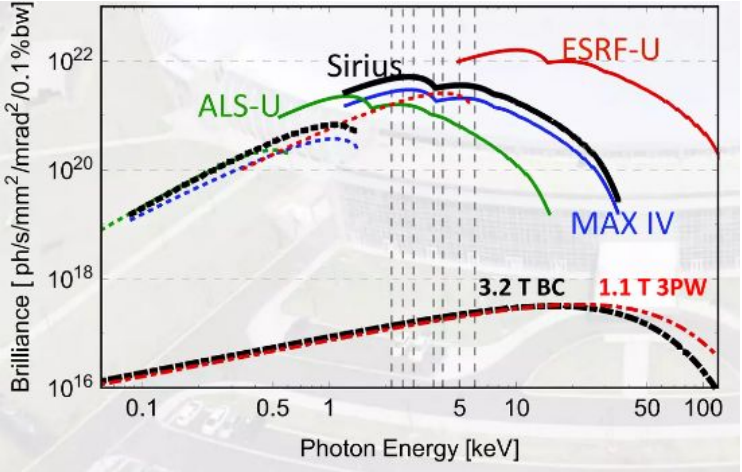


IHEP-IME LGAD test structure for ATLAS HGTD being probed at the USP semiconductor sensor lab.

Introduction

Motivation

- 4th generation and newer light sources facilities poses many challenges for detectors due to high intensity and fast timing bunch structure
- LGADs are natural candidates for facing these challenges :
  - Extensive R&D for HL-LHC timing detectors (ATLAS & CMS)
  - Intrinsic gain provides good signal-to-noise ratio (important for low energy photon detection)
  - Very fast timing (time-resolved applications)
  - Radiation hard (TID) ⇛ operation under very high intensity beams
- However, these synchrotron light application will require :
  - Very fine (few μm) spatial resolution
  - Active region facing the beam
  - Full characterization of LGADs performance for X-ray photons, under different conditions



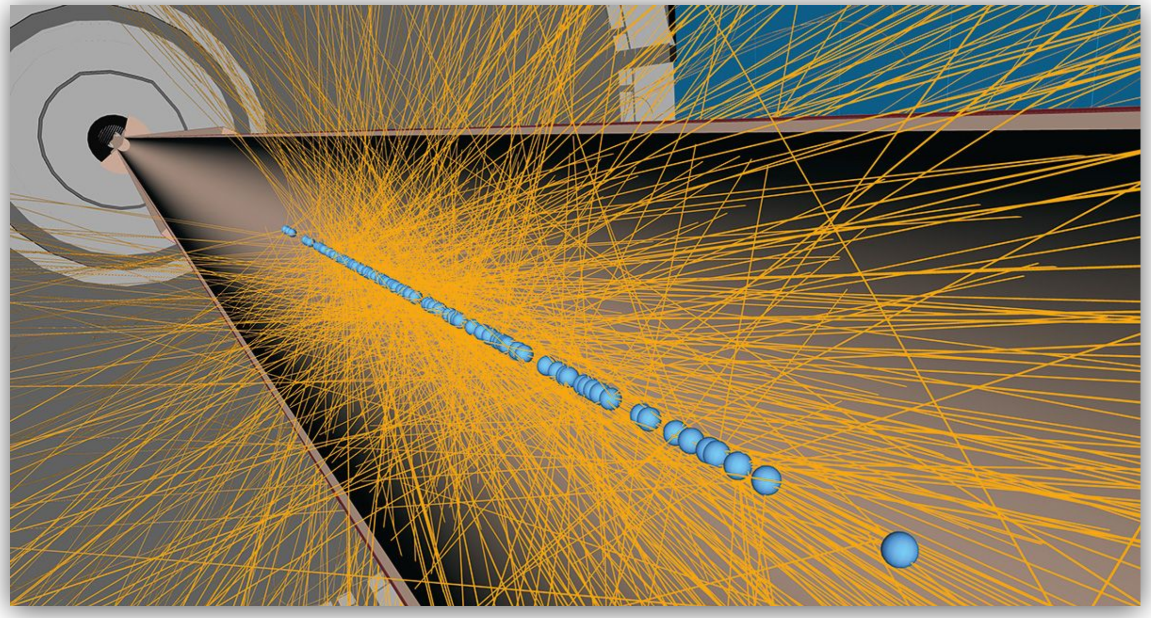
- We will discuss some of the results of recent characterization campaigns at **synchrotron light source facilities** for

