SCIPP and RD50

- Greetings from the SCIPP group!
  - I have been around for only 10 workshops but I immediately realized it's a fantastic collaboration
  - I feel honored to start off the last session of RD50
- **Words from Hartmut: "we can compare the friendly, collegial, supportive atmosphere within RD50 shown in the talks with the one we try to maintain at SCIPP."**
- Let's continue working together in DRD3!
  - Maybe with a workshop in sunny California

Fabrication of DJ-LGAD in RD50

Unrelated bonus

- Proposed Fabrication within RD50 of DJLGAD at FBK
  - Establishment of deep junction technology using epitaxial growth
- **12 institutes are contributing to the production**
- Approved few months ago, I thank RD50 for the support!
- First short loop production (Epitaxial growth) will start soon

Deep-Junction LGAD to achieve high granularity and radiation hardness

Contact Person	Dr. Simone Michele Mazza, Santa Cruz Institute for Particle Physics University of California, Santa Cruz 1156 High St., Santa Cruz, CA, 95064, U.S. simazza@ucsc.edu
Institutes	1. University of California Santa Cruz (S.M. Mazza, B. Schumm) 2. FBK (M. Boscardin, M. Centis Vignali, G. Paternoster) 3. CERN (M. Moll, V. Kraus, M. Wiehe, M. Fernandez Garcia, N. Sorgenfrei) 4. UNM (S. Seidel, J. Si, R. Novotny, J. Sorenson, H. Farook, A. Gentry) 5. KIT (M. Caselle, A. Dierlamm) 6. PSI (J. Zhang, A. Bergamaschi, M. Carulla) 7. HEPHY (T. Bergauer, A. Hirtl, M/ Dragicevic) 8. UCG (G. Lastovicka-Medin, V. Backovic, I. Bozovic, J. Doknic) 9. Nikhef (M. van Beuzekom, F. Filthaut, M. Wu, H. Snoek) 10. UZH (B. Kilminster, A. Macchiolo, M. Senger) 11. IHEP Beiking (Z. Liang, M. Zhao, Y. Fan) 12. Manchester (O.A. De Aguiar Francisco, E. Ejopu, M. Gersabeck, A. Oh)
Total project	101.600 €
RD50 request	50.000 €

Synchrotron light source X-ray detection with LGADs

43° RD50 Workshop (2023, CERN)

Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)
On behalf of the SCIPP and Sao Paolo group

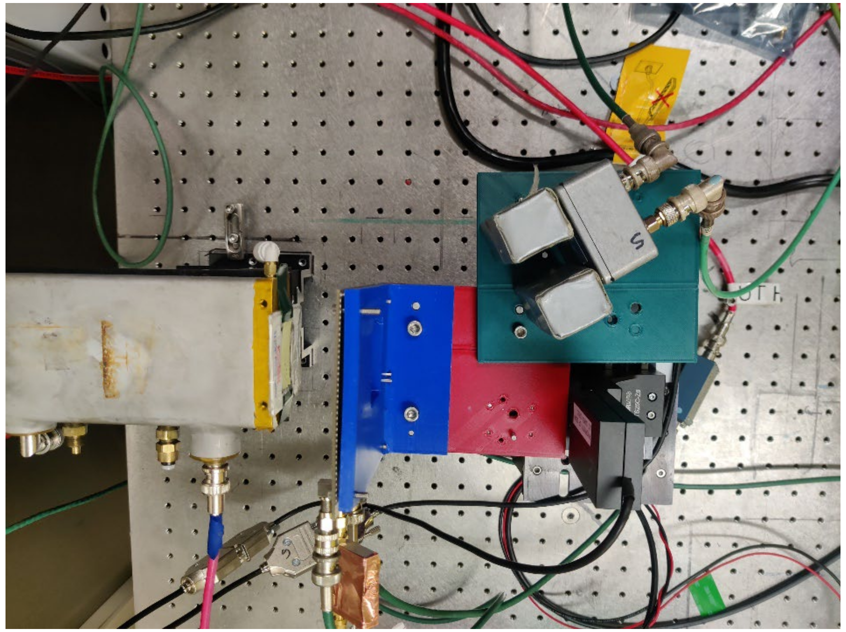
S.M. Mazza[1] G. Saito[2] Y. Zhao[1] T. Kirkes[1] N. Yoho[1] D. Yerdea[1] N. Nagel[1] J. Ott[1] M. Nizam[1] M. Leite[2] M. Moralles[4] H. F.-W. Sadrozinski[1] A. Seiden[1] B. Schumm[1] F. McKinney-Martinez[1] G. Giacomini[3] W. Chen[3]

LGADs for X-rays detection

SLAC NATIONAL ACCELERATOR LABORATORY

- LGAD tested for X-ray detection at the **SLAC** Stanford Synchrotron Radiation Light source **(SSRL)**
  - https://www-ssrl.slac.stanford.edu/
- X-rays of energy in a wide range: 5 - 70 KeV
- **Why LGADs?**
  - LGADs are thin: fast charge collection, higher repetition rate
  - LGADs have gain: detection of low energy X-rays
- Studied energy linearity/resolution, time resolution, gain suppression
  - Both for LGADs, PIN and AC-LGADs

SSRL

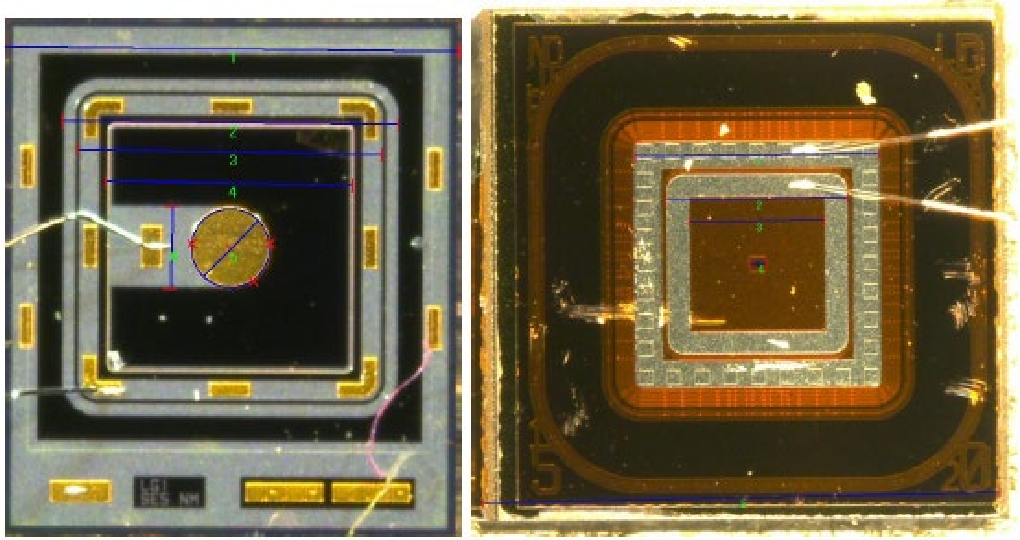


- Collaboration of SCIPP and U. Sao Paolo (DOI 10.1088/1748-0221/18/10/P10006)

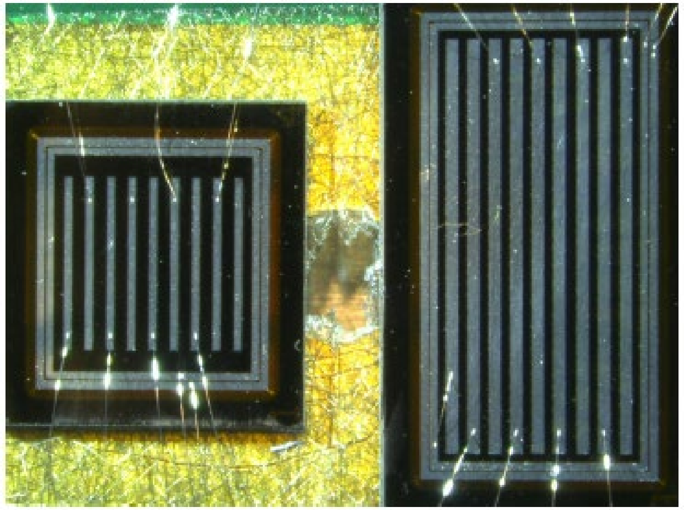
Sensors studied

- 50 um-thick HPK LGADs and PIN produced for ATLAS and CMS (old production)
- 20 um-thick BNL LGAD
- 50 um-thick BNL strip AC-LGADs
- Sensors mounted on 1ch "SiGe" Santa Cruz boards or FNAL 16ch boards
  - Read out by 13GHz oscilloscope or CAEN 16ch DT5742

*Thanks to G. Giacomini and W. Chen for providing the BNL sensors!



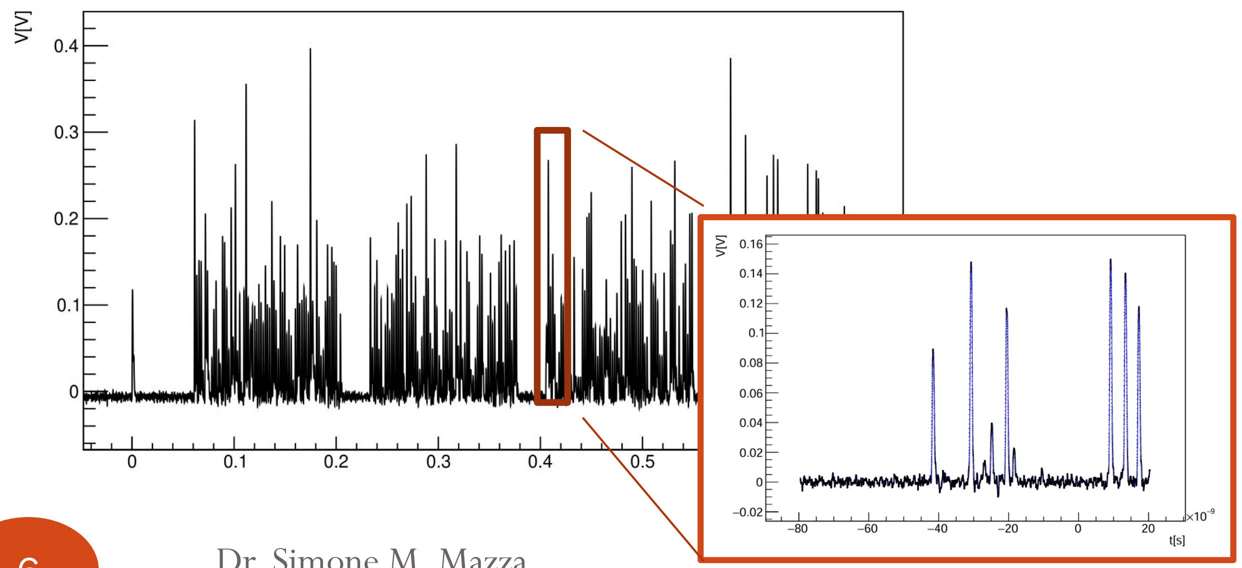
Device	Producer	BV	Thickness	Gain layer	Geometry
HPK 3.1	HPK	230 V	50 μm	shallow	1.3x1.3 mm^2
HPK 3.2	HPK	130 V	50 μm	deep	1.3x1.3 mm^2
HPK PIN	HPK	400 V	50 μm	no gain	1.3x1.3 mm^2
BNL 20um	BNL	100 V	20 μm	shallow	1.3x1.3 mm^2
BNL AC-LGAD 10mm	BNL	250 V	50 μm	shallow	5x10 mm^2
BNL AC-LGAD 5mm	BNL	250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



