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

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- → Data taking setup
- → LGAD X-ray response
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LGADs as X-ray detectors

Low-Gain Avalanche Diodes - LGAD

State-of-the-art in time measurement for the **LHC detectors**

Originally intended for **charged particles** detection

A type of silicon PIN diode with a **moderate internal gain**:

➔ Allows detection of low-energy X-rays
➔ Good time resolution - > very high repetition rate

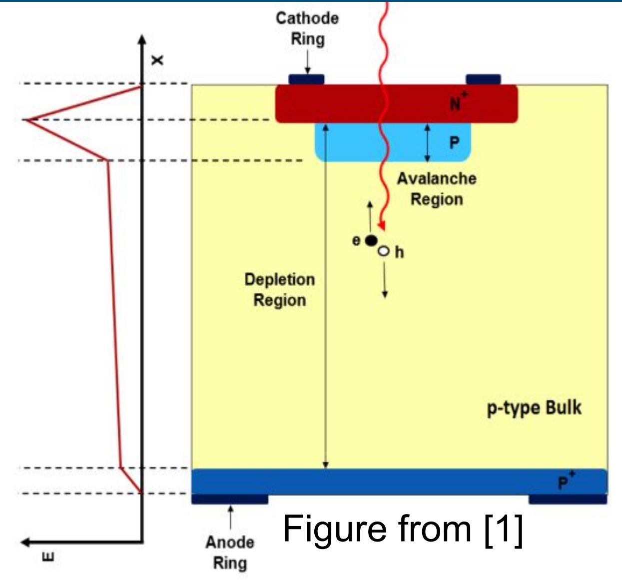


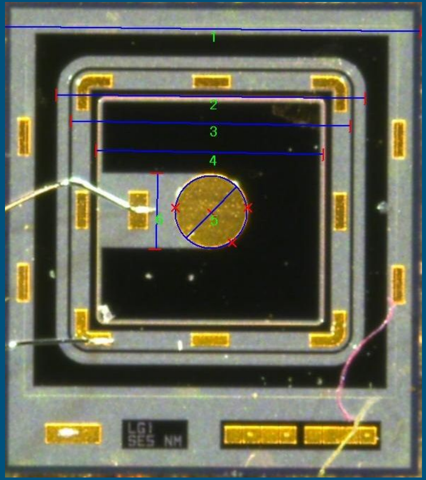
Figure from [1]

Advanced techniques on X-ray imaging will feature **repetition rates of GHz** and **require µm resolution**

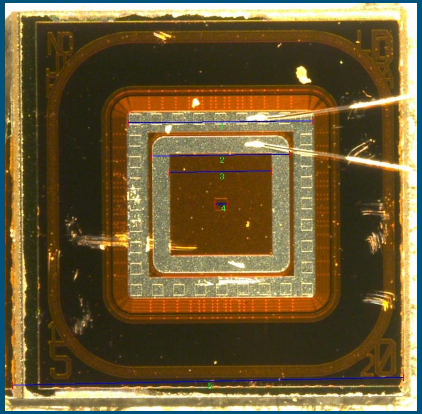
Devices Tested

Device	Active Thickness	Gain Layer	Breakdown
HPK LGAD type 3.1	50 µm	shallow	~230 V
HPK LGAD type 3.2	50 µm	deep	~130 V
HPK PIN	50 µm	no gain layer	~400 V
BNL LGAD 20um	20 µm	shallow	~100 V

HPK device



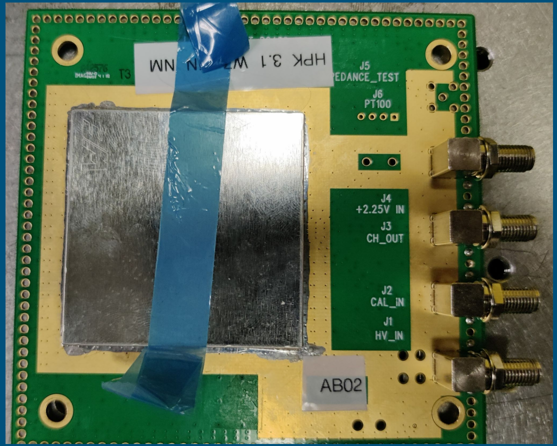
BNL 20um



All devices are single pad
1.3 x 1.3 mm^2

Shallow: ~1µm
Deep: ~2µm

PCB with LGAD and 1-channel amplifier

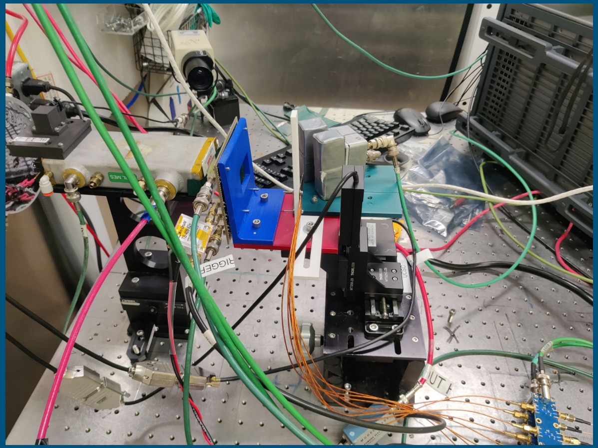


HPK: Hamamatsu Photonics
BNL: Brookhaven National Laboratory

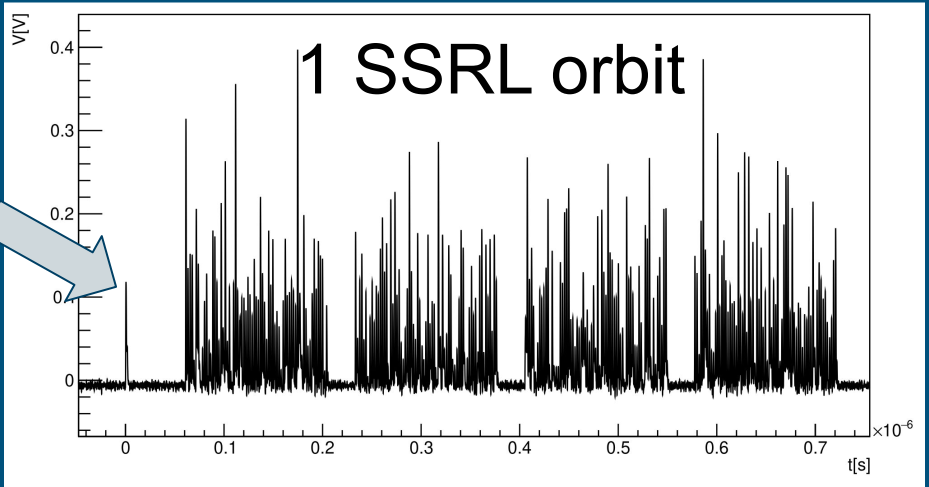
Data taking setup on SSRL

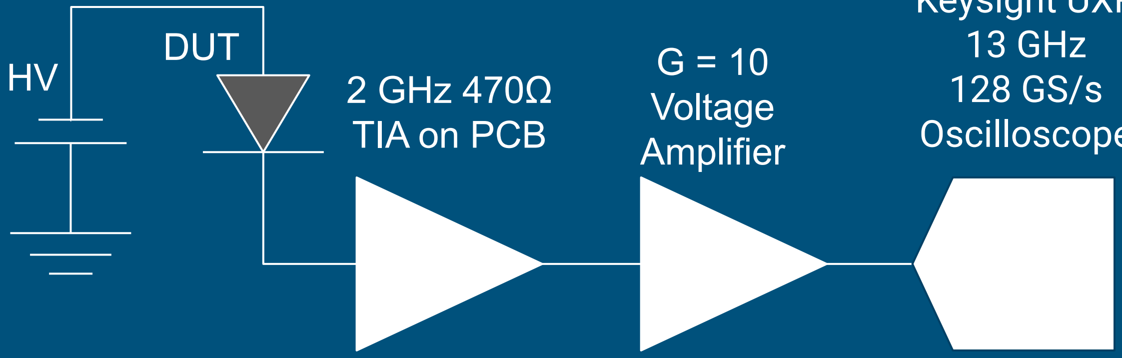
Stanford Synchrotron Radiation Lightsource SSRL 11-2 beamline

