Synchrotron light source X-ray detection with Low-Gain Avalanche Diodes

Marco Leite[1]
leite@usp.br

for the UCSC-USP-LNLS collaboration :

Abraham Seiden[2], A. Molnar[2], Bruce Andrew Schumm[2] , Fernando Henrique Cardoso[3], Geovane Grossi Araujo de Souza[1], Guilherme Tomio Saito[1] , Hartmut Sadrozinski[2] , Jean Marie Polli[3], Jennifer Ott[2], Luana Santos Araujo[3], Marco Leite[1], Raul Back Campanelli[3], Rodrigo Estevam De Paula[1] , Simone Michele Mazza[2] , Yuzhan Zhao[2]

(1) Universidade de São Paulo - USP
(2) Santa Cruz Institute for Particle Physics - UC Santa Cruz
(3) Laboratório Nacional de Luz Síncrotron - CNPEM

1st DRD3 Workshop

CERN, June 18th 2024

Universidade de São Paulo

SCIPP SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS UC SANTA CRUZ

Laboratório Nacional de Luz Síncrotron

FAPESP FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

INCT CERN BRASIL

CNPq

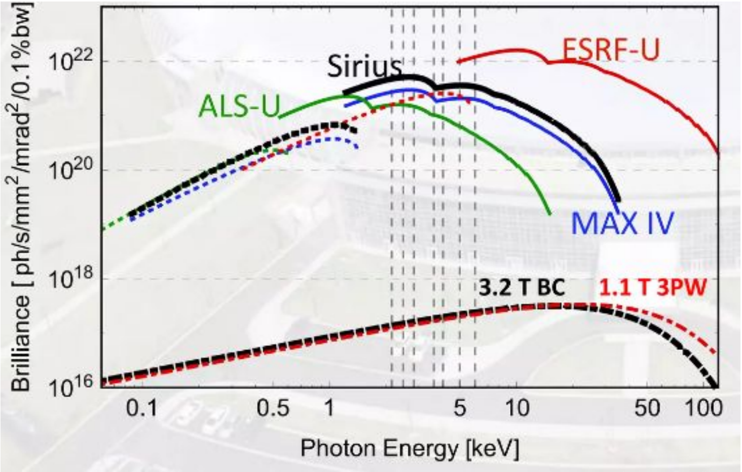
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

GOVERNO FEDERAL BRASIL UNIÃO E RECONSTRUÇÃO

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 to face these challenges :
  - Extensive R&D for HL-LHC timing detectors (ATLAS & CMS)
  - Intrinsic gain provides good signal-to-noise ratio (important low energy photon detection)
  - Very fast timing (timing-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

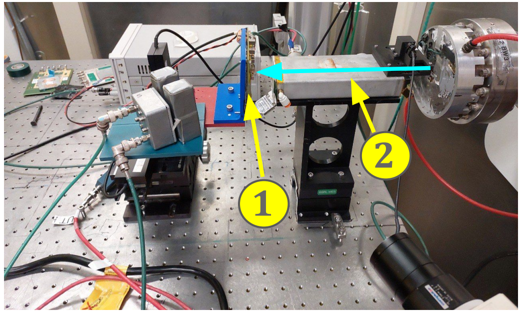
  III - AC-LGADS and Trench Isolated (TI) LGADS

Intro : The light source facilities

SSRL (SLAC) at Stanford (USA)

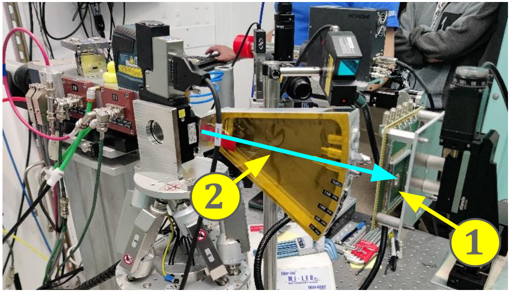
Sirius at LNLS-CNPEM in São Paulo (Brazil)

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}	$2 \times 30\ mm^2$

Beam Line 7-2 @ SSRL



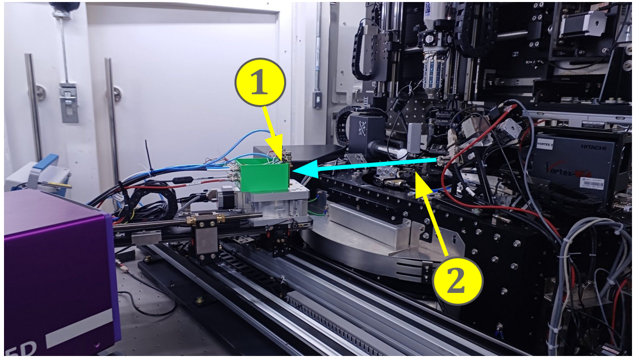
Source

20-pole, 2-Tesla wiggler, 0.5 mrad acceptance

Energy Range	Resolution ΔE/E	Spot Size
5000-16,200 eV	$1x10^{-4}$	50 and 100 micron

(1) LGAD (2) Beam direction

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.*

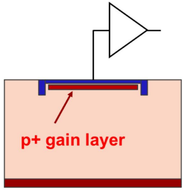
Both sites provide high intensity, quasi-monochromatic pulsed X-ray beams (10 ps wide pulses, 2 ns appart) with several geometries

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

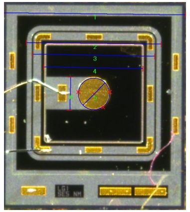
https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006

- "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

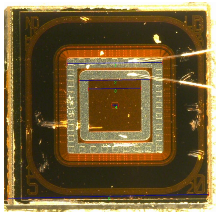
Ferrero et al.



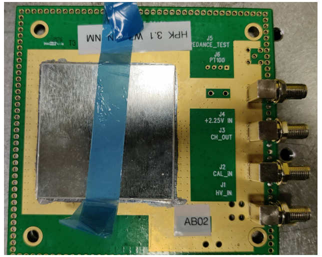
Low Gain Avalanche Diode



HPK DC LGAD



BNL DC LGAD



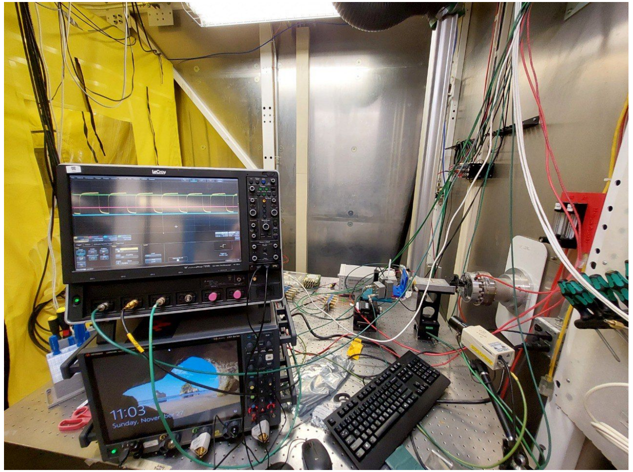
Santa Cruz board with LGAD and 1-ch. amplifier

Devices Tested

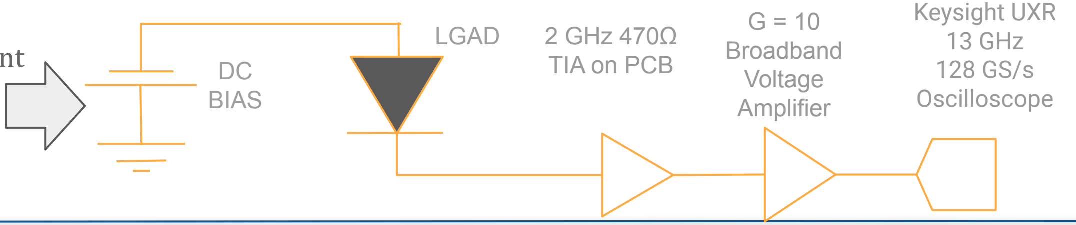
Device	Active Thick.	Gain Layer	Breakdown
HPK LGAD type 3.1	50 µm	shallow (1µm)	~230 V
HPK LGAD type 3.2	50 µm	deep (2µm)	~130 V
HPK PIN	50 µm	no gain layer	~400 V
BNL LGAD 20um	20 µm	shallow (1µm)	~100 V

This talk (HPK LGAD type 3.1)

See *Mazza et al* (HPK LGAD type 3.2, HPK PIN, BNL LGAD 20um)



