Ultra-fast low gain avalanche diodes for synchrotron X-rays detection

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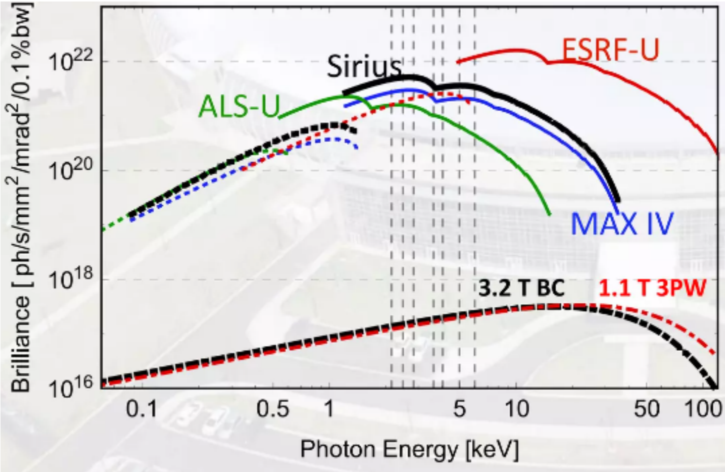
IHEP/CAS Experimental Physics Department Seminar

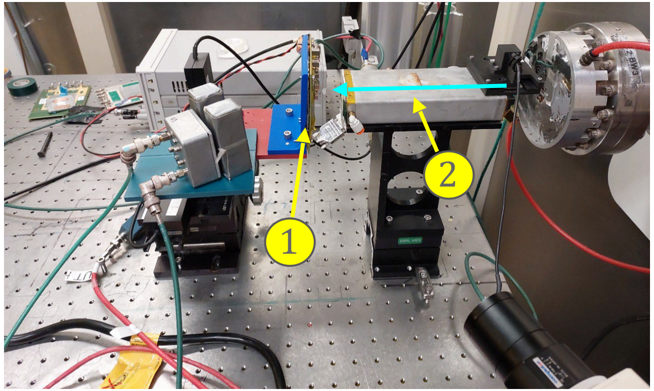
Beijing, Dec. 18th 2025

- New 4th generation light sources poses many challenges for detectors due to high intensity and fast timing bunch structure (e.g. HEPS, Sirius)
- LGADs are natural sensor candidates to face these challenges :
  - Intrinsic gain ⇒ good signal-to-noise ratio ⇒ low energy photons
  - Very fast timing ⇒ time-resolved applications
  - Radiation hard (TID) ⇒ operation at very high intensity beams
  - LHC timing detectors (ATLAS & CMS) ⇒ Extensive R&D
- However, synchrotron light application will require :
  - Very fine (few μm) spatial resolution sensors
  - Active region facing the beam
  - Different energy ranges ⇒ Sensor thickness optimization



SSRL (SLAC) at Stanford (USA)

Beam Line 11-2 @ SSRL



Beam Line Specifications

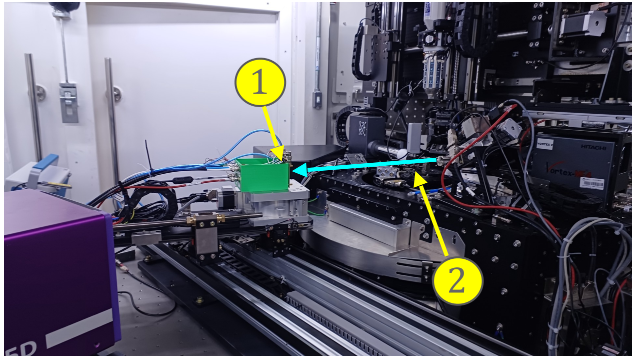
Source

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

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

Sirius at LNLS-CNPEM in São Paulo (Brazil)

Carnaúba beam line @ Sirius



① LGAD setup

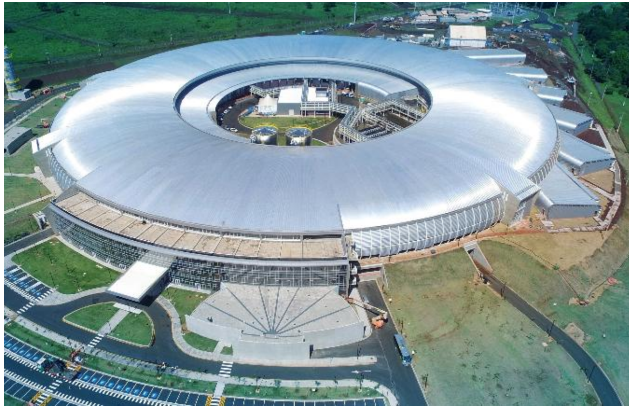
② Beam direction

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.

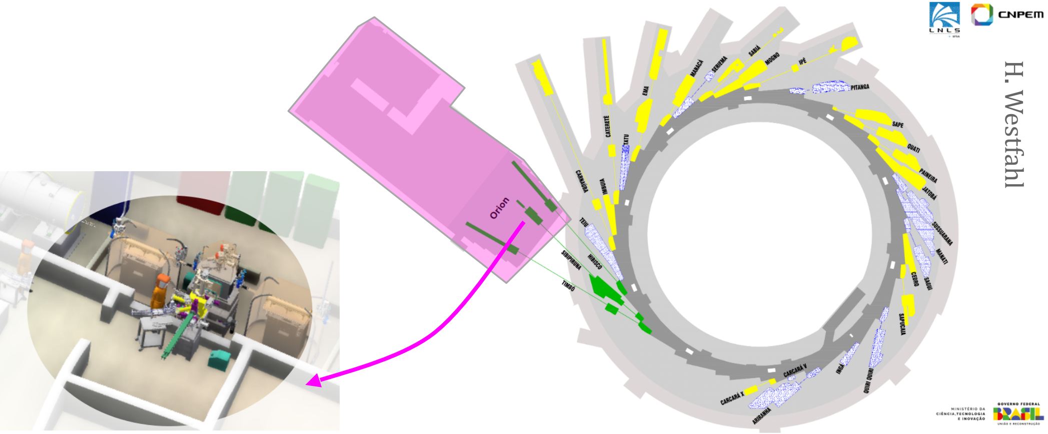
Both sites provide high intensity, quasi-monochromatic pulsed X-ray beams (10 ps wide pulses, 2 ns appart) with several geometries



Orion Project at Sirius (link)

- 3 new beam lines for soft, tender and hard x-Rays
- Installed in a Level 4 biosecurity laboratory
- State-of-the-art facility for highly contagious pathogens research
- New generation of detectors (and sensors) are needed for high frame rate/ high resolution imaging of biological samples

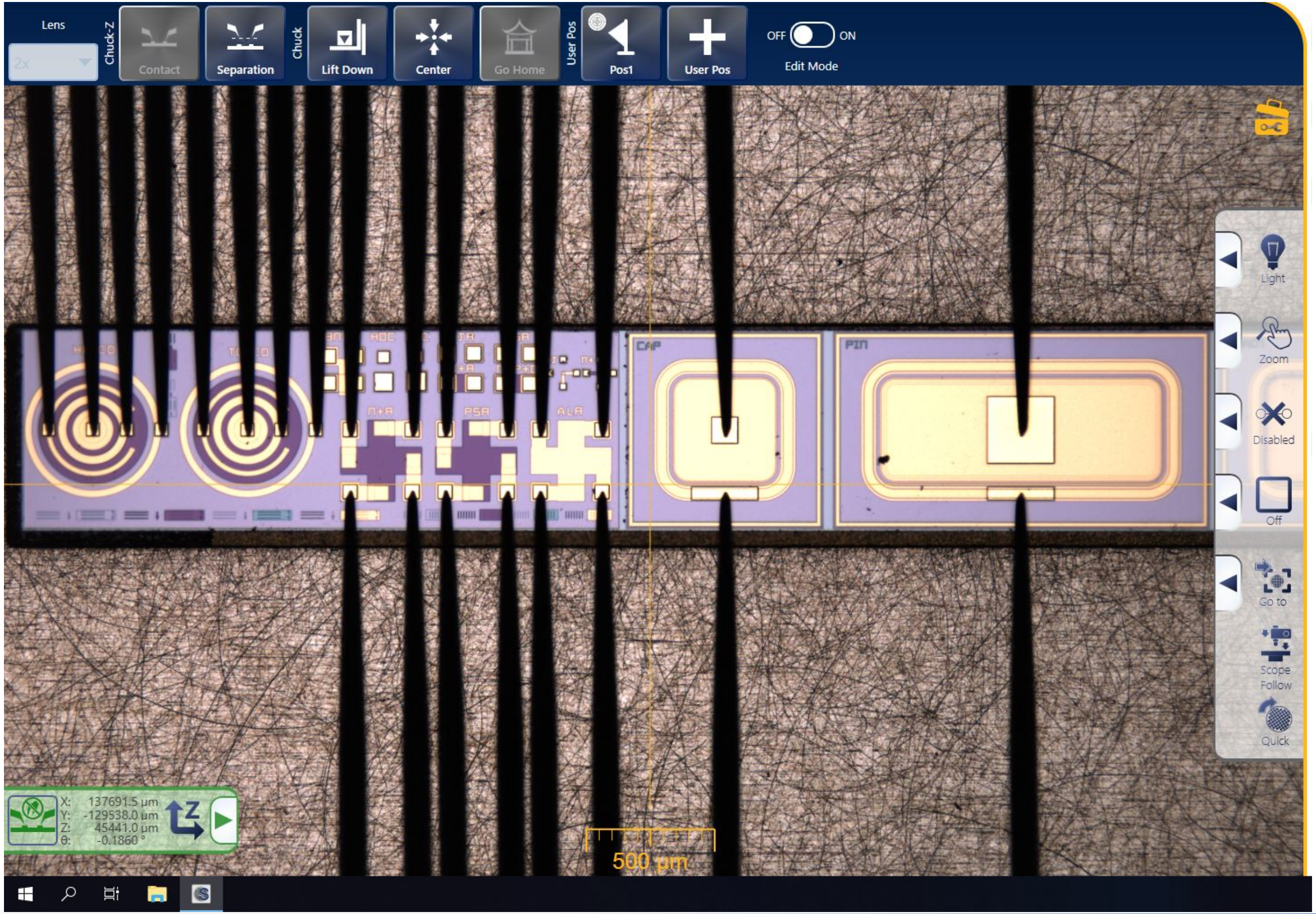
- 4th generation light source (National Laboratory *link*)
- 27 beamlines (2019 - 2028)
- Phase I (200mA) :
  - 10 operational beam lines, 2 commissioning , 2 construction
- Fase II (350mA) :
  - 1 in construction, 9 in project
- Increasing demand for faster X-ray detectors for imaging and non-imaging applications.



H. Westfahl

High intensity, quasi-monochromatic focused pulsed X-ray beams (10 ps wide pulses, 2 ns appart)

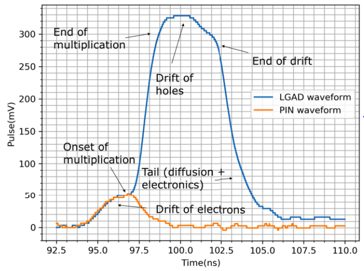
Low Gain Avalanche Diodes



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

Low Gain Avalanche Diodes (LGAD)

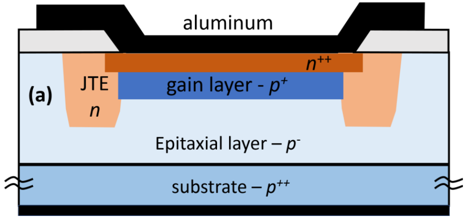
- Proposal made by the RD50 collaboration (Sadrozinski et al) ~ 2013 aiming at very radiation hard devices for LHC etc.
- LGADs are PiN Si diodes + an intrinsic gain layer for charge multiplication
  - Moderate gain (10 ~ 50) ⇒ low energy X-rays
  - Very fast response (< 30 ps for MIP) ⇒ time resolved applications
  - Devices can be fabricated from ~30 μm to ~300 μm active thickness



N. Moffat, 2018

LGAD response to ^{90}Sr electrons

LGAD structure



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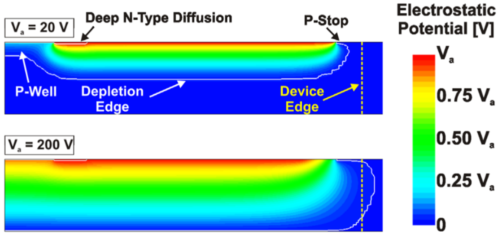
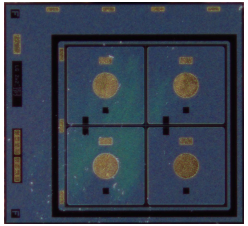
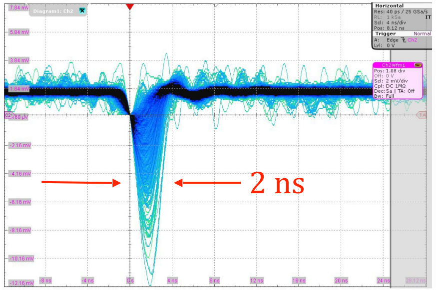
LGAD Internal Electrical Field



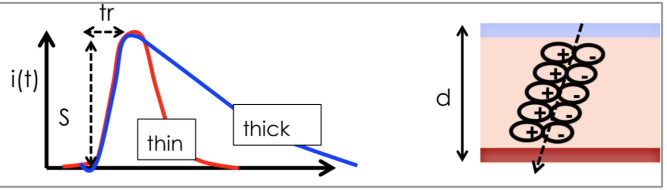
2x2 LGAD (HPK)





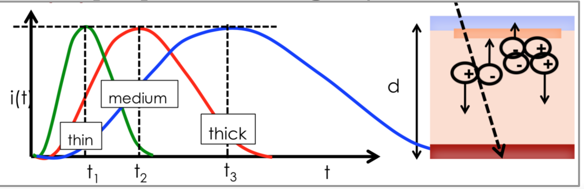
Planar detector: fixed rise time

$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$



LGAD: rise time proportional to gain/thickness

$$\frac{dV}{dt} \propto \frac{G}{d}$$

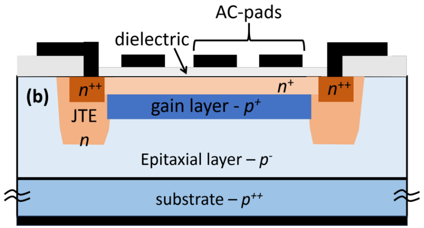


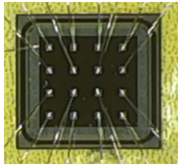
Cartiglia 2016

Fact: DC-LGADs (e.g from ATLAS and CMS) have a coarse spatial resolution and large inter pad (inactive) region (~50 μm to 100 μm)

Challenge: How to fabricate devices with optimal spatial resolution (μm) and small upstream dead-region?