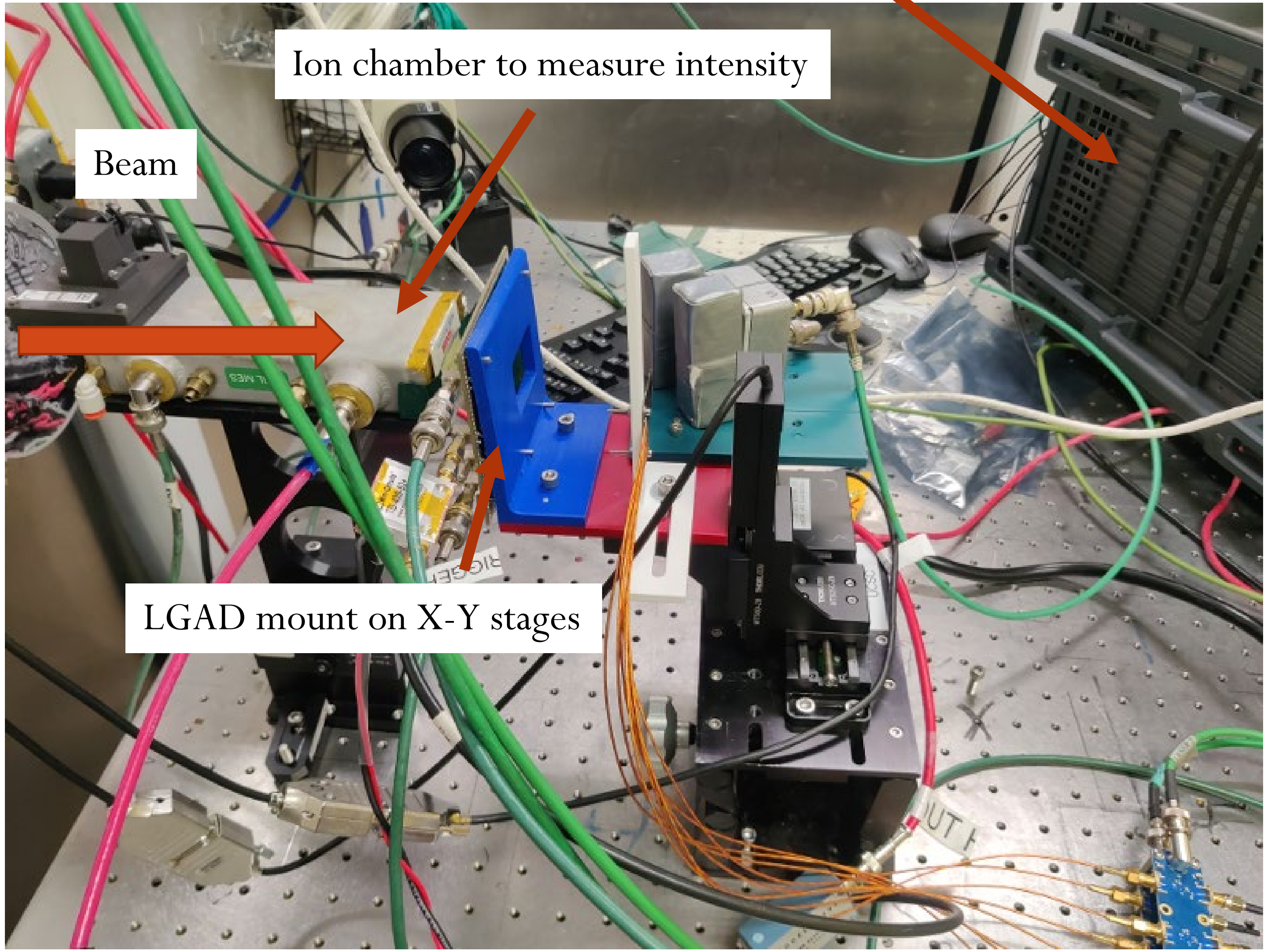
SSRL apparatus

- SSRL beam line 11-2
  - Energy 5-35 KeV, with harmonic 2x component
  - Energy resolution $\Delta E/E \sim 10^{-4}$
  - Monochromator to filter harmonics
- Beam size: 25x1mm
- Beam structure: 4 groups of 70 bunches
  - 10 ps length (RMS)
  - Separated by 2.1 ns
- Triggered on timing signal with low jitter

50um sensor response to one SSRL orbit bunch structure

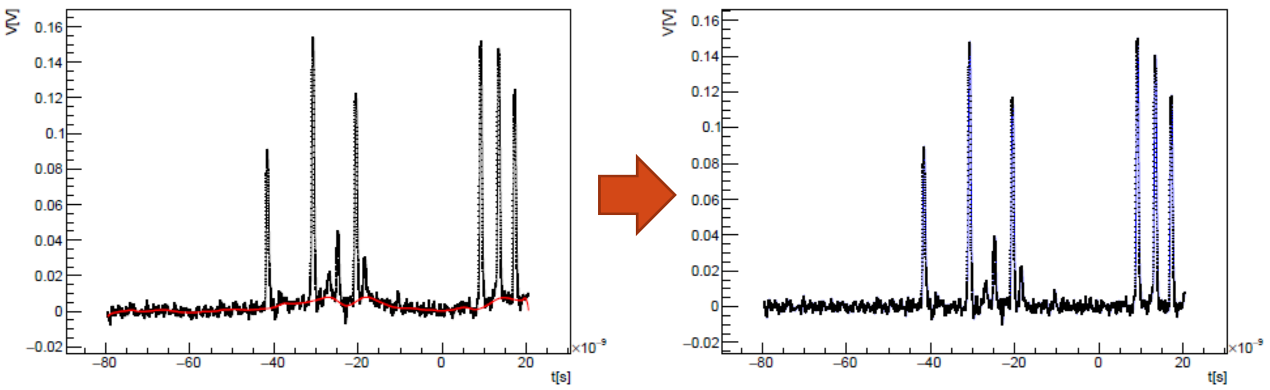


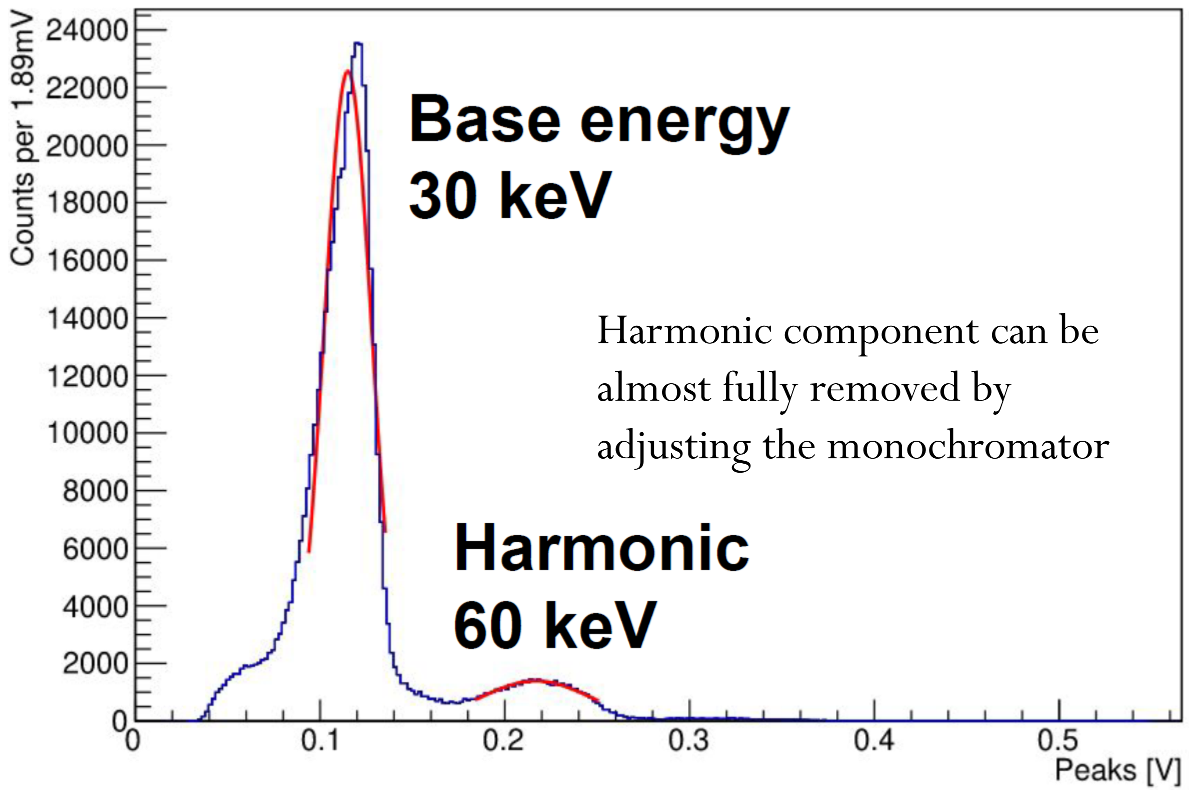
13 GHz oscilloscope for readout
(Keysight UXR 13GHz, 128 Gs/s)



