Silicon Photomultipliers in a Liquid Xenon Time Projection Chamber

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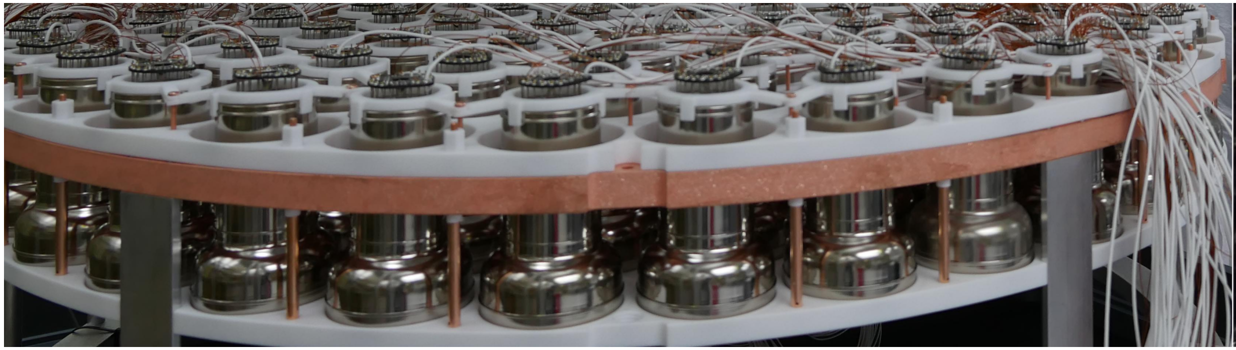
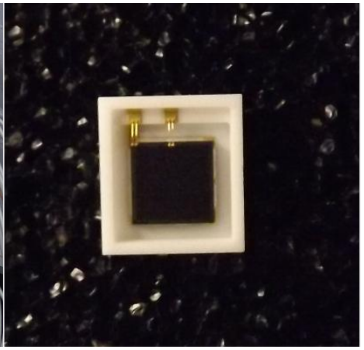
Bundesministerium
für Bildung
und Forschung

Motivation

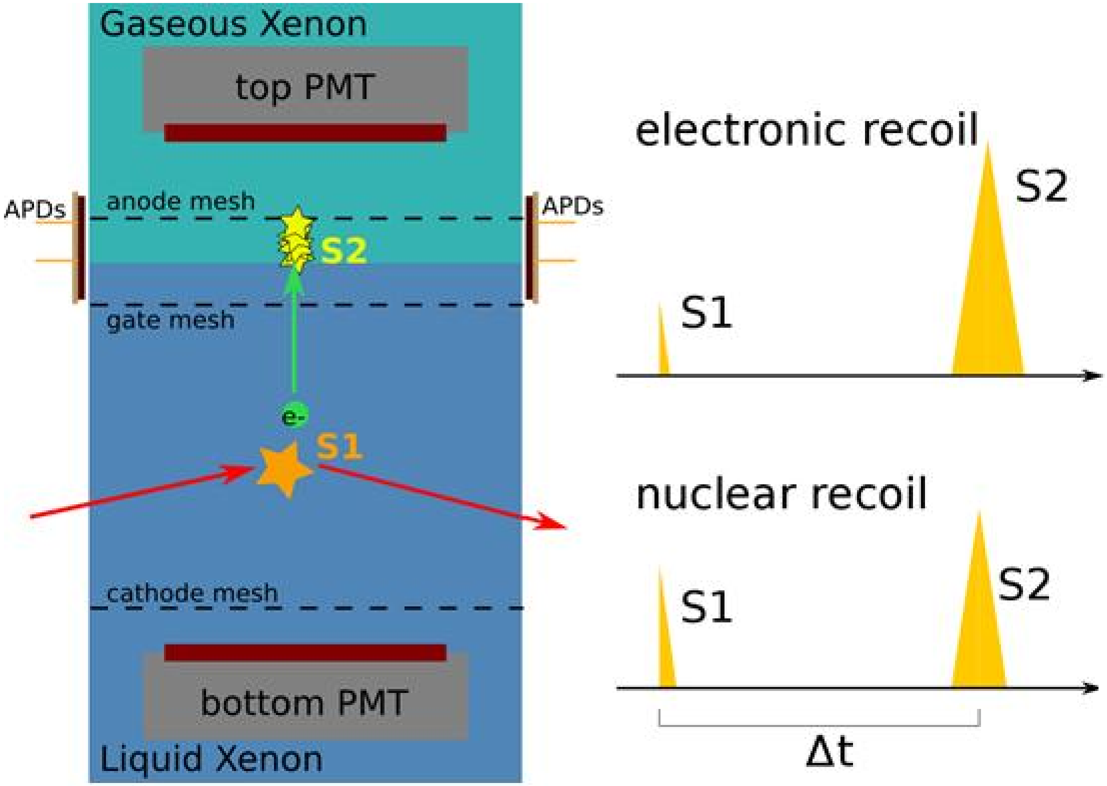



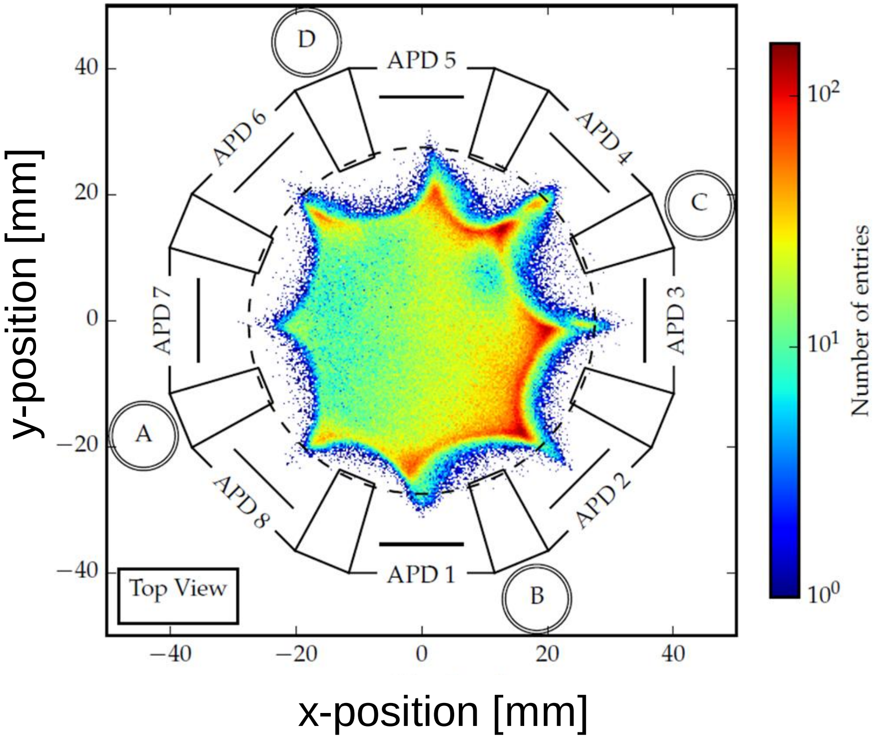
- High Granularity
- Compact design
- Radiopurity for usage in low background detector
- SiPMs reach a gain of up to 10^6, comparable to PMTs
- Low bias voltage needed: 20 – 70 V (PMT: ~1500V)

LXe-Time Projection Chamber

TPC working principle:

- 3D position reconstruction
- recoil type identification





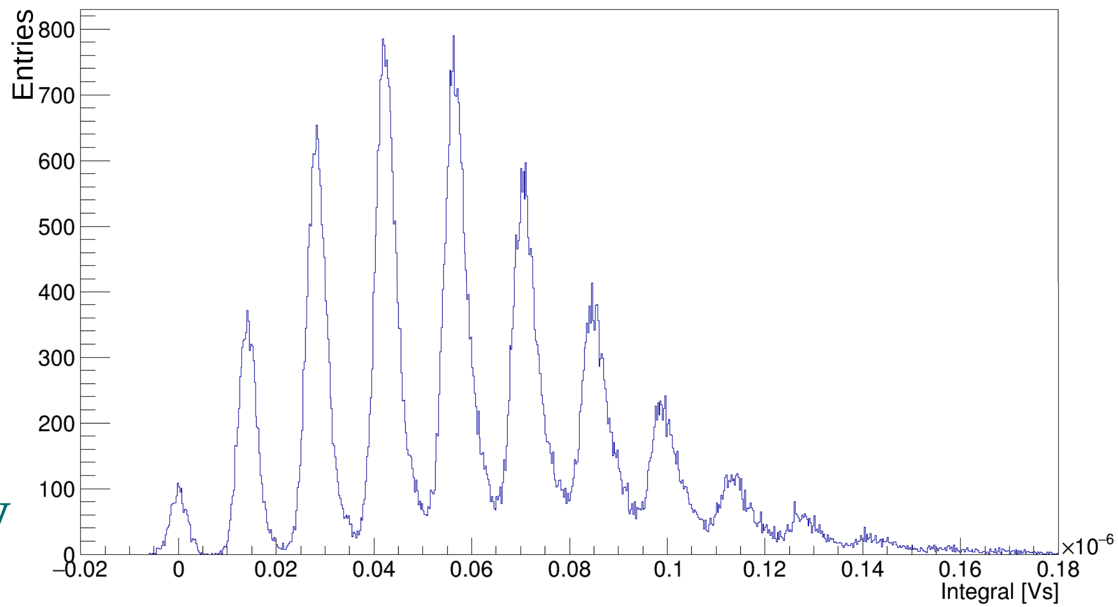
[Bastian Beskers, PhD Thesis 2017, JGU Mainz; Daniel Wenz, Master thesis 2018, JGU Mainz]