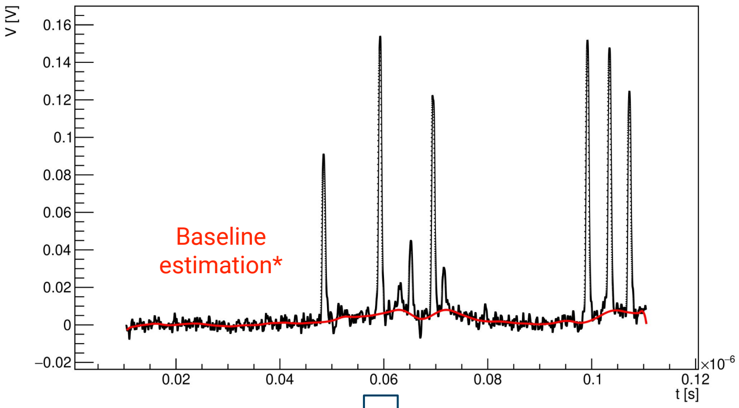
Measurement Setup

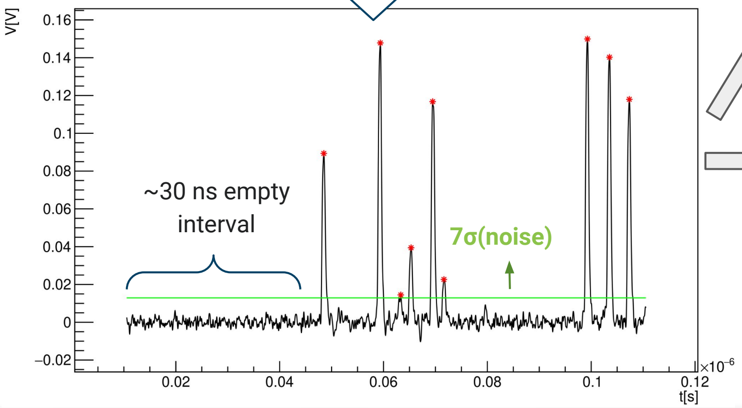


I - Single pad LGADS data processing

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

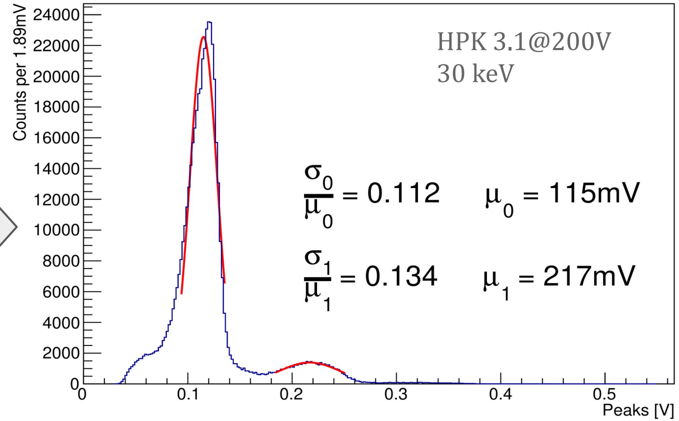
- All data from oscilloscope digitized waveforms





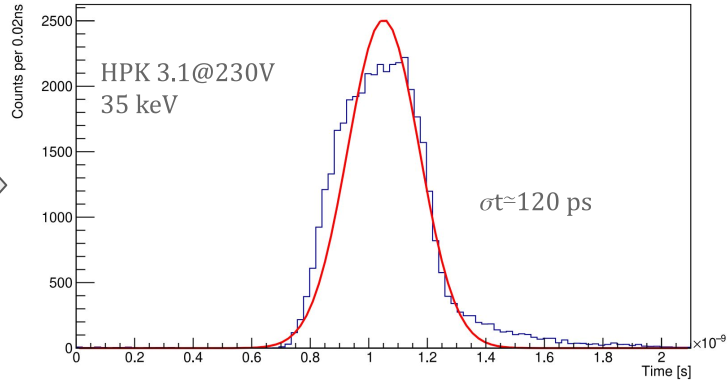
Energy

σE/E from Amplitude distribution



Timing

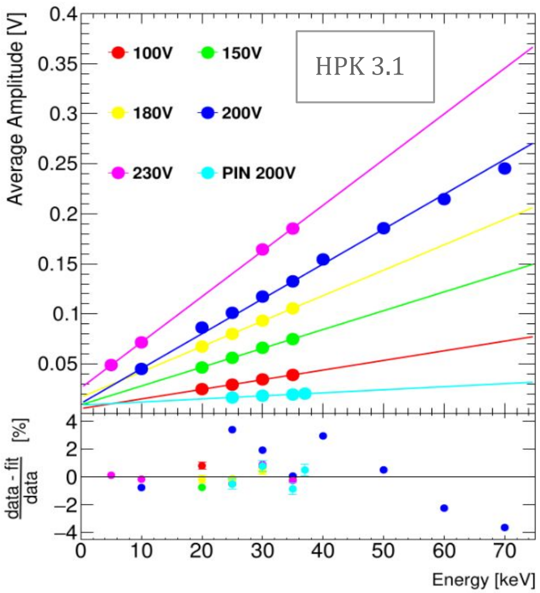
σt based on 2.1 ns interval (20% CFD)

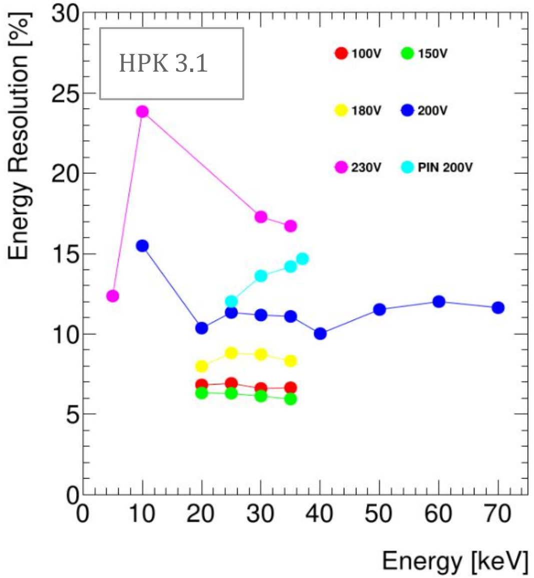


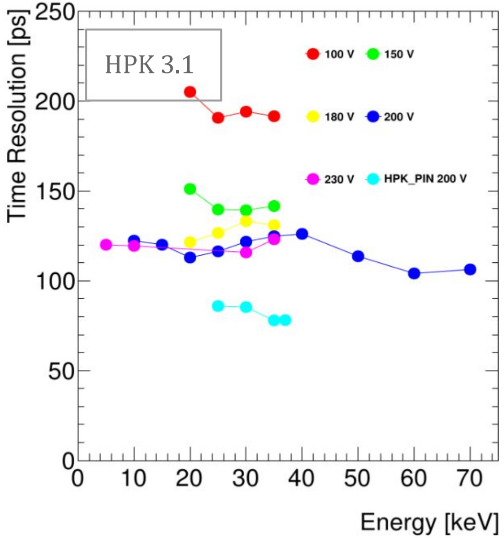
**asymmetric reweighted penalized least squares smoothing*

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**

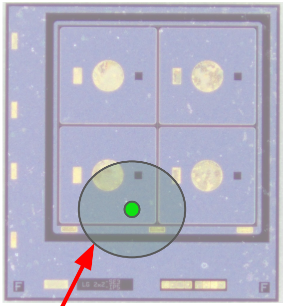
Bias [V]	150 V	230 V
Energy resolution	6%	17%
Energy response	75 mV	185 mV
Timing resolution*	141 ps	123 ps

For mip ~40 ps

*Note: BNL 20μm achieved 60ps

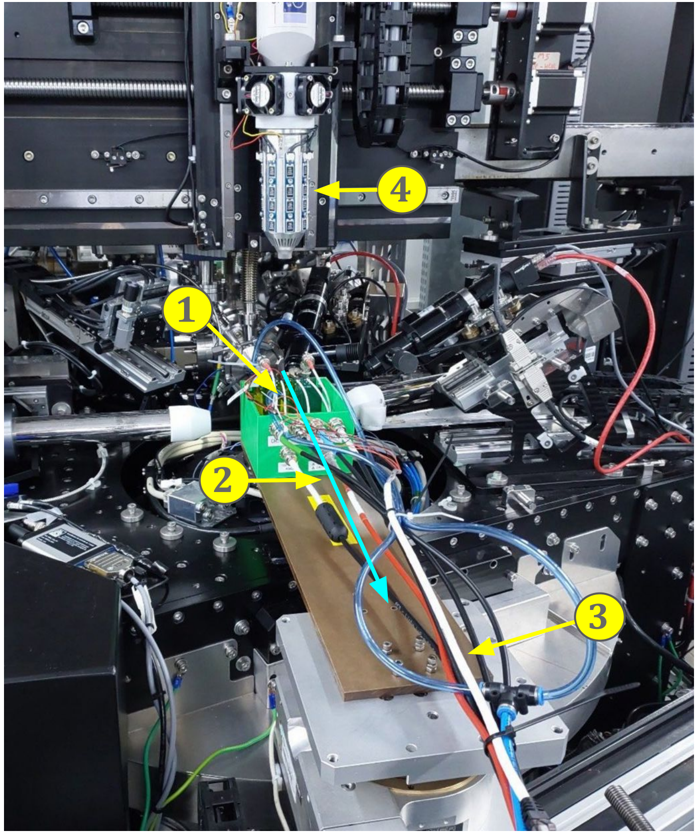
II - 2x2 LGADs (HPK 3.1) tests @ Sirius Carnaúba BL