  I - Single pad DC-LGADs

  II - 2x2 DC-LGADs

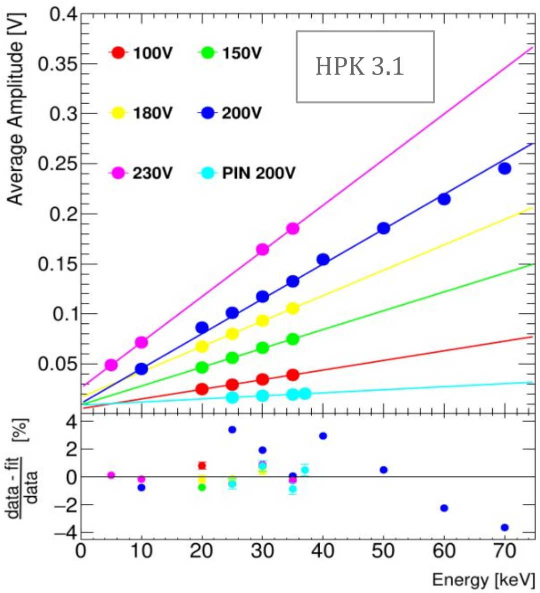
  III - AC-LGADs

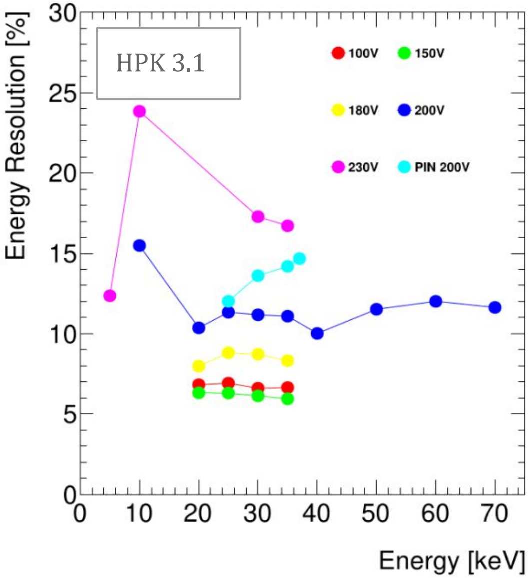
But before,
One slide on how this started…



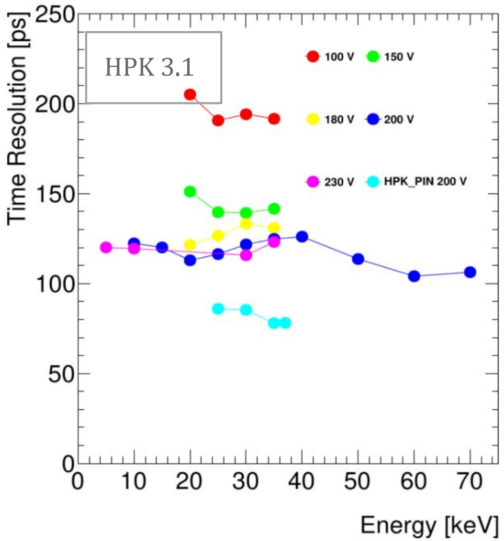
Simulated pp collision at 14 TeV at the HL-LHC, including approximately 200 pileup interactions

I - Single pad LGADs (HPK 3.1) summary results





https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006



HPK 3.1 single pad **best energy resolution** and **best timing resolution** for **35 keV X-Rays**

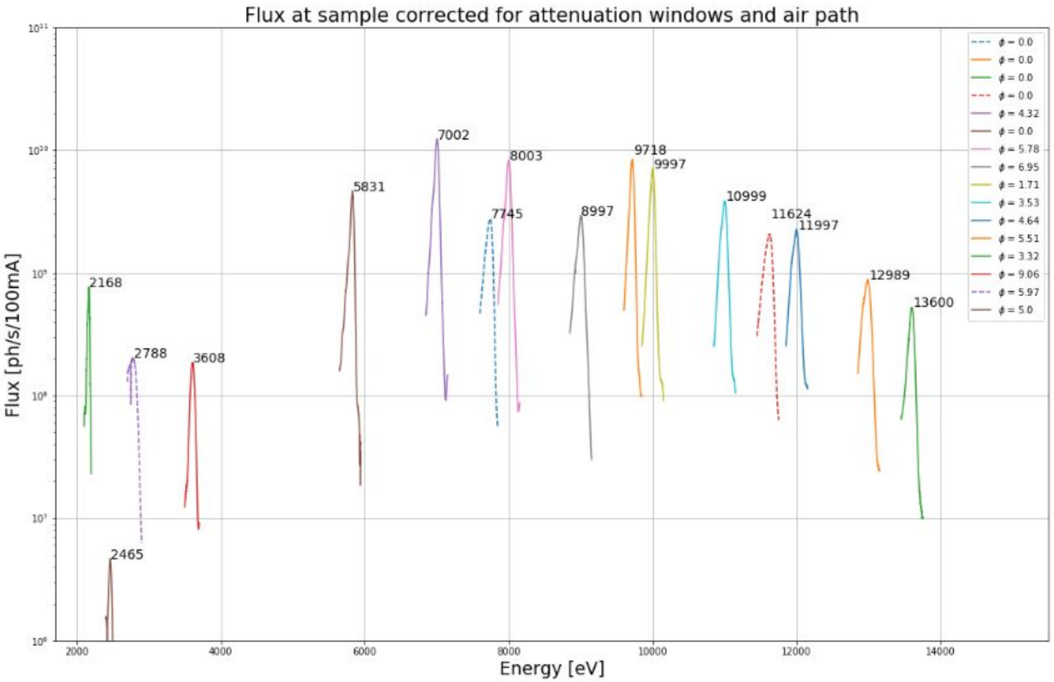
Bias [V]	150 V	230 V
Energy resolution	6%	17%
Energy response	75 mV	185 mV
Timing resolution*	141 ps	123 ps