SiPM Properties

- Optical cross-talk
- After-pulses
- Dark-count rate

- Single photon count capability
- Photon detection efficiency

Charge spectrum (LED Measurement)



$$\text{PDE} = \frac{\text{number of generated Signals}}{\text{Number of impinging photons } (\lambda)}$$

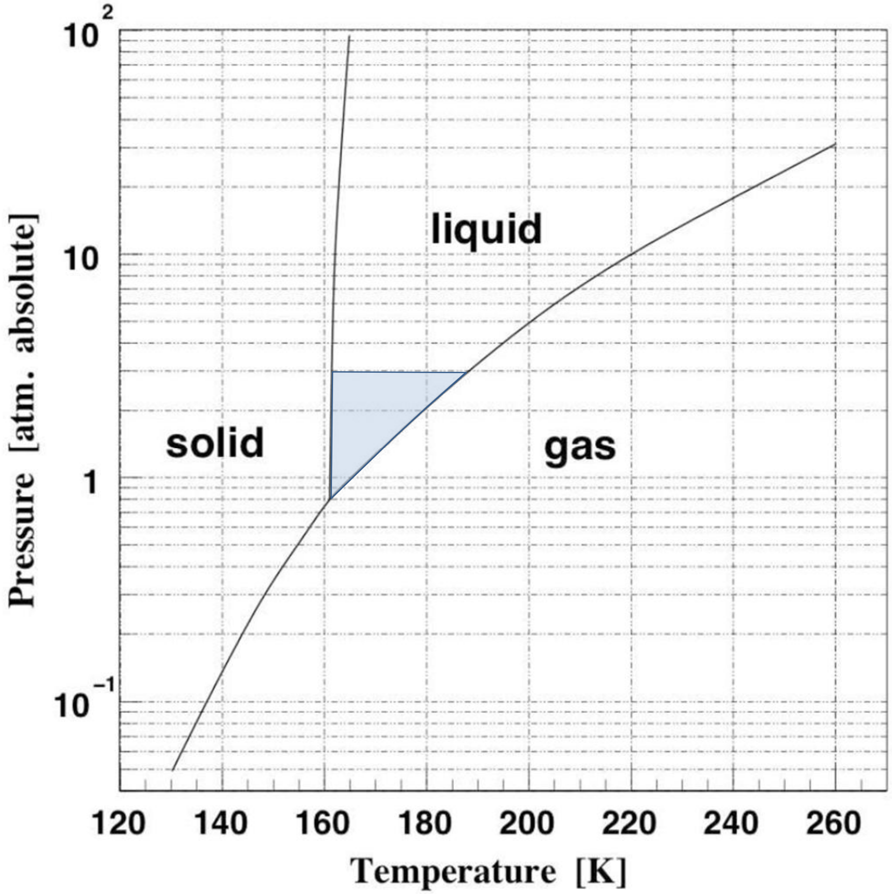
$$\text{PDE} = \text{QE}(\lambda) \cdot \text{F} \cdot \varepsilon$$

QE: quantum efficiency
F: fill factor
ε: avalanche trigger probability

Liquid Xenon: Cryogenic properties

SiPM:

- Behaviour in cryogenic environment



[E. Aprile and T. Doke, Liquid Xenon Detectors for Particle Physics and Astrophysics]

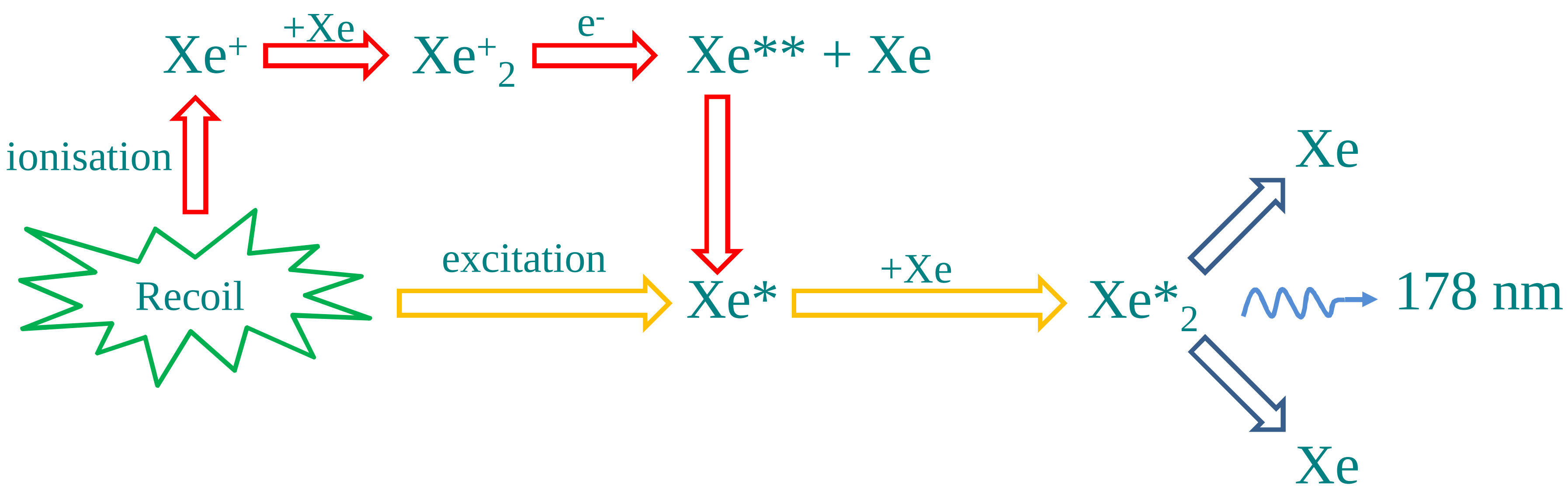
Liquid xenon properties:

- Temperature ~175 K
- Pressure 2 - 3 bar(a)
- multiple cooldown cycles

Liquid Xenon: Scintillation mechanisms

SiPM:
- Behaviour in cryogenic environment
- **VUV sensitivity**

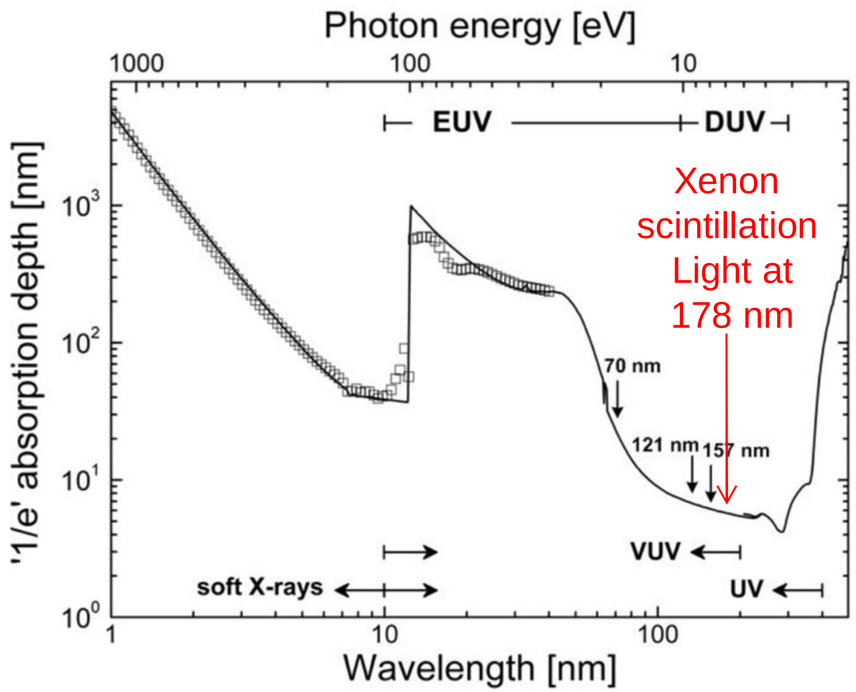
Light production mechanisms in xenon:
- two processes involving excited atoms (Xe^*) and ions (Xe^+):



Liquid Xenon: SiPM sensitivity

SiPM:
- Behaviour in cryogenic environment
- **VUV sensitivity**

Low sensitivity in VUV due to absorbtion properties of silicon:

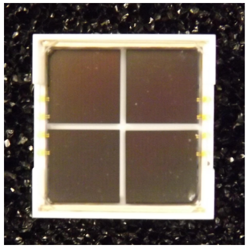
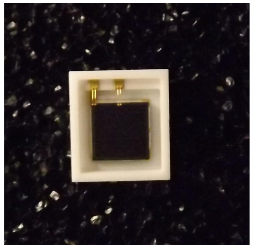
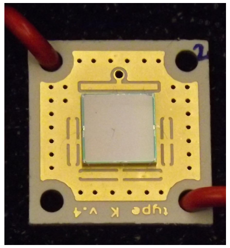


[L. Shi and S. Nihtianov, Comparative study of Silicon-Based Ultraviolet Photodetectors, IEEE Sensors Journal, Vol. 12, No.7, July 2012]