AC-LGAD (link, link)

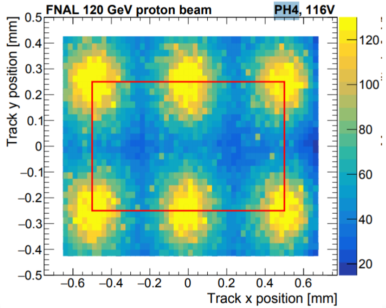




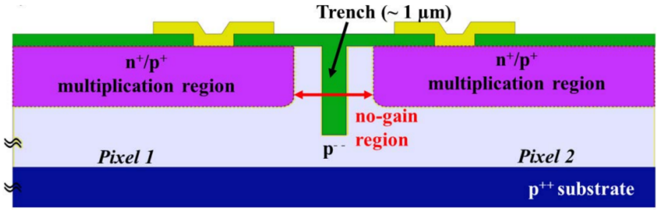
HPK AC-LGAD 150 μm; 500 μm

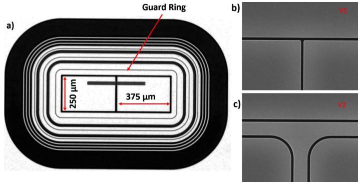
$\sigma_t \approx 21$ ps

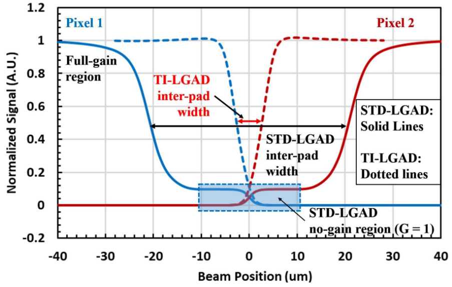
$\sigma_s \approx 41\ \mu m$



Trench Isolated (TI-LGAD) (link)

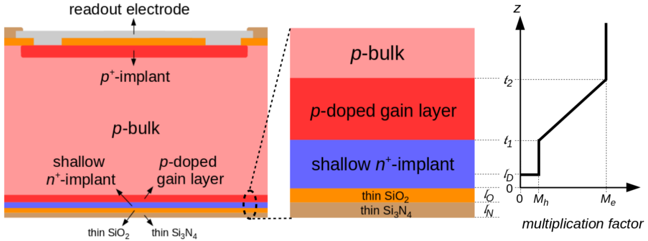


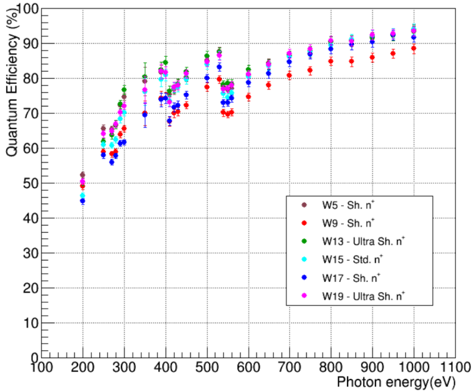


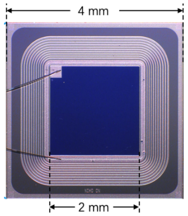


TCAD simulation: IP~5 μm

Inverted LGAD (link)







X-rays down to 200eV

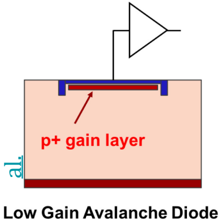
Characterizing the performance of

Low Gain Avalanche Diodes

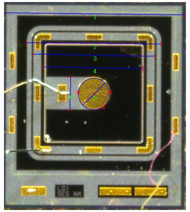
using synchrotron radiation

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

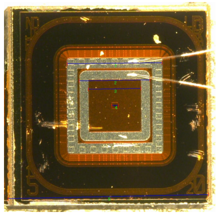
- "Flat" beam : 25mm x 1 mm (nominal)
- Energy scan from 5 to 37 keV (70 keV with harmonics)
- Bias Scan
- Single pad (1.3 x 1.3 mm²) LGADs



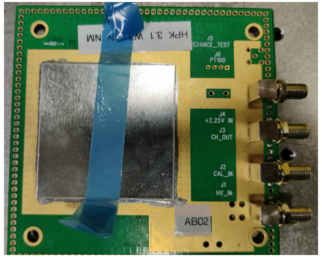
Ferrero et al.



HPK
DC LGAD



BNL
DC LGAD



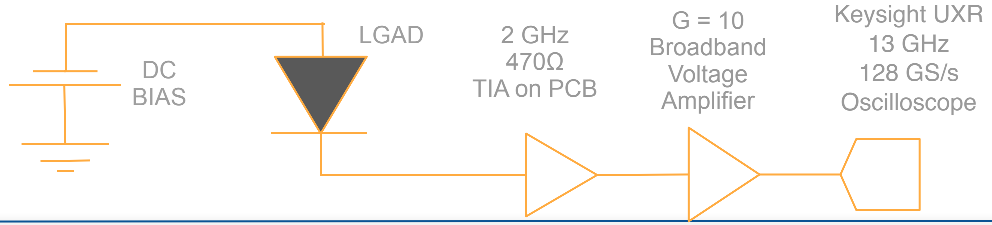
Santa Cruz board with LGAD and 1-ch. amplifier

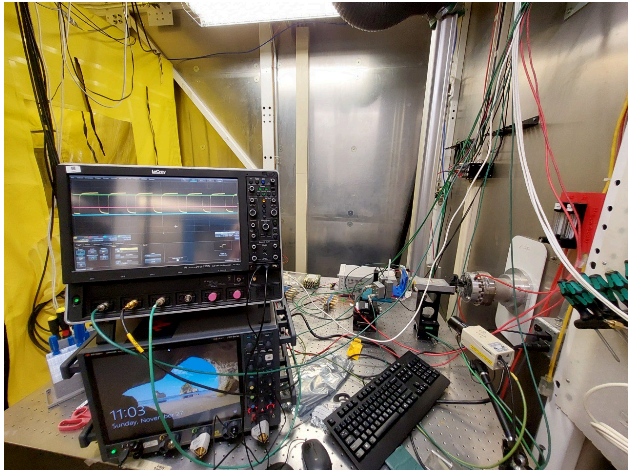
Devices Tested

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

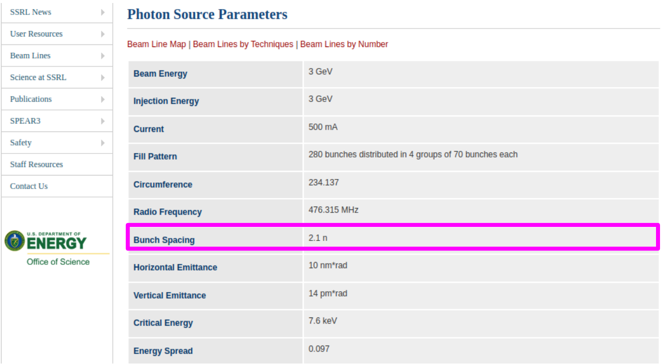
For details, See Ref.

Simple Measurement Setup

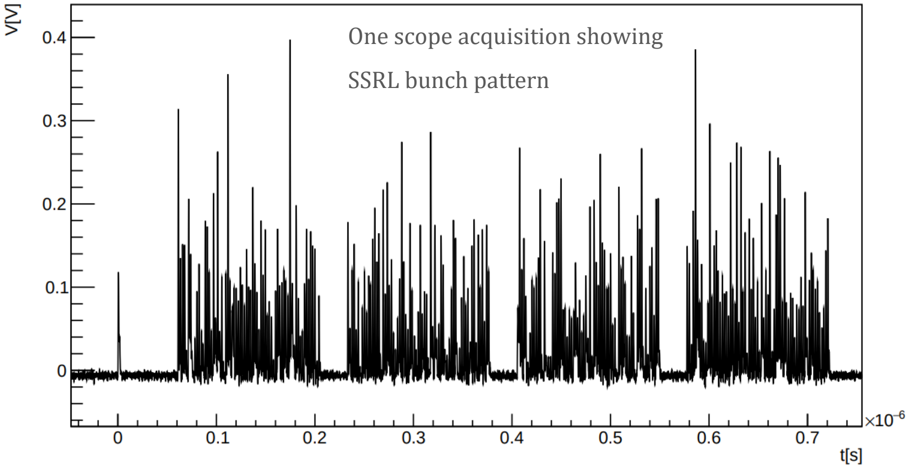


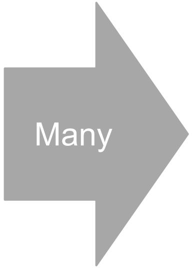


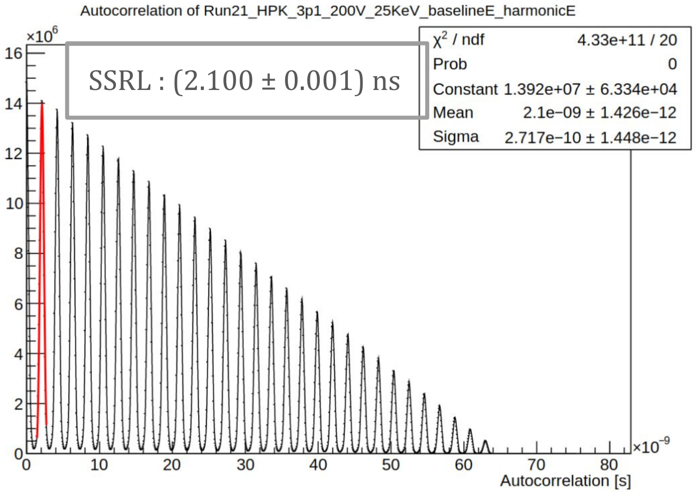
- For MIP, we use a telescope for timing measurement (Δt) ; for X-rays we have to resort to something else
- We can rely on the very uniform bunch separation of 2.1ns
- This can be measured using the LGAD !
- The SSRL fill structure is : …1–0–fill–0–fill–0–fill–0–fill–0…



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

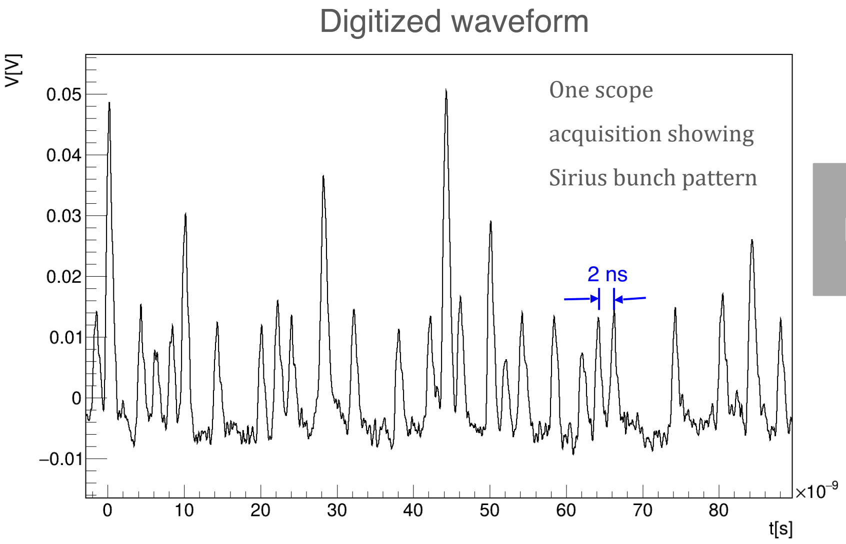




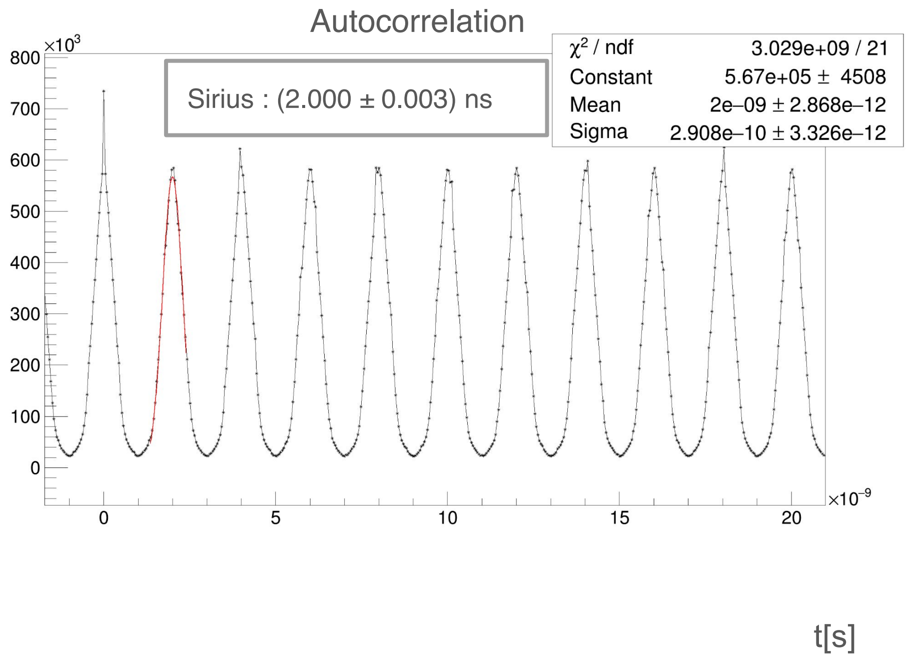


Signal processing - I : How to measure timing ?