For mip ~40 ps

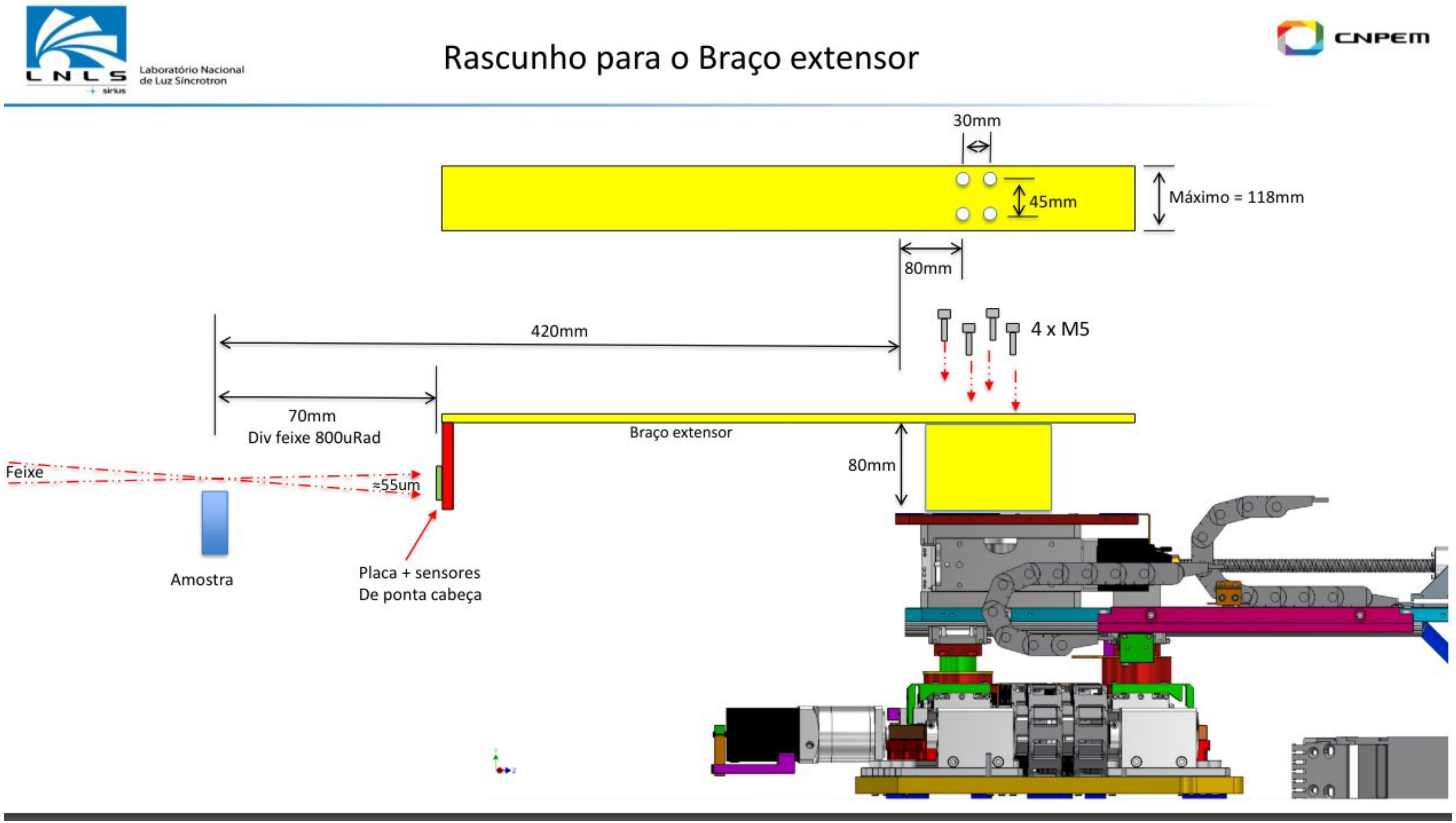
*Note: BNL 20μm achieved 60ps

Carnaúba beam line energies

Flux at sample corrected for attenuation (log plot)