Results – energy response

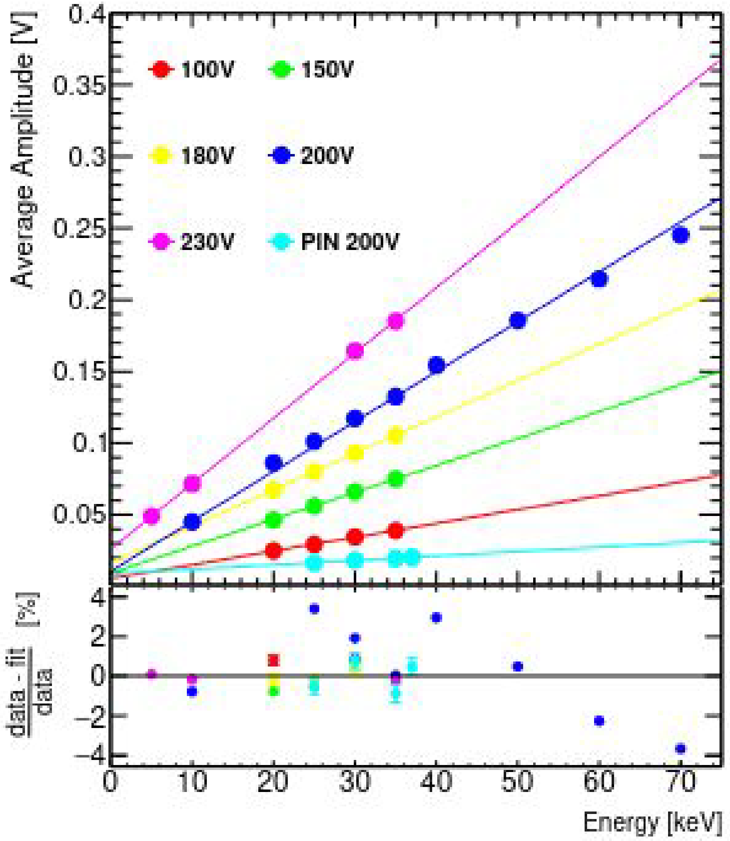
- The signal maximum (peak) is used as estimator for X-rays energy
  - Using pulse area gives roughly the same result
- Baseline correction* is applied to reduce fluctuation from amplification circuit
  - Signal peak at least > 7σ noise
  - Time separation between peaks at least 2.1 ns
- Using mean(μ) and width(σ) of the Gaussian fit to the peaks distribution:
  - Energy response: μ
  - Energy resolution: σ/μ



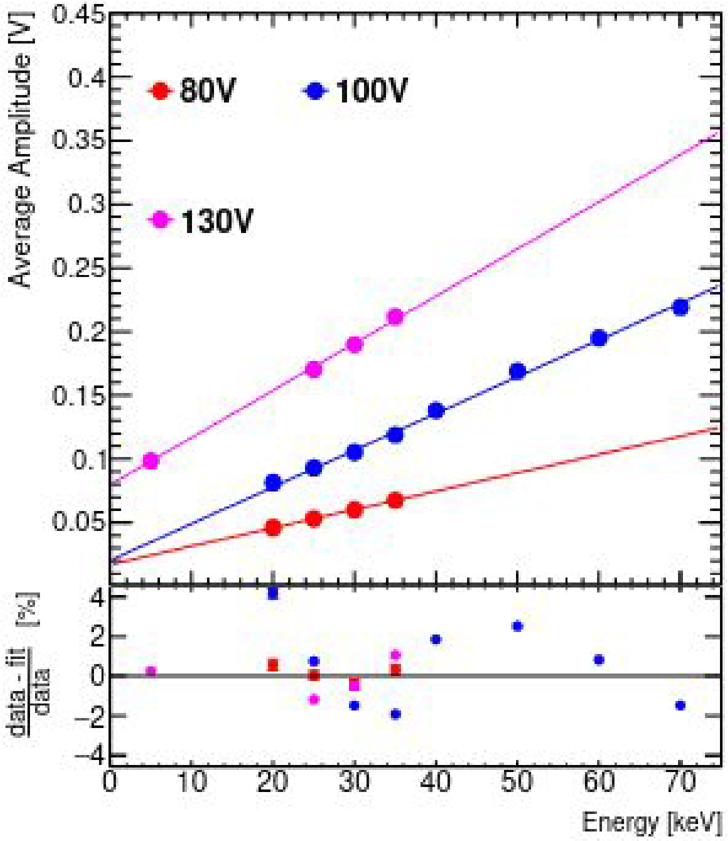


* S.-J. Baek, A. Park, Y.-J. Ahn and J. Choo, Baseline correction using asymmetrically reweighted penalized least squares smoothing, Analyst 140 (2015) 250–257.

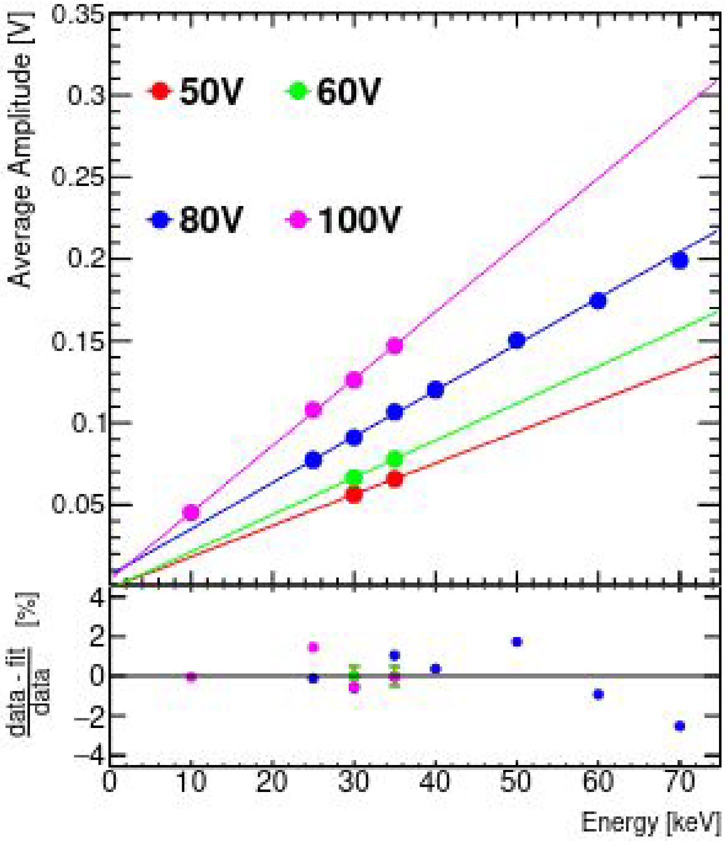
Results – Energy linearity



(a) HPK PIN and type 3.1 LGAD



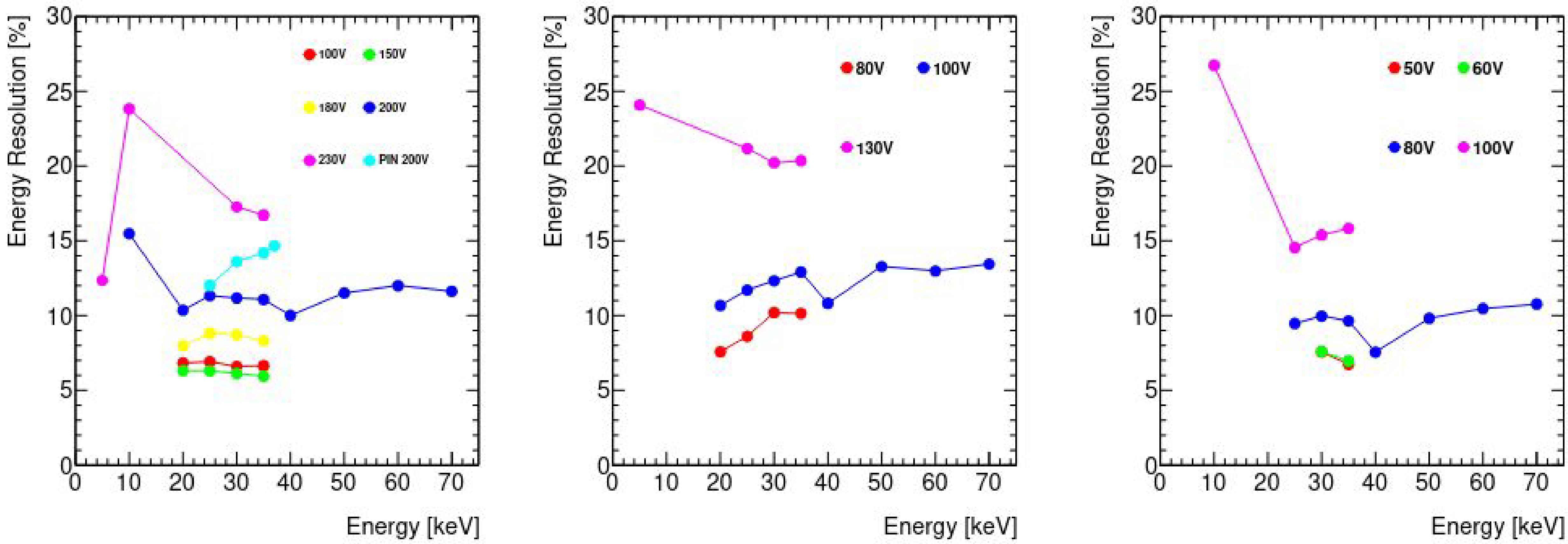
(b) HPK type 3.2 LGAD



(c) BNL 20um LGAD

Results – Energy resolution

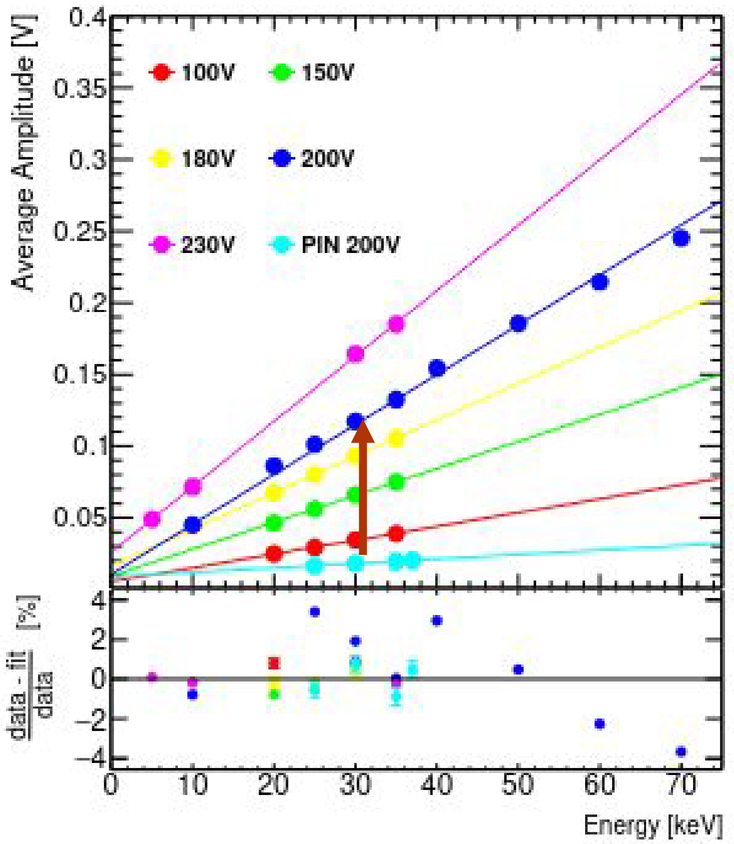
- Energy resolution between 5-10%, lower at very high gain, best at medium-low gain