- For Sirius, every bunch in the orbit is filled (2 ns separation)

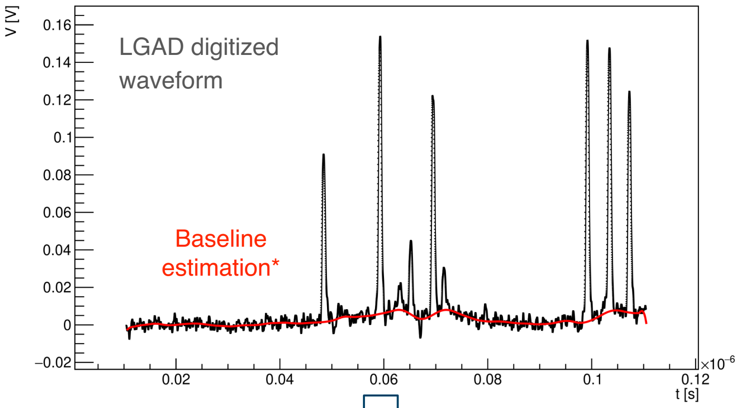


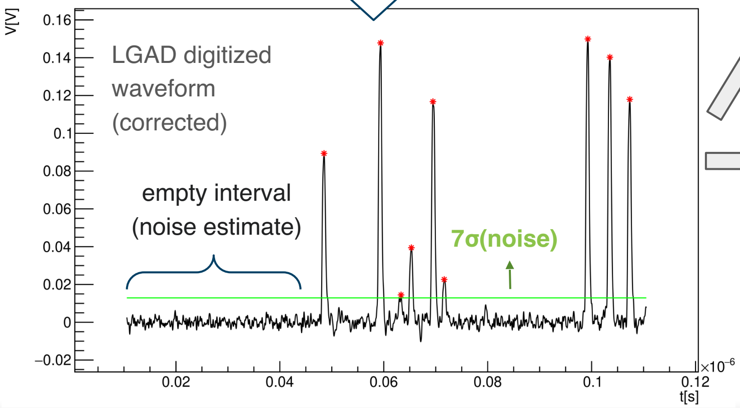
Many



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

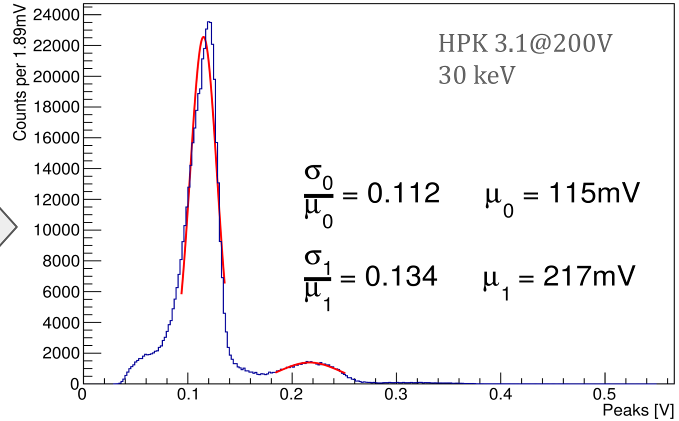
- All data from oscilloscope digitized waveforms





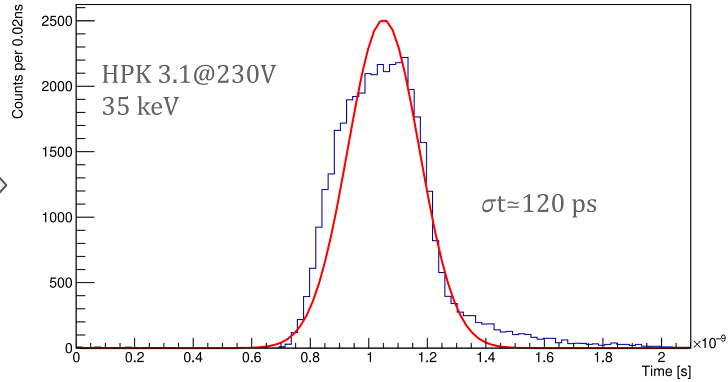
Energy

σE/E from Amplitude distribution



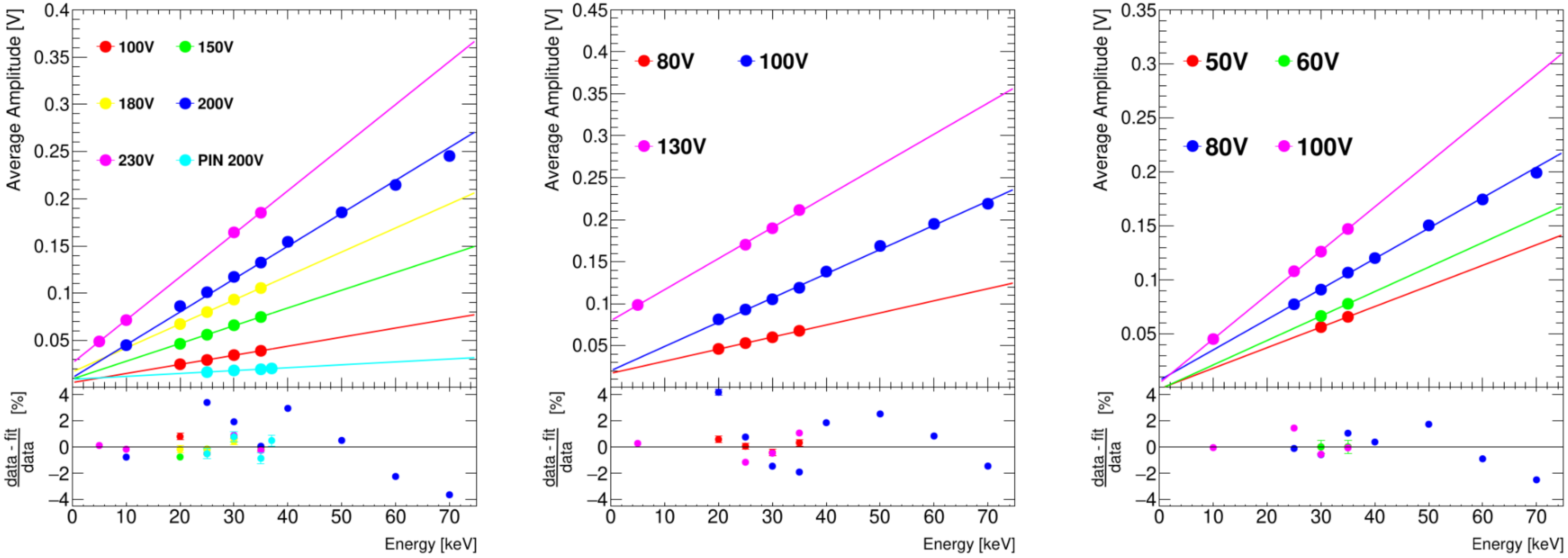
Timing

σt based on 2.1 ns interval (20% CFD)



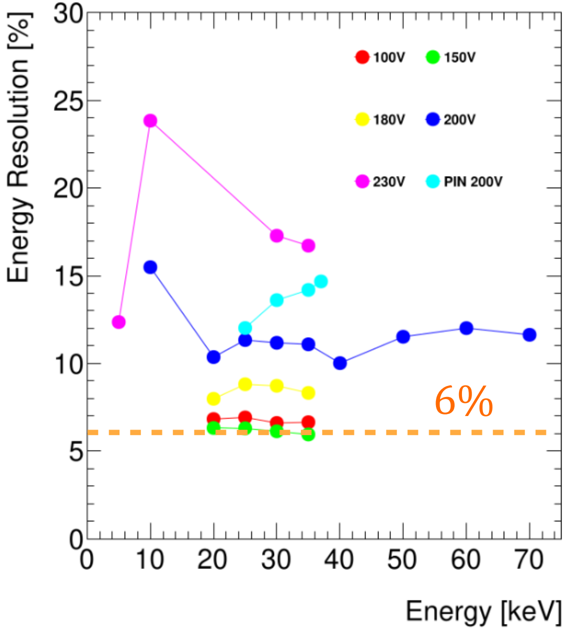
*asymmetric reweighted penalized least squares smoothing