- ➔ 25 mm x 1 mm
- ➔ 5 to 70 keV
  - ◆ $\Delta E/E \approx 10^{-4}$
  - ◆ Monochromator to filter harmonics
- ➔ 4 groups of 70 bunches
  - ◆ 10 ps length (RMS)
  - ◆ Separated by 2.1 ns
- ➔ Room temperature



In phase with trigger from the beamline: Used on time resolution estimation





Signal Analysis

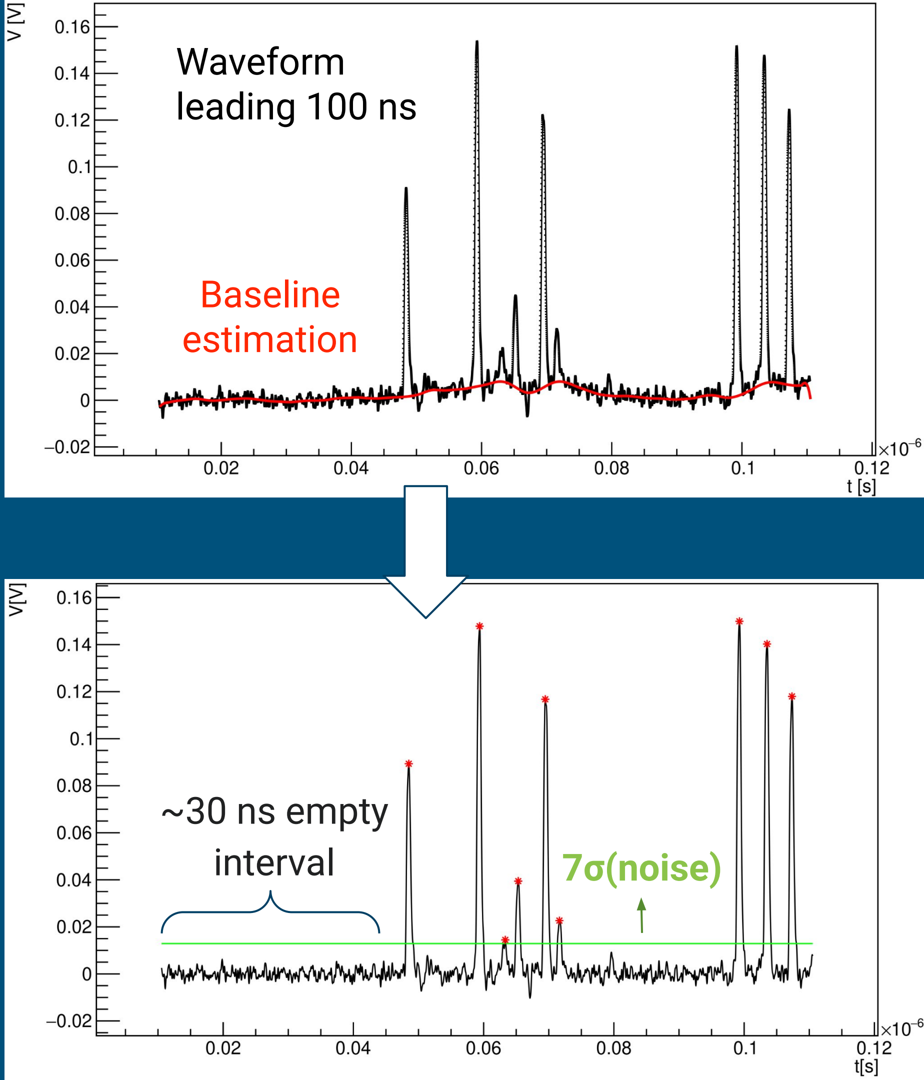
Non-negligible baseline shift:

- Corrected with asymmetrically re-weighted penalized least squares smoothing [2]

Peak Finding:

➔ Amplitude > 7σ(noise on empty interval)
➔ At least 2.1 ns separation

Signal amplitude as energy estimator



Energy Estimation

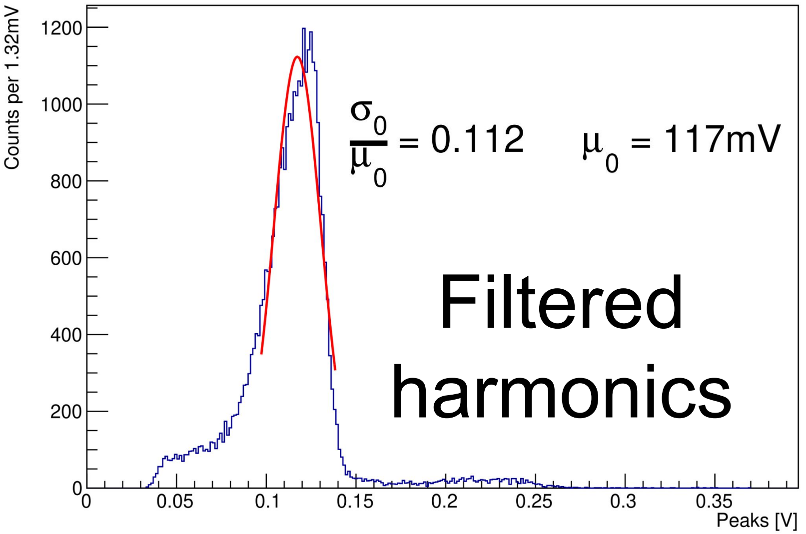
For **each** energy, bias voltage and sensor:

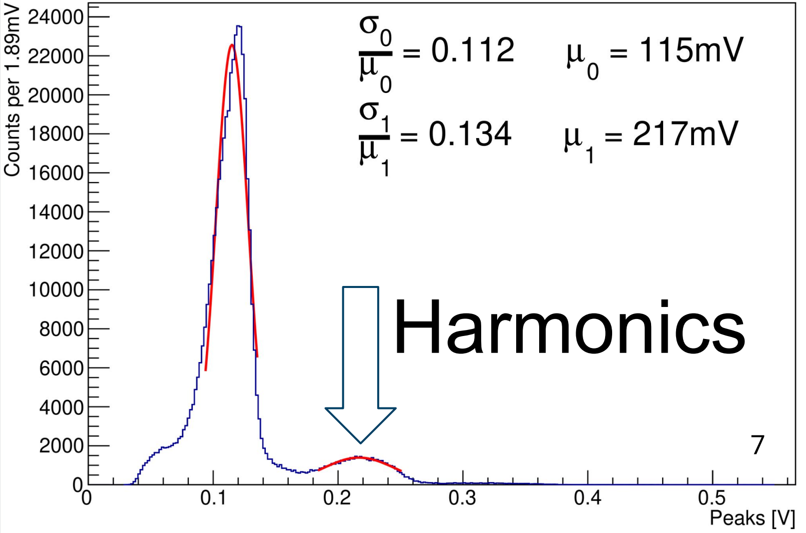
- ➔ Distribution of all signal amplitudes
- ➔ σ and μ from **Gaussian fit** on tallest peak
  - Energy: μ
  - Resolution: σ / μ

Harmonics:

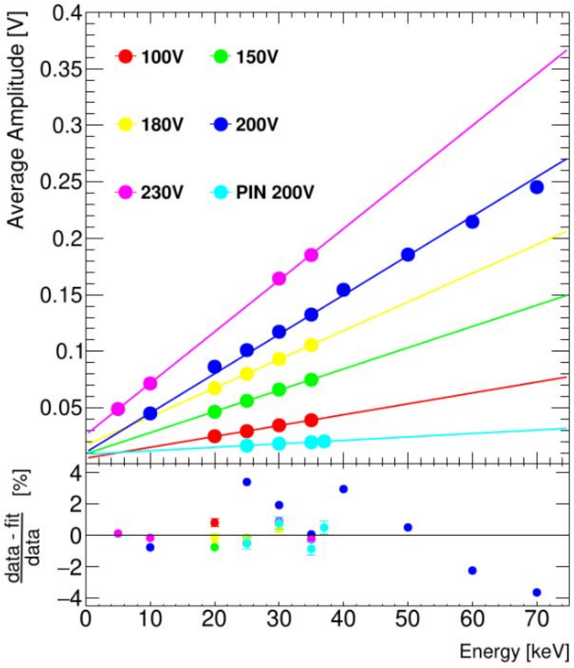
Same procedure on distribution twice the voltage