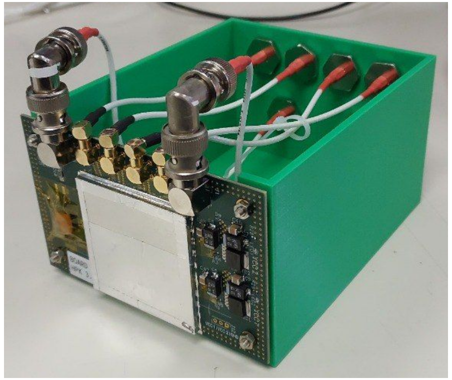
- ATLAS HPK 3.1 2x2 array prototype
- Beam size **350 μm** or **150 nm**
- Detector can move and rotate wrt to the beam
- LN2 nozzle can be used to **change temperature**
- **Energy/timing** resolution wrt
  - X-ray energy, bias and temperature
- EPIC by Sirius to control/store conditions
- Readout similar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

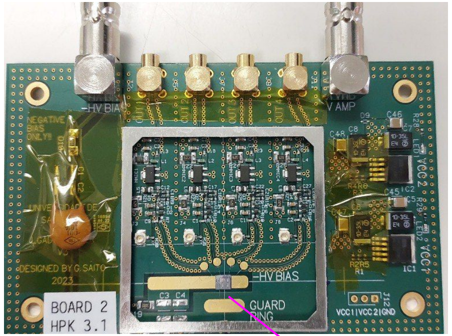


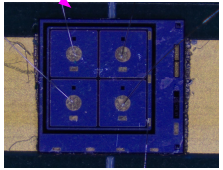
2x2 HPK 3.1 LGAD array

150 nm or 350 μm X-ray beam





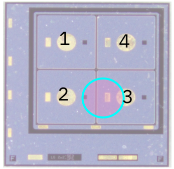




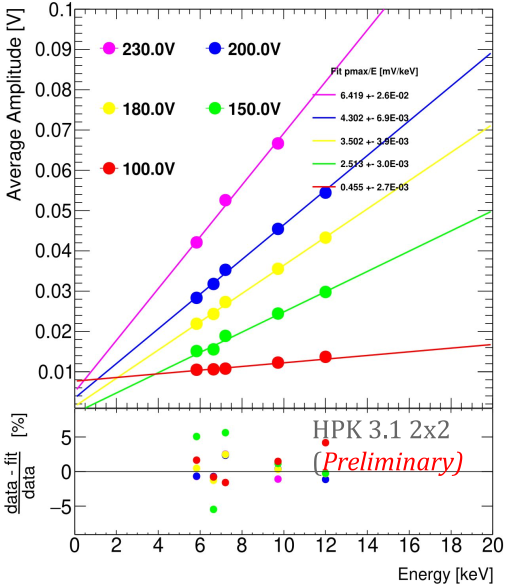
(1) **LGAD** (2) **Beam direction** (3) **Linear stage** (4) **Cooling nozzle**

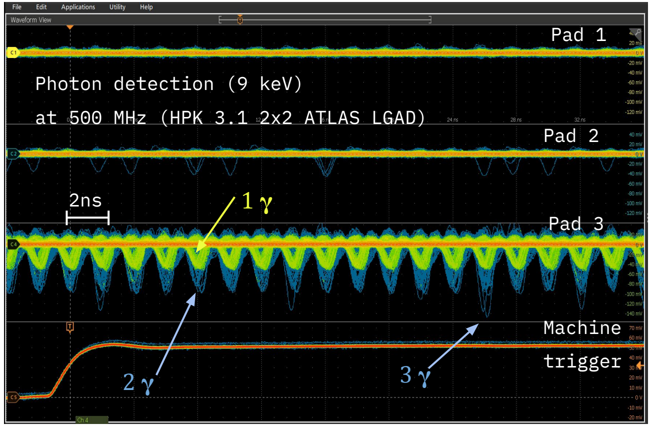
II - 2x2 LGADs (HPK 3.1) Energy response

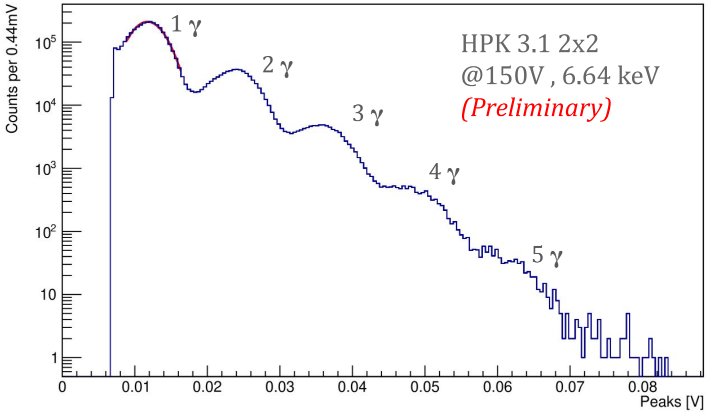
- Beam size 350 μm

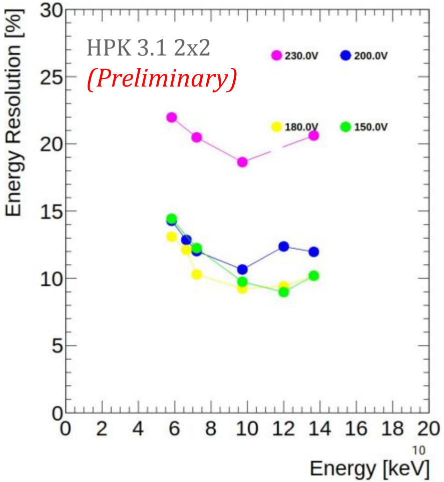


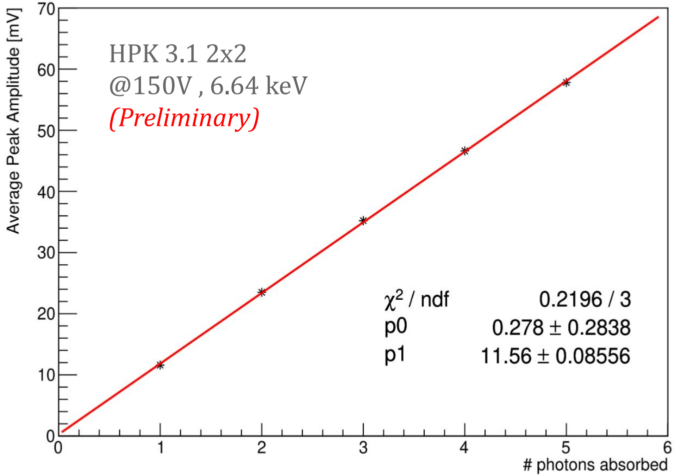
- Different X-ray energies, bias
- Multiple photon conversions