Linearity of response

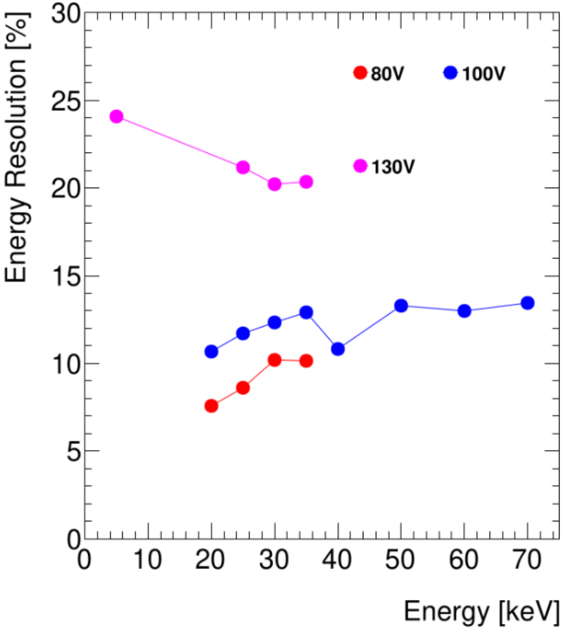


(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

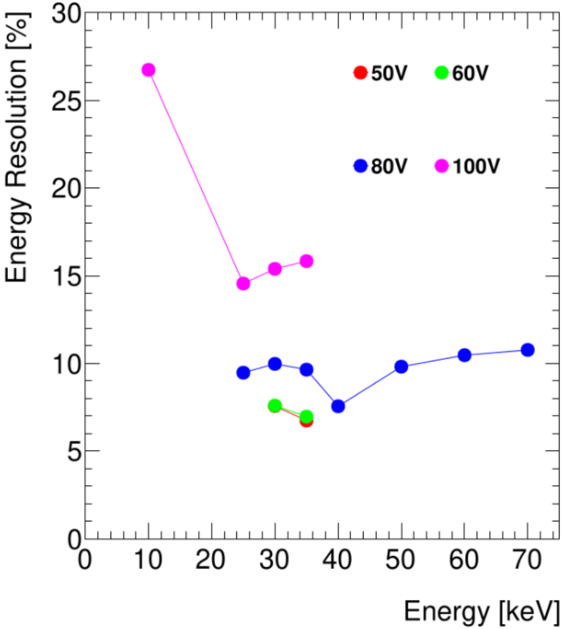
Energy resolution



(a) HPK PIN and type 3.1 LGAD

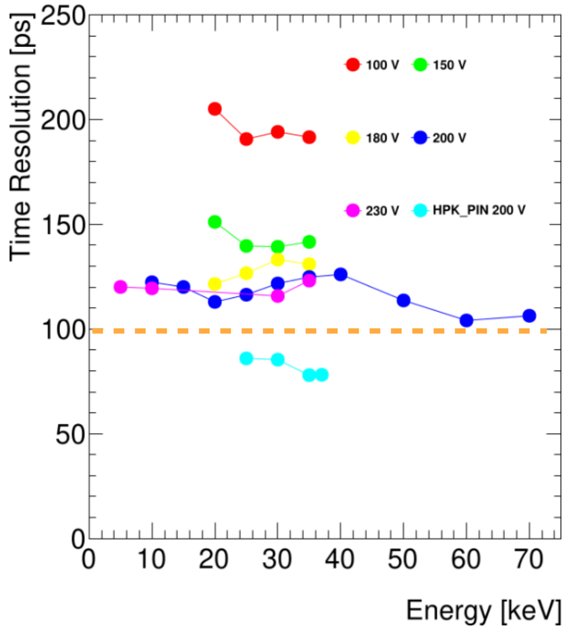


(b) HPK type 3.2 LGAD

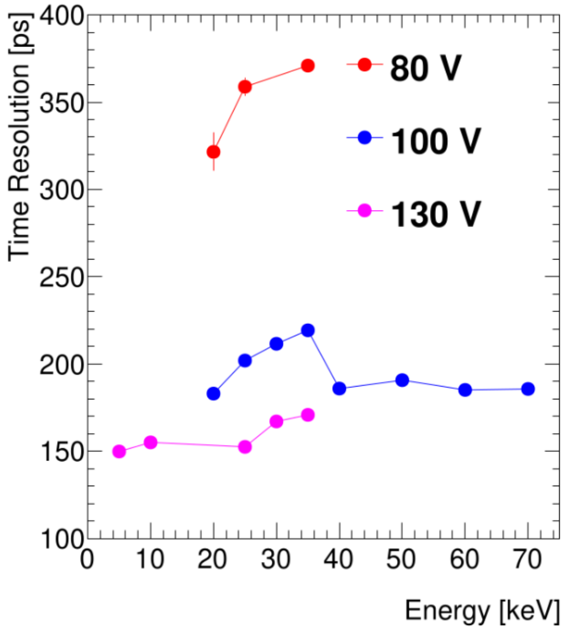


(c) BNL 20um LGAD

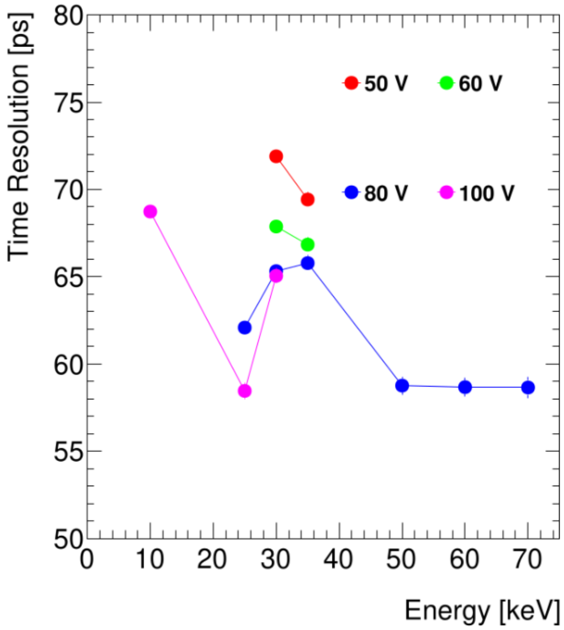
Time resolution



(a) HPK PIN and type 3.1 LGAD



(b) HPK type 3.2 LGAD



(c) BNL 20um LGAD

Best energy resolution

Best time resolution

	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.

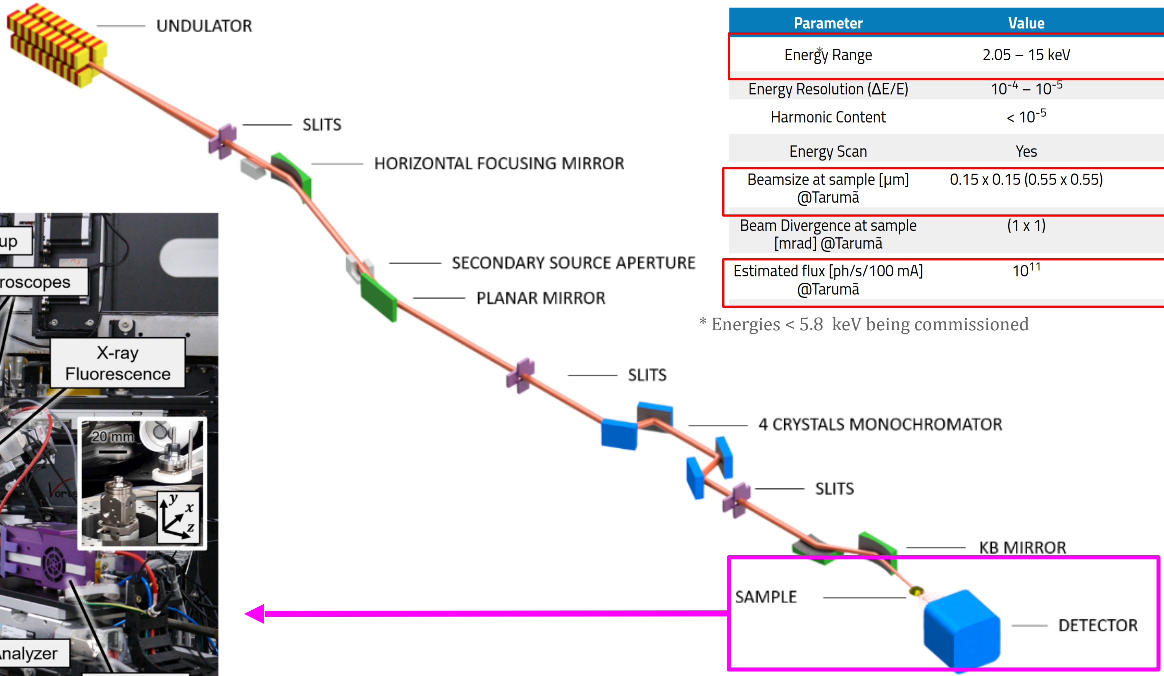
- One of the 10 operational beam lines
- Fully instrumented
- 2.1 to 15 keV X-rays
- Beam size from 150 nm to 350 μm

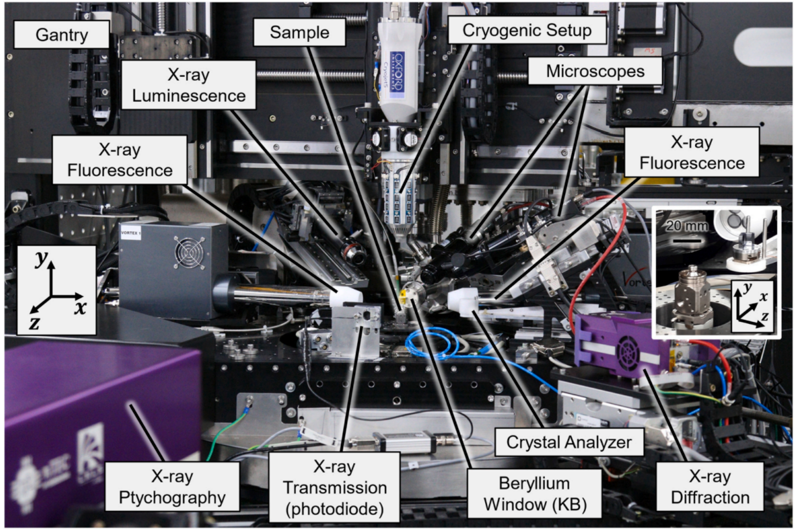
link, *Tolentino 2023*

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}	–

* Energies < 5.8 keV being commissioned

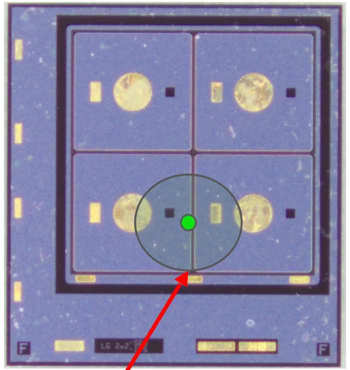




High intensity, quasi-monochromatic focused pulsed X-ray beams (10 ps wide pulses, 2 ns appart)

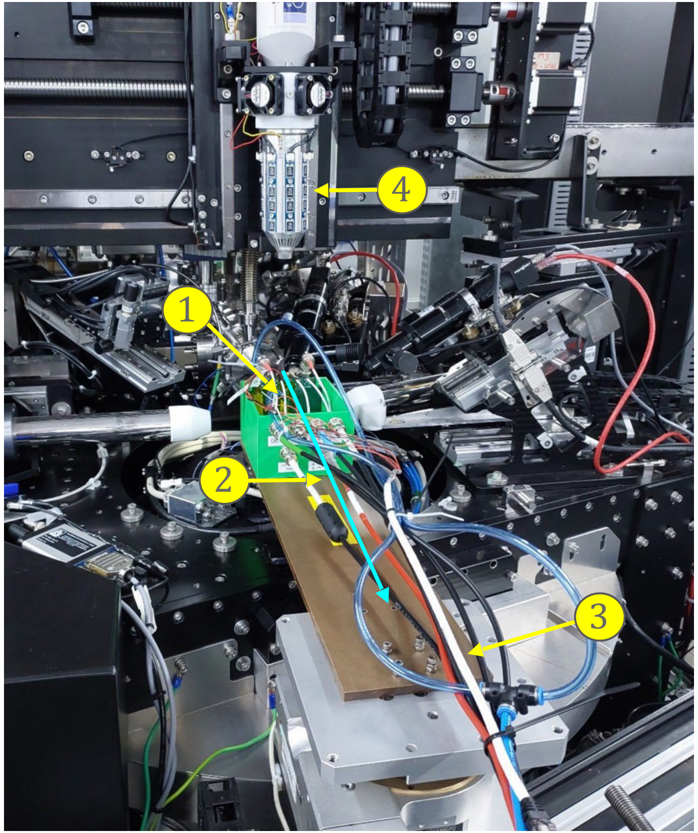
2x2 LGADs (HPK 3.1) tests @ Sirius Carnaúba beamline

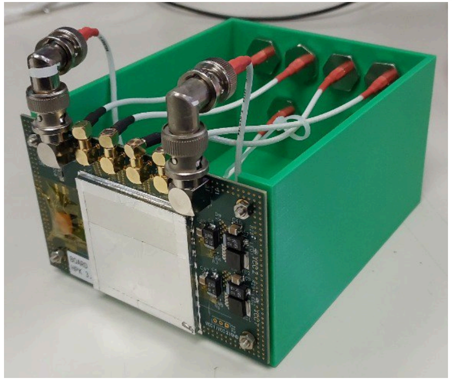
- ATLAS HGTD HPK 3.1 2x2 array prototype
- 50 μm active thickness , IP 70μm
- gain : 12 (150 V) ~ 32 (230 V)
- Detector can move and rotate wrt to the beam
- LN2 nozzle can be used to cool down the DUT
- Energy/timing resolution wrt :
  - X-ray energy, bias and temperature
- Interface to EPICS from machine to access experimental conditions (beam intensity, linear stage position, shutters etc.)

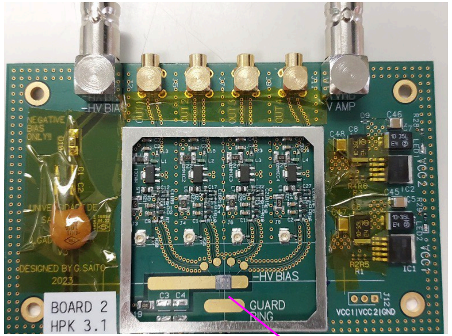


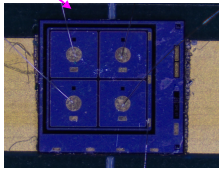
2x2 HPK 3.1 LGAD array

350 μm or 150 nm X-ray beam



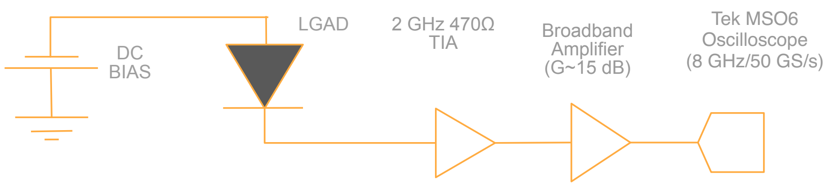


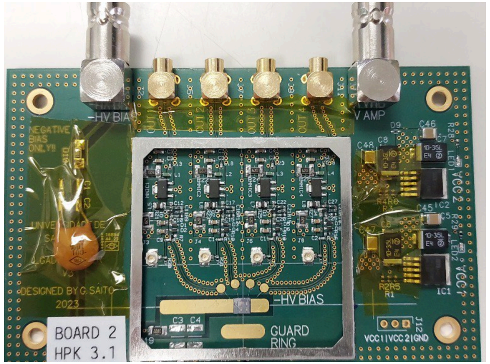




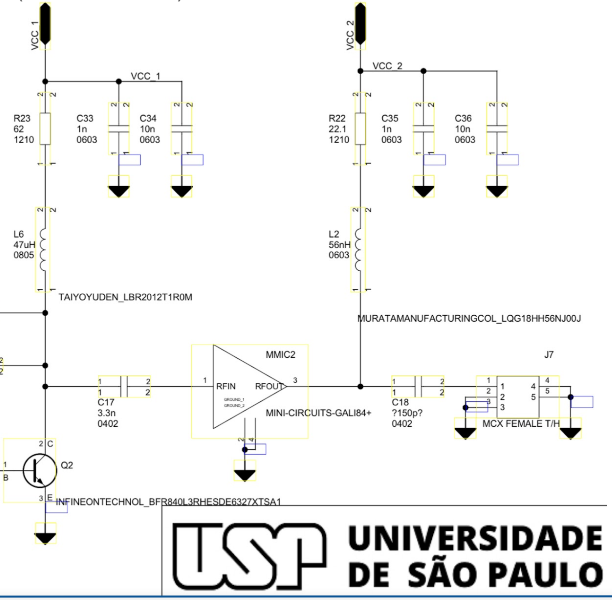
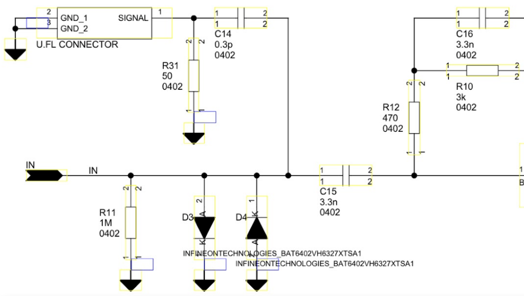
1 LGAD 2 Beam direction 3 Linear stage 4 Cooling nozzle

- 4 channel 2-stage amplifier board
- Signal (charge) injection
- Jitter from electronics < 1 ps
- Onboard voltage regulators
- Data acquisition : 8GHz, 50GS/s Oscilloscope ⇒ store digitized waveforms