Example of 30 keV X-rays on a HPK3.1 at 200V

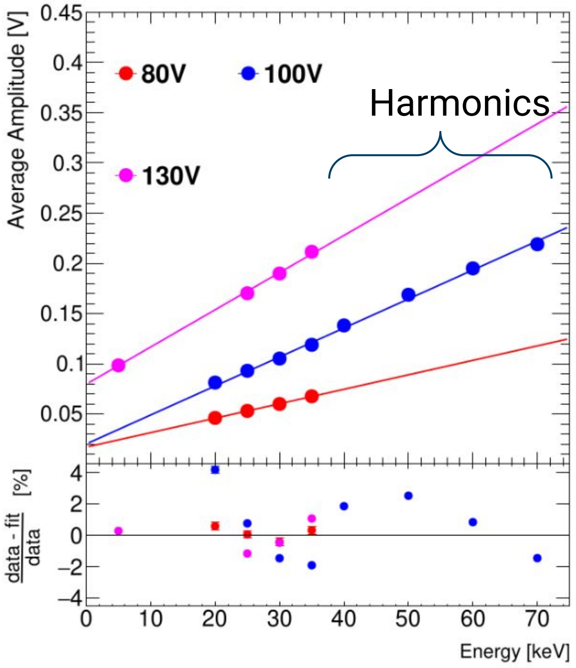




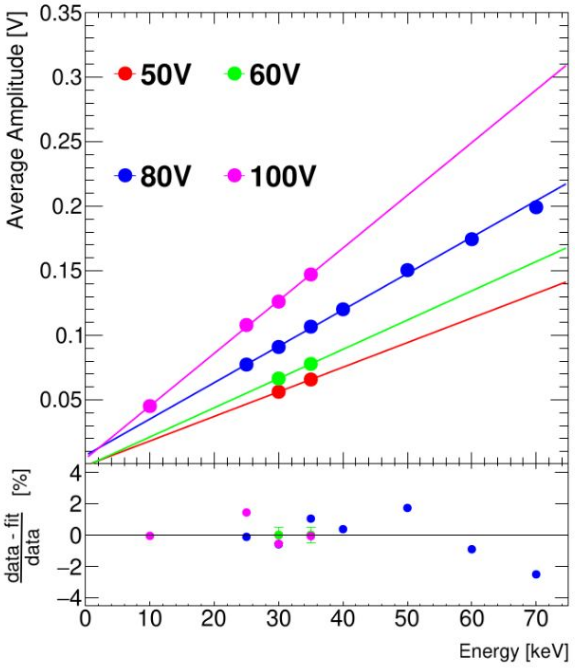
Energy Linearity



(a) HPK PIN and type 3.1 LGAD

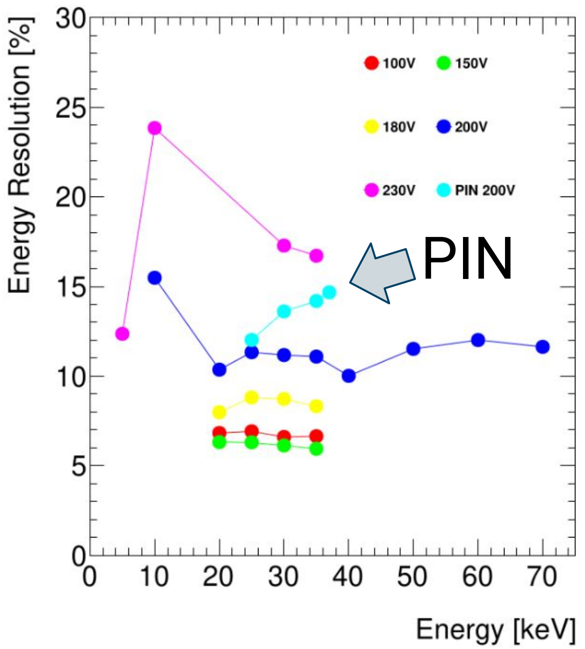


(b) HPK type 3.2 LGAD

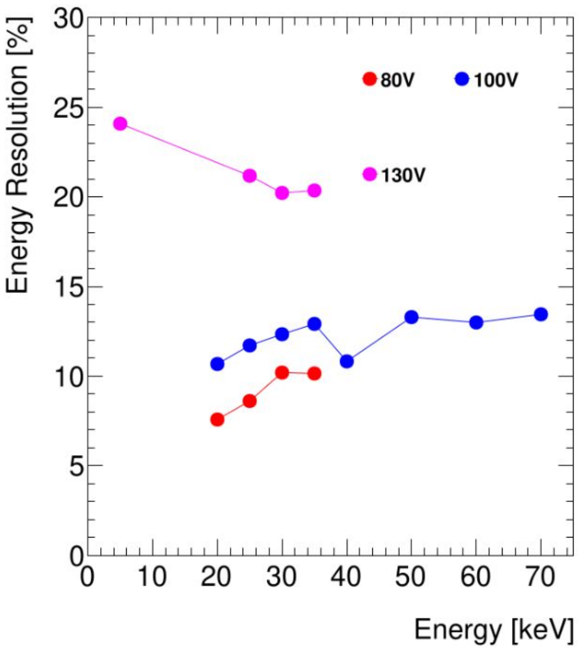


(c) BNL 20um LGAD

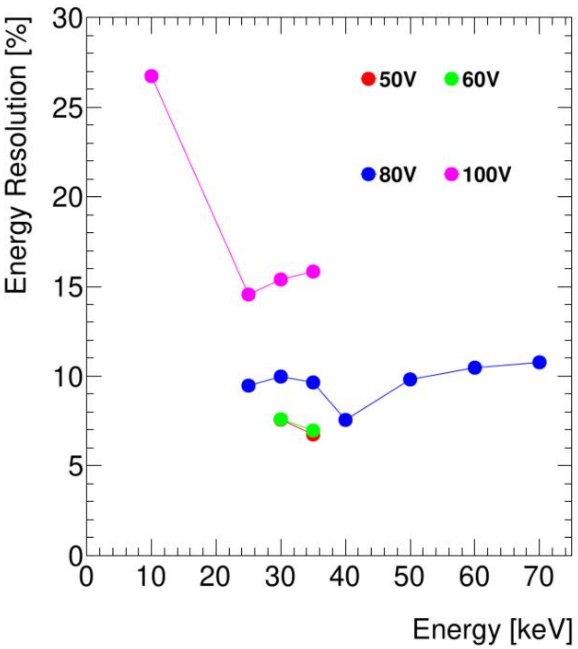
Energy Resolution



(a) HPK PIN and type 3.1 LGAD



(b) HPK type 3.2 LGAD



(c) BNL 20um LGAD

Time Resolution

Major Timewalk effect

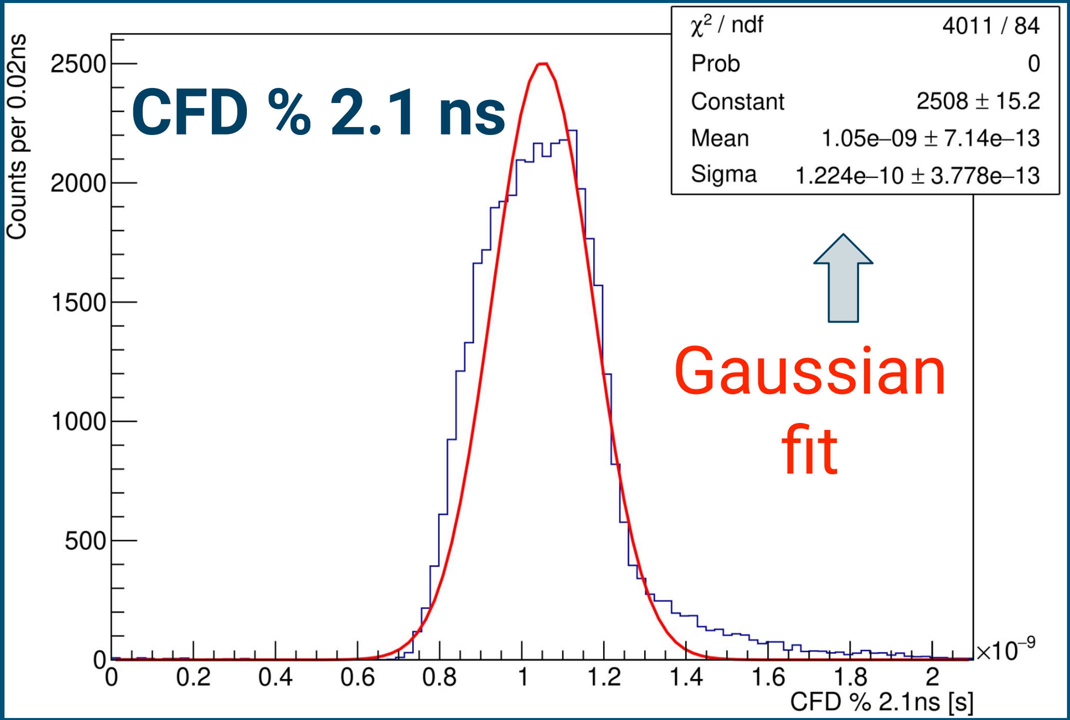
- Photon absorption can occur anywhere inside the sensor