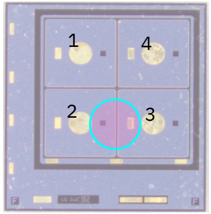


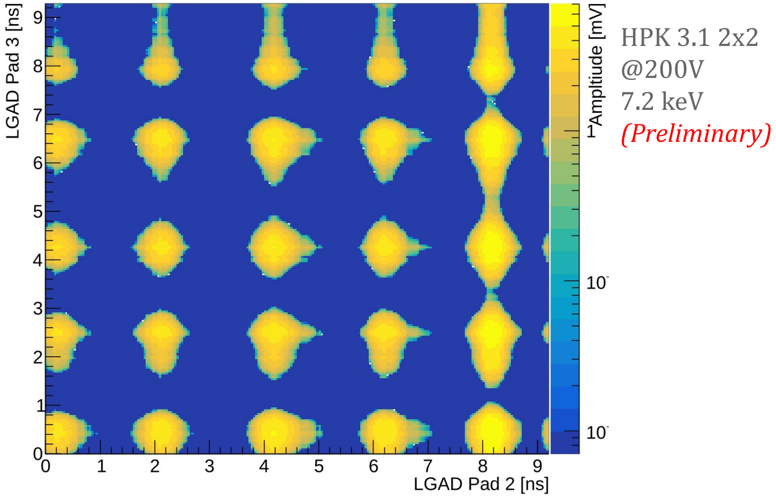


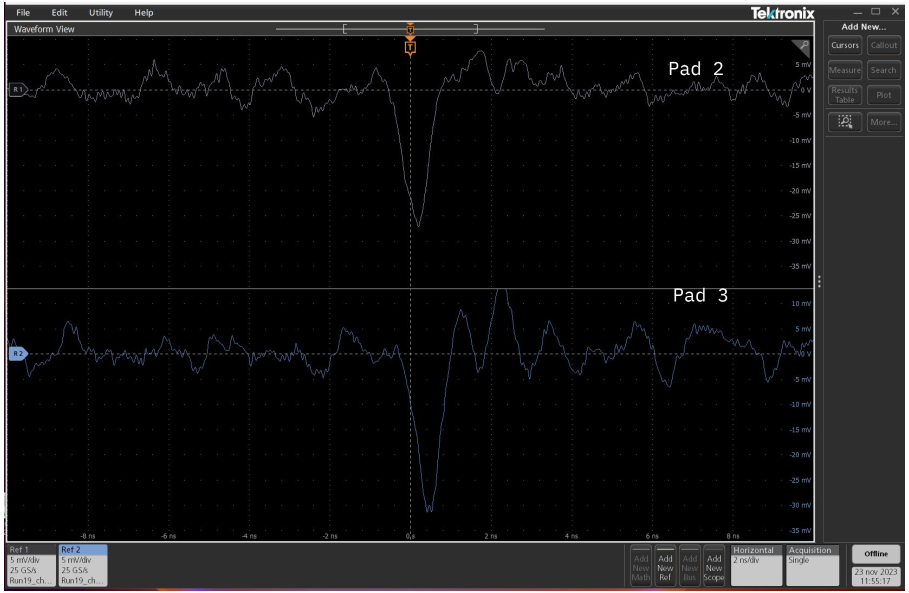


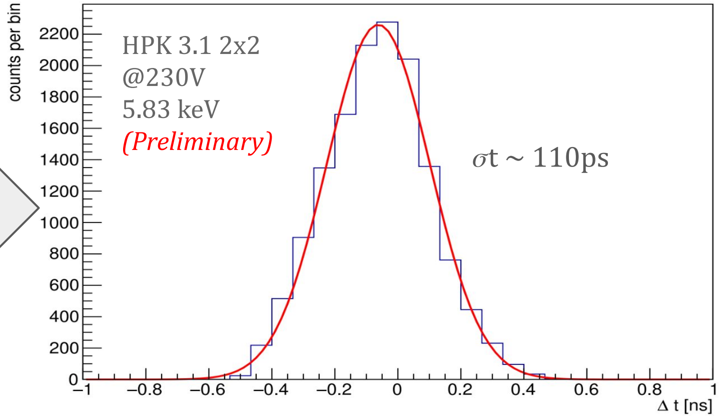
II - 2x2 LGADs (HPK 3.1) Timing response

- 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



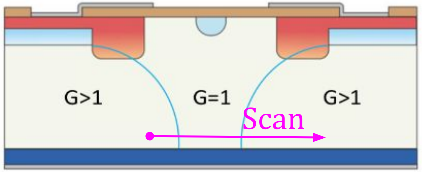




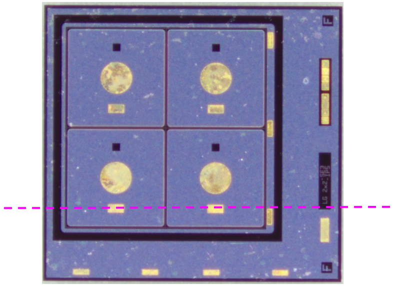


II - 2x2 LGADs (HPK 3.1) Interpad measurements

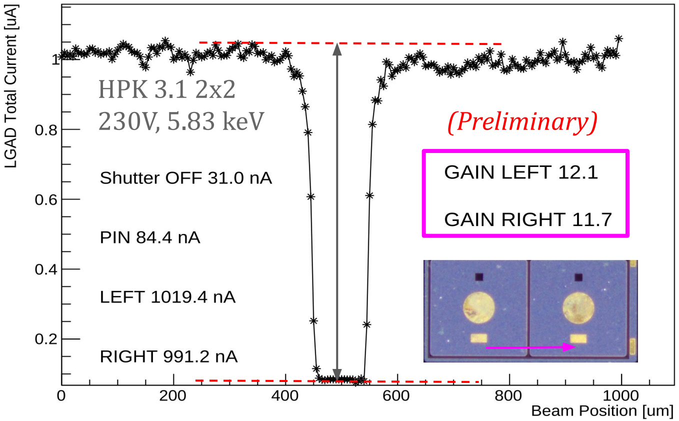
- **150 nm beam**
- $5\mu m$ step beam lateral scan

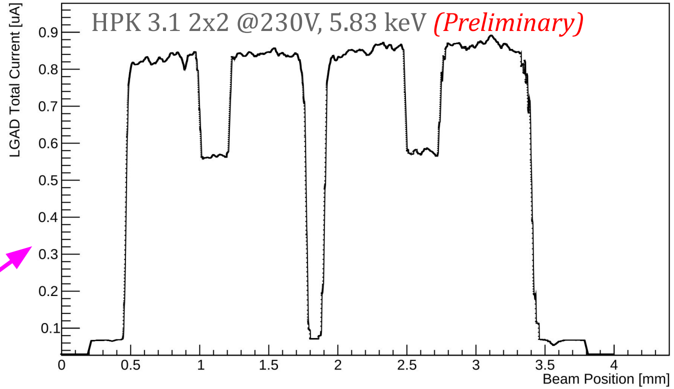


- Extract device gain from ratio (G>1) / (G=1) region (Skomina et al)

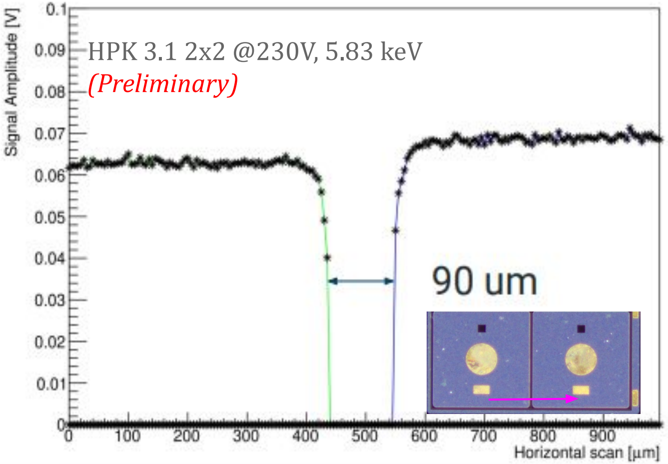


LGAD **CURRENT** profile





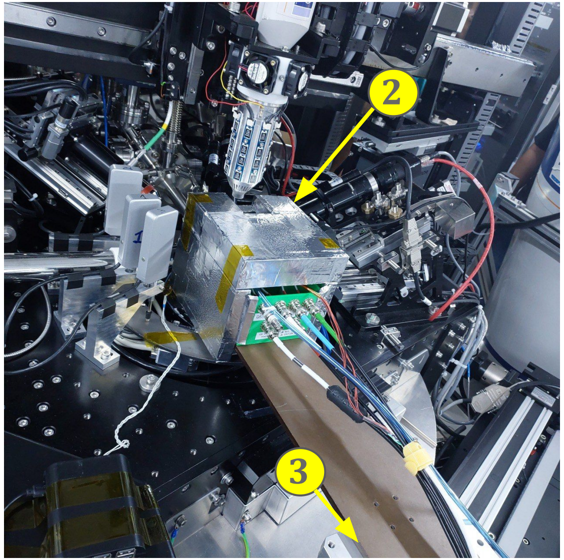
LGAD **PULSE AMPLITUDE** profile

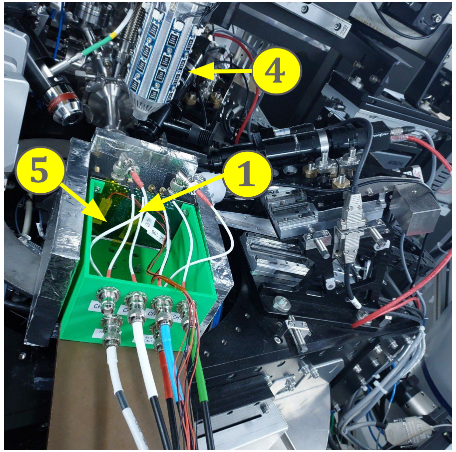


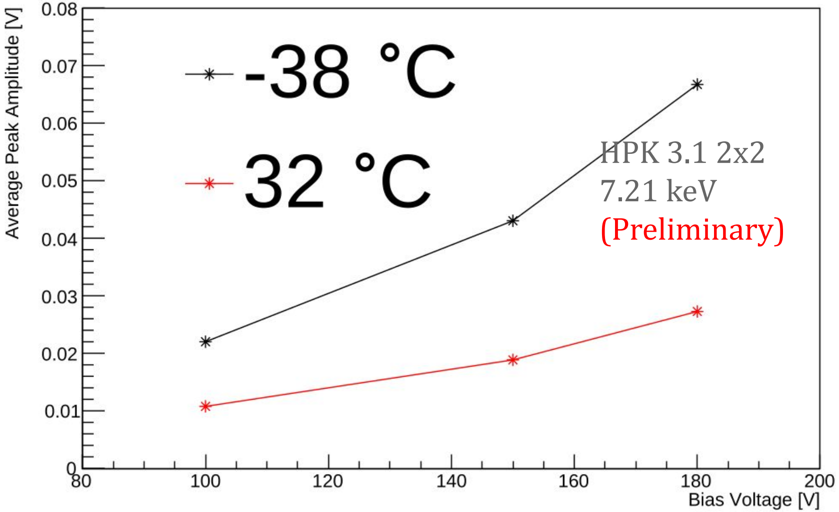
II - 2x2 LGADs (HPK 3.1) temperature response