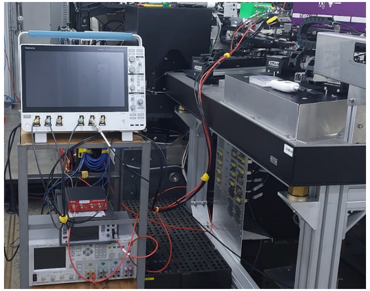


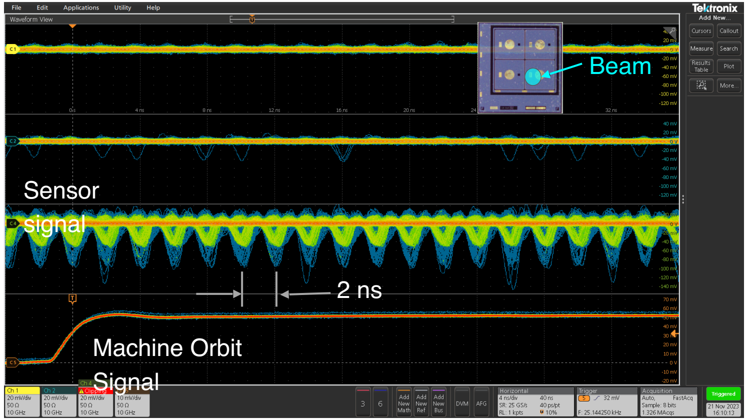


UC St. Cruz 1st stage amplifier + broadband amplifier (MMIC Gali84+)

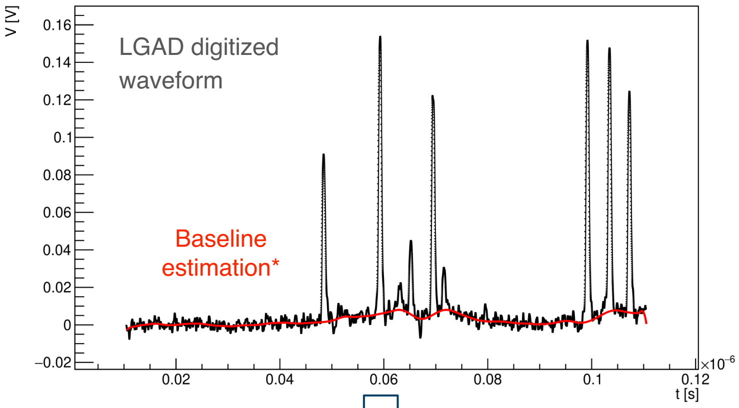



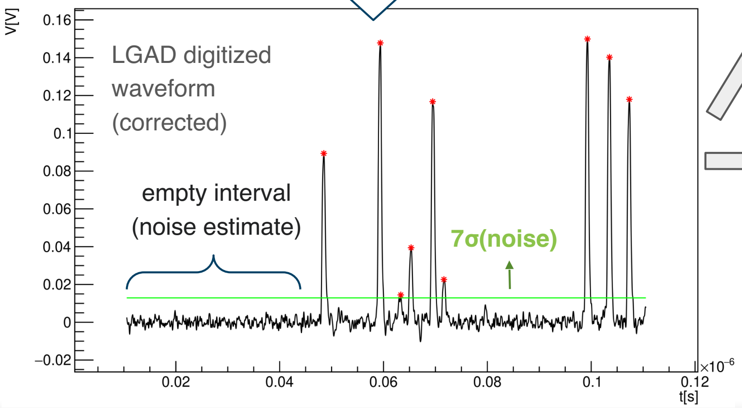
UNIVERSIDADE DE SÃO PAULO





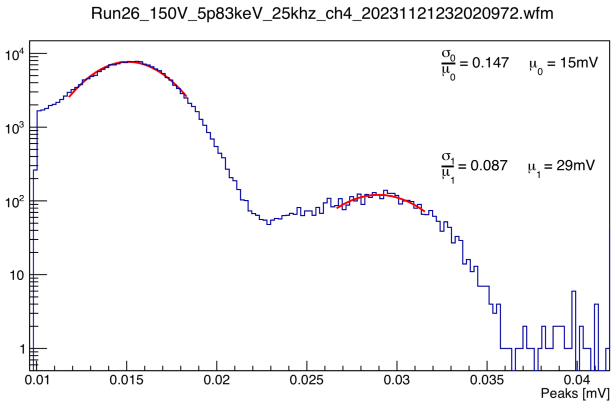
- Digitized signal has significant baseline shift ⇒ correct offline





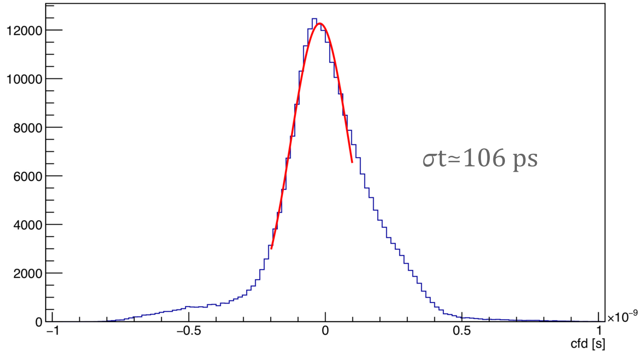
Energy

σE/E from Amplitude distribution



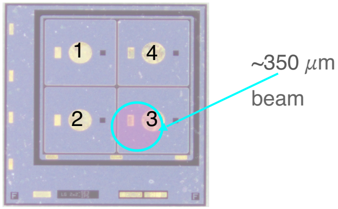
Timing

σ_t based on 2 ns bunch interval (20% CFD)

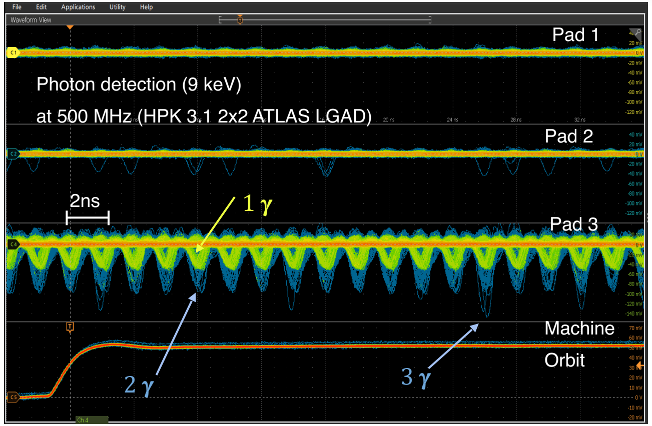


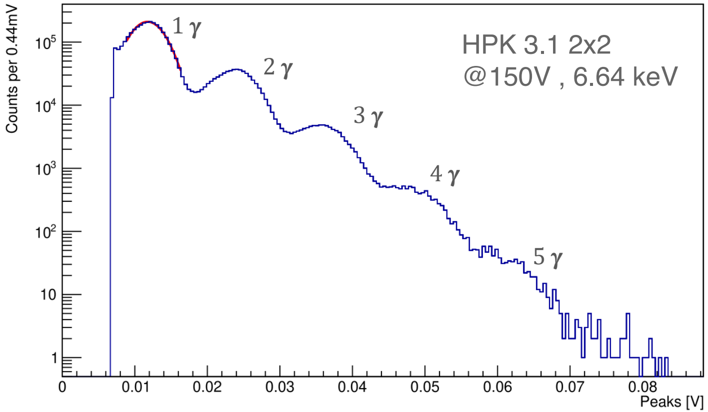
*asymmetric reweighted penalized least squares smoothing

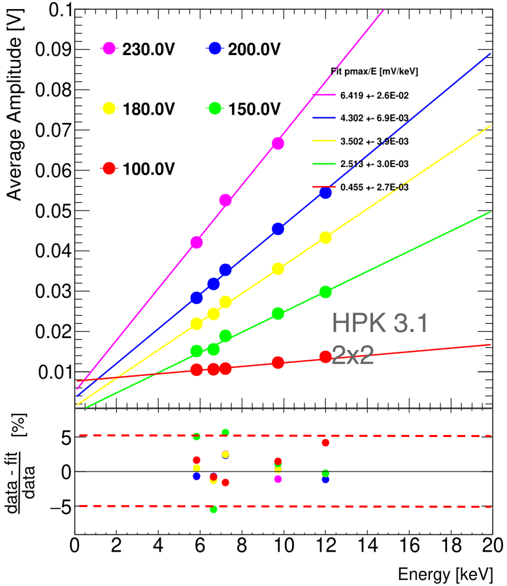
2x2 LGADs (HPK 3.1) Energy response

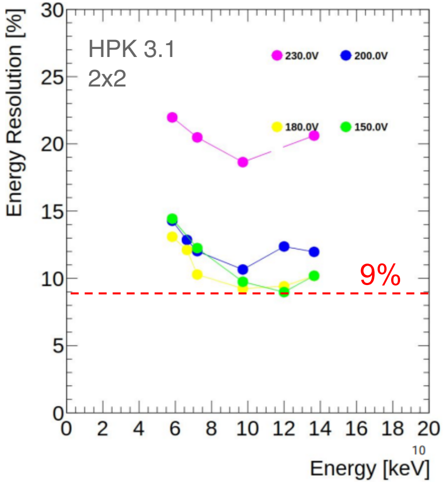


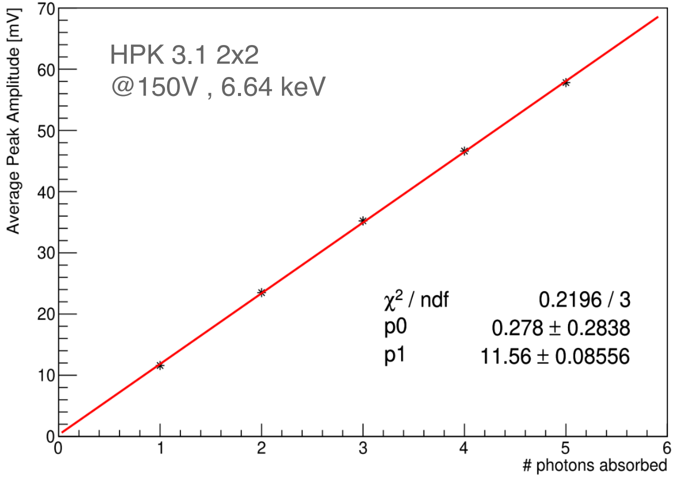
- Different X-ray energies and bias
- Multiple photon conversions



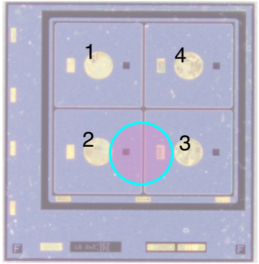


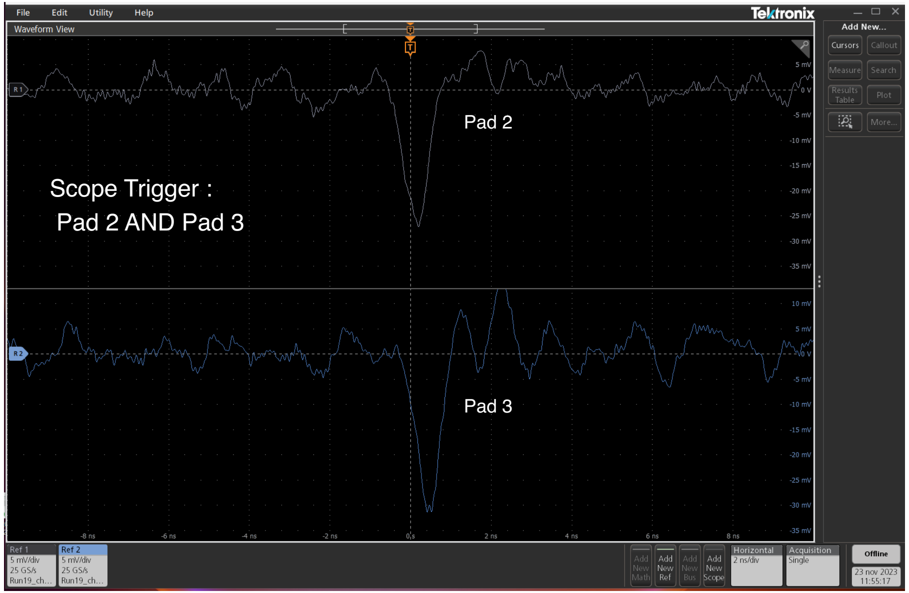


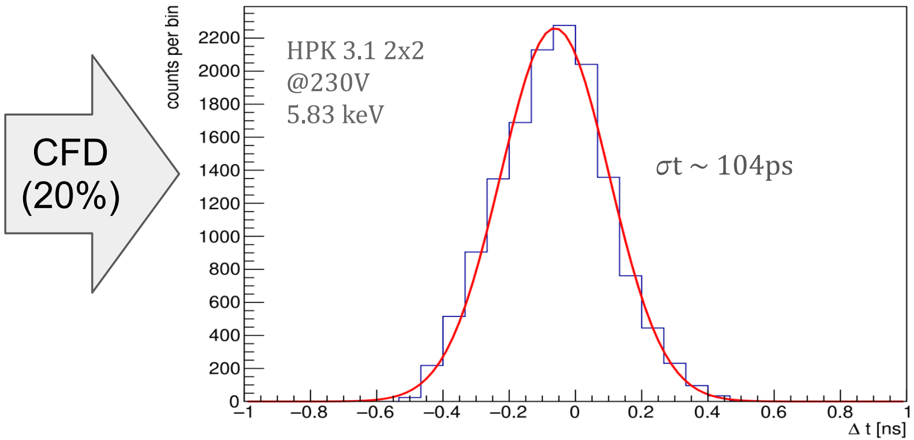




- Multiple photon conversions can be used to measure the intrinsic timing resolution
  - $\sigma(t_2 - t_3)$
- Data was taken with AND between two pads signals