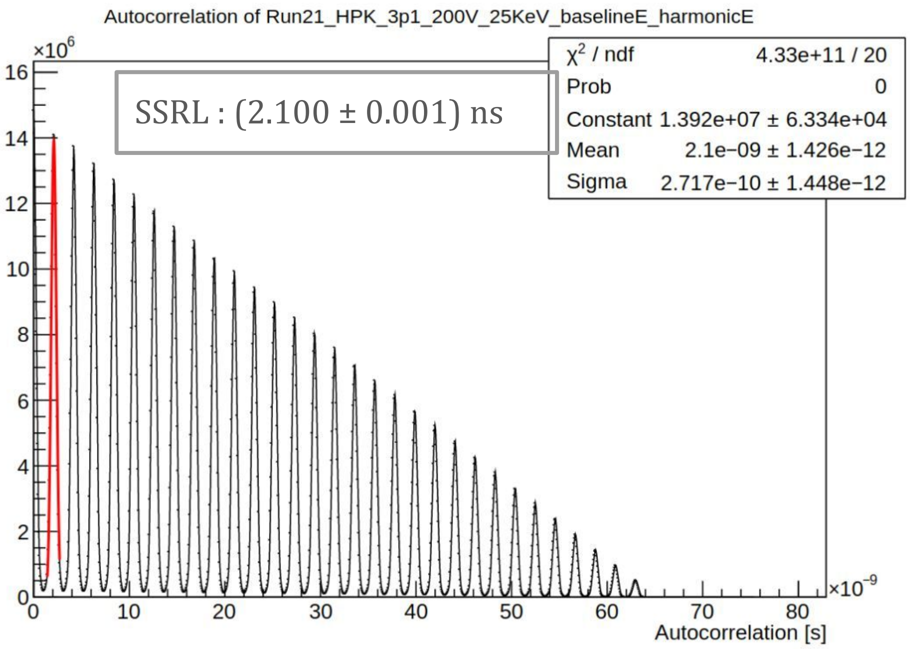


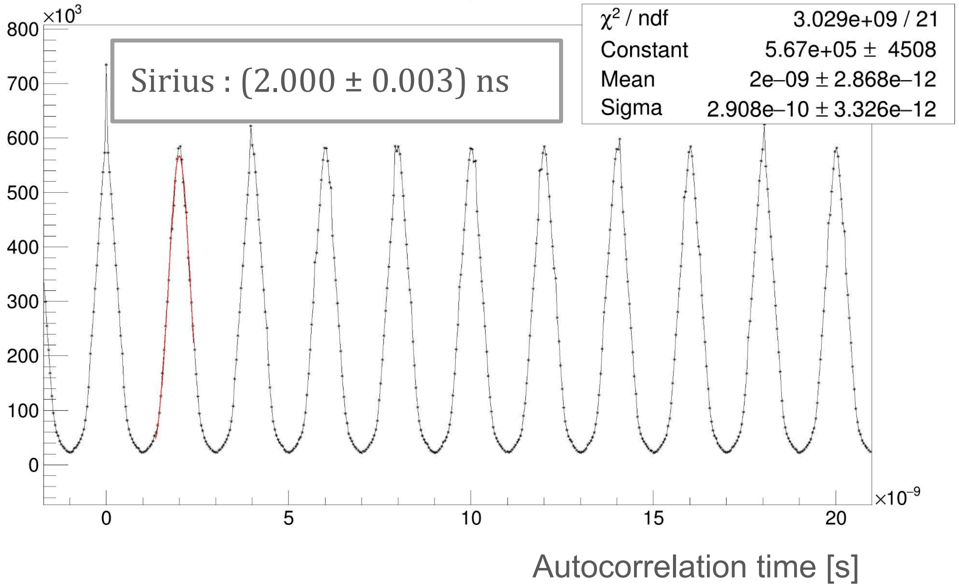
Carnaúba beam line setup



Autocorrelation of Digitized Signals

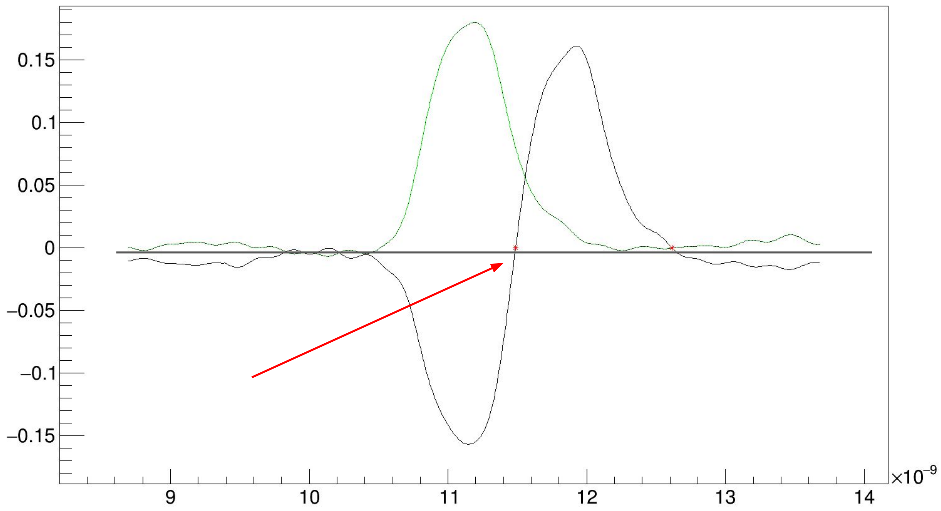
- Used to measure the bunch separation
- SSRL had a non-uniform filling (empty-1 bunch - empty-fill) per orbit
- Sirius had full orbit filled with bunches