- 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





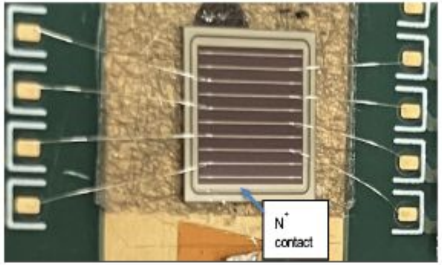


1 LGAD **2 Insulator box** **3 Linear stage** **4 N2 Nozzle** **5 PT100**

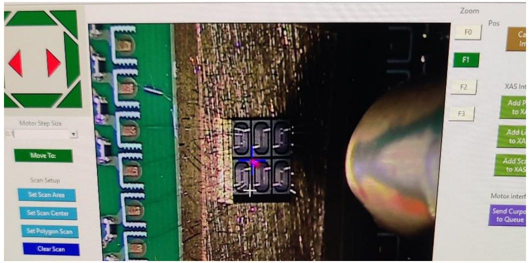
III - AC-LGADs and TI-LGADS tests at SLAC BL 7-2

- Beamline SSRL 7-2, focused beam (~30μm) with 6-16 keV
- Tested sensors reported here :
  - AC-LGADs strips
  - TI-LGADs strips and 2x1

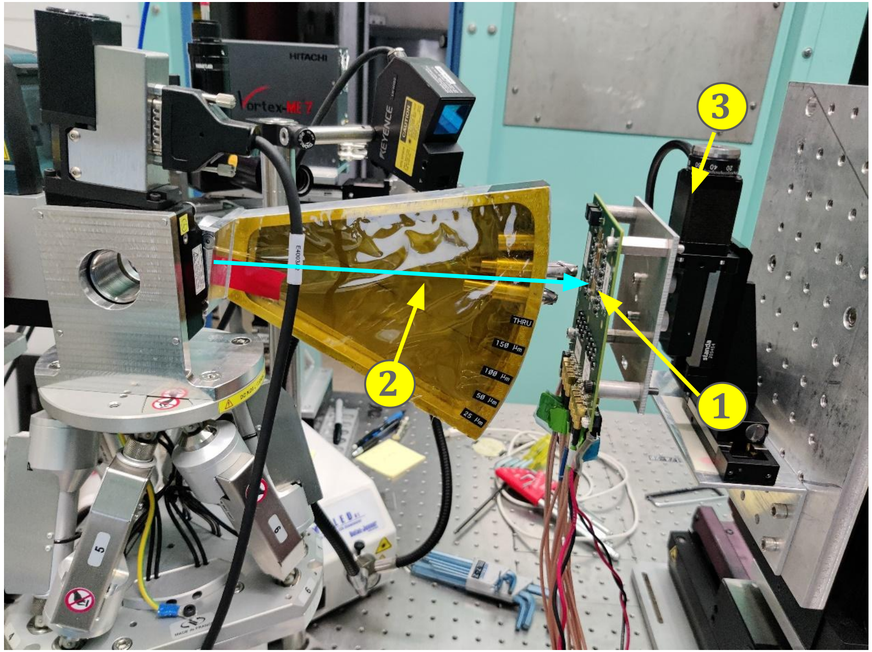
HPK AC-LGAD strips



FBK TI-LGAD 2x1

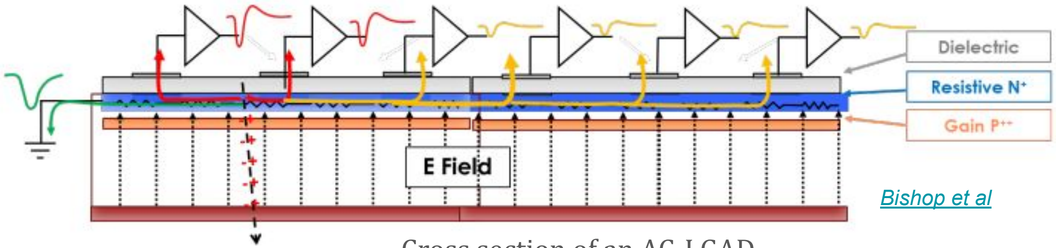


- Sensors mounted on FNAL 16ch boards



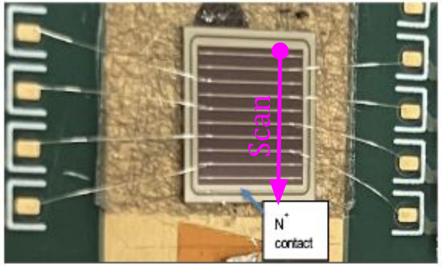
1 **LGAD** 2 **Beam** 3 **Linear stage**