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

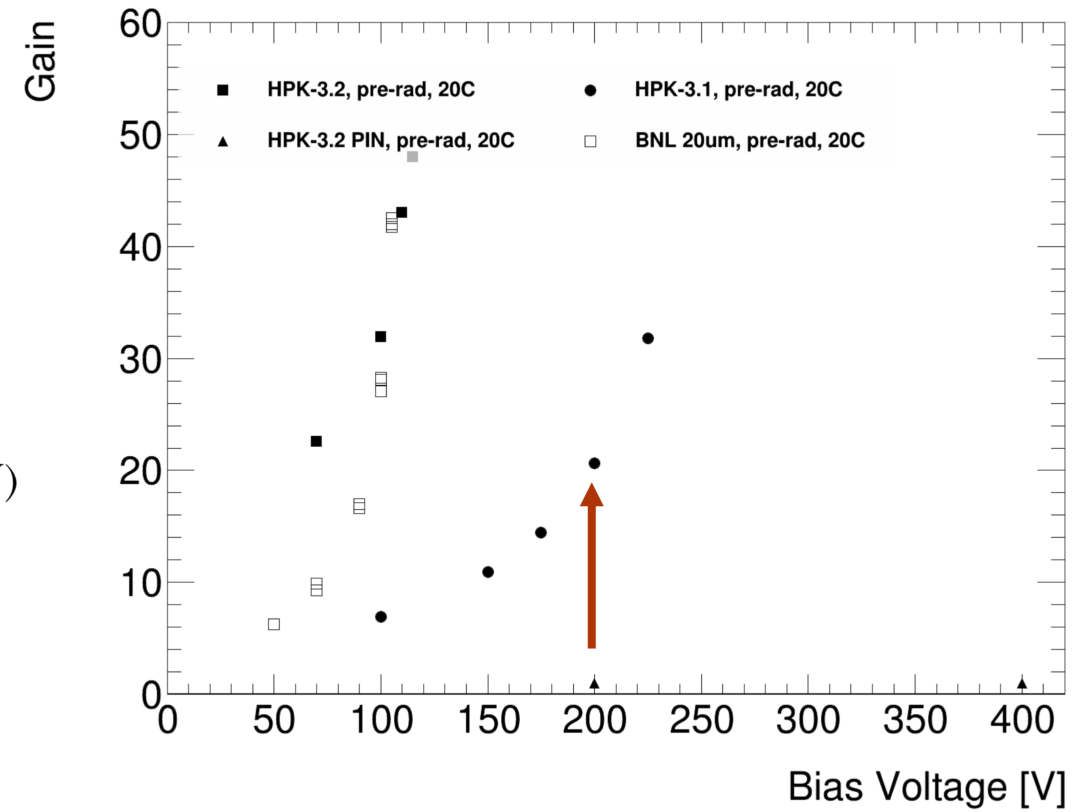
Gain mismatch

- The gain measured with X-rays is not in agreement with the one measured using a Sr90 beta source (MiP-like deposition)



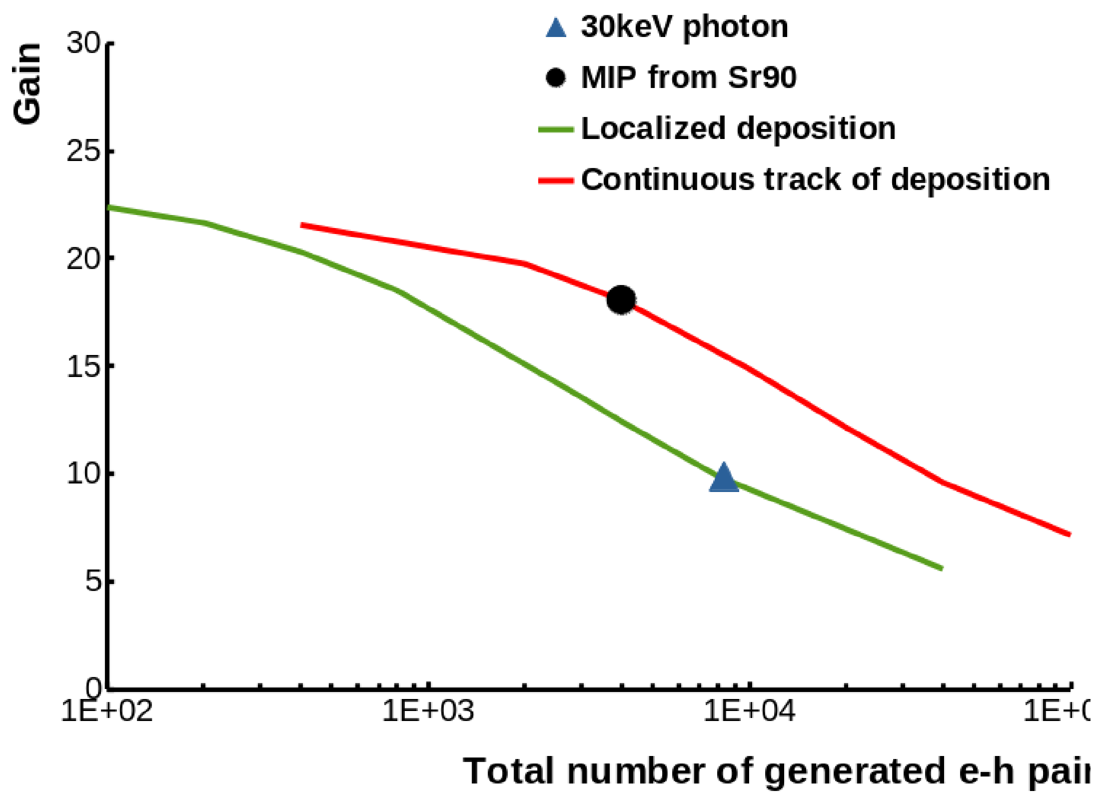
E.g. HPK 3.1 at 200V
Gain from 30 KeV X-ray ~10
But expected for MIPS ~20

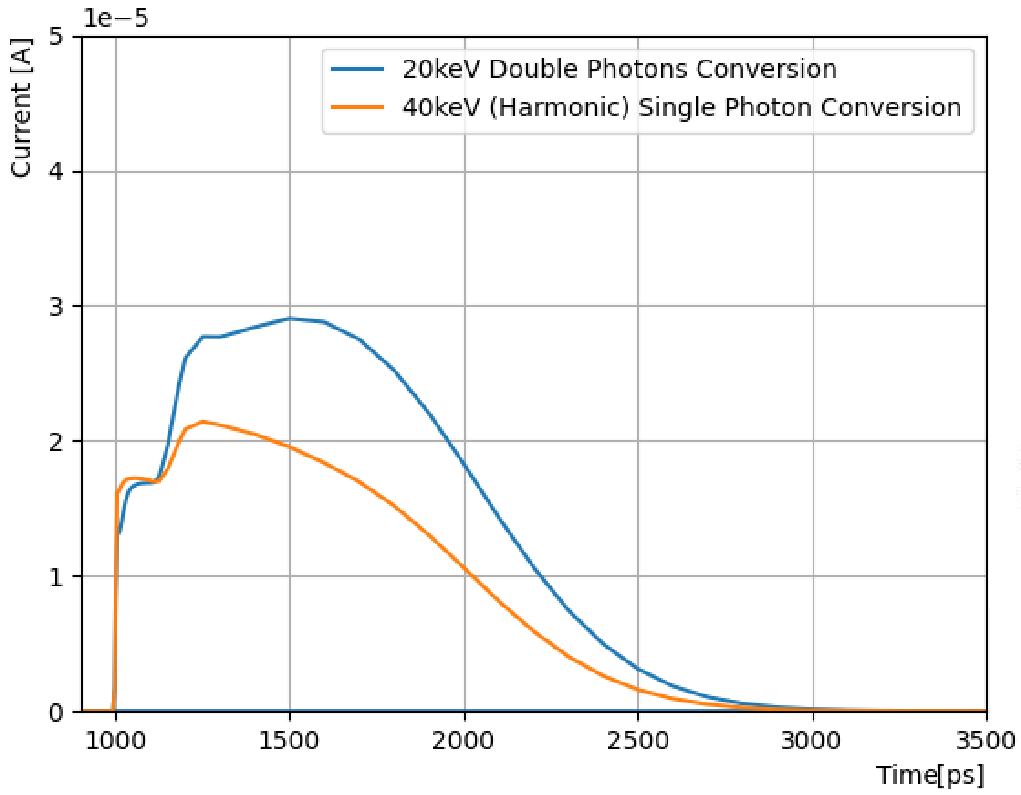
(A MiP should be around 20-30 KeV)