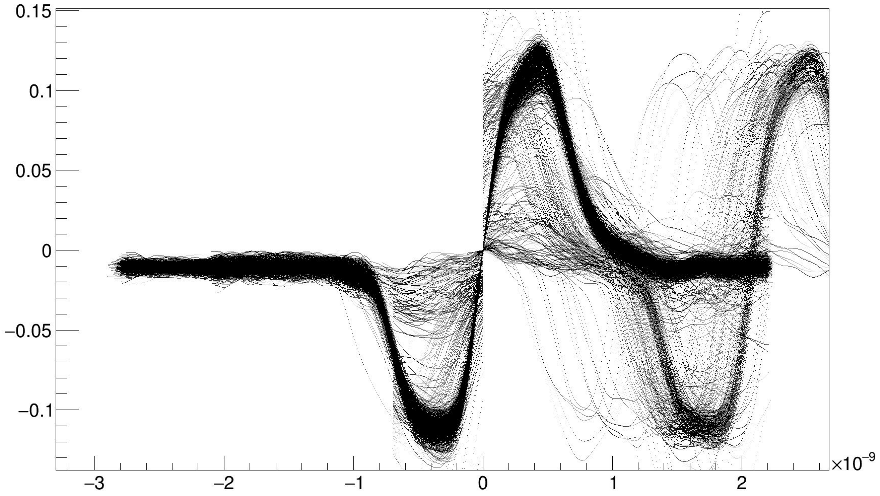




Constant Fraction Discriminator

- Fraction = 20%
- Signal window = 5ns
- Delay = 1.75ns





34

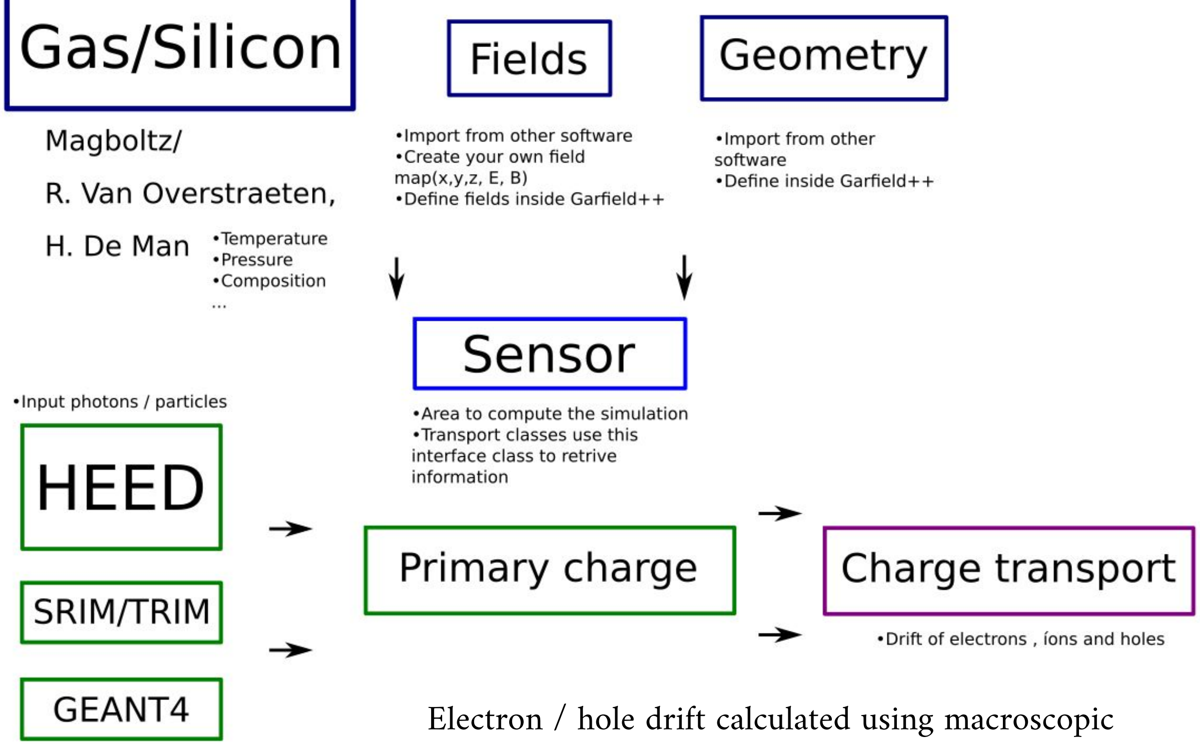
Garfield++

A framework for signal simulation in detectors (mainly gaseous detectors, but now being developed for semiconductors).

For silicon mainly TCAD

Impact ionization coefficient models:

- R. Van Overstraeten and H. de Man (default)
- Grant
- Okuto and Crowell
- and Massey.