Constant Fraction Discriminator

- 20% fraction

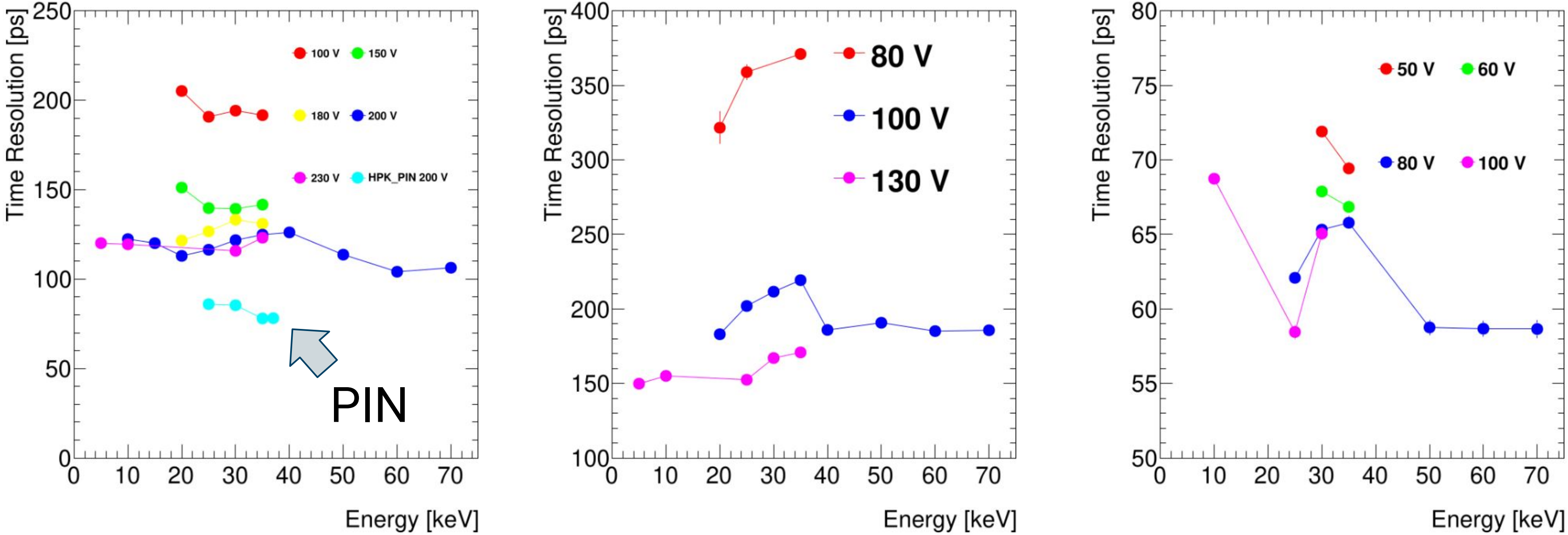
➔ Very precise 2.1ns bunch separation as fiducial time marking
➔ Synchronization signal from SSRL as oscilloscope trigger

Resolution is σ(CFD % 2.1 ns)



Example of a 35 keV X-rays on a HPK3.1 at 230V

Time Resolution



(a) HPK PIN and type 3.1 LGAD

(b) HPK type 3.2 LGAD

(c) BNL 20um LGAD

Summary

For 35 keV X-ray:

	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

Lowest bias voltage

- Best energy resolution

Highest bias voltage

- Best time resolution

- **BNL 20um**

  Same energy resolution as HPK3.1

  Much better time resolution!

Final Remarks

- LGADs can resolve a beam with repetition rate >500 MHz
- 6% to 20% energy resolution
- Thinner detection volume helps with time resolution
    - ~ 65ps for a 20μm device at RT

THANKS!

But… to be more useful on X-ray applications LGADs should have better spatial resolution

- **AC-LGAD and others**

Results presented are available on arxiv.org/abs/2306.15798

Acknowledgements

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References

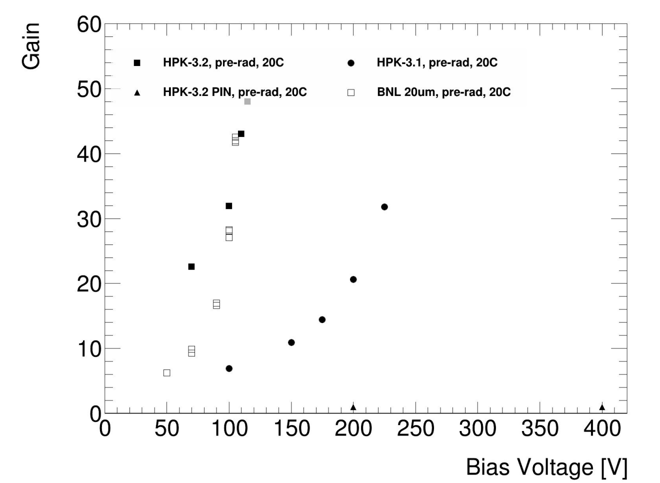
[1] X. Shi. et al. Radiation campaign of HPK prototype LGAD sensors for the High-Granularity Timing Detector (HGTD). Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, v. 979, 164382, 11 2020. ISSN 01689002. https://doi.org/10.1016/j.nima.2020.164382

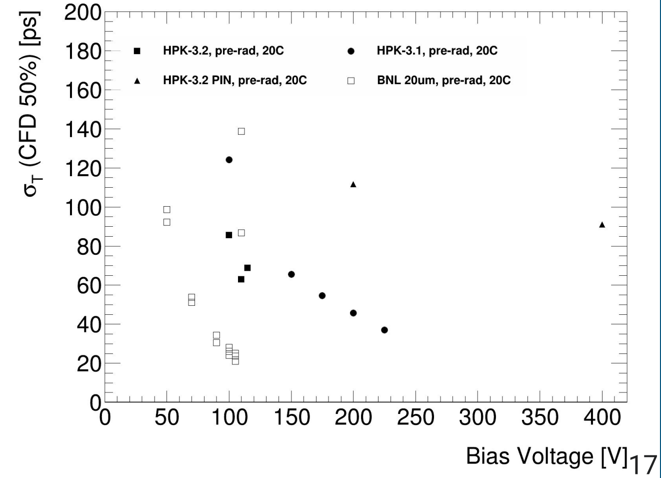
[2] S.-J. Baek, A. Park, Y.-J. Ahn and J. Choo, Baseline correction using asymmetrically reweighted penalized least squares smoothing, Analyst 140 (2015) 250–257.