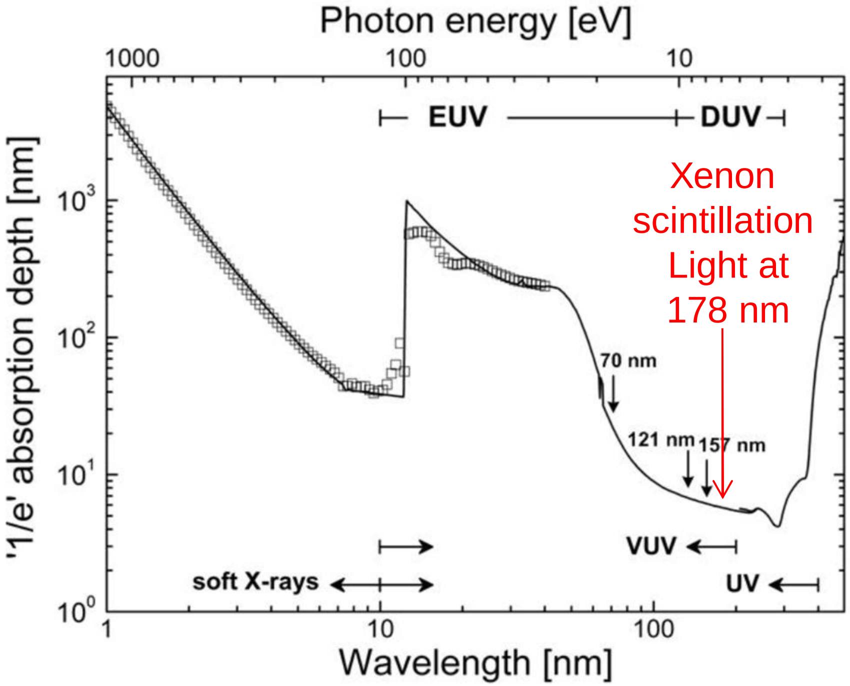
Liquid Xenon: SiPM sensitivity

SiPM:
- Behaviour in cryogenic environment
- **VUV sensitivity**

Low sensitivity in VUV due to absorbtion properties of silicon:

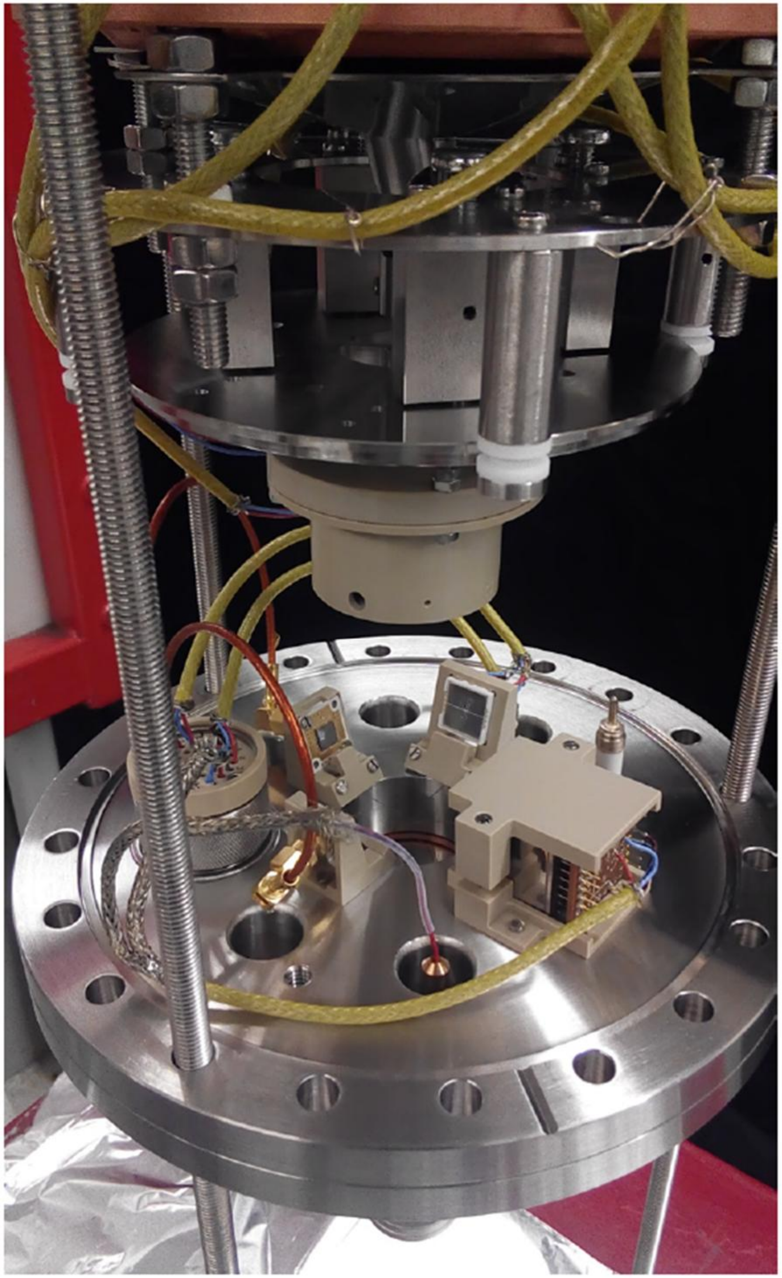
Hamamatsu Generation 3 (S10942)	Hamamatsu Generation 4 (S13370)	modified Ketek
		
6x6 mm²	3x3 mm²	6x6 mm²

Specific developments, | modification of commercial design

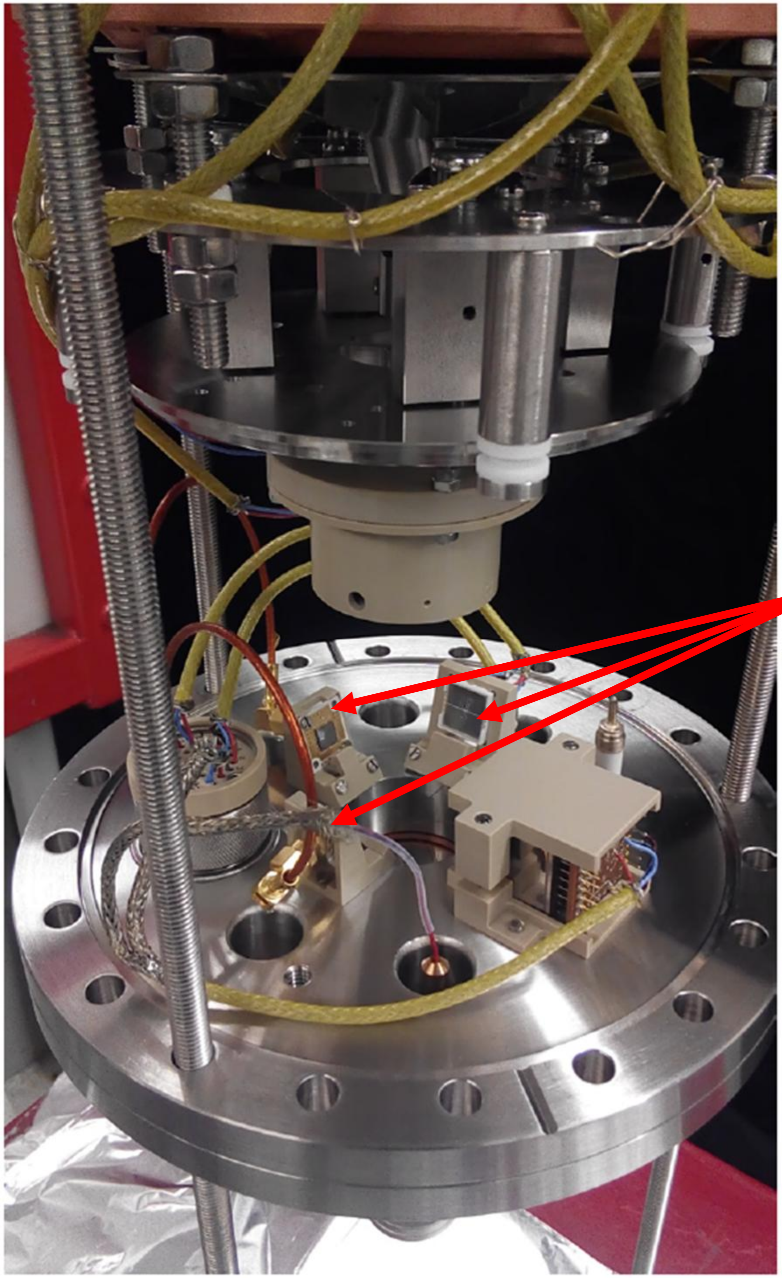


[L. Shi and S. Nihtianov, Comparative study of Silicon-Based Ultraviolet Photodetectors, IEEE Sensors Journal, Vol. 12, No.7, July 2012]