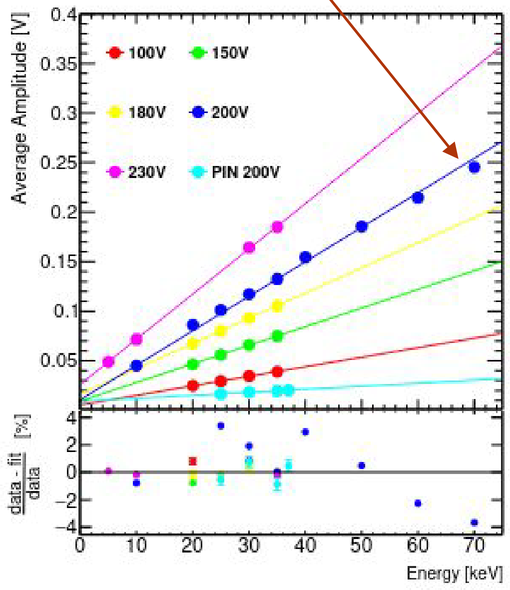
TCAD simulations – gain mismatch

- Effect can be explained by the different kind of ionization (line vs spot charge deposition)
- TCAD simulation of the two types of ionizations shows the factor ~2 gain suppression we see in data
- Also seen in TCAD simulation depositing 2x 20KeV photons and a single 40KeV photon
  - Two photon deposition should not be the same as the harmonic X-ray with twice the energy
  - Gain suppression is local in time (few hundred ps) and space (< 5 um)

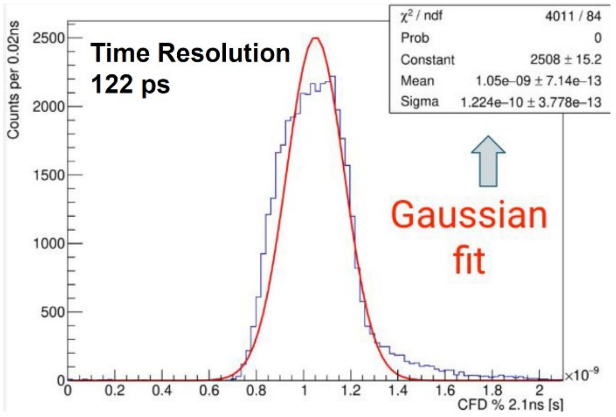




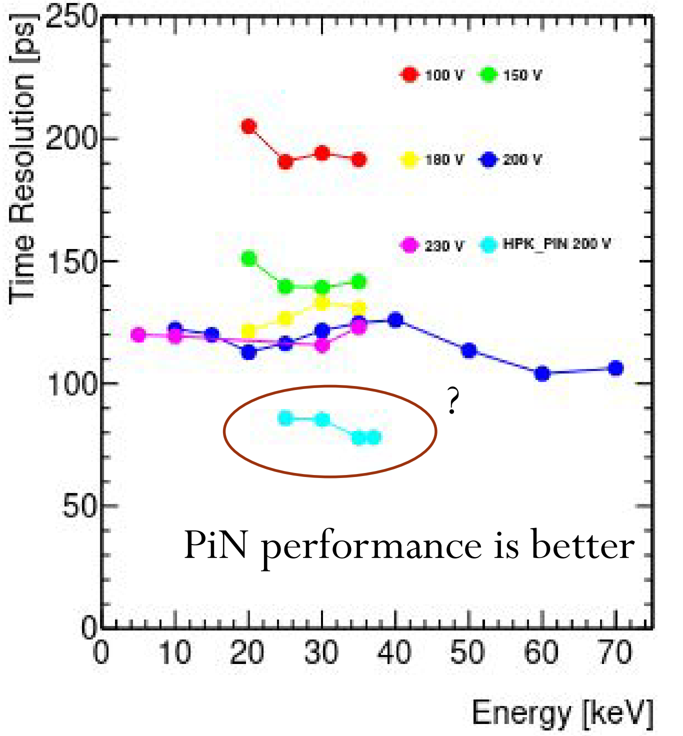
Slightly sub-linear



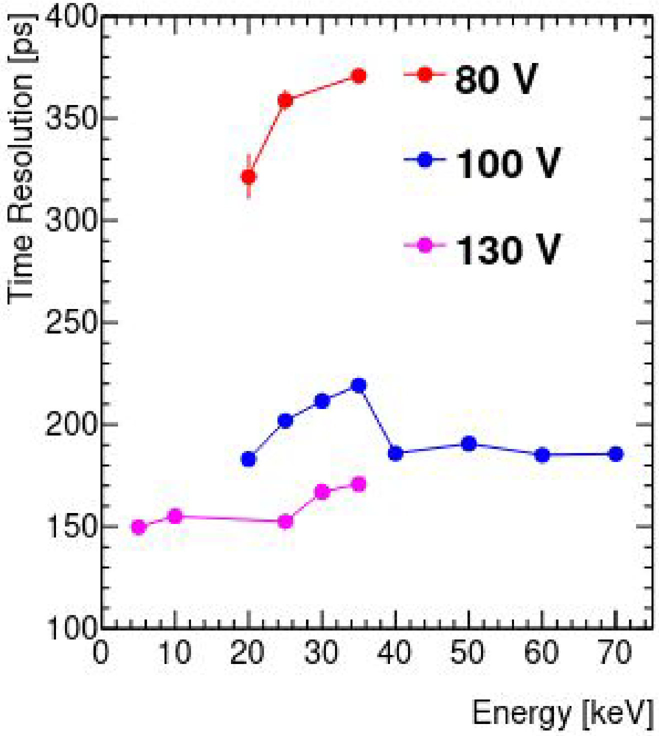
Results – time resolution



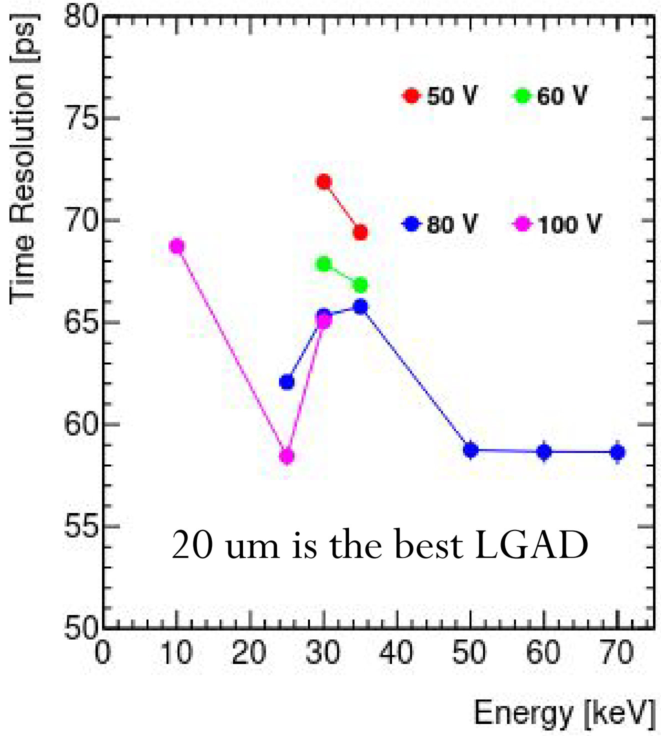
- Measured as CFD20% time of arrival of two peaks with 2.1 ns separation
- Distribution is fitted with a Gaussian, sigma is time resolution
- Results are quite worse than LGAD performance with MIP (sub 50 ps)