Backup

More information on tested LGAD

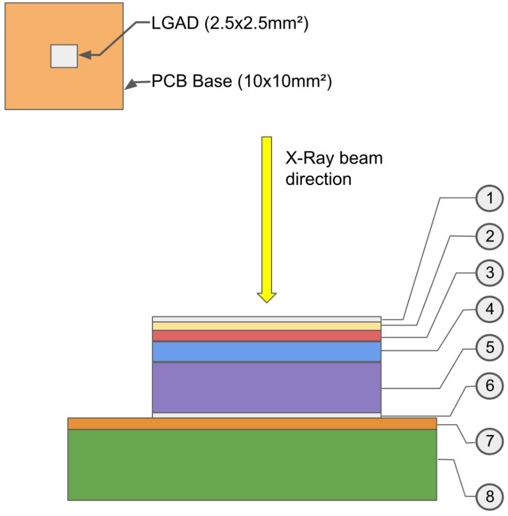
Using a ^{90}Sr source





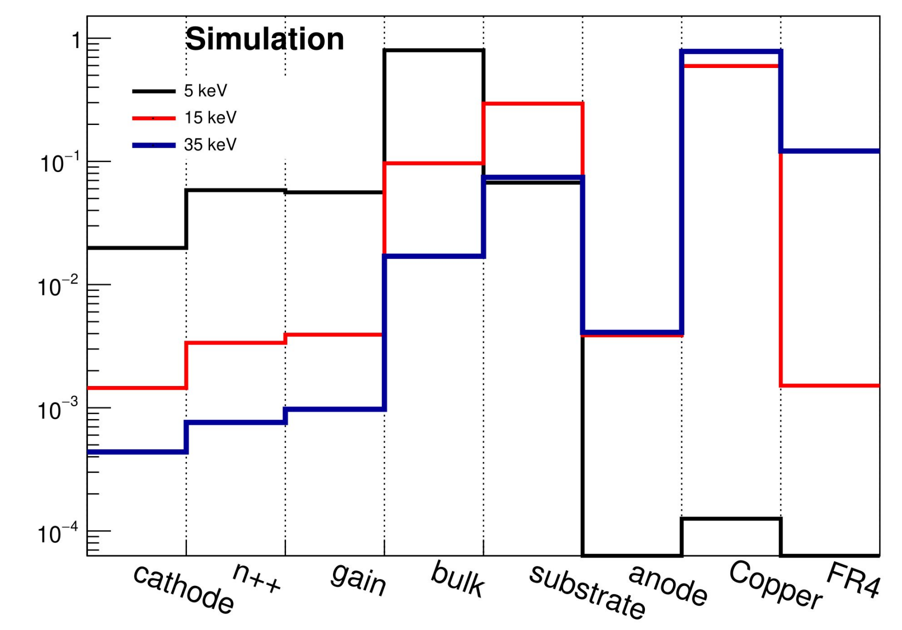
Device	Producer	BV	Thickness	Gain layer	Geometry
HPK 3.1	HPK	230 V	50 μm	shallow	1.3x1.3 mm^2
HPK 3.2	HPK	130 V	50 μm	deep	1.3x1.3 mm^2
HPK PiN	HPK	400 V	50 μm	no gain	1.3x1.3 mm^2
BNL 20um	BNL	100 V	20 μm	shallow	1.3x1.3 mm^2
BNL AC-LGAD 10mm	BNL	250 V	50 μm	shallow	5x10 mm^2
BNL AC-LGAD 5mm	BNL	250 V	50 μm	shallow	5x5 mm^2

Geant4 Simulations



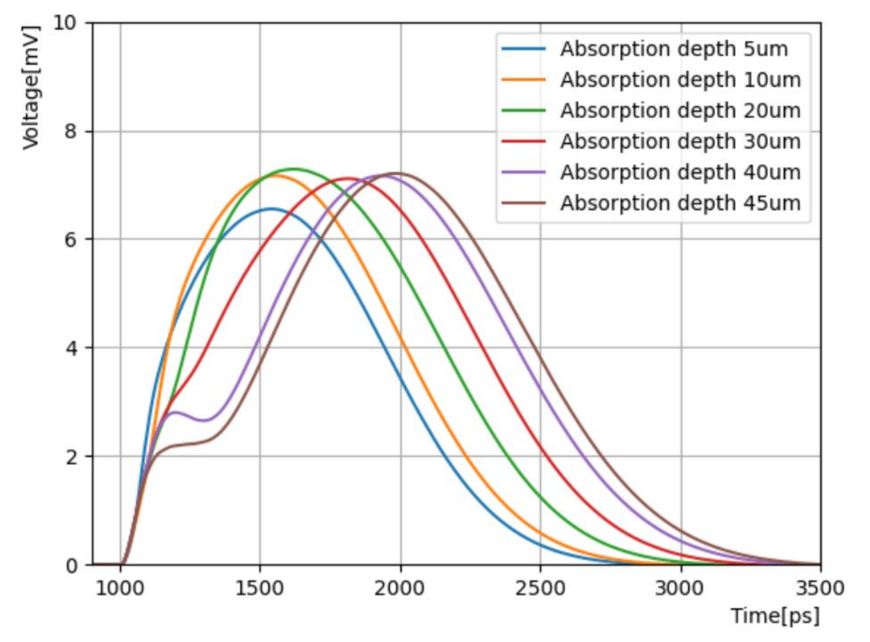
	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

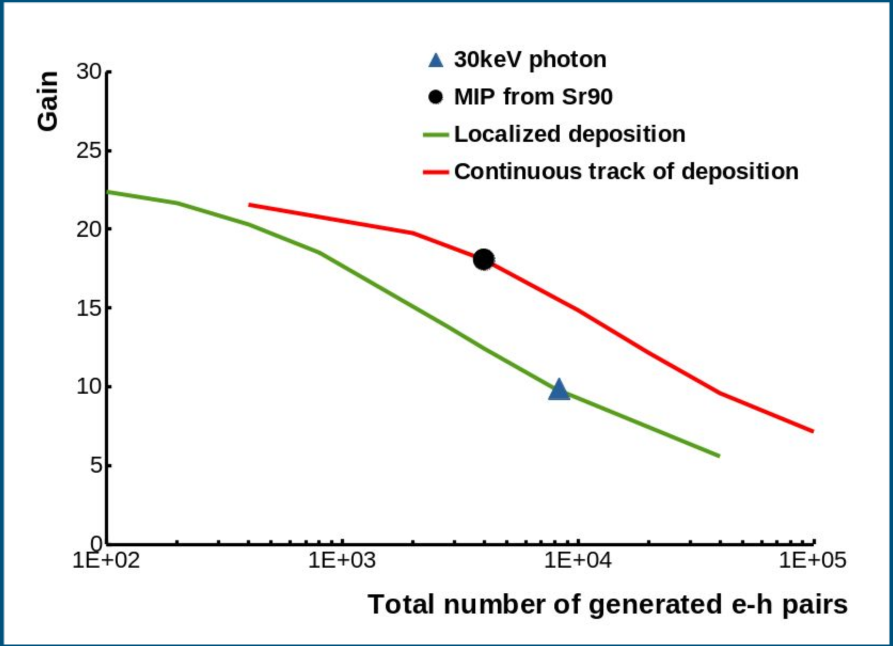
	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600