Measurement chamber

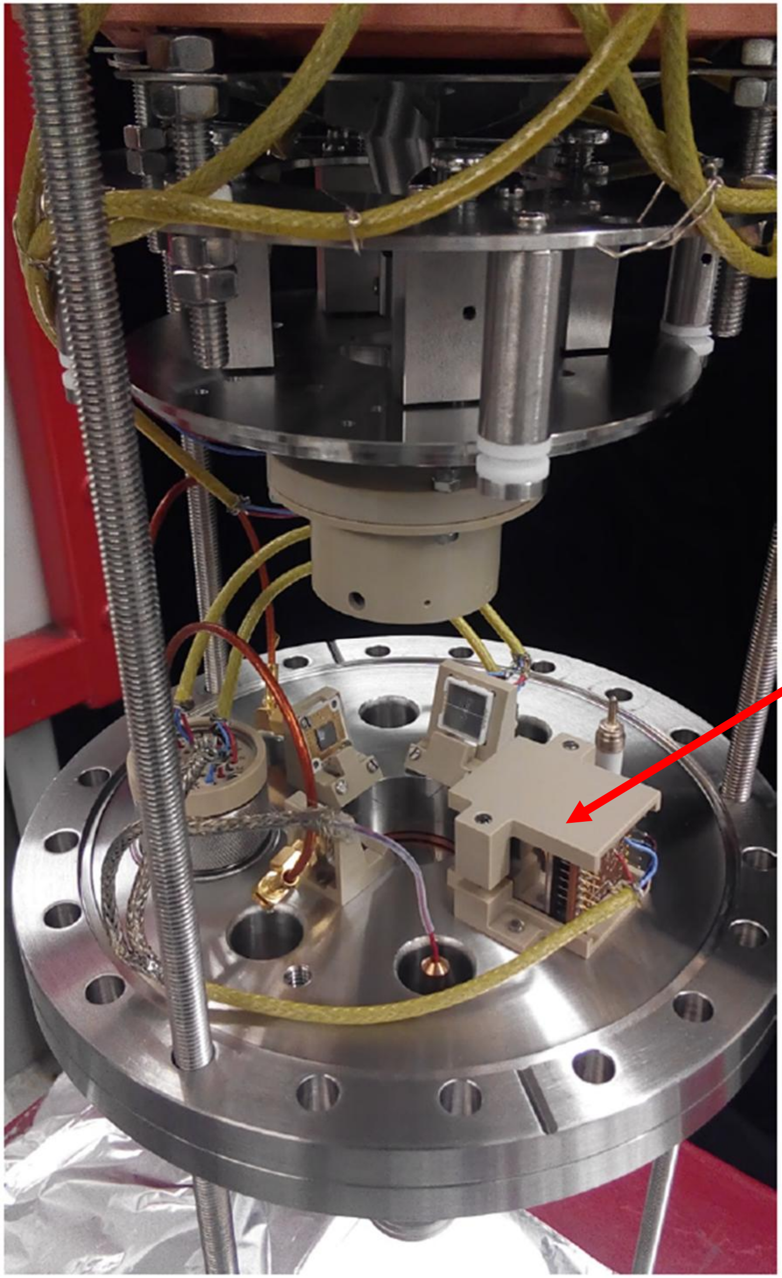


Measurement chamber



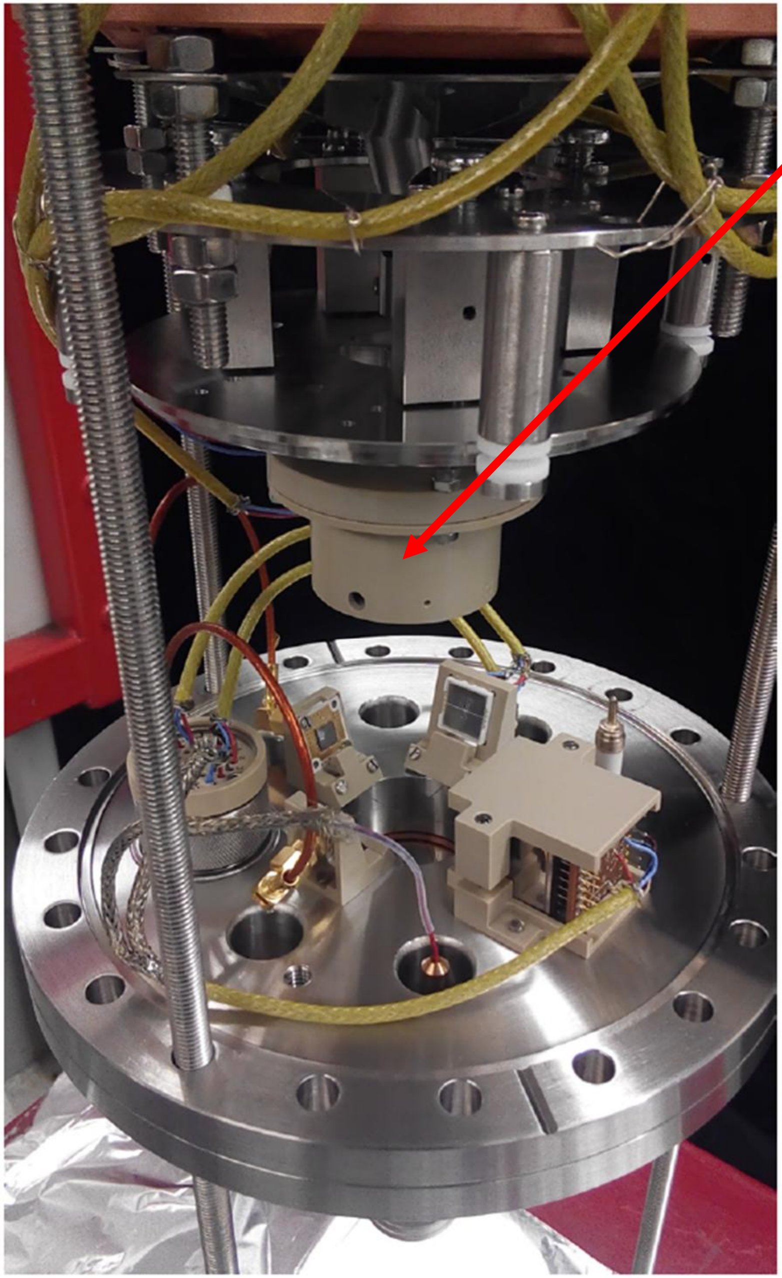
- up to 3 SiPM samples

Measurement chamber



- up to 3 SiPM samples
- 1” Hamamatsu PMT for reference

Measurement chamber



- Am-241 source (scintillation)
  →Illumination strength can be chosen with different sized openings in a rotatable cylinder

- up to 3 SiPM samples
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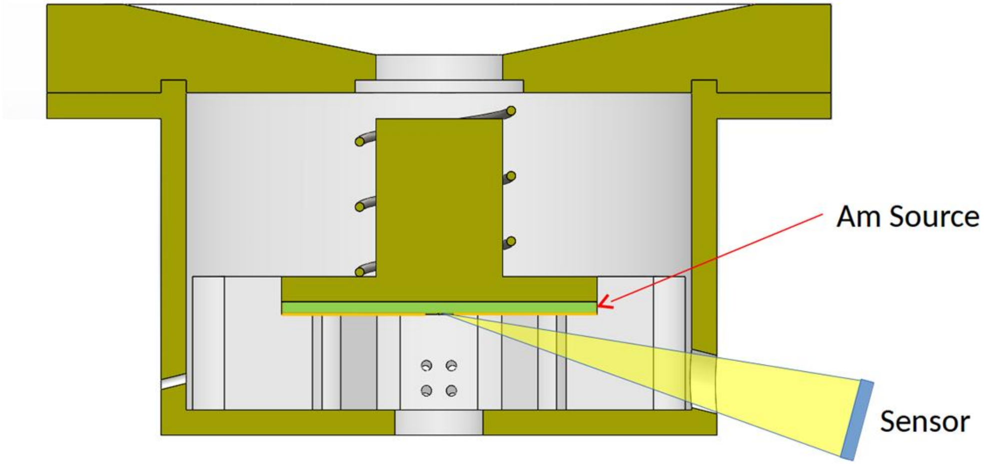
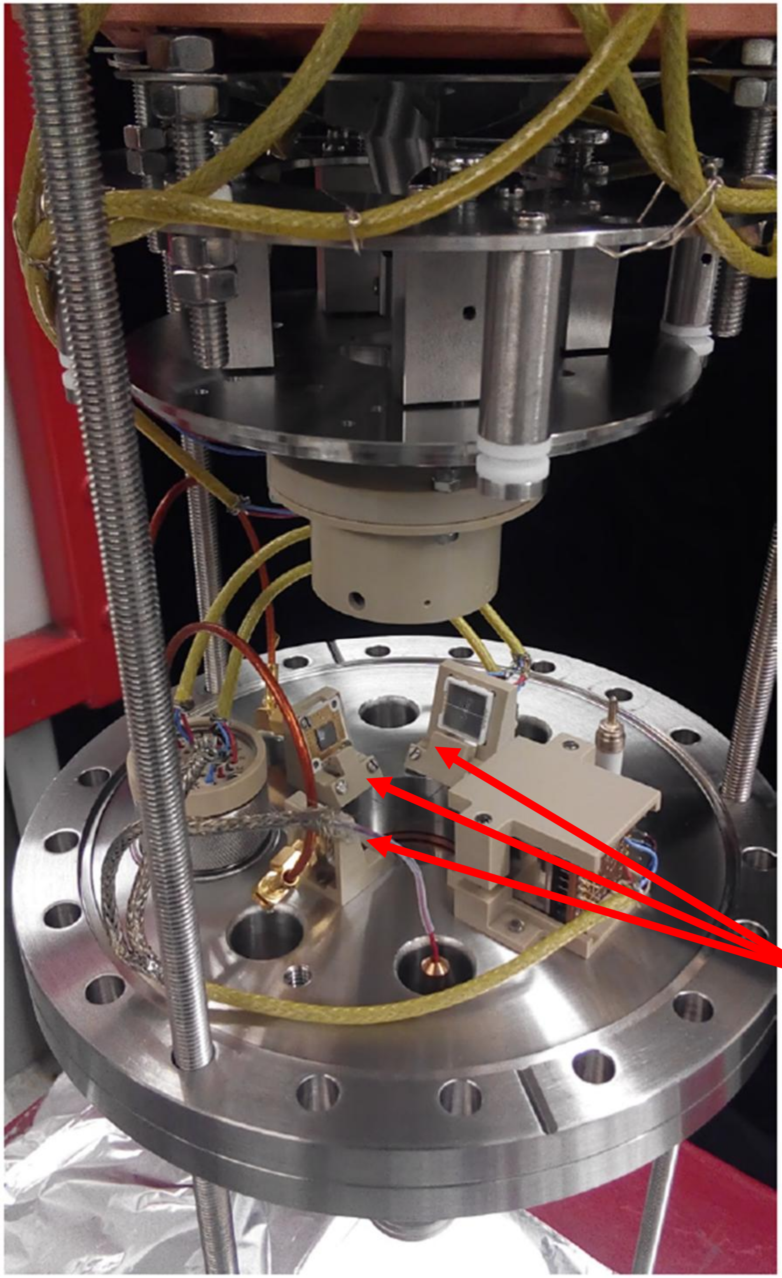