(a) HPK PIN and type 3.1 LGAD



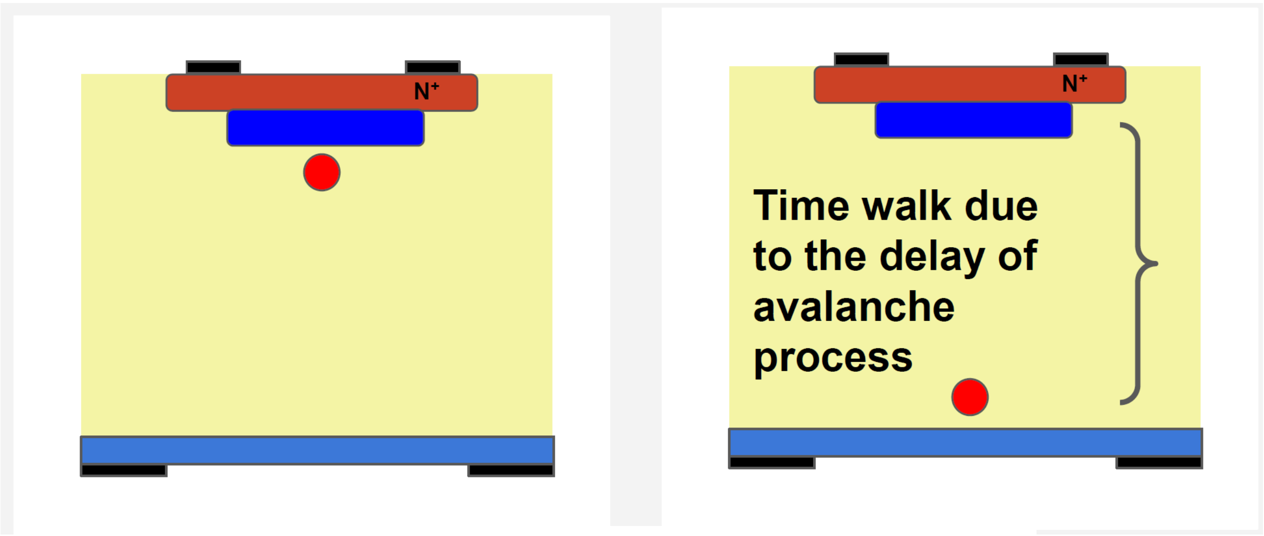
(b) HPK type 3.2 LGAD

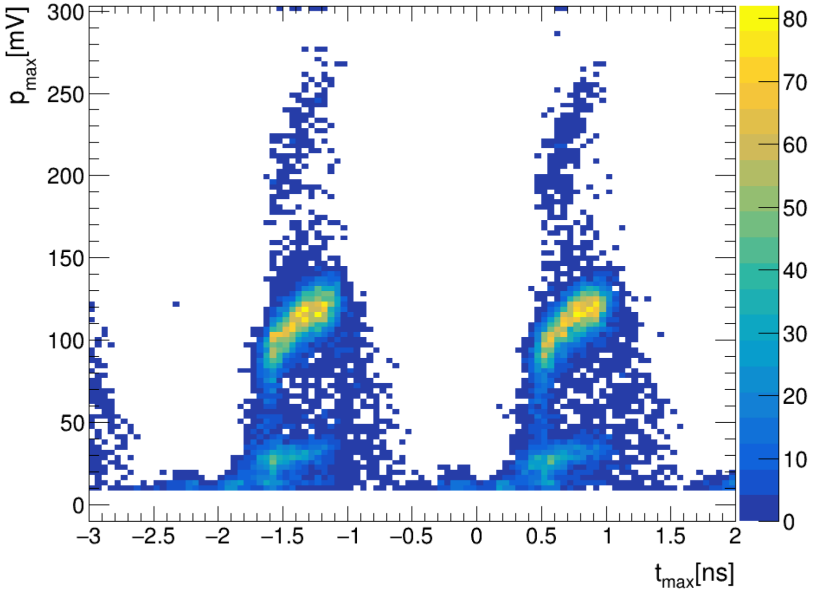


(c) BNL 20um LGAD

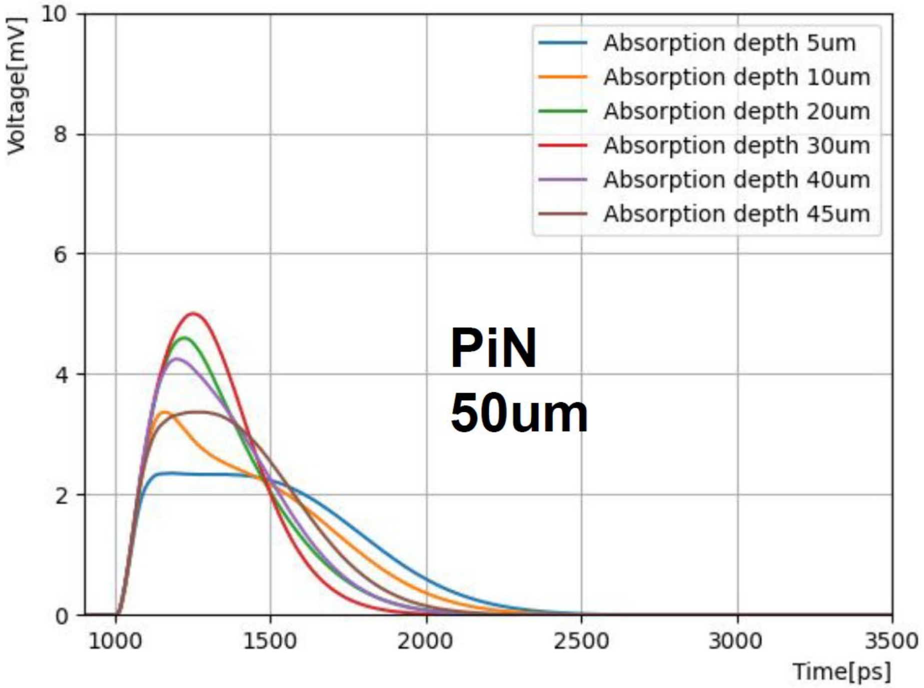
Why the bad time resolution?

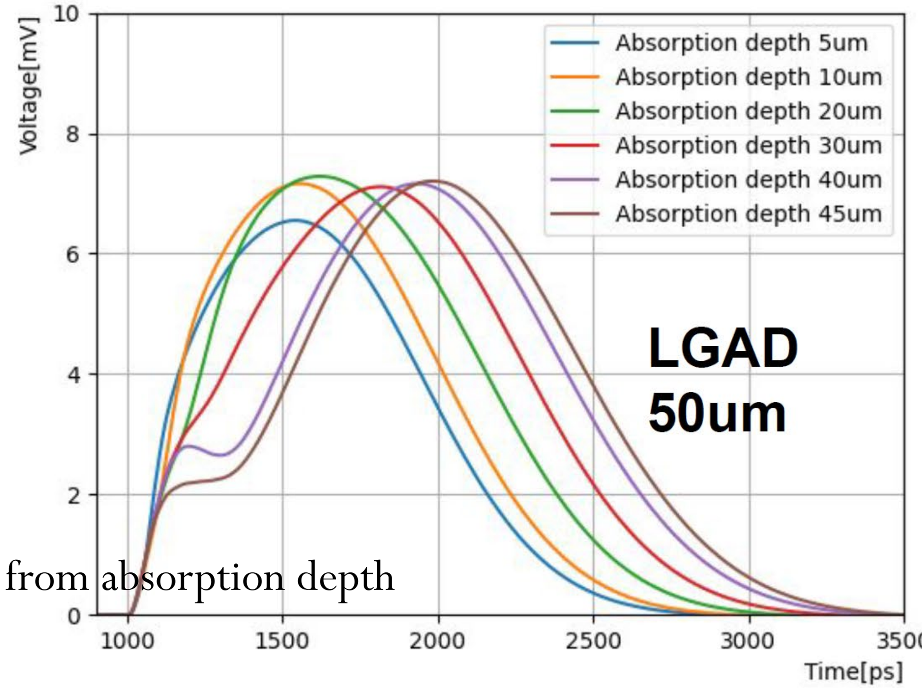
- The major time walk effect from photon absorption at different depth inside the sensor contributes to the time resolution
  - PIN is not affected by the delay (current is istantaneous)
- Using 20% CFD reduces the effect but doesn't remove it completely
- The absorption depth also affects the gain of the device
  - Tmax vs Pmax plot in data shows correlation
  - Absorption on the back has more gain due to charge cloud expansion during drift





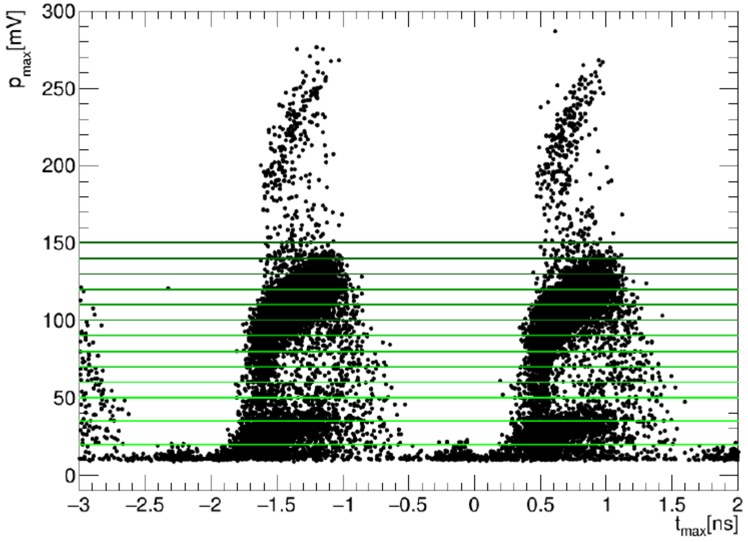
TCAD simulation of different absorption depths

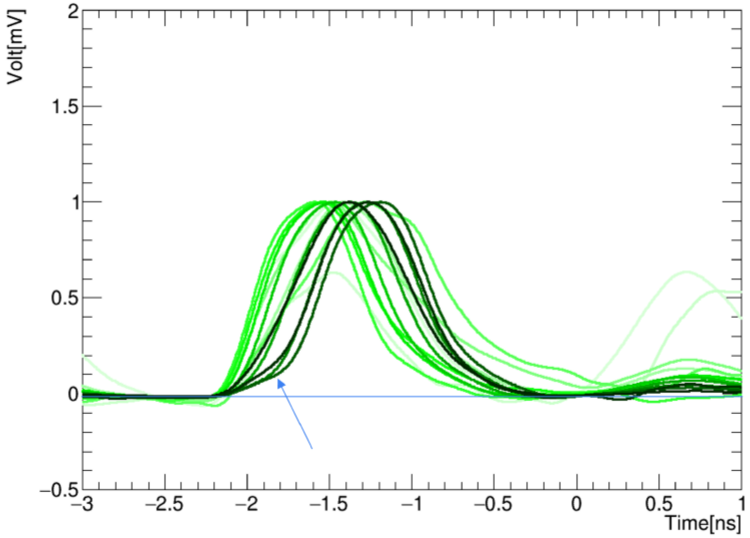




Delay from absorption depth

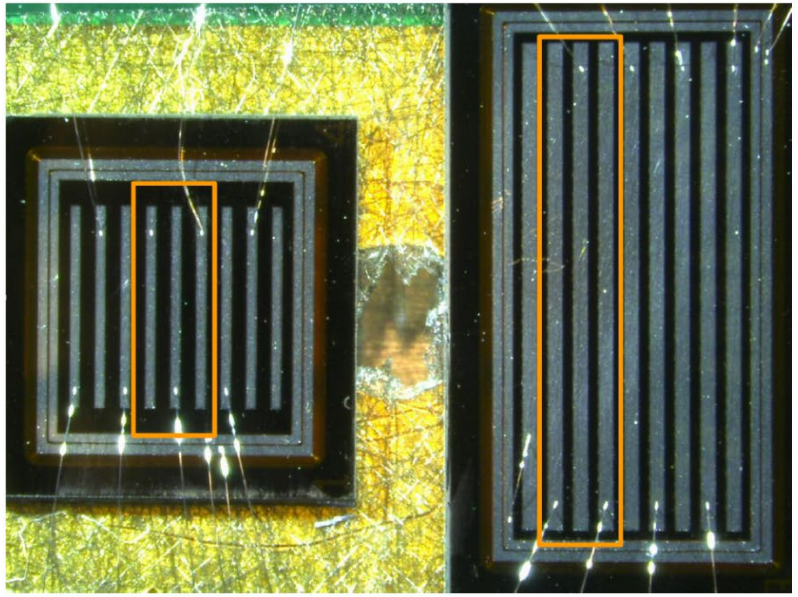
Averaged waveforms from data, sliced for pmax differences and normalized