III - HPK (E600) AC-LGADs position scan



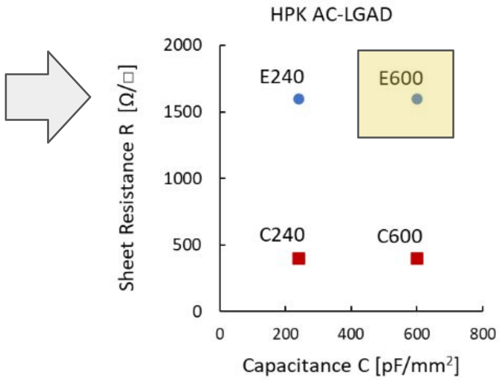
Cross section of an AC-LGAD

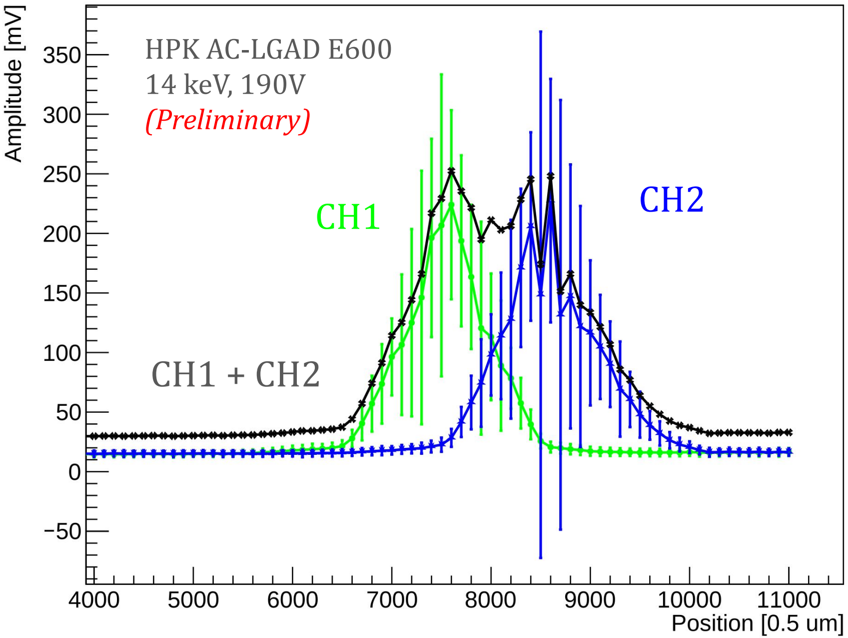
Length 5mm,
pitch 500μm,
width 50μm



X-RAY SCAN

HPK AC-LGAD
flavors

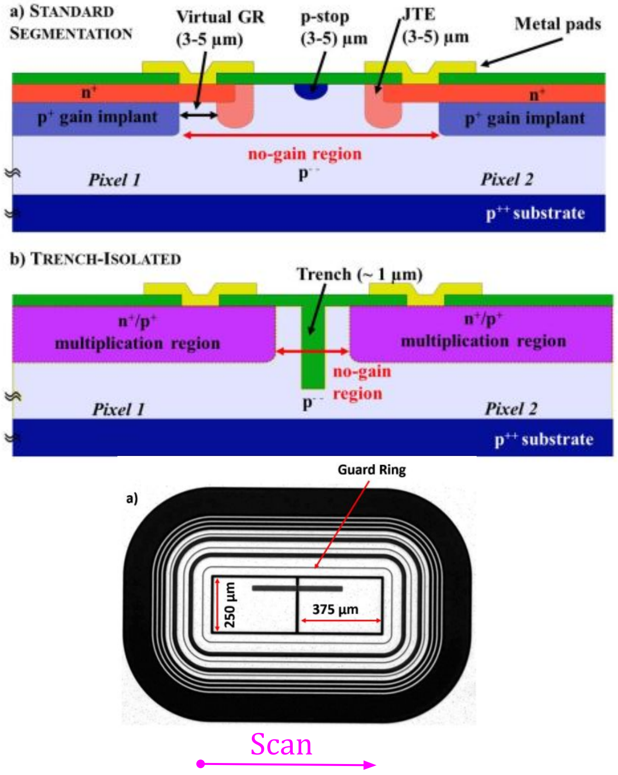


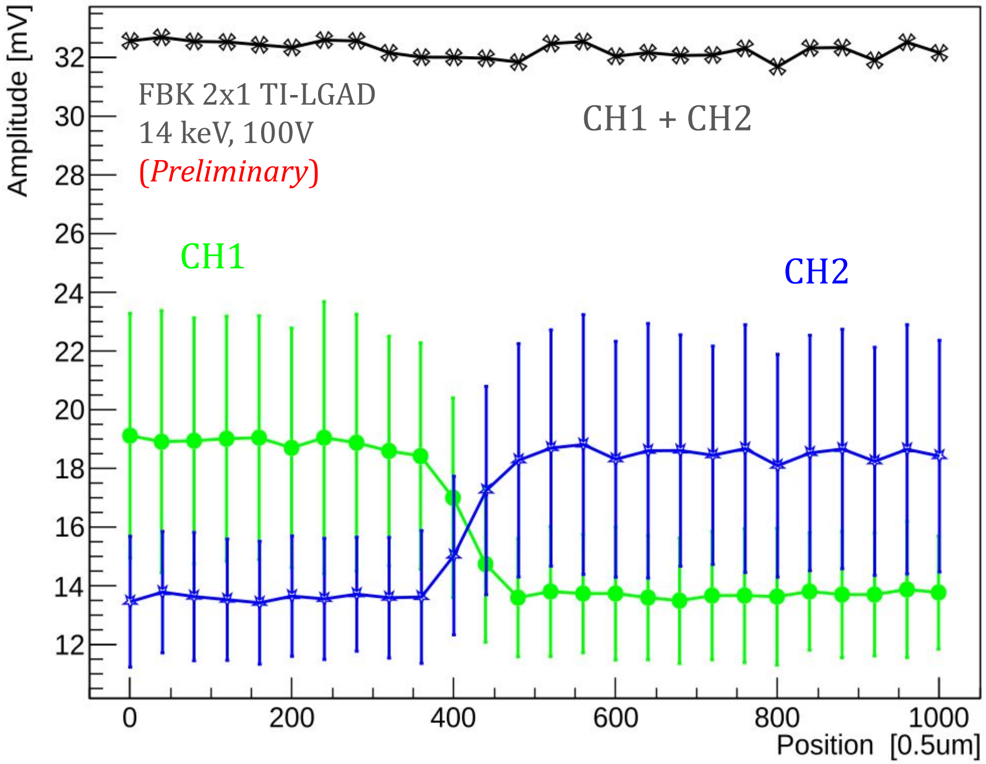


III - TI-LGADs 2x1 (FBK) position scan

- FBK TI-LGAD sensor from RD50 production, test structures 2x1 (Paternoster et al)
- **Showing no loss in the inter pad region for the sum**

Paternoster et al





Final Remarks

- 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 mm size devices can be used at beam lines for diagnostics and beam studies
- We plan to continue the tests on both facilities, focusing on alternative segmented LGAD designs
  - Sirius will soon start the construction of two new beamlines dedicated for instrumentation development
- In parallel, we will continue developing the simulation studies to better understand the LGAD response under X-rays
- The gained knowledge can provide feedback to collider applications as well

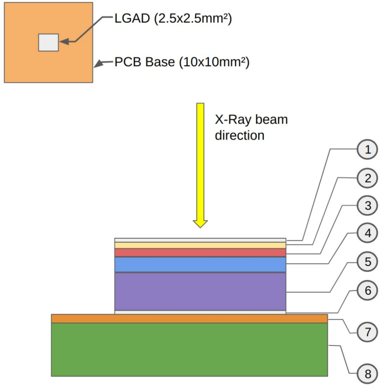
Thank you !

BACKUP

IV -Simulations (HPK 3.1 single pad)

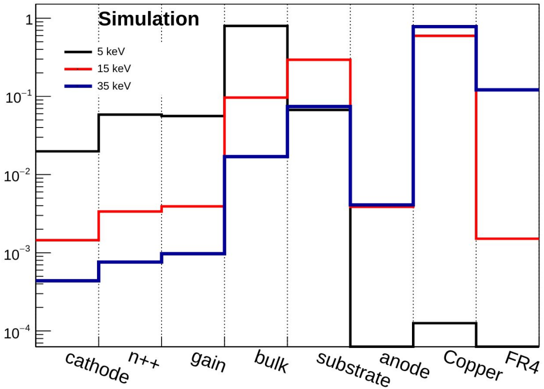
https://iopscience.iop.org/article/10.1088/1748-0221/18/10/P10006

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

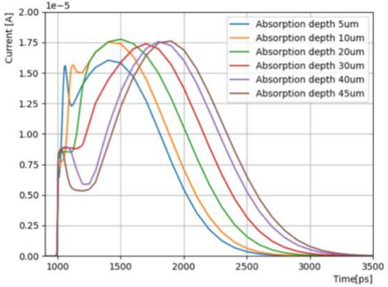


	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

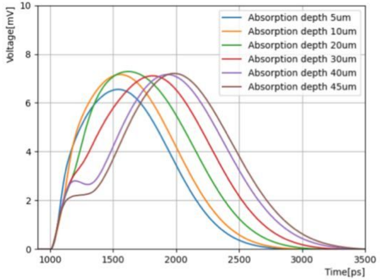
	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600



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.

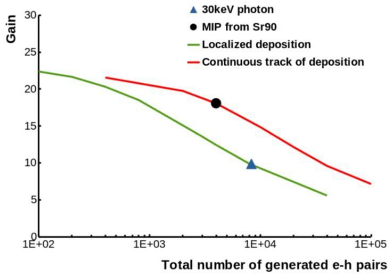
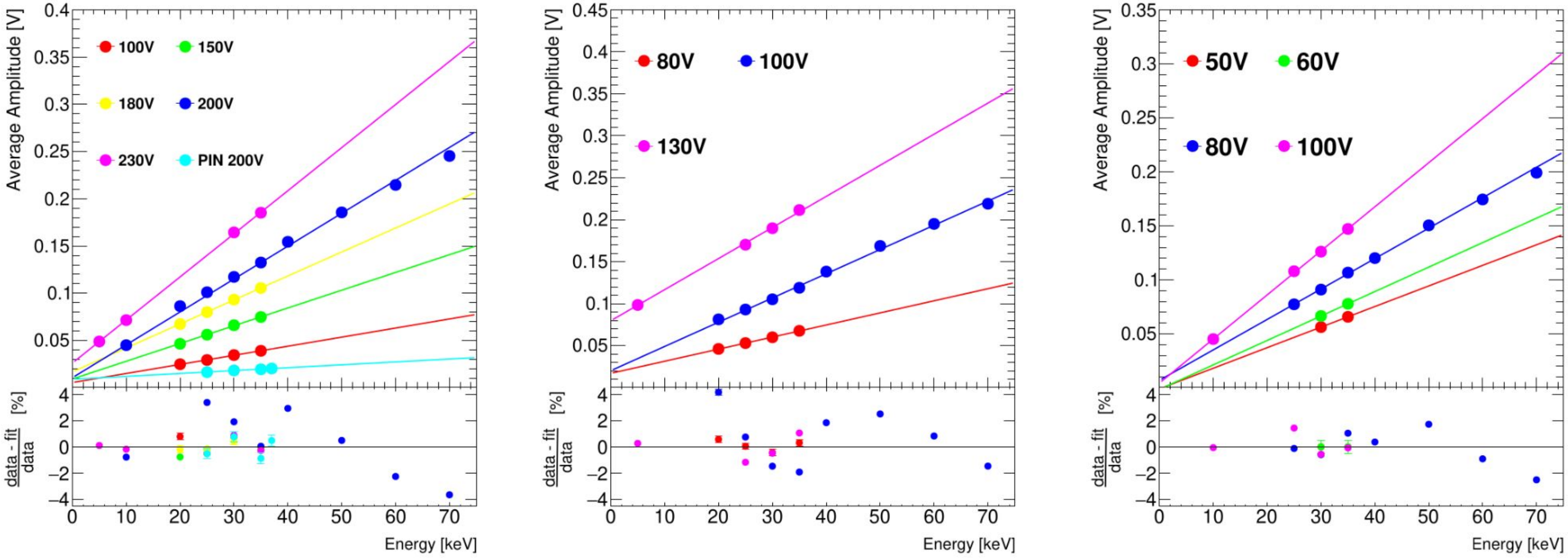


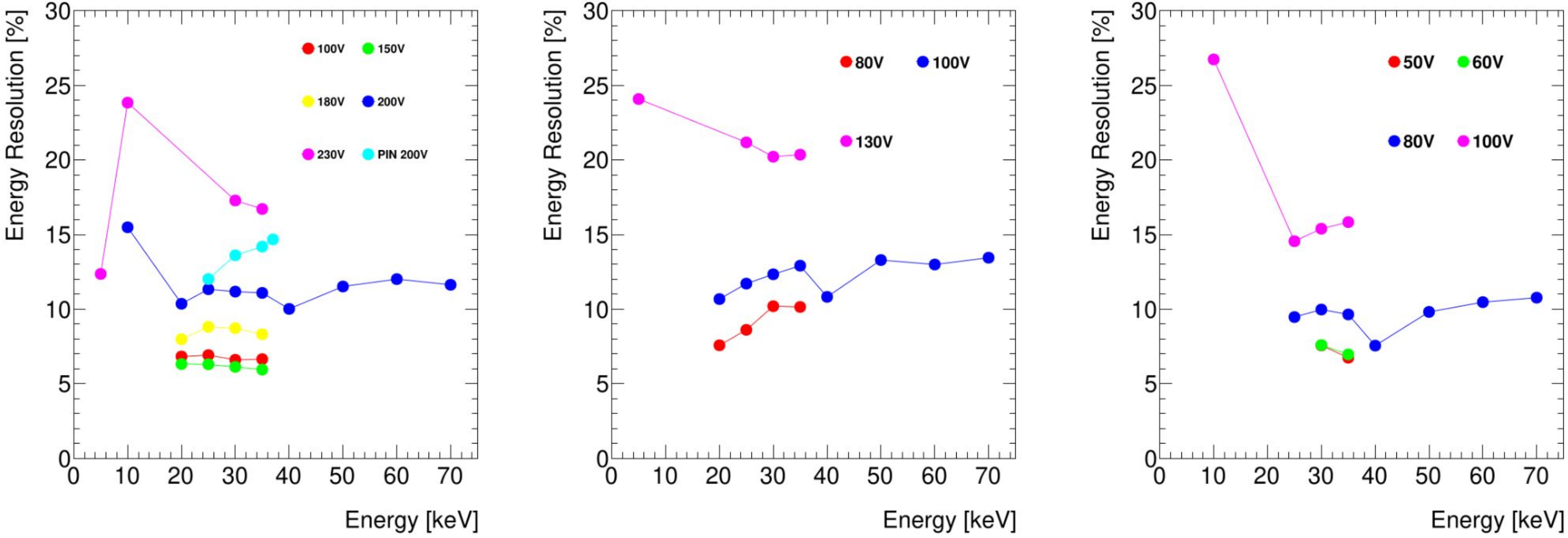
Figure 9: TCAD simulated gain for continuous track of energy deposition (MIP) and localized energy deposition (X-ray). The gain corresponding to a MIP from ^{90}Sr and a 30 keV X-ray are highlighted in the plot.