Measurement chamber



- Am-241 source (scintillation)
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- up to 3 SiPM samples
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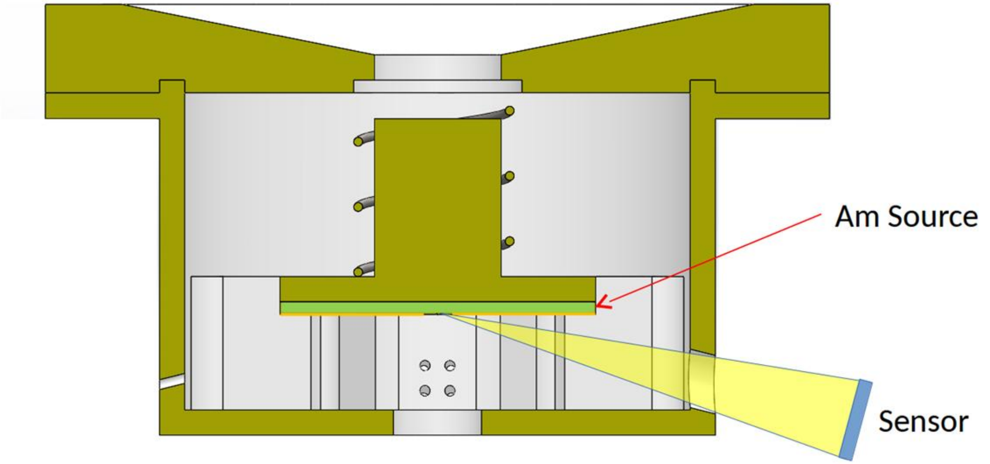
- LED