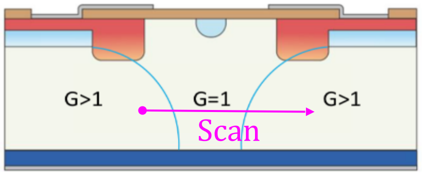




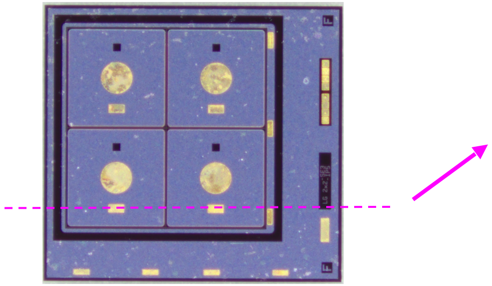
Gain and interpad measurements

- Use a focused 150 nm beam
- 5 μm step lateral scan between 2 pads

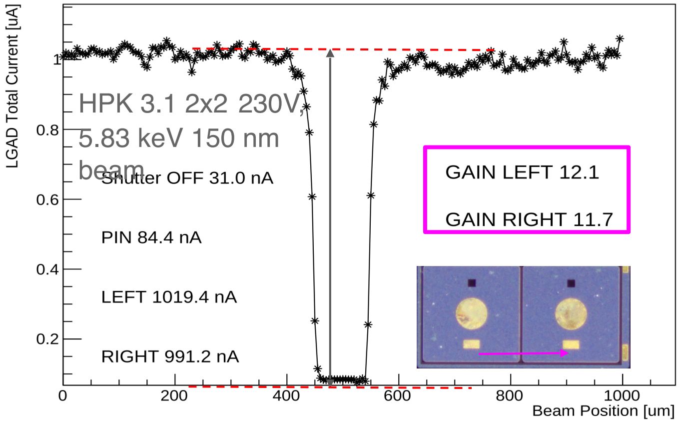
Skomina et al

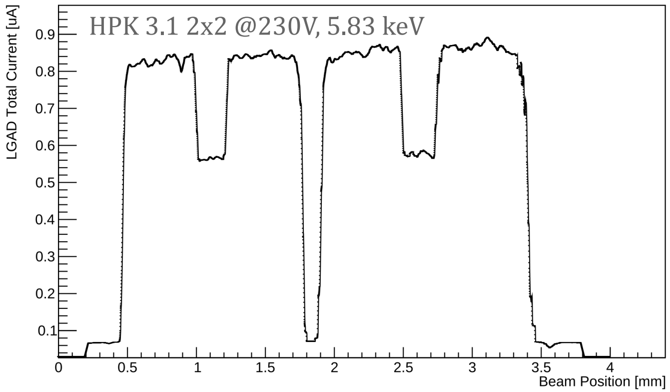


- Extract device gain and from ratio (G>1) / (G=1) by current or pulse amplitude
- Also interpad distance

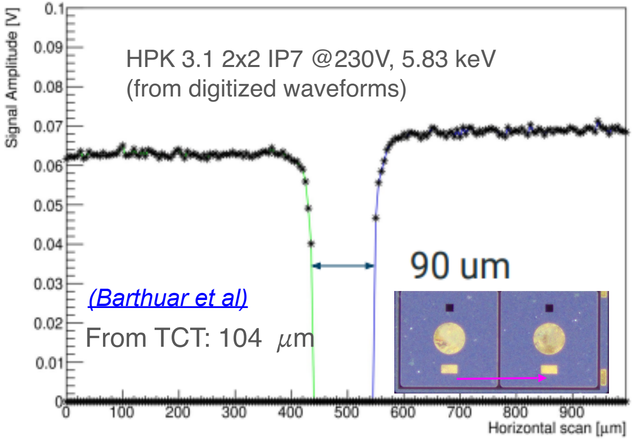


LGAD CURRENT profile



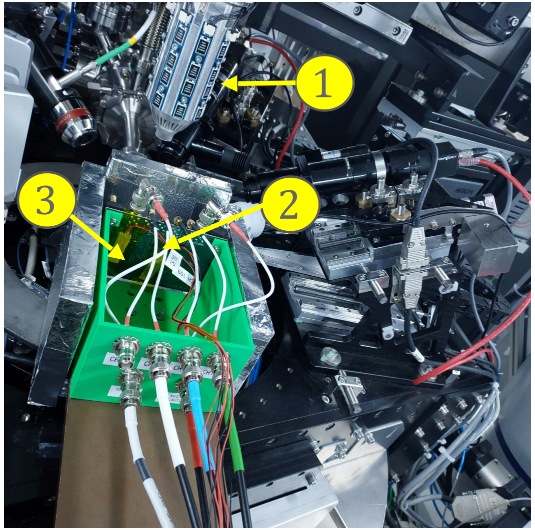


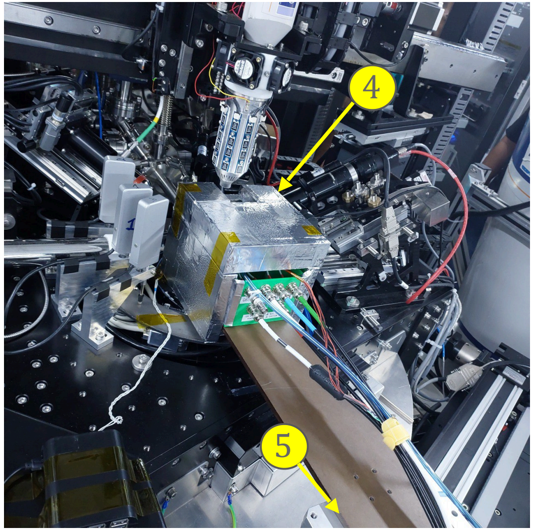
LGAD PULSE AMPLITUDE profile

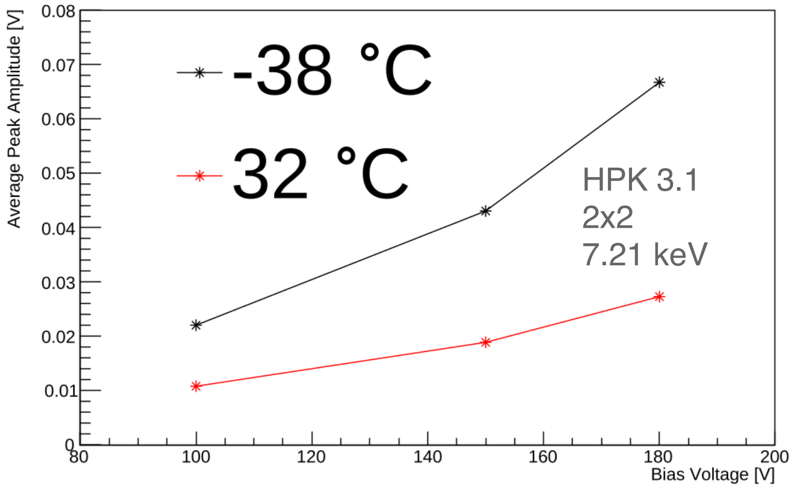


- HPK 3.1 2x2 array
- N2 cooling nozzle and detector position remotely controlled
- Temperature recorded by 2 PT100 on the PCB

- Beam line using a focused beam at 7.21 keV
- Bias and temperature scan
- Gain increases as temperature decreases
  - as expected (W. Sun et al)



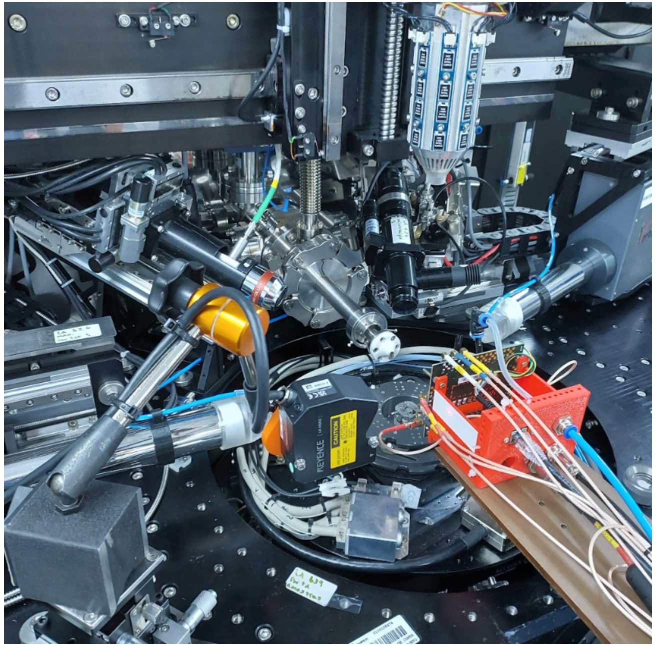


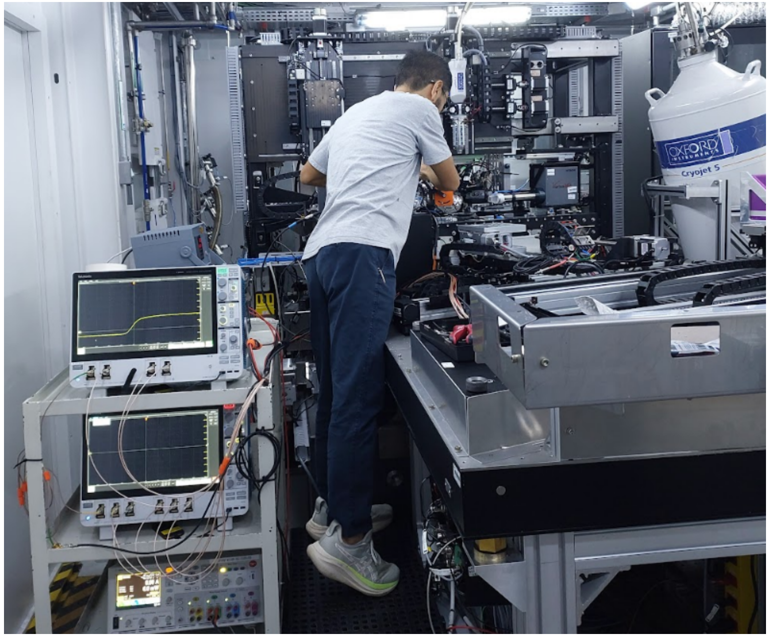


(1) N2 Nozzle (2) LGAD (3) PT100 (4) Insulation box (5) Linear stage

IHEP-IME and FBK TI-LGAD recent tests @ Sirius

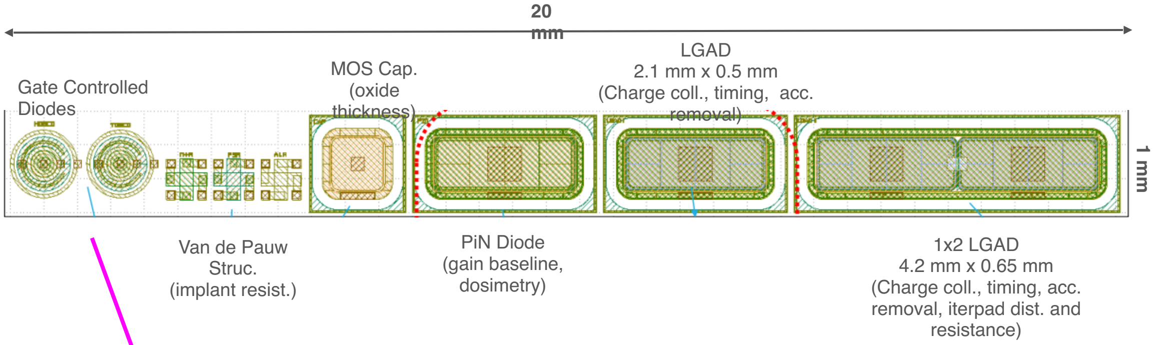
PRELIMINARY

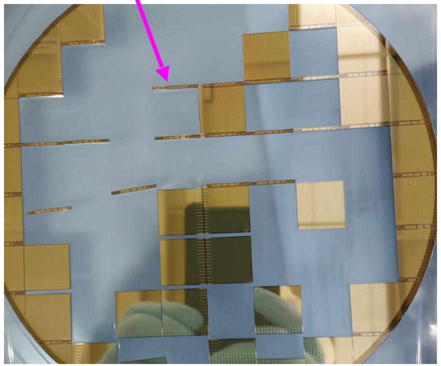


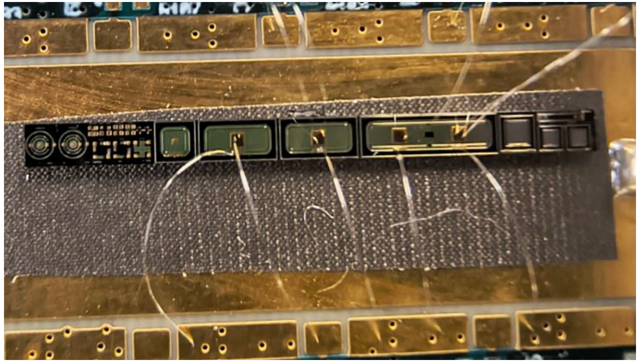


IHEP-IME and FBK TI-LGAD recent tests @ Sirius

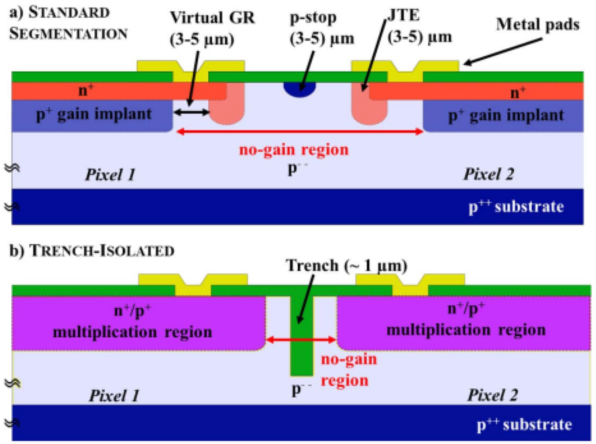
- ATLAS HGTD IHEP-IME QA/QC test structure with carbon-enriched "standard" DC-LGADs
- 50 μm active thickness , gain ~ 30 @150V