DC LGADs Tests at Light sources



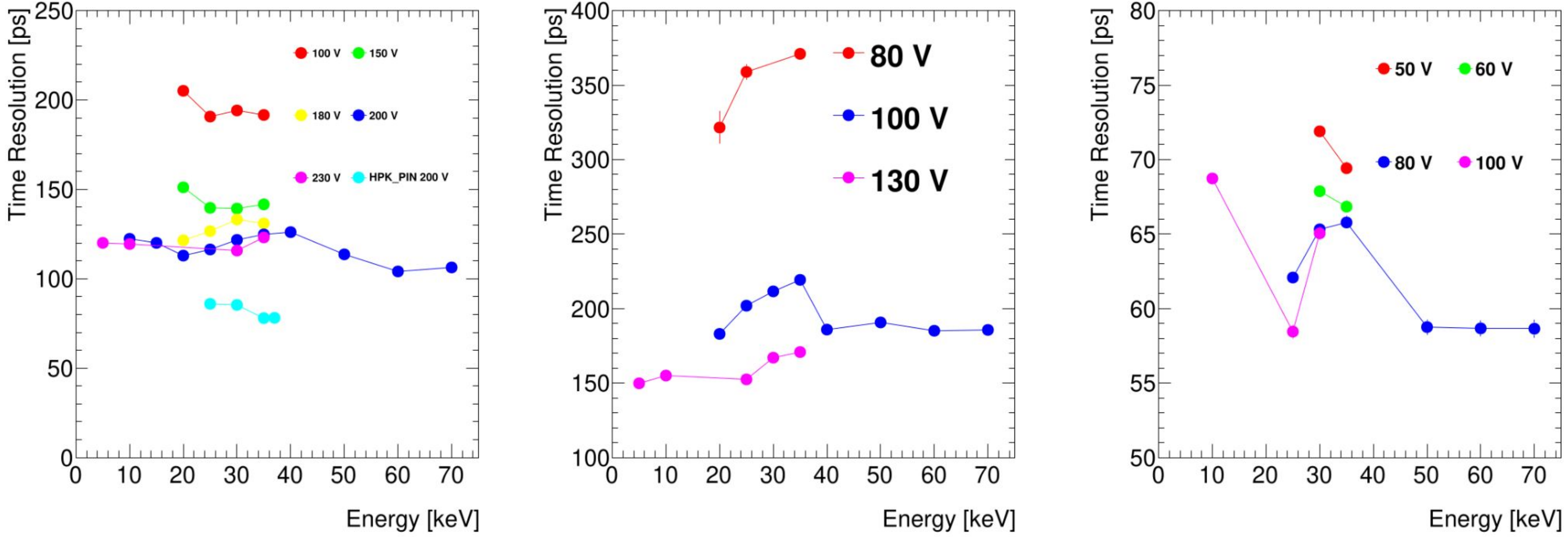
(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

DC LGADs Tests at Light sources



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

DC LGADs Tests at Light sources



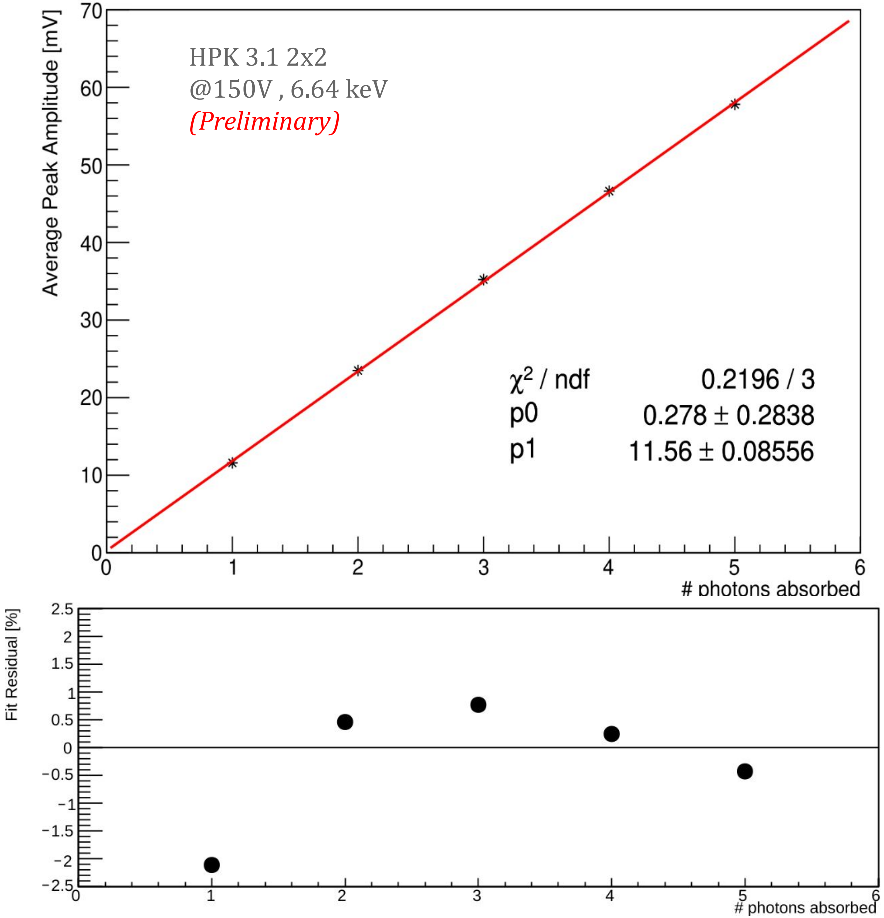
(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

DC LGADs Tests at Light sources

	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

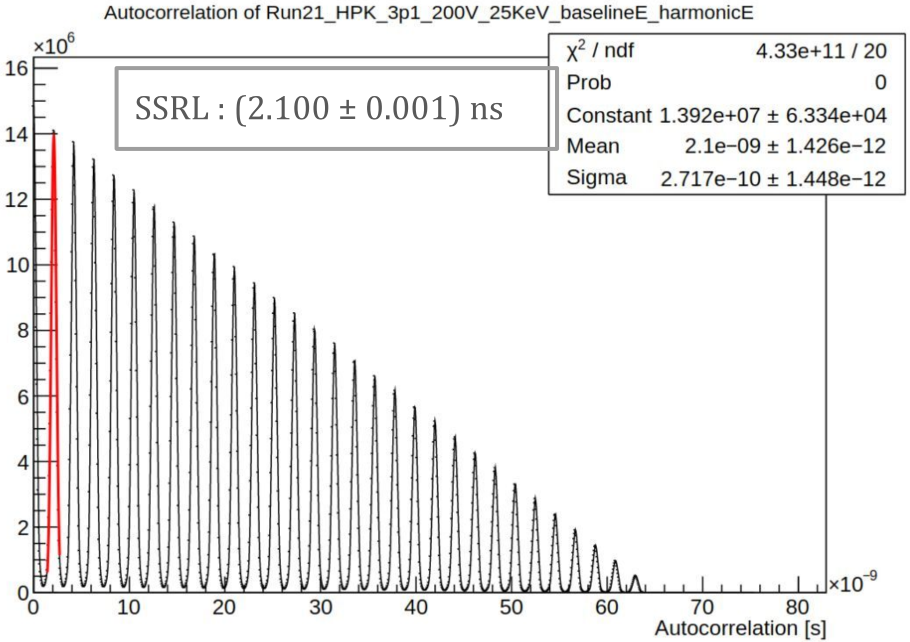
Table 2: Summary of energy and time resolution for the three tested sensors for the different bias voltages that yield the best energy and best time resolution for a 35 keV X-ray beam energy.