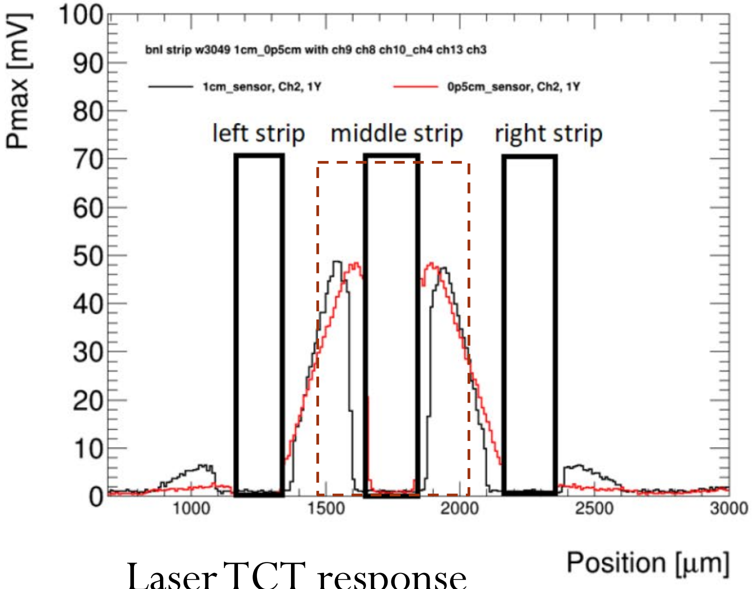




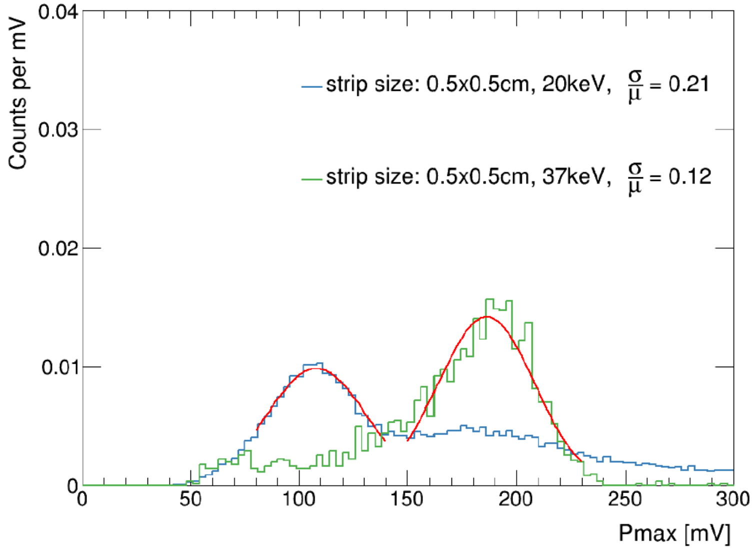
AC-LGADs

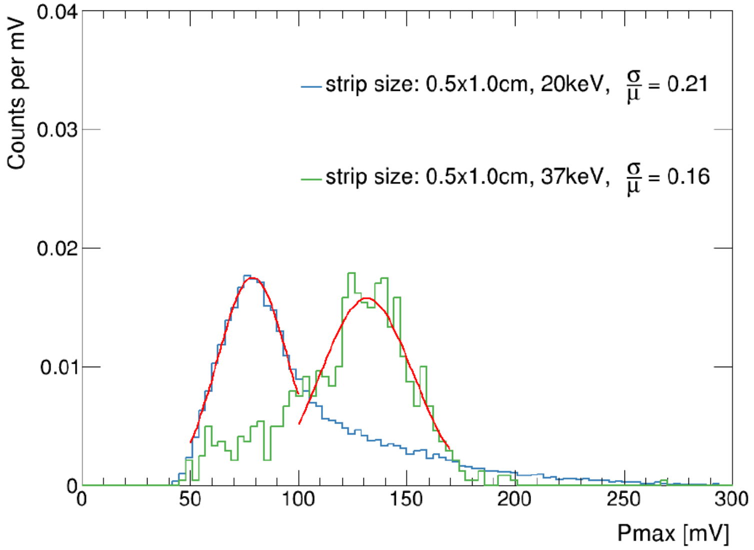
- AC-LGAD sensors tested in the same beam line with 16ch FNAL board and CAEN DT5742 16ch digitizer
- Since beam is broad there's no information on position
  - AC-LGADs rely on charge sharing
  - But from TCT studies on the same devices the response is know: everything is mostly contained in 3 strips
- Searching for events with one middle strip with higher response than its two neighbors and no response on the remaining strips
  - Sum the three pulses to get the total energy response
- Energy response roughly linear as expected
  - Energy resolution between 12% and 21%, slightly worse than DC devices
  - Better for 5cm device with reduced charge sharing





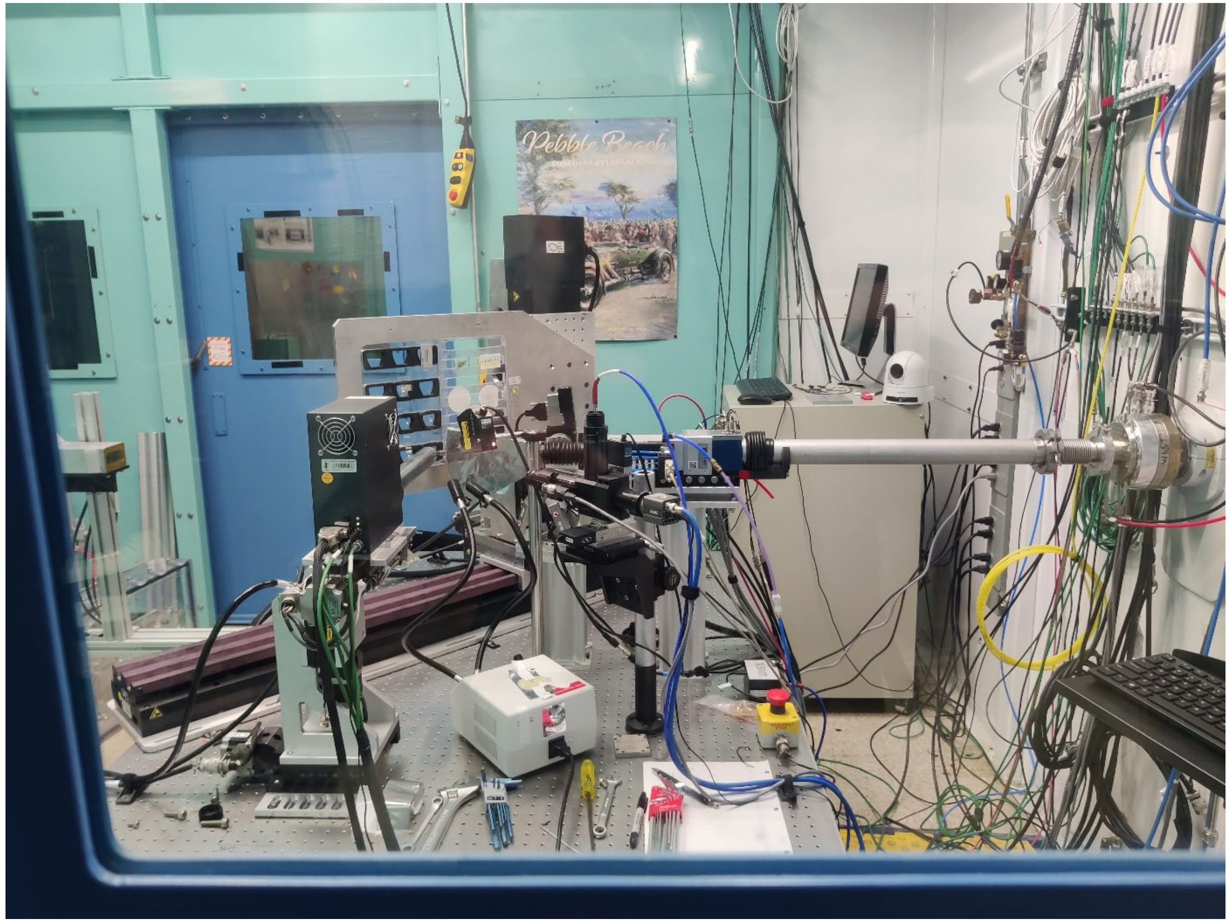
Laser TCT response
Selected event in the dashed box





Next steps

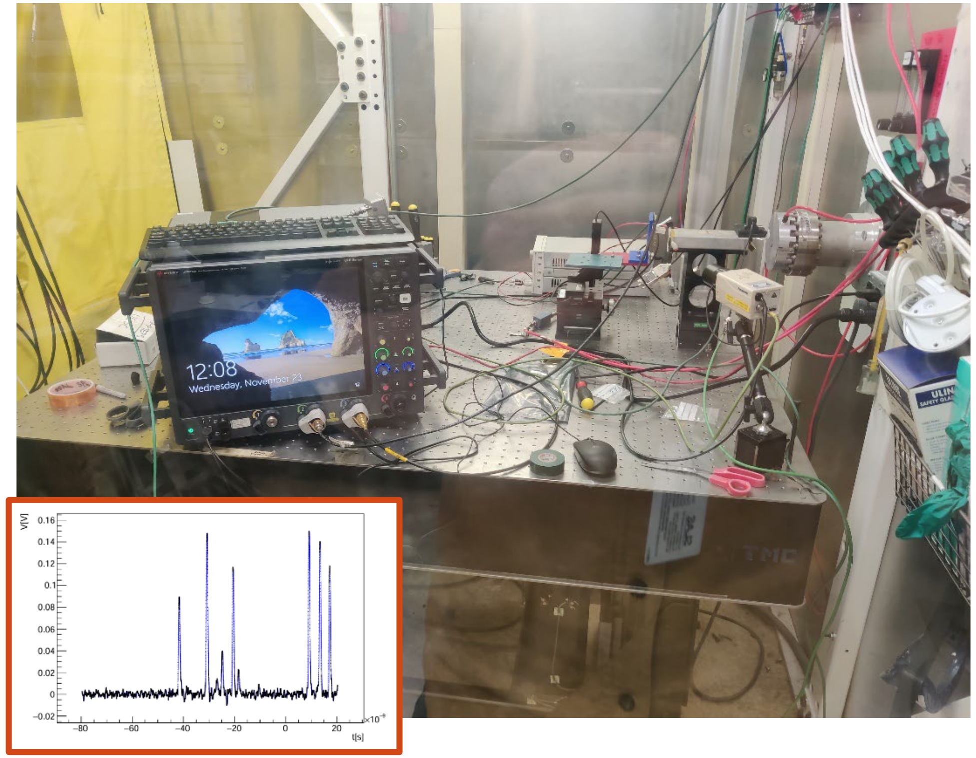
- Next test beam scheduled for February 2024
  - (Actually was scheduled for February 2023, but there was a unexpected SSRL shutdown)
- Beam line 7-2 with focused beam (50x100um)
  - Allows for better study of standard LGADs (beam is always contained in the sensor)
  - Test of LGAD array interfaces
  - AC-LGAD can be studied properly using the rough position information
- Tentative measurement of Compton response using a SiPM trigger/tag
  - Tried in previous test beam but unsuccessful
- Other areas in SSRL can go to sub-KeV
  - Eventually test LGADs suitable for that