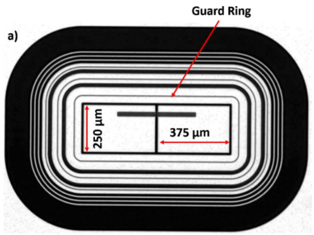


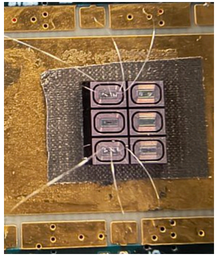


- FBK TI-LGAD sensor (V1) from RD50 production, test structures 2x1 (Paternoster et al)
- 50 μm active thickness , gain ~ 20 @150V



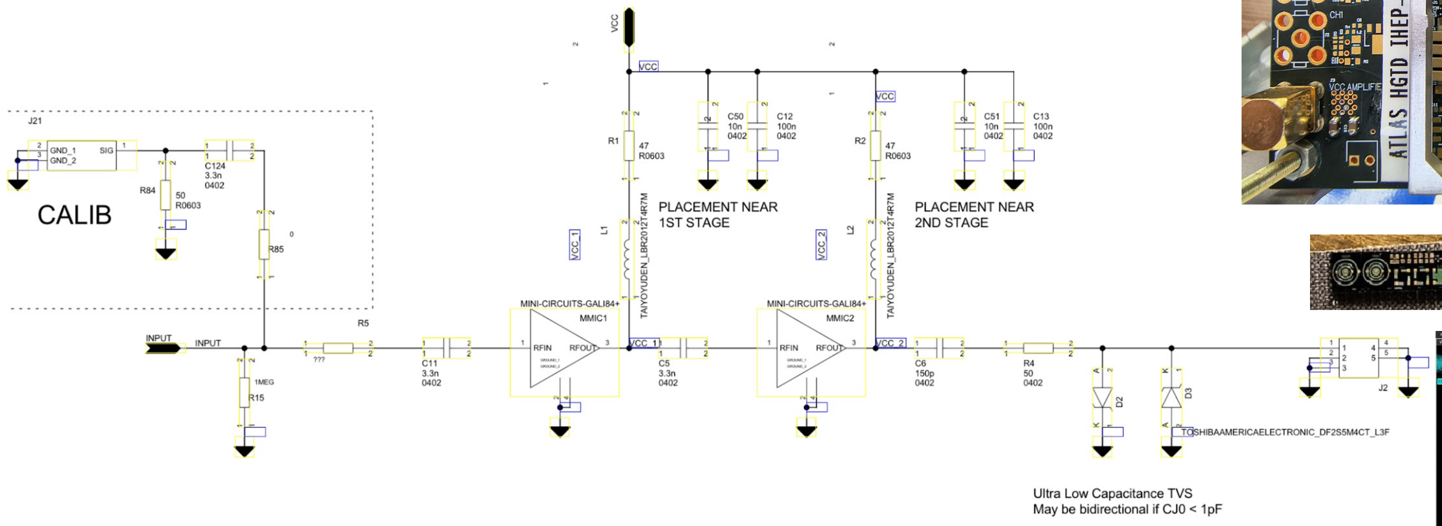
Paternoster et al

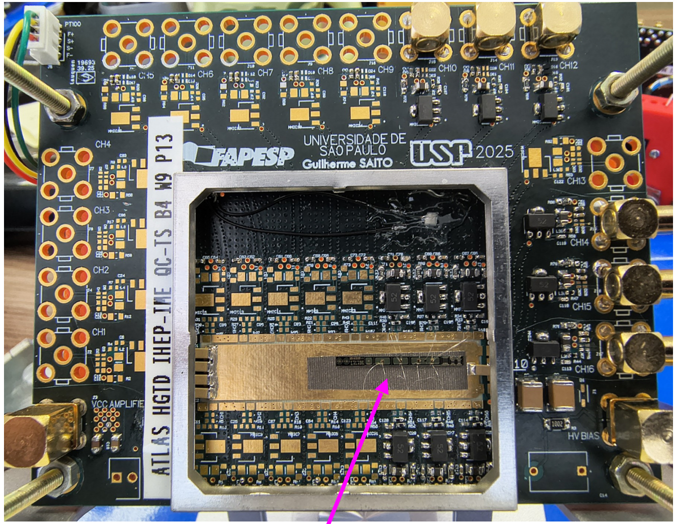


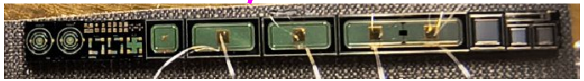


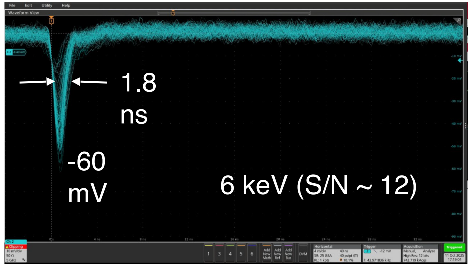
New 16ch amplifier board

- “New” board (based on [arxiv 2504.08932v2](https://arxiv.org/abs/2504.08932v2))
- 2-stage amplifiers (MMIC Gali 52+, 2GHz , 18 dB)
- Individual charge injection
- Temperature measurement
- Removed on-board regulation due to heating …
- Jitter < 1ps (calibration signal)





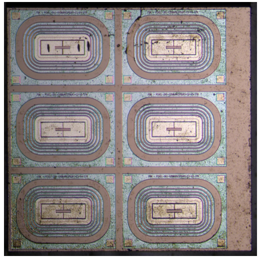




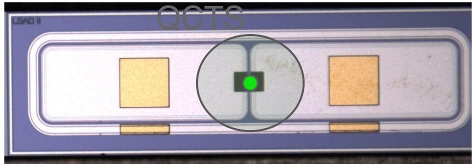
Once channel schematics (16 channels in one board)

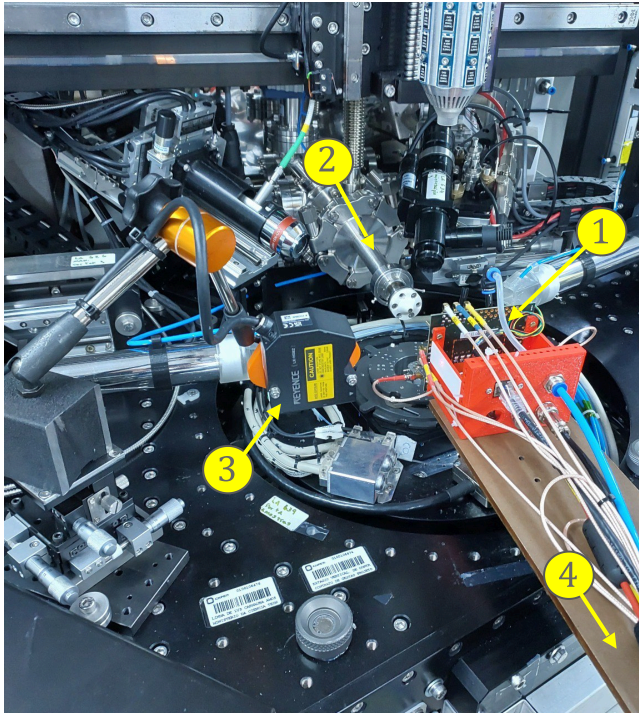
- Added a precision (< 1 μm) laser displacement sensor
- 2 oscilloscopes (up to 10 channels)
- Board is air-cooled an temperature monitored
- Beam size : 350 μm or 150 nm
- Energy and timing measurements
- Low Energy scan (2.1 keV to 6 keV)
- Measurements:
  - Position scan, timing and very high flux response

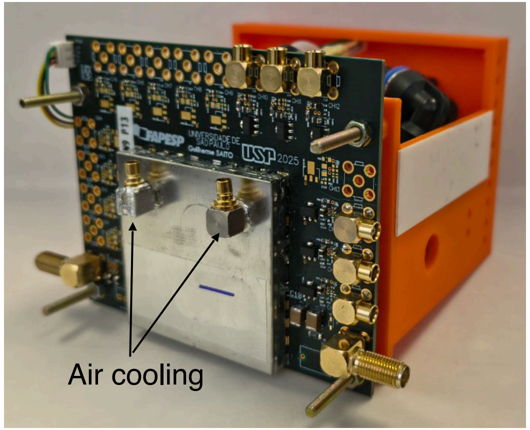
FBK TI-LGAD

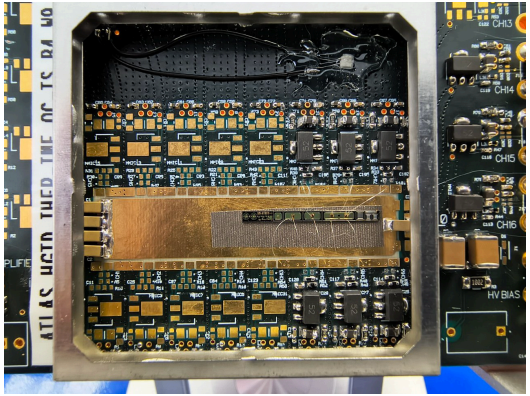


IHEP/IME





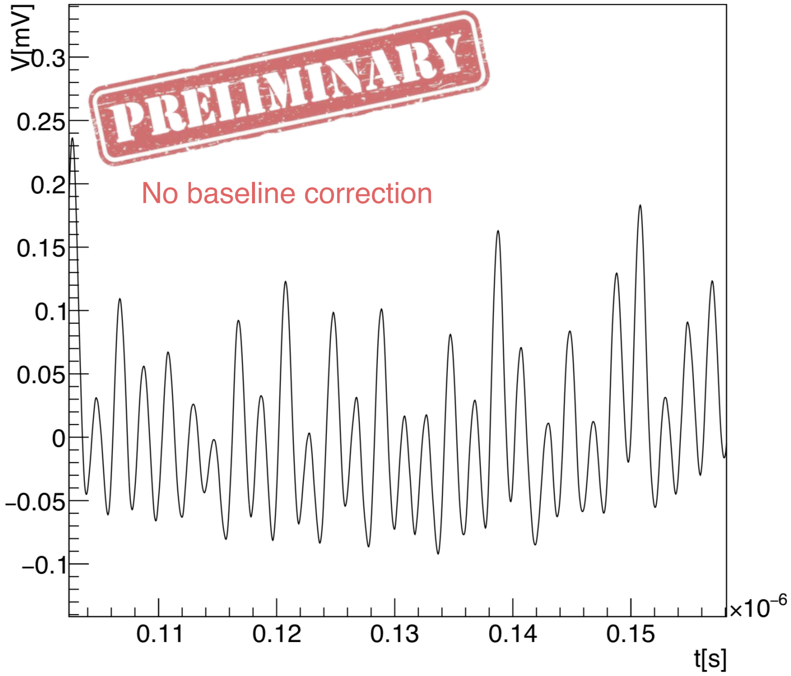




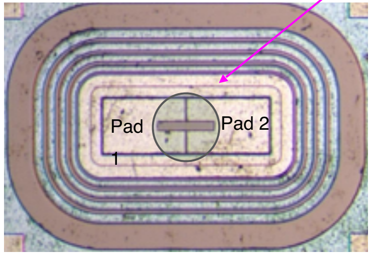
1 LGAD   2 Beam pipe   3 Laser displacement sensor   4 Linear stage

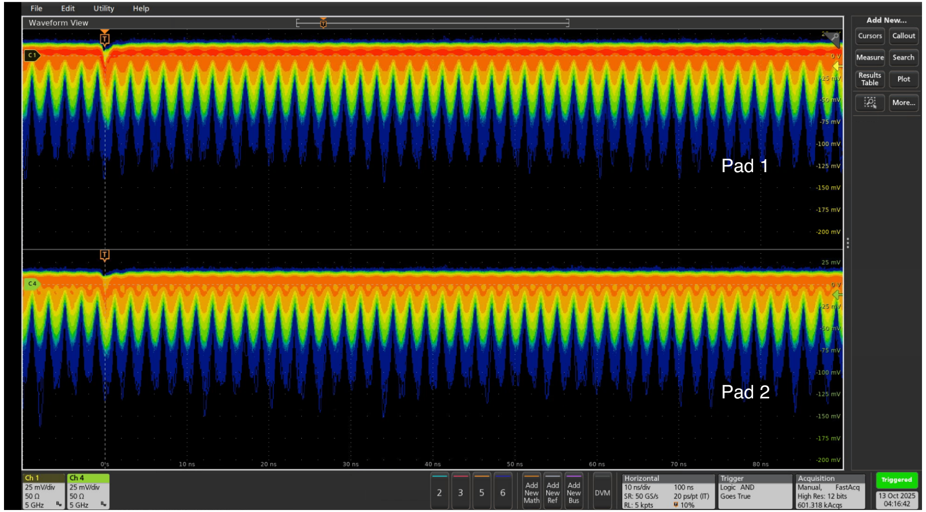
IHEP-IME LGAD response to very high flux