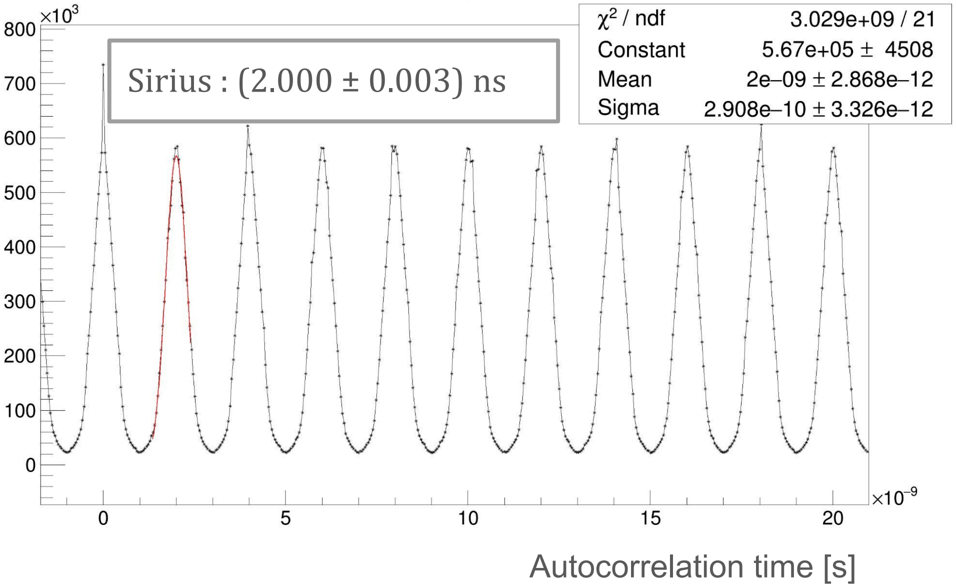
II - 2x2 LGADs (HPK 3.1) Energy response



Autocorrelation of Digitized Signals

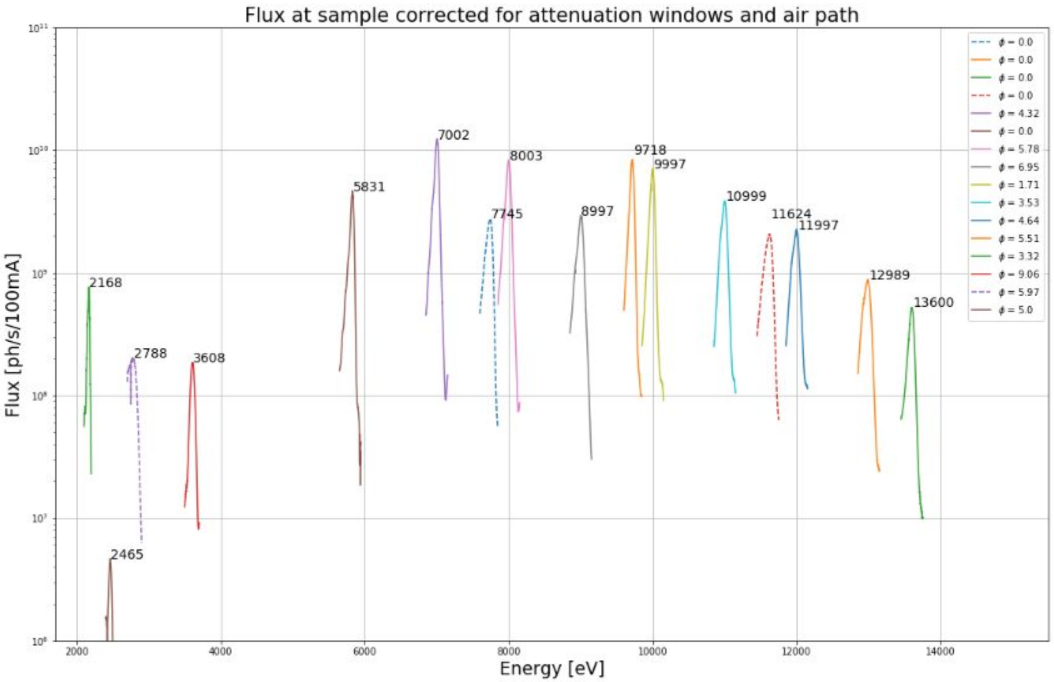
- Used to measure the bunch separation
- SSRL had a non-uniform filling (empty-1 bunch - empty-fill) per orbit
- Sirius had full orbit filled with bunches





Carnaúba beam line energies

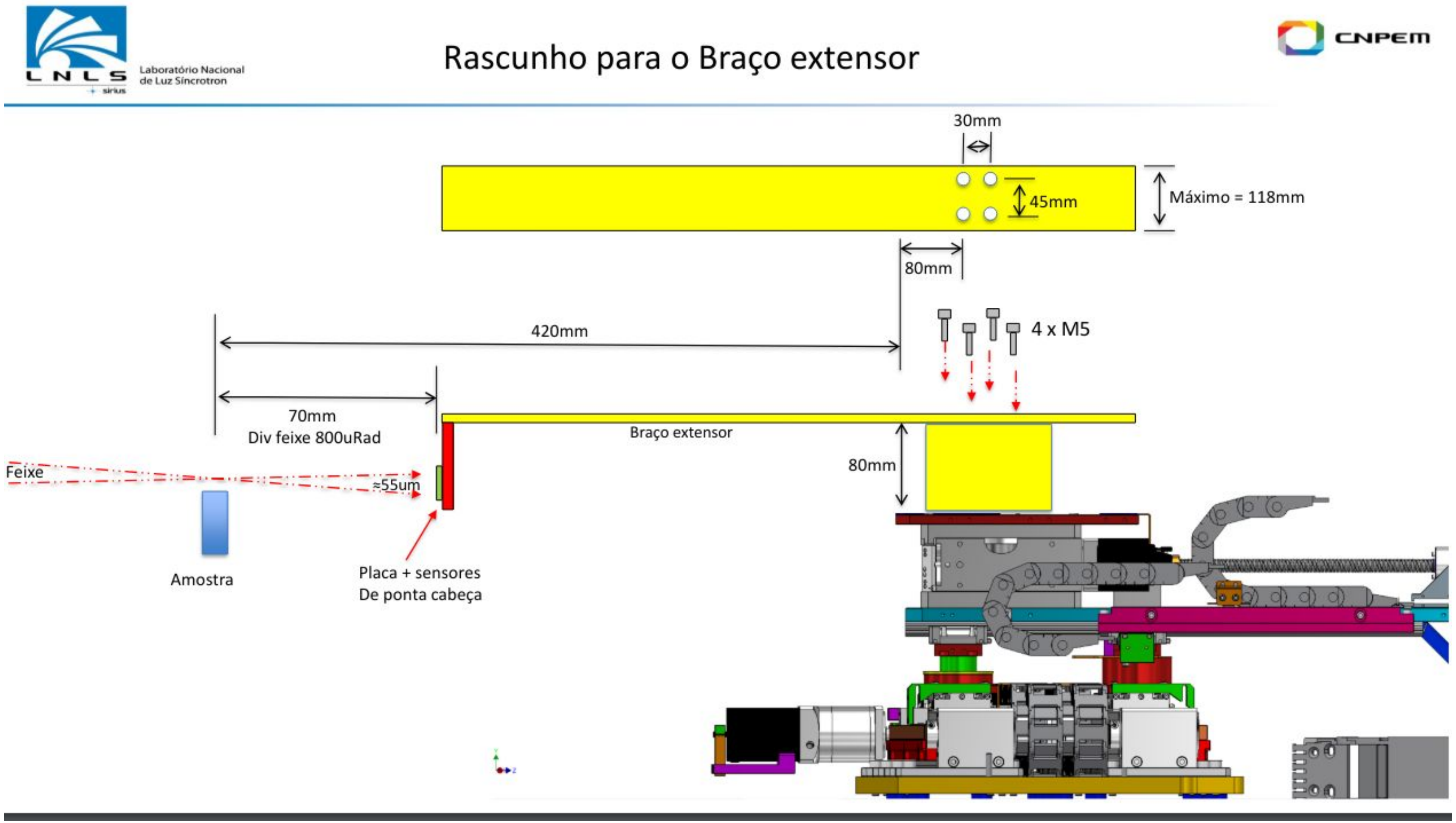
Flux at sample corrected for attenuation (log plot)



MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

GOVERNO FEDERAL BRASIL UNIÃO E RECONSTRUÇÃO

Carnaúba beam line setup



HPK AC-LGADS

Table 1: Parameters of the tested HPK AC-LGAD

		Wafer			Strip		
	Wafer #	N^+ Sheet Resistance [Ω/□]	Dielectric C (pF/mm^2)	Bulk Thickness T [µm]	Lenght L (mm)	Width W (µm)	Pitch P (µm)
HPK1	W02	E: 1600	240	50	5	50	500
HPK3	W05	E: 1600	600	50	5	50	500
HPK4	W08	C: 400	600	50	5	50	500
HPK8	W04	C: 400	240	50	5	100	500
HPK21	W05	E: 1600	600	50	10	100	500
HPK22	W08	C: 400	600	50	10	100	500
HPK27	W05	E: 1600	600	50	20	50	500
HPK28	W08	C: 400	600	50	20	50	500
HPK29	W09	E: 1600	600	20	20	50	500
HPK35	W09	E: 1600	600	20	20	100	500