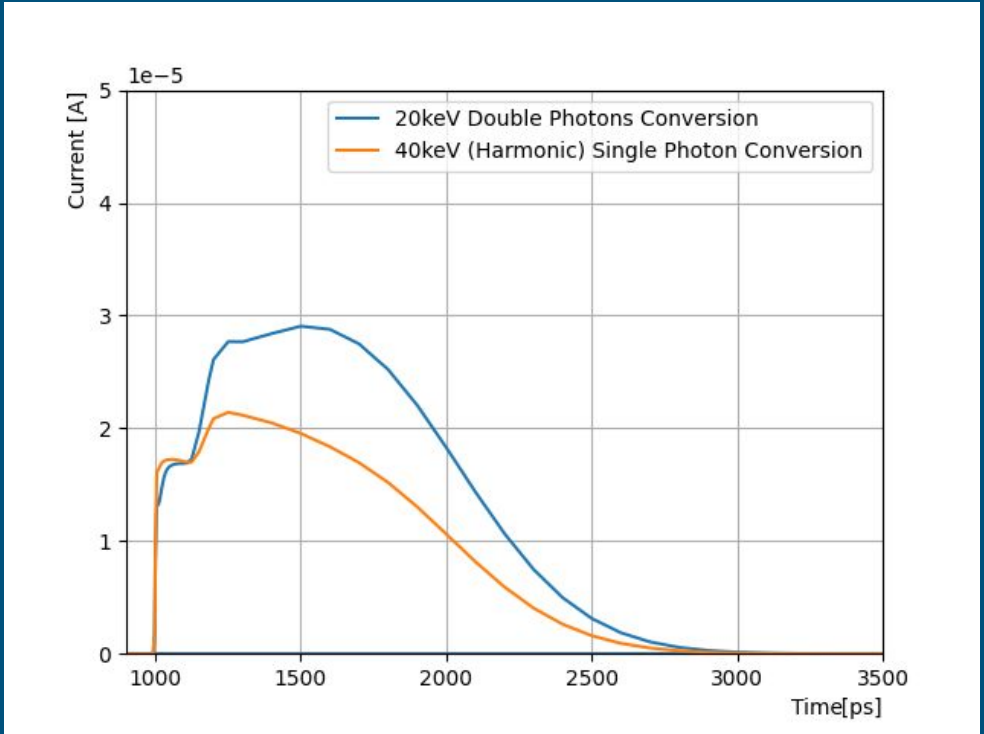
TCAD Simulations

Convoluted voltage signal with TIA





Multiple photons conversion

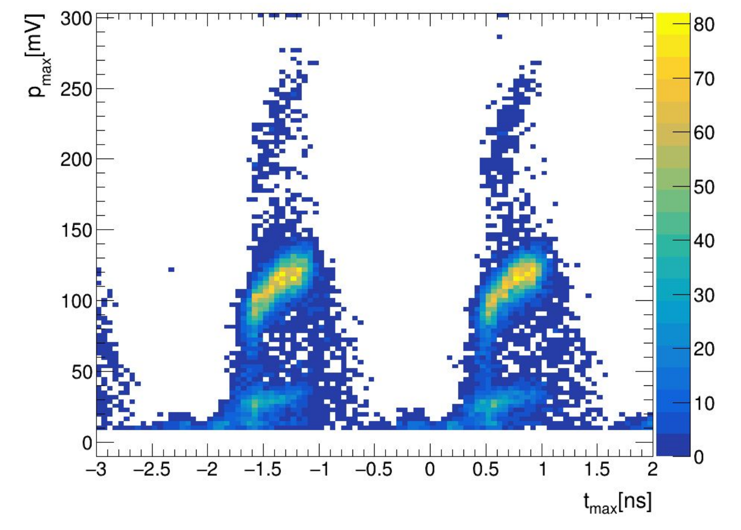


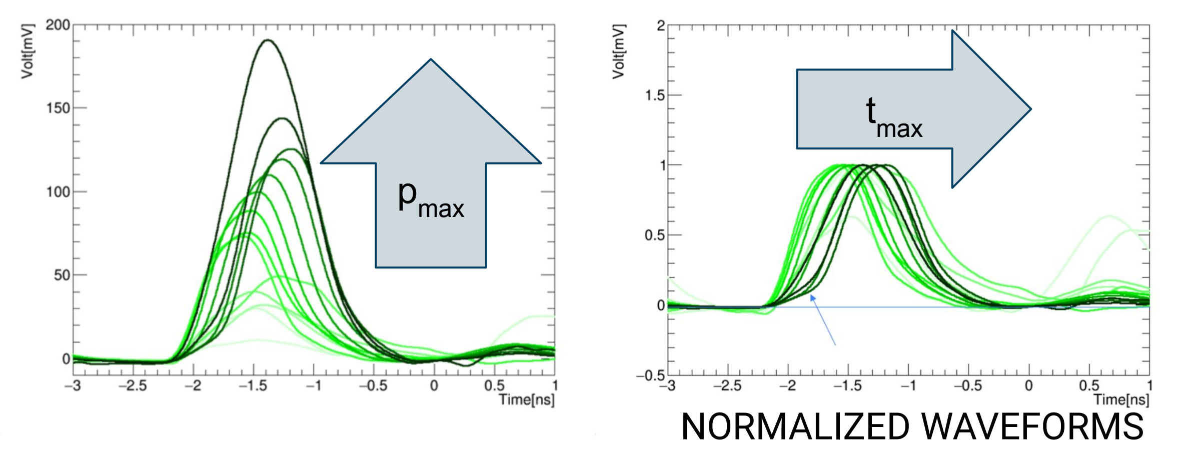
p_{max} x t_{max}

HPK3.1

200 V

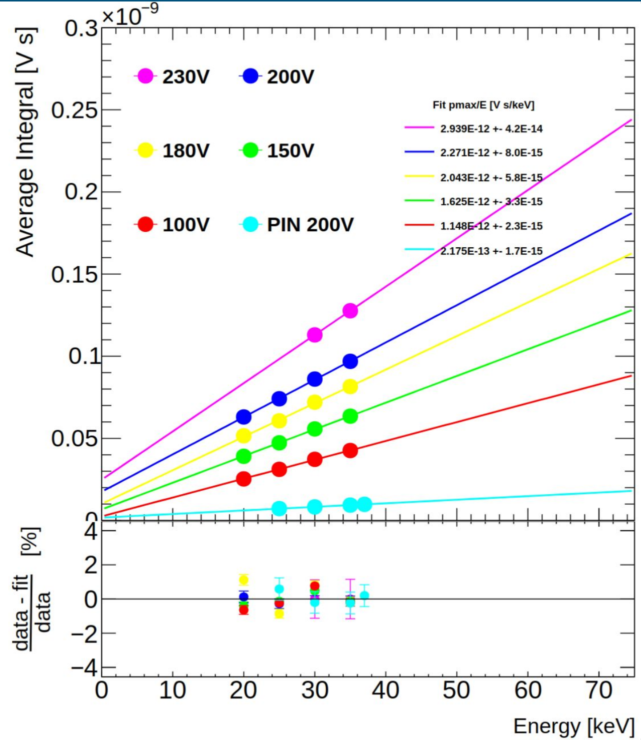
30 keV

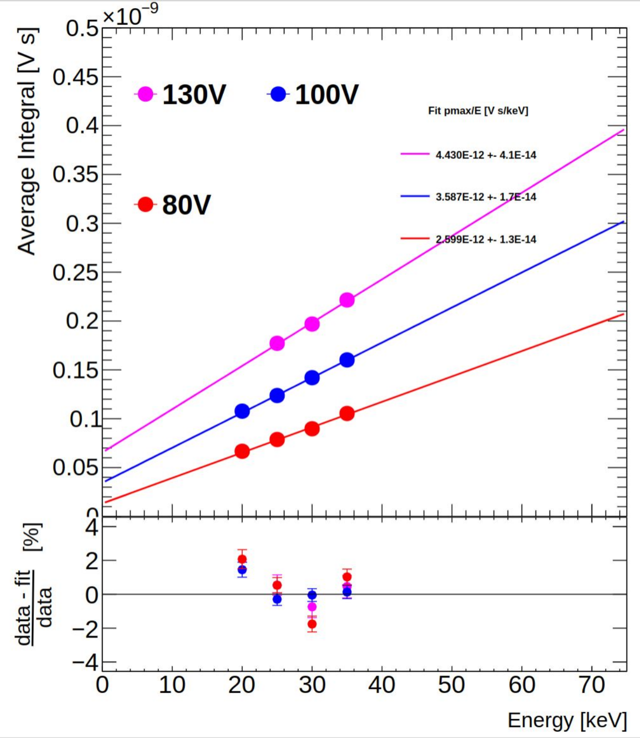


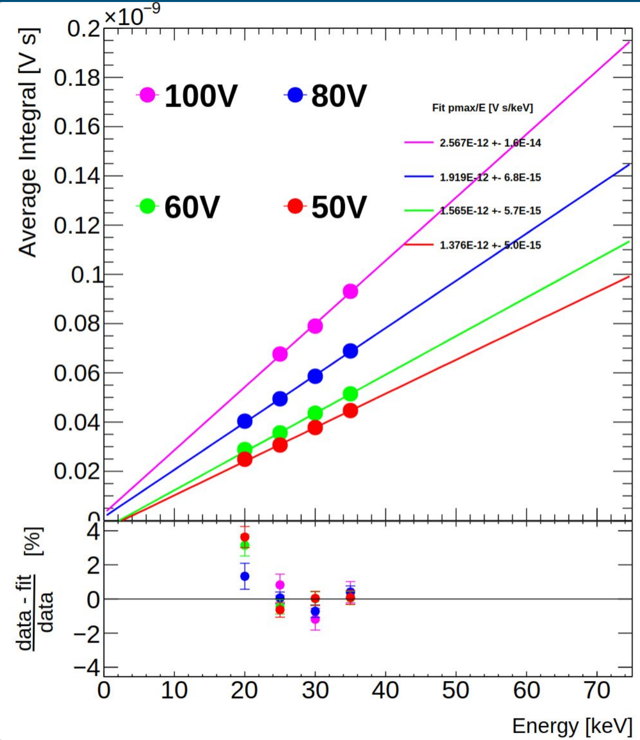


(a) (b)