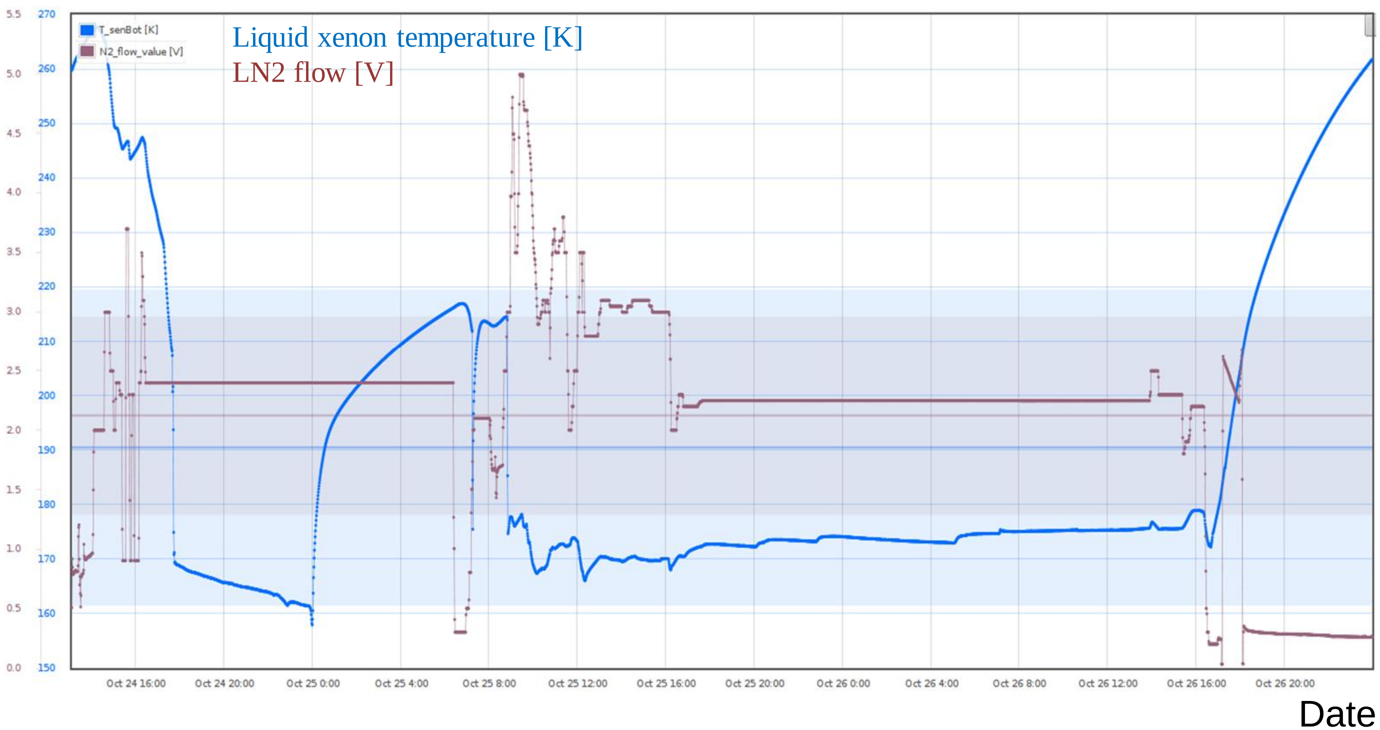


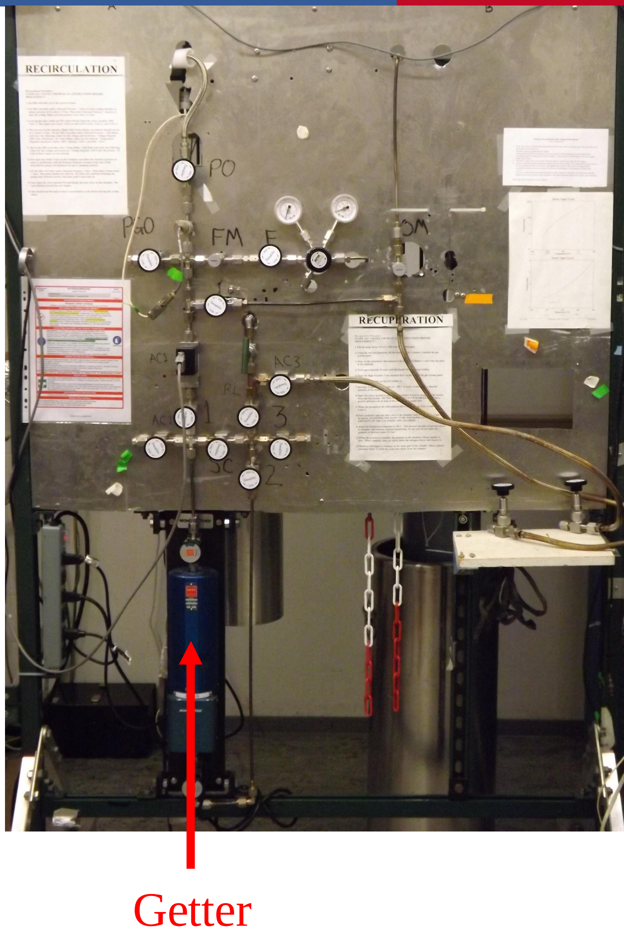
Xenon recirculation system

-Cooling with liquid nitrogen

-Xenon purification with recirculation system

-Very stable conditions during measurement runs





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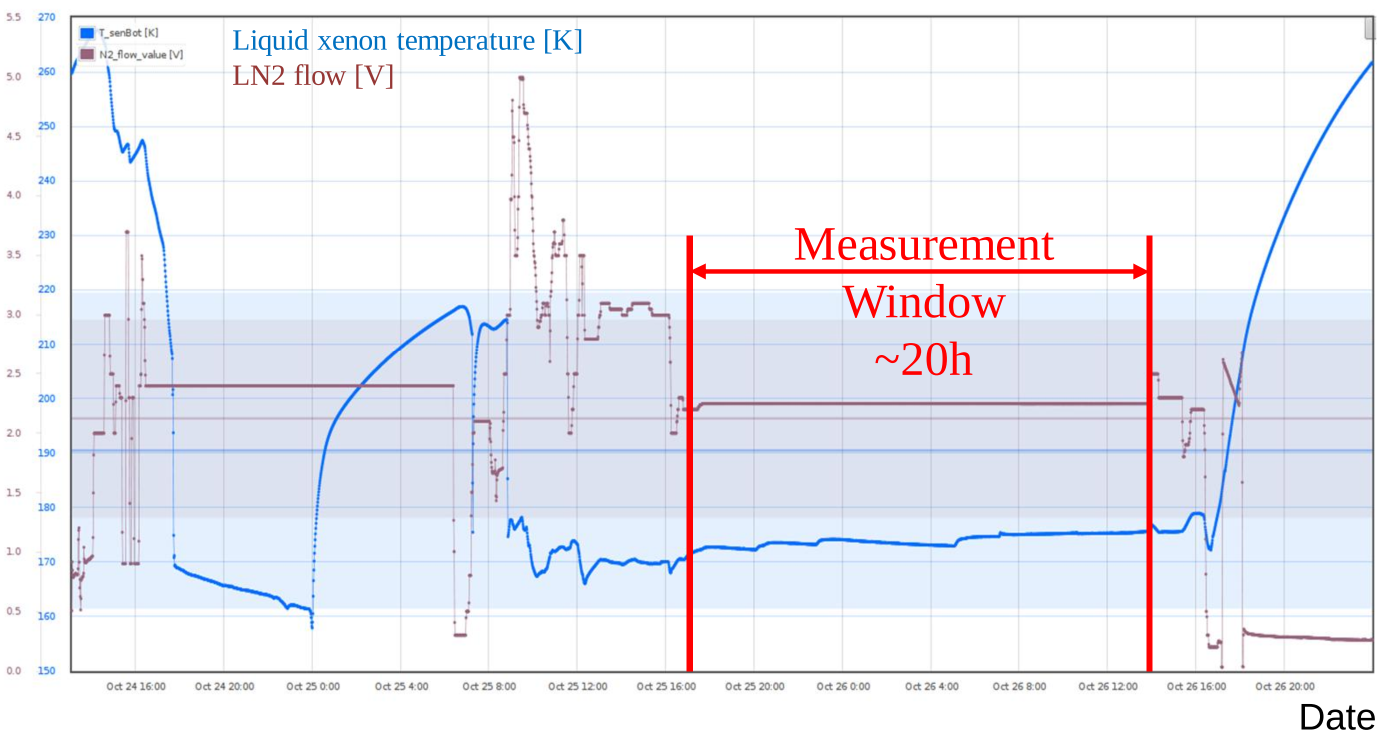