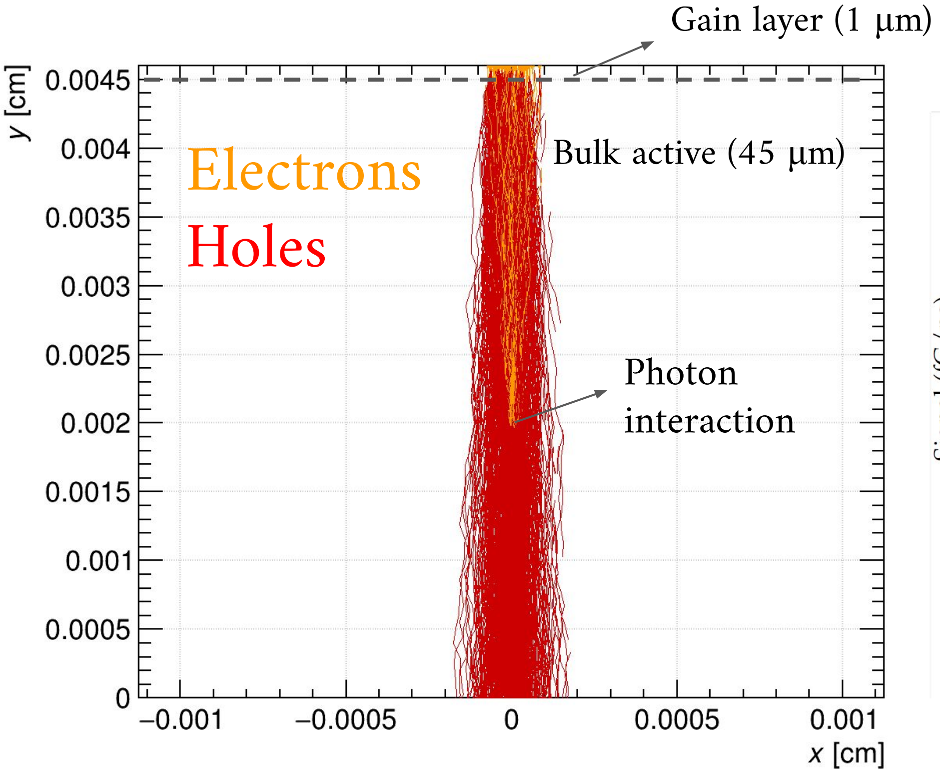


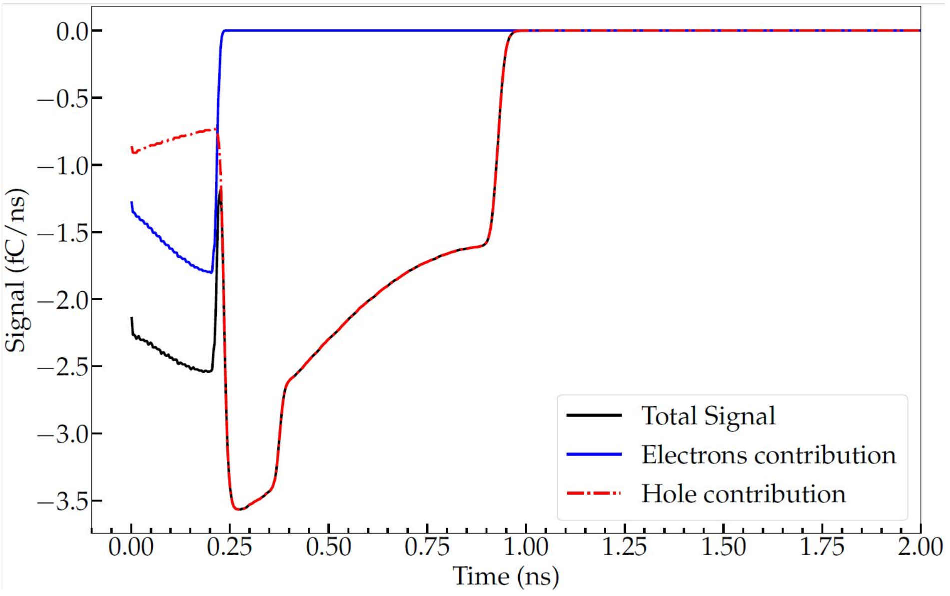
- HEED: Ionization produced by relativistic charged particles and photons
- Low-energy ions calculated by the SRIM software can be imported.

Electron / hole drift calculated using macroscopic transport parameters (D_L e D_T) and Monte Carlo integration tools

http://garfieldpp.web.cern.ch/garfieldpp/

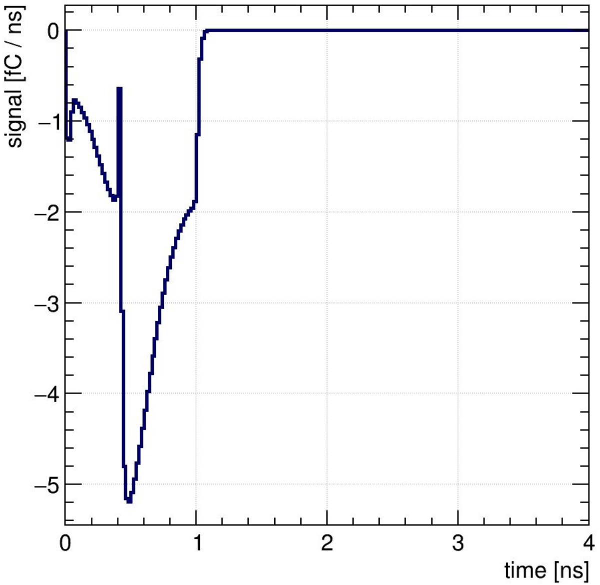
Garfield++: signal produced by a 5.83 keV photon