Analysis with Signal Integral

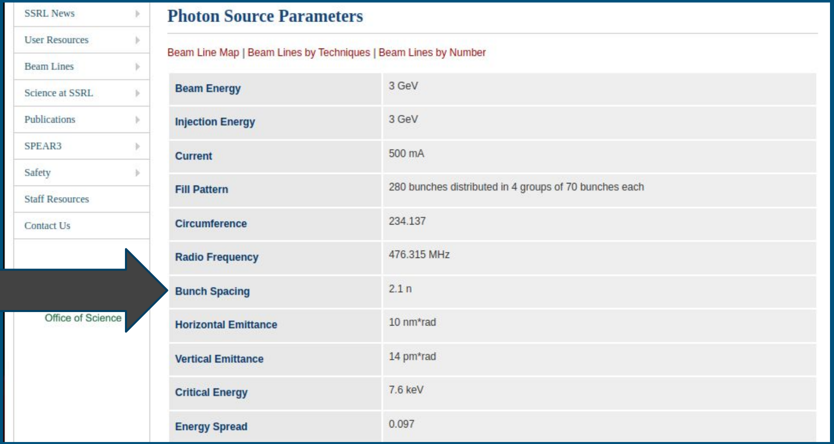






Waveform Autocorrelation

From SSRL website



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- Science at SSRL
- Publications
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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