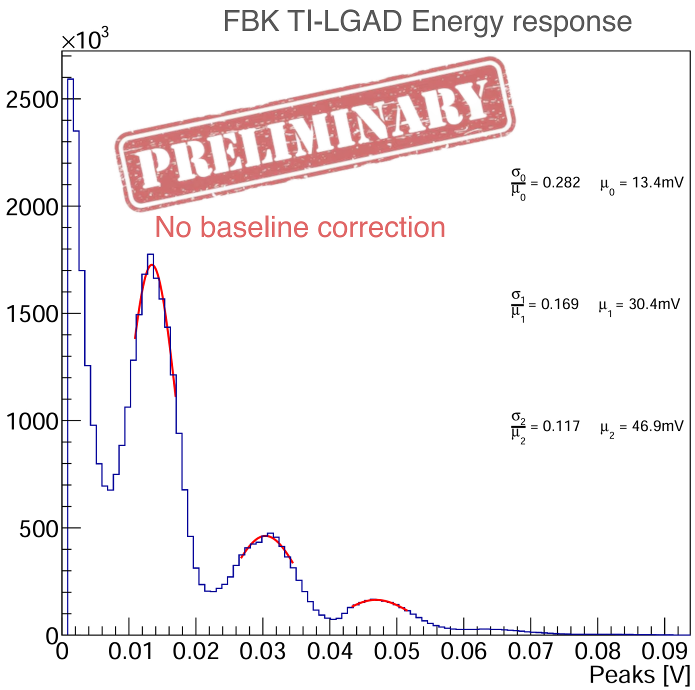
- An attempt to kill the sensor, but it survived ...
- Maximum flux (10^9 γ/s, 350 μm spot size) @ 6 keV
- 18uA current from sensor ⇛ no increase in the current in ~10 min operation
- 500 MHz rate, signal recorded at every bunch



- 6 keV X-rays (350 μm spot size)





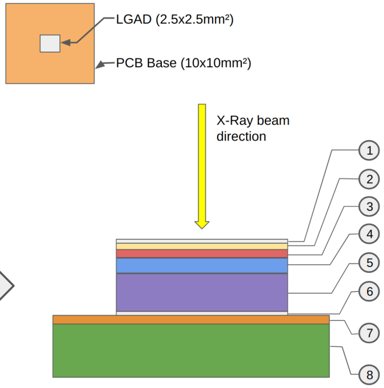


Large amount of data from both sensors (2.1 keV to 6 keV) still being analyzed ....

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

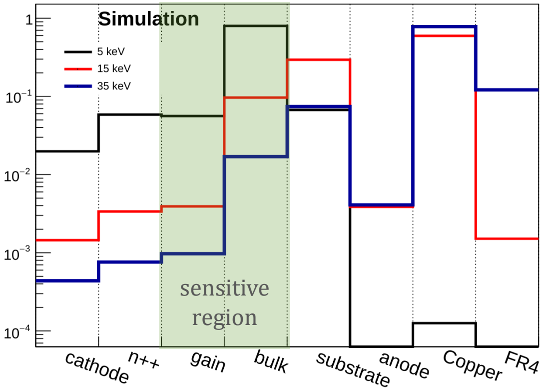
Simulations for HPK 3.1, single pad

GEANT-4 simulation of absorbed photon fraction per LGAD layer for 5, 15 and 35 keV

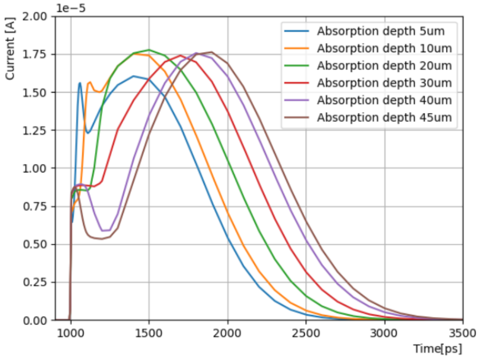


	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

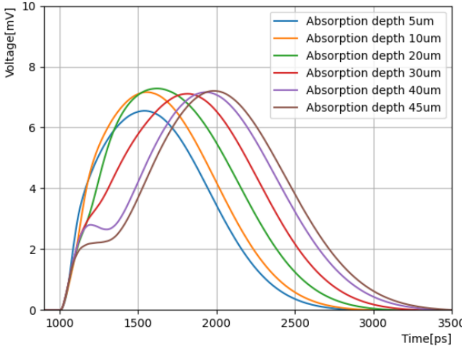
	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600



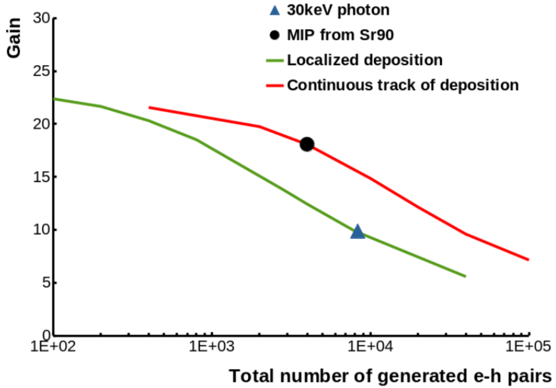
TCAD simulation of 50 μm LGAD signal response to a single 20 keV photon at different absorption depth.



(a) Current signal at the device level.



(b) Convoluted voltage signal with TIA.



Where to go from here

- None of the devices discussed here have been optimized for X-ray applications
  - However, results are very encouraging
- What we will need for photon sciences :
  - Higher energies needs thicker devices
  - Lower energies needs inverted design
  - X-rays produces localized primary charges -> Electrical field screening at different energies (see *Mazza et all*)
  - Wee need to understand better signal formation for X-ray (simulations)
- Final goal : explore the response of pixel devices (AC, TI LGAD)
- However, several applications in photon sciences can use coarse (un)segmented DC-LGADS
  - Machine development studies
  - Nuclear Resonance Scattering (NRS) experiments
  - etc ...
- Faster sensors ⇛ faster detectors ⇛ faster DAQ

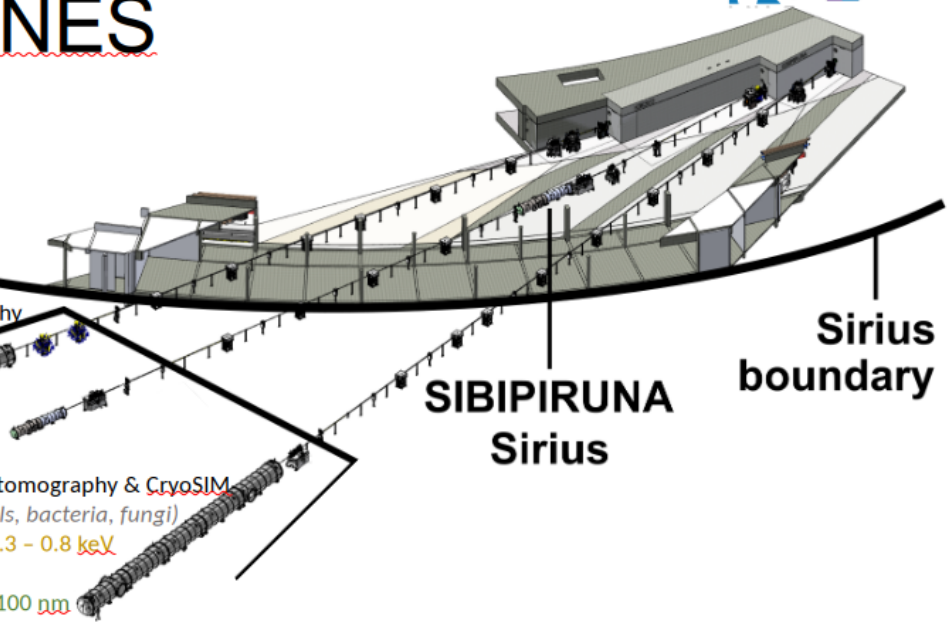
非常感谢！

This work was supported by
FAPESP (2022/14150-3, 2020/04867-2) and
MCTI/CNPq (INCT CERN Brasil 406672/2022-9).

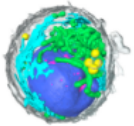
BACKUP

ORION BEAMLINES

H. Westfahl



HIBISCO
In-vivo propagation-based phase-contrast tomography
(insects, rodents, small NHPs)
Energy Range: 16 – 45 keV
FOV: 4-60 mm
Resolution: 1-100 mm

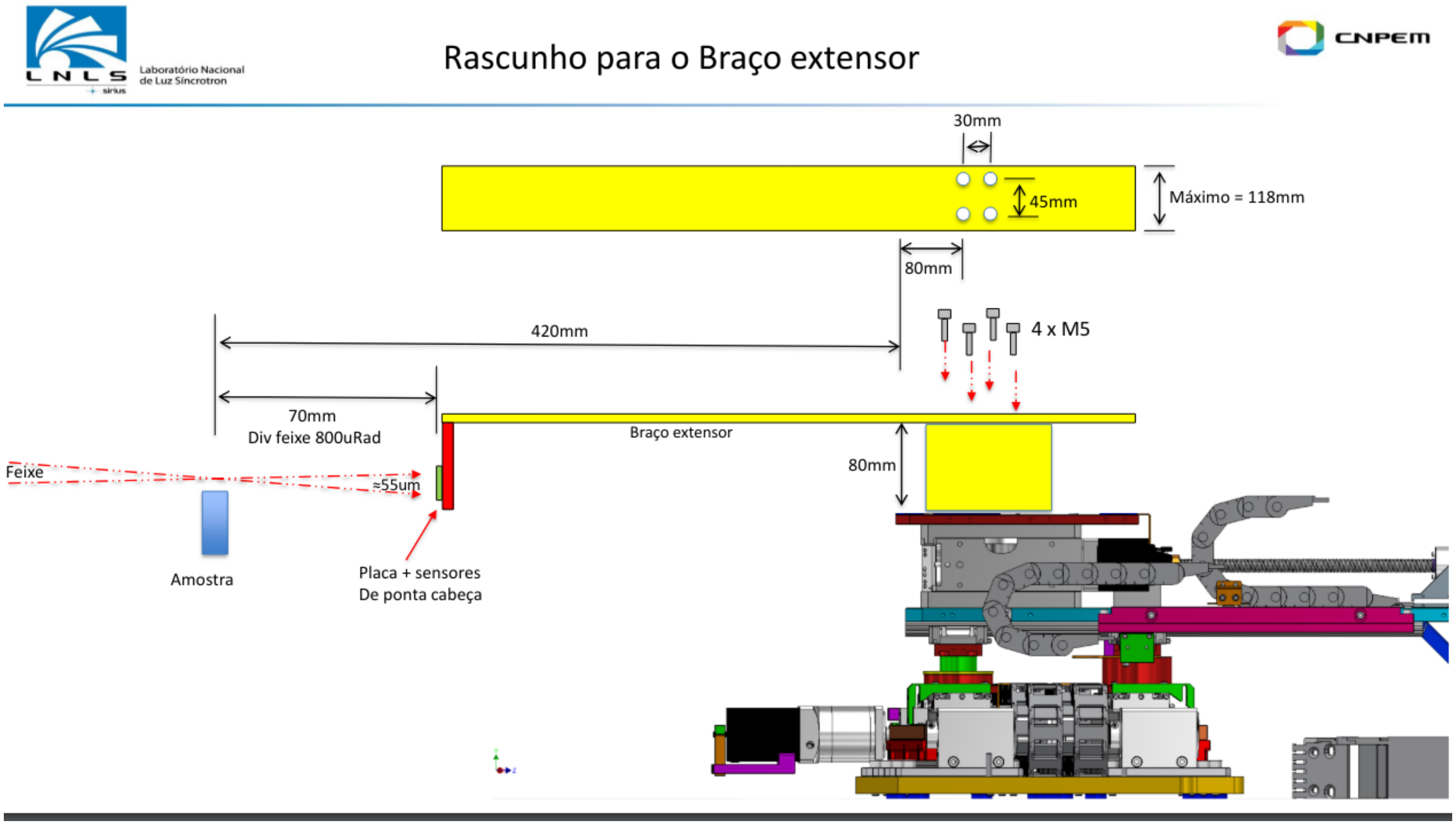


Loconte et al.,Cell Rep. Met. (2021)

SIBIPIRUNA
Cryo Soft X-Ray tomography & CryoSIM
(mammalian cells, bacteria, fungi)
Energy Range: 0.3 – 0.8 keV
FOV: 1-30 mm
Resolution: 30 -100 nm

Song et al. Cell (2024)

TIMBÓ
Cryo X-Ray ptychography of tissues
(virtual 3D histology)
Energy Range: 5 – 20 keV
FOV: 100 mm – 4 mm
Resolution: 50 nm – 1 mm


Laboratório Nacional
de Luz Síncrotron
LNLS
sirius
CNPEM
Rascunho para o Braço extensor
30mm
45mm
Máximo = 118mm
80mm
4 x M5
420mm
70mm
Div feixe 800uRad
Braço extensor
80mm
Feixe
≈55um
Amostra
Placa + sensores
De ponta cabeça