Conclusions

- LGAD show very promising performance for the detection of X-rays in synchrotron facilities
- Energy resolution between 6% to 20%, tested down to 5 KeV
  - LGADs can detect even down to few KeV (limited by entry window)
- Time resolution is between 50 to 200 ps, worse than with MIPs
  - Effect of deposition depth and drift to the gain layer
- Easily resolve the 500 MHz repetition rate
- A gain reduction effect was observed for X-rays in comparison to MiP due to charge deposition profile

	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



Backup

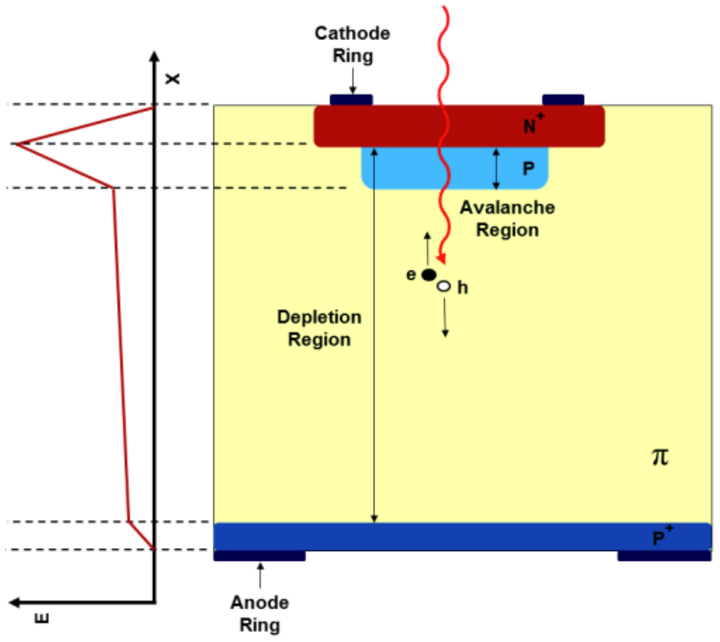
This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286.

Use of the Stanford Synchrotron Radiation Light source, SLAC National Accelerator Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy

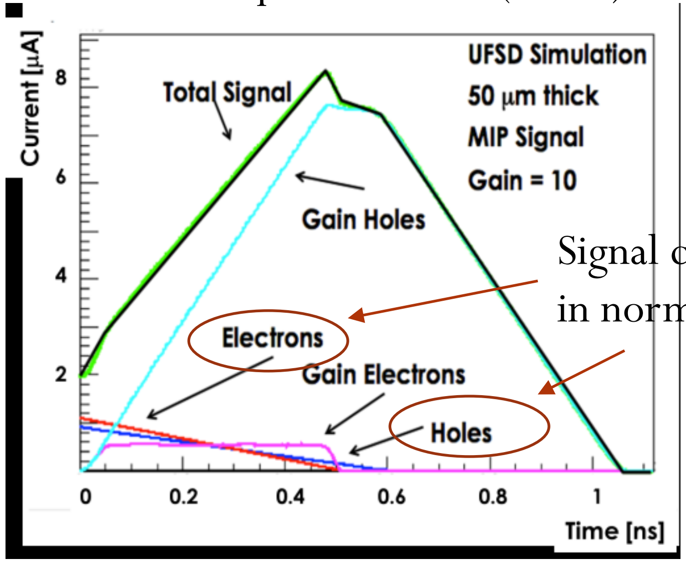
Sciences under Contract No. DE-AC02-76SF00515. The group from USP acknowledges support from FAPESP (grant 2020/04867-2) and CAPES.

Low Gain Avalanche Detectors

- Sensors envisioned for the ATAR are Low Gain Avalanche Detectors (LGADs)
- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer,
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
- Great hit time resolution and fast full collection time



Entire pulse is ~1ns (50um)

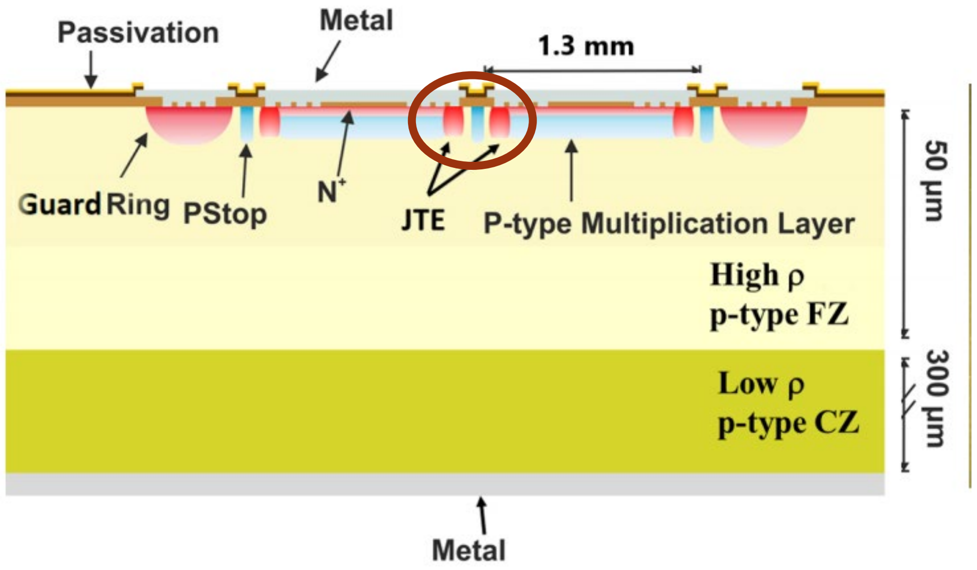


Signal components in normal silicon

Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

LGAD arrays

- Granularity is a current limitation for LGADs
- Due to high fields in the multiplication layer the pads needs electrical insulation
  - Protection structure: Junction Termination Extension (JTE)
  - Causes inter pad (IP) gap to 50-150um, also changes with applied bias voltage
  - Limits LGAD granularity to mm scale
- However 50um pitch (and lower) is required for next generation colliders and 4D tracking
  - At least same level as the ATLAS new inner tracker (ITk) needed
- Several possible solutions are being investigated by the community
  - AC-coupled (RSD) LGADs, Trench insulated LGADs, inverted LGADS…



Inter-pixel region in Standard LGADs

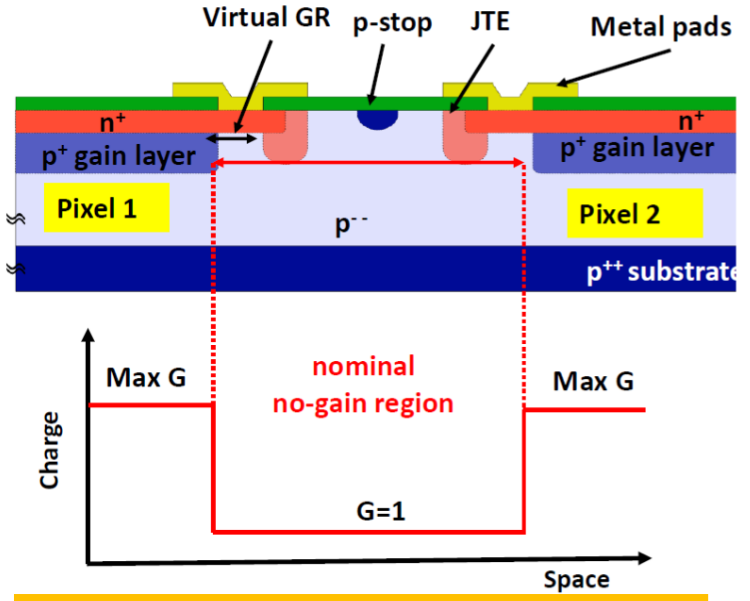
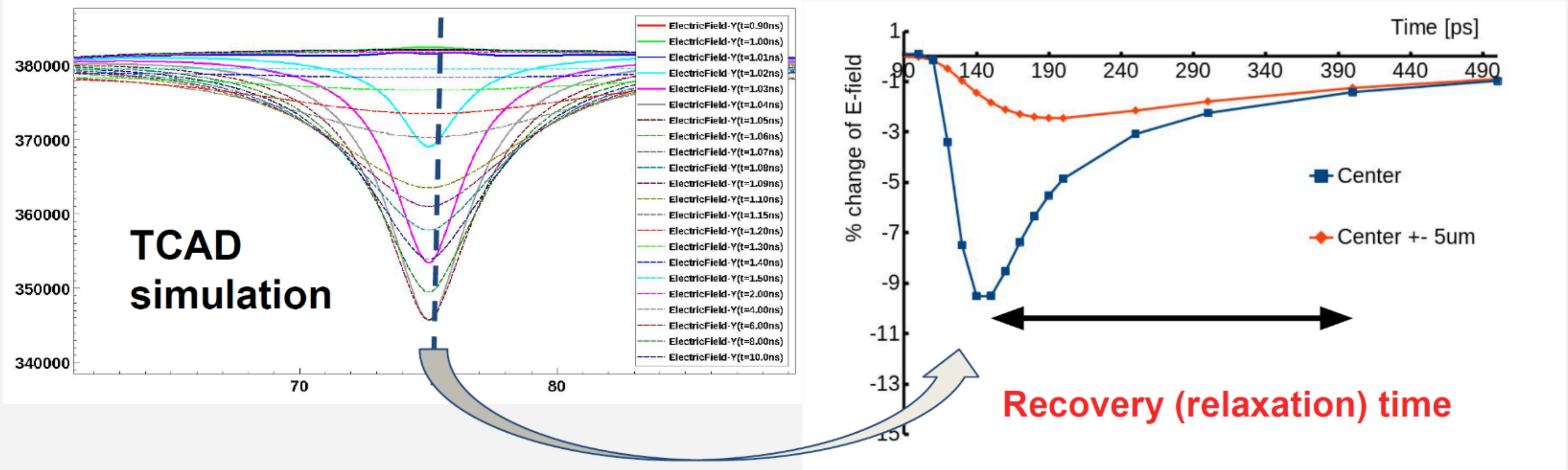


Diagram credit: FBK, Trento, Italy

Gain Suppression

- One possible explanation to this is related to the generated e-h density and the gain layer E-field relaxation process.
- This variation of E-field depends on the generated e-h paris density per unit distance.
- MiP generates less e-h paris per unit distance comparing to point-like X-rays deposition.



Snapshot of the electric field within the gain layer at different time for localized input charge.

Note: the impact ionization has exponential dependence on the field.

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Y. Zhao