Waveform Autocorrelation Period

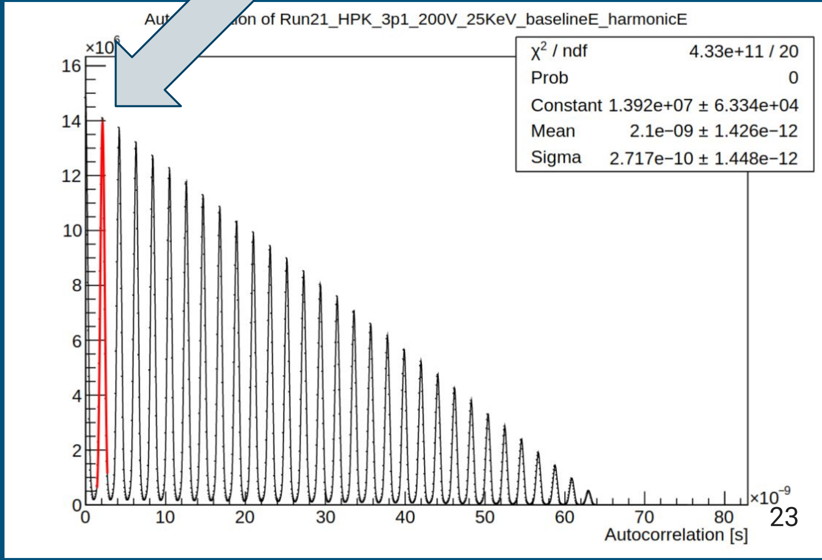
≈

Average t_{max} interval

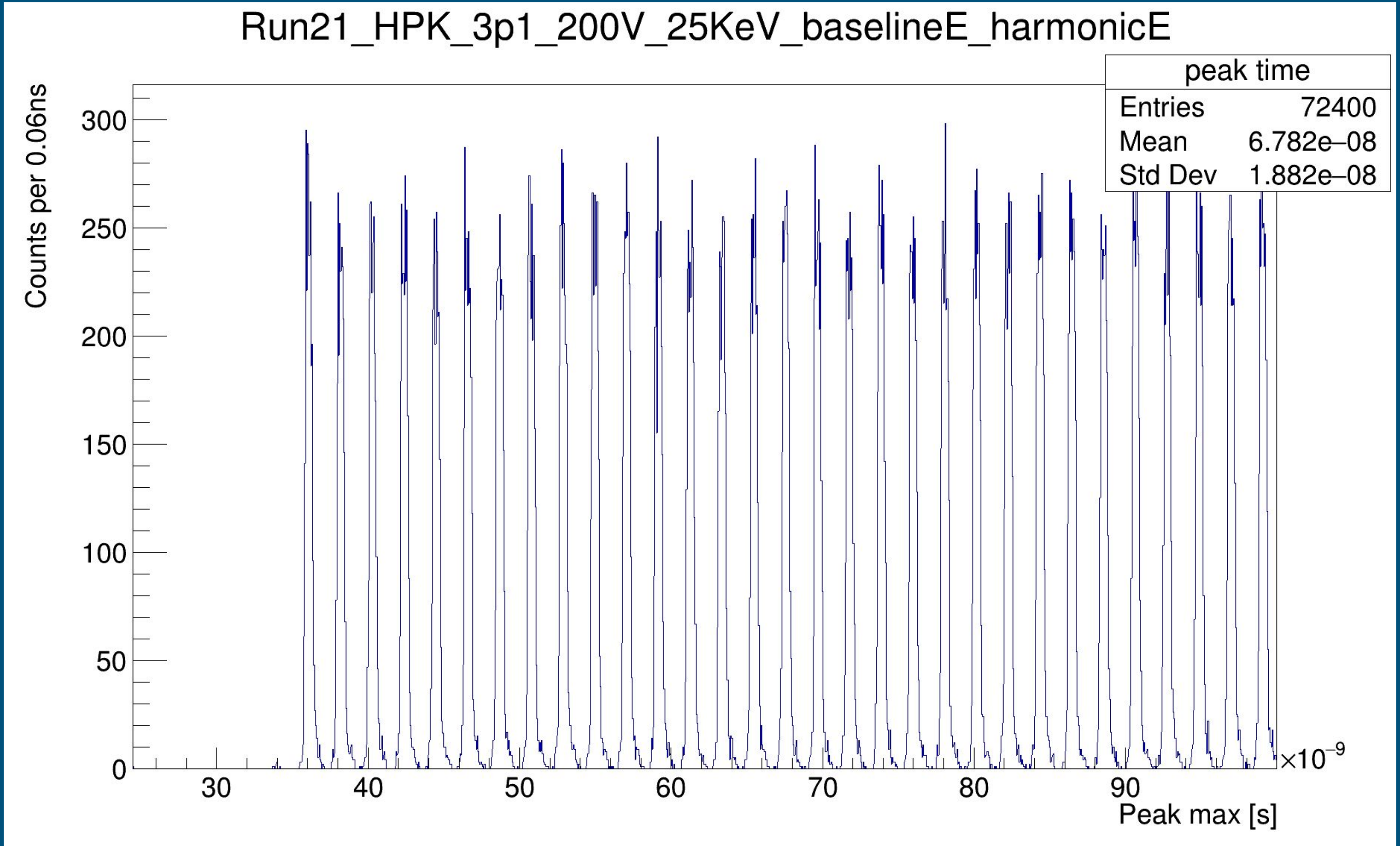
≈

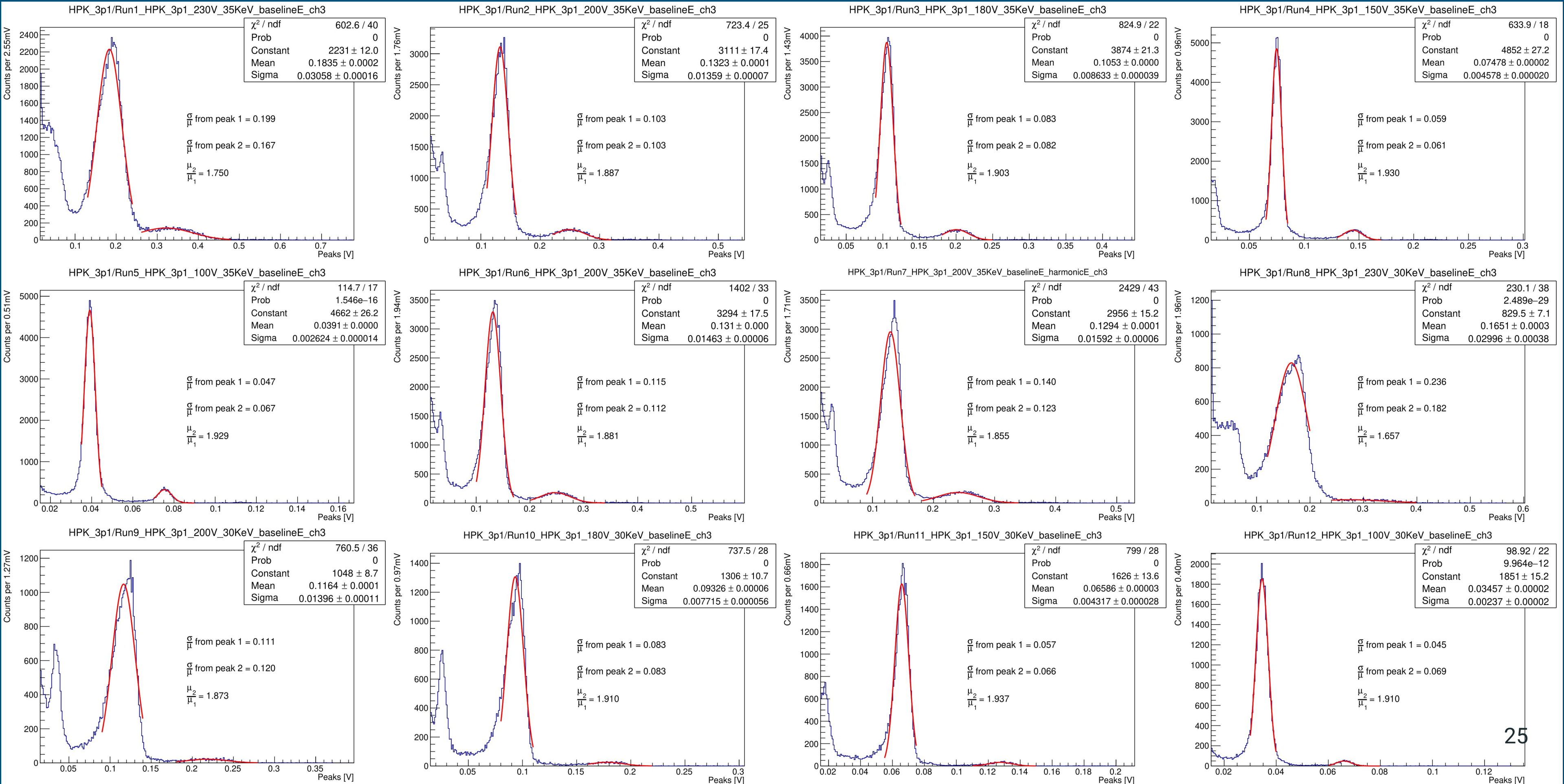
Bunch Spacing

2.100 ns +- 1.426 ps



Bunch Train


Run21_HPK_3p1_200V_25KeV_baselineE_harmonicE
peak time
Entries 72400
Mean 6.782e−08
Std Dev 1.882e−08
Counts per 0.06ns
0
50
100
150
200
250
300
30
40
50
60
70
80
90
×10⁻⁹
Peak max [s]


HPK_3p1/Run1_HPK_3p1_230V_35KeV_baselineE_ch3
χ² / ndf 602.6 / 40
Prob 0
Constant 2231 ± 12.0
Mean 0.1835 ± 0.0002
Sigma 0.03058 ± 0.00016
σ/μ from peak 1 = 0.199
σ/μ from peak 2 = 0.167
μ2/μ1 = 1.750
Counts per 2.55mV
Peaks [V]
HPK_3p1/Run2_HPK_3p1_200V_35KeV_baselineE_ch3
χ² / ndf 723.4 / 25
Prob 0
Constant 3111 ± 17.4
Mean 0.1323 ± 0.0001
Sigma 0.01359 ± 0.00007
σ/μ from peak 1 = 0.103
σ/μ from peak 2 = 0.103
μ2/μ1 = 1.887
Counts per 1.76mV
Peaks [V]
HPK_3p1/Run3_HPK_3p1_180V_35KeV_baselineE_ch3
χ² / ndf 824.9 / 22
Prob 0
Constant 3874 ± 21.3
Mean 0.1053 ± 0.0000
Sigma 0.008633 ± 0.000039
σ/μ from peak 1 = 0.083
σ/μ from peak 2 = 0.082
μ2/μ1 = 1.903
Counts per 1.43mV
Peaks [V]
HPK_3p1/Run4_HPK_3p1_150V_35KeV_baselineE_ch3
χ² / ndf 633.9 / 18
Prob 0
Constant 4852 ± 27.2
Mean 0.07478 ± 0.00002
Sigma 0.004578 ± 0.000020
σ/μ from peak 1 = 0.059
σ/μ from peak 2 = 0.061
μ2/μ1 = 1.930
Counts per 0.96mV
Peaks [V]
HPK_3p1/Run5_HPK_3p1_100V_35KeV_baselineE_ch3
χ² / ndf 114.7 / 17
Prob 1.546e−16
Constant 4662 ± 26.2
Mean 0.0391 ± 0.0000
Sigma 0.002624 ± 0.000014
σ/μ from peak 1 = 0.047
σ/μ from peak 2 = 0.067
μ2/μ1 = 1.929
Counts per 0.51mV
Peaks [V]
HPK_3p1/Run6_HPK_3p1_200V_35KeV_baselineE_ch3
χ² / ndf 1402 / 33
Prob 0
Constant 3294 ± 17.5
Mean 0.131 ± 0.000
Sigma 0.01463 ± 0.00006
σ/μ from peak 1 = 0.115
σ/μ from peak 2 = 0.112
μ2/μ1 = 1.881
Counts per 1.94mV
Peaks [V]
HPK_3p1/Run7_HPK_3p1_200V_35KeV_baselineE_harmonicE_ch3
χ² / ndf 2429 / 43
Prob 0
Constant 2956 ± 15.2
Mean 0.1294 ± 0.0001
Sigma 0.01592 ± 0.00006
σ/μ from peak 1 = 0.140
σ/μ from peak 2 = 0.123
μ2/μ1 = 1.855
Counts per 1.71mV
Peaks [V]
HPK_3p1/Run8_HPK_3p1_230V_30KeV_baselineE_ch3
χ² / ndf 230.1 / 38
Prob 2.489e−29
Constant 829.5 ± 7.1
Mean 0.1651 ± 0.0003
Sigma 0.02996 ± 0.00038
σ/μ from peak 1 = 0.236
σ/μ from peak 2 = 0.182
μ2/μ1 = 1.657
Counts per 1.96mV
Peaks [V]
HPK_3p1/Run9_HPK_3p1_200V_30KeV_baselineE_ch3
χ² / ndf 760.5 / 36
Prob 0
Constant 1048 ± 8.7
Mean 0.1164 ± 0.0001
Sigma 0.01396 ± 0.00011
σ/μ from peak 1 = 0.111
σ/μ from peak 2 = 0.120
μ2/μ1 = 1.873
Counts per 1.27mV
Peaks [V]
HPK_3p1/Run10_HPK_3p1_180V_30KeV_baselineE_ch3
χ² / ndf 737.5 / 28
Prob 0
Constant 1306 ± 10.7
Mean 0.09326 ± 0.00006
Sigma 0.007715 ± 0.000056
σ/μ from peak 1 = 0.083
σ/μ from peak 2 = 0.083
μ2/μ1 = 1.910
Counts per 0.97mV
Peaks [V]
HPK_3p1/Run11_HPK_3p1_150V_30KeV_baselineE_ch3
χ² / ndf 799 / 28
Prob 0
Constant 1626 ± 13.6
Mean 0.06586 ± 0.00003
Sigma 0.004317 ± 0.000028
σ/μ from peak 1 = 0.057
σ/μ from peak 2 = 0.066
μ2/μ1 = 1.937
Counts per 0.66mV
Peaks [V]
HPK_3p1/Run12_HPK_3p1_100V_30KeV_baselineE_ch3
χ² / ndf 98.92 / 22
Prob 9.964e−12
Constant 1851 ± 15.2
Mean 0.03457 ± 0.00002
Sigma 0.00237 ± 0.00002
σ/μ from peak 1 = 0.045
σ/μ from peak 2 = 0.069
μ2/μ1 = 1.910
Counts per 0.40mV
Peaks [V]