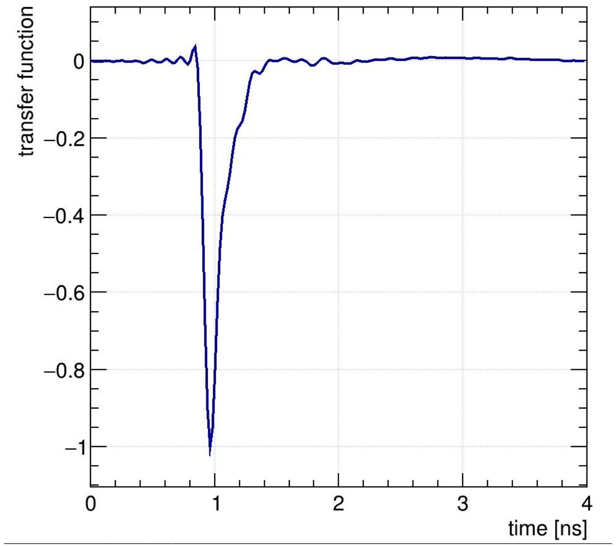


The simulation results presented in this work were obtained using the internal field generation and geometry tools of Garfield++.

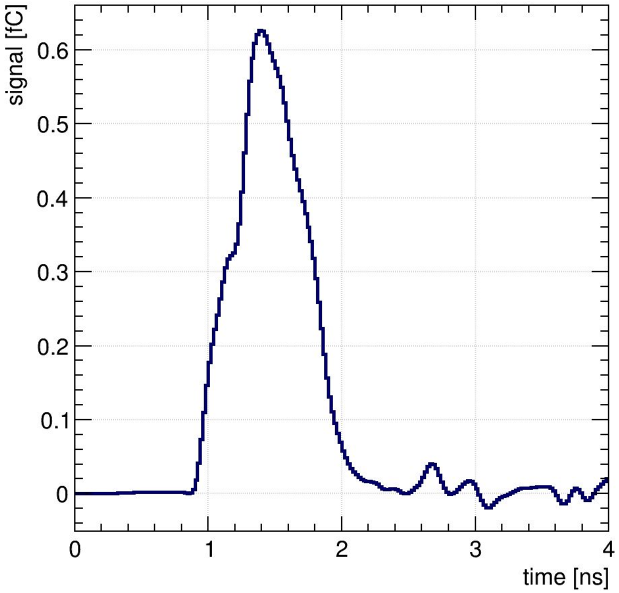
Garfield++: We can model the signal at the output of the front-end electronics by convolving the induced current with the transfer function (or delta response function)



Raw signal + 100 e- ENC

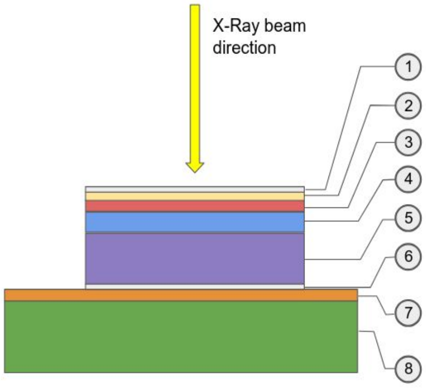


Electronics transfer function
Optimize for timing



Induced signal

Sensor efficiency for X-rays:



	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600

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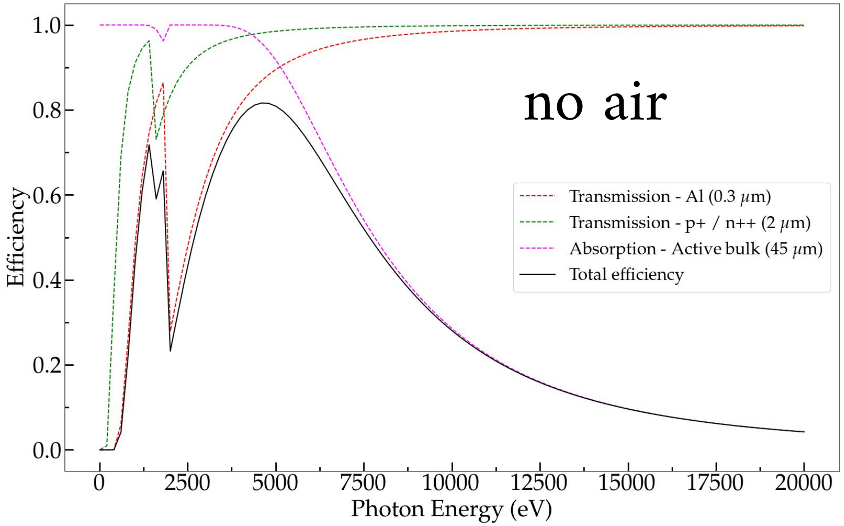
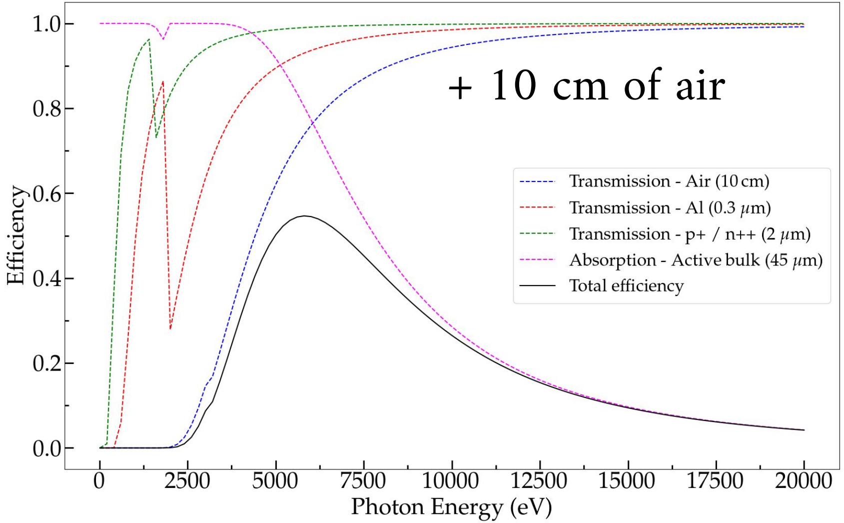
Calculated using the database from:

B.L. Henke, E.M. Gullikson, and J.C. Davis. *X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92*, Atomic Data and Nuclear Data Tables Vol. **54** (no.2), 181-342 (July 1993).





The Challenge That Lies Ahead

- ~14 TeV is our limit so far
- So many questions still …
- We took only ~5% of (HL)LHC data promised

- Increase the number of collisions per bunch crossing (3x of the today)

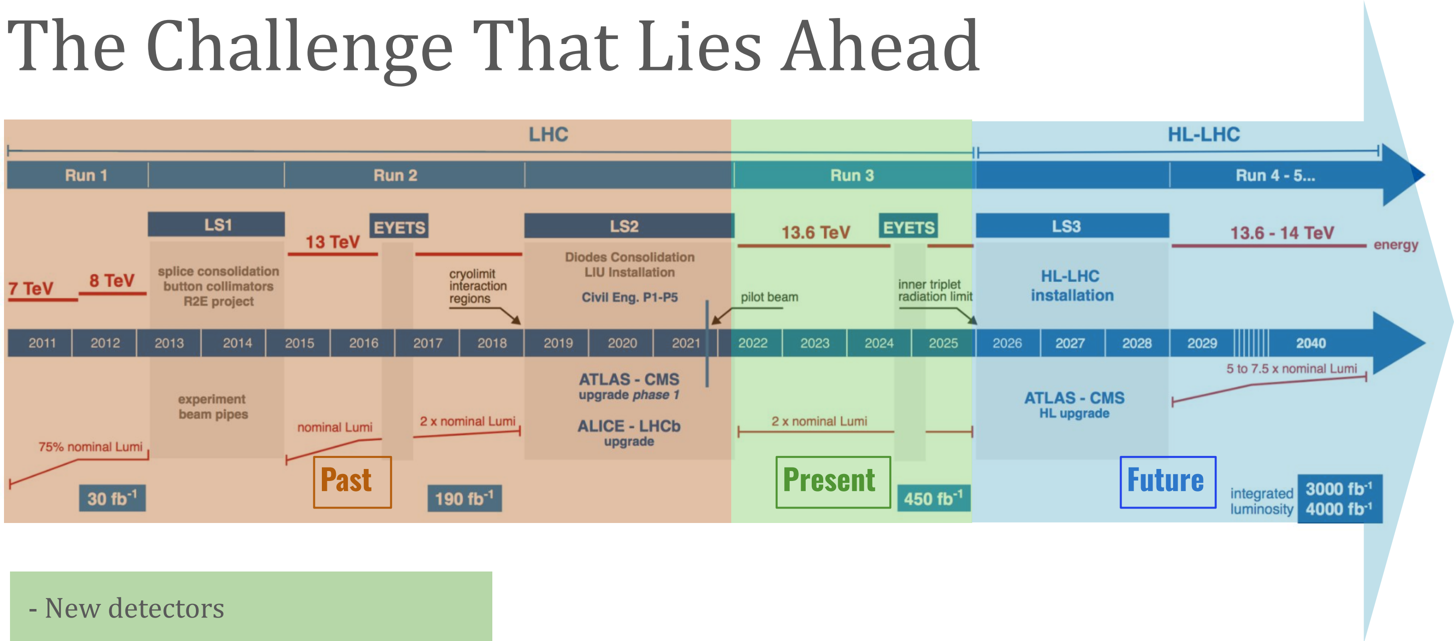
- Complex topology (pileup)

+

- Pressure on trigger and DAQ

+

- (Very) High radiation



- New detectors
- New electronics
- New methods for reconstruction
- New strategies for event generation (MC)
- Precise luminosity determination (bunch-by-bunch, leveling)