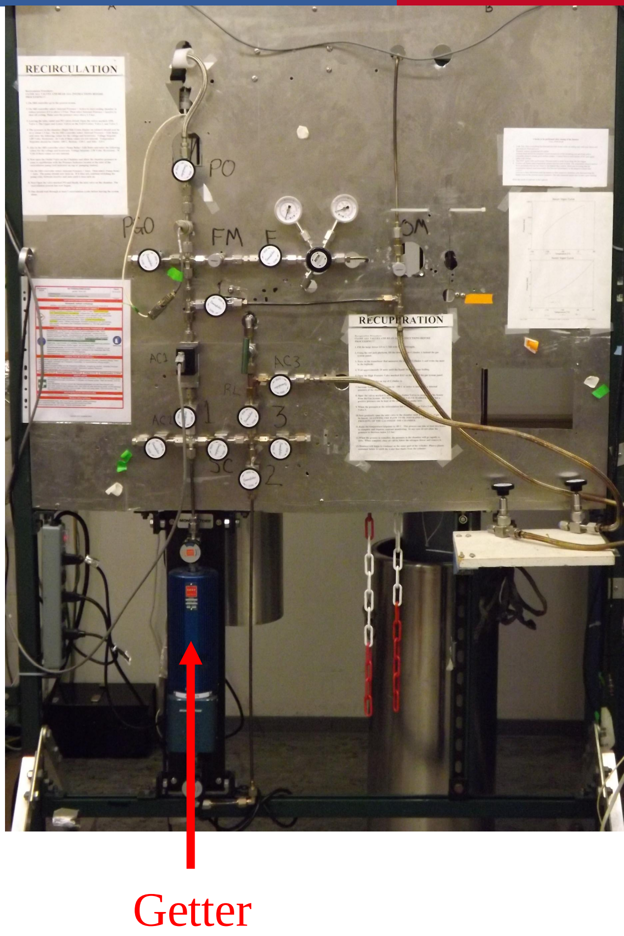

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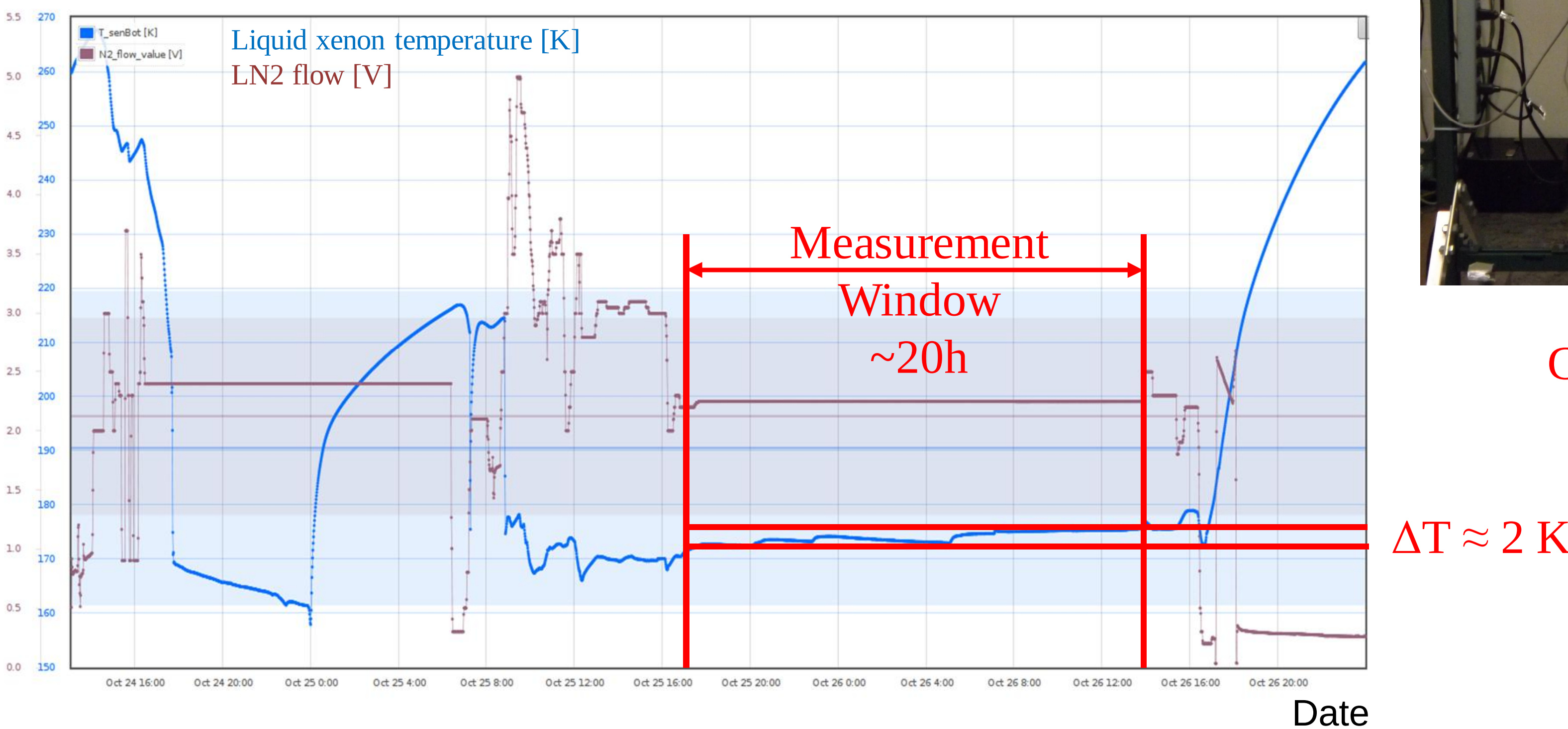
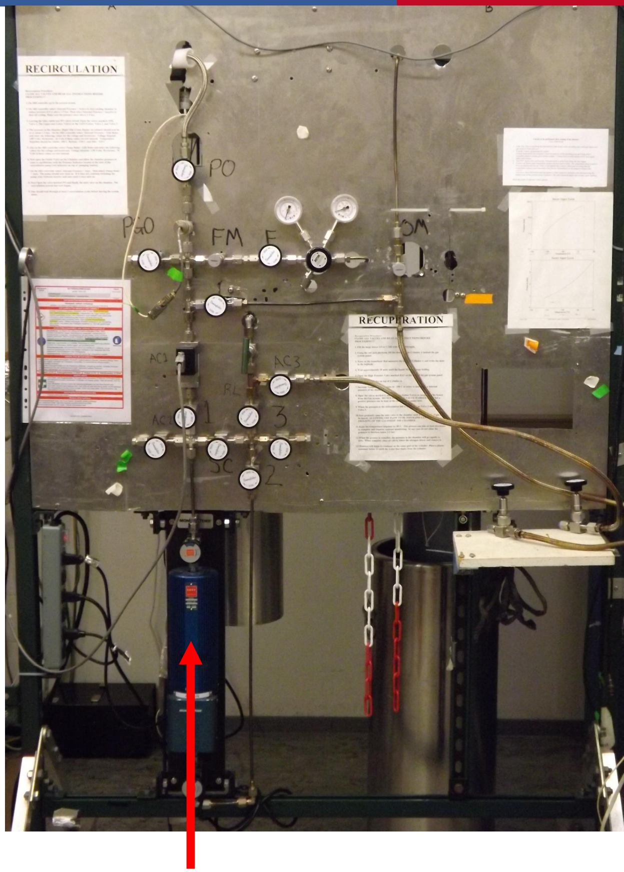
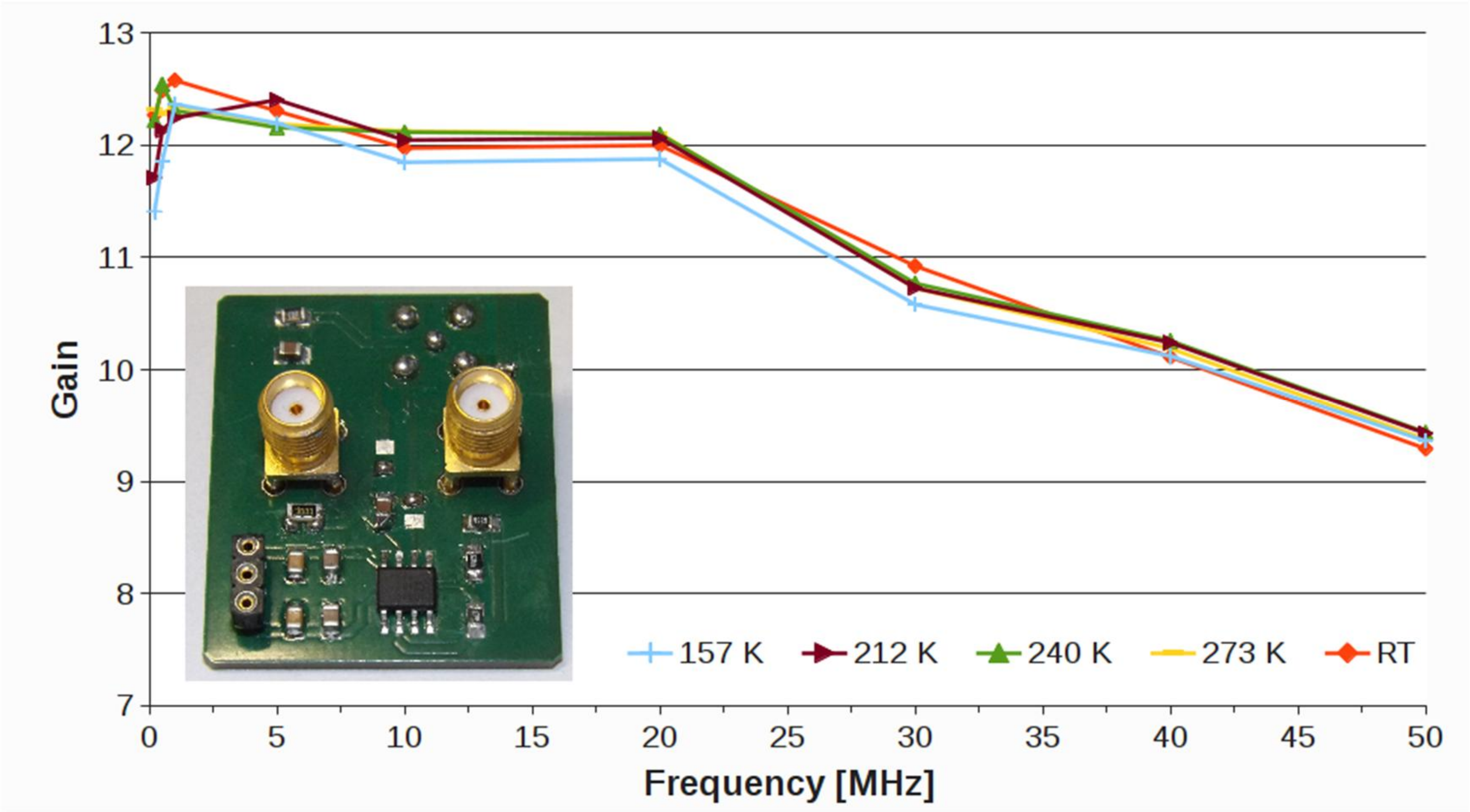




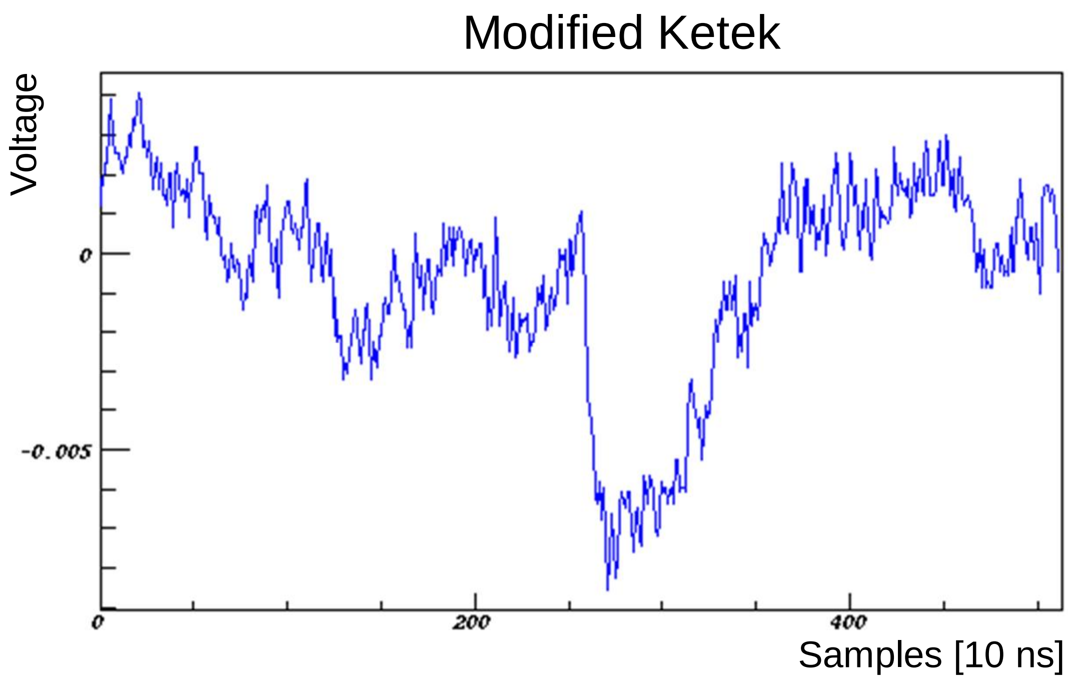
Electronics: Amplifier

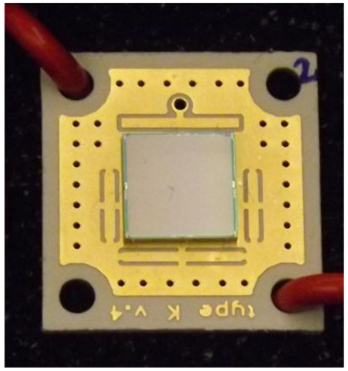
- Using inhouse built amplifier board for signal amplification
- Gain 10 amplifier
- Temperature stability of boards verified



Last measurement: Amplifier at room temperature

Waveform analysis:





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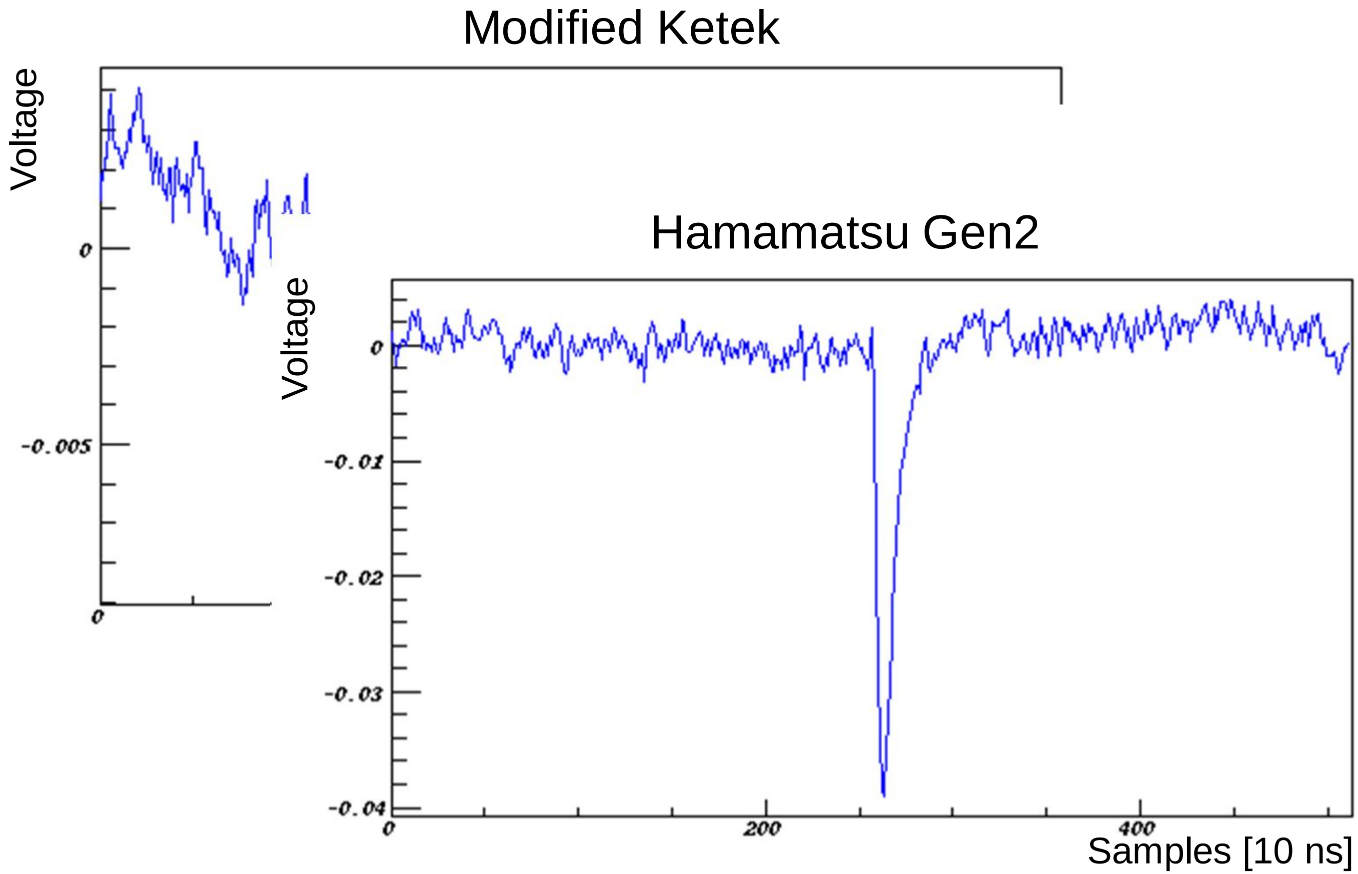

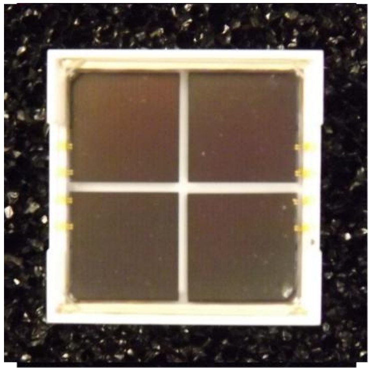

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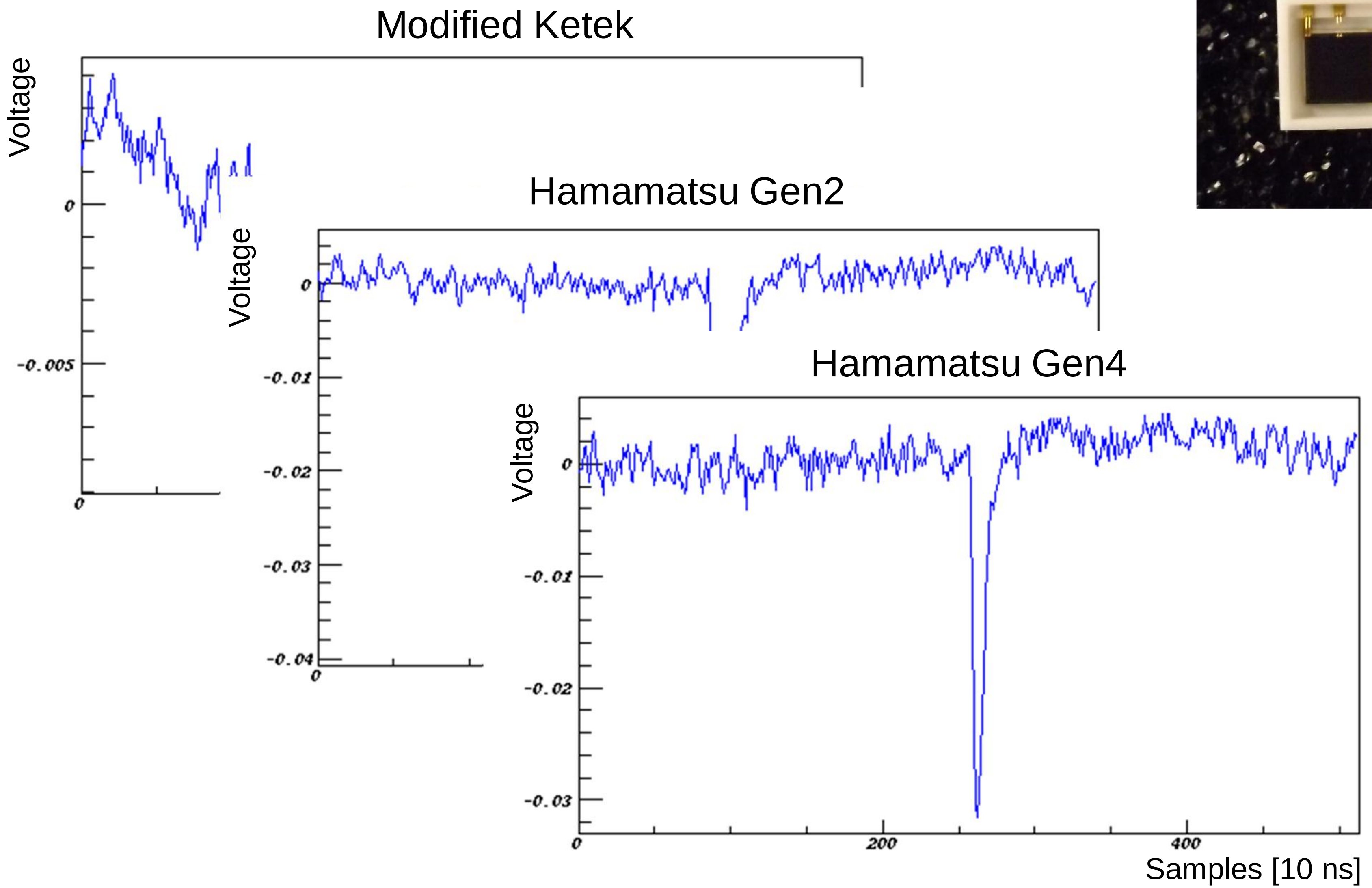
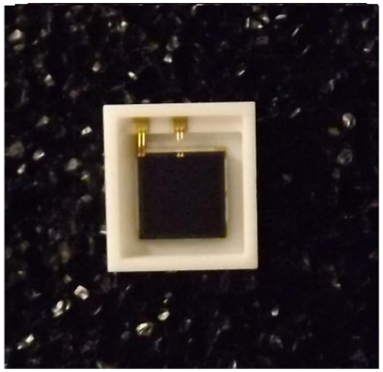
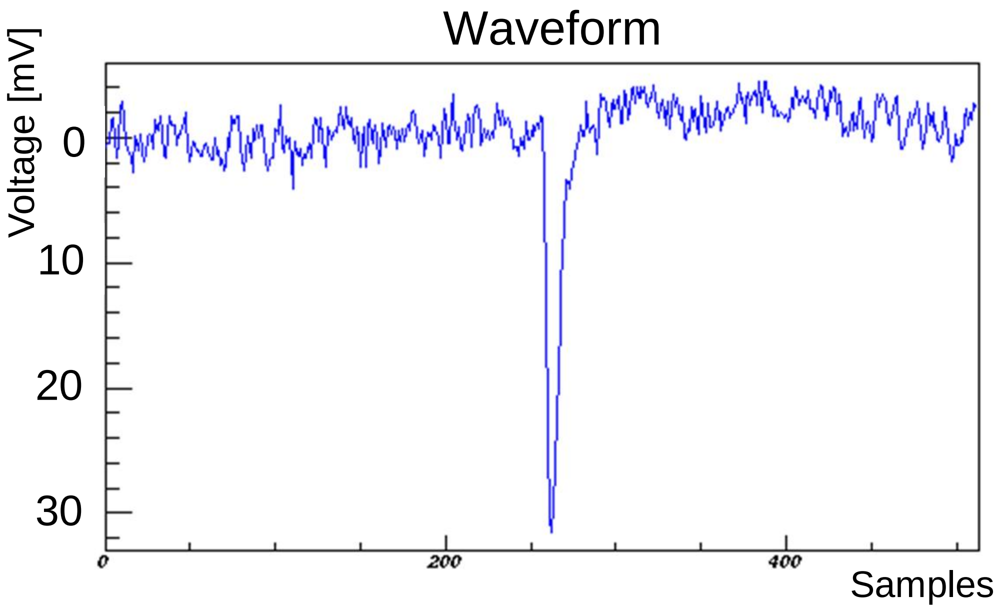




Analysis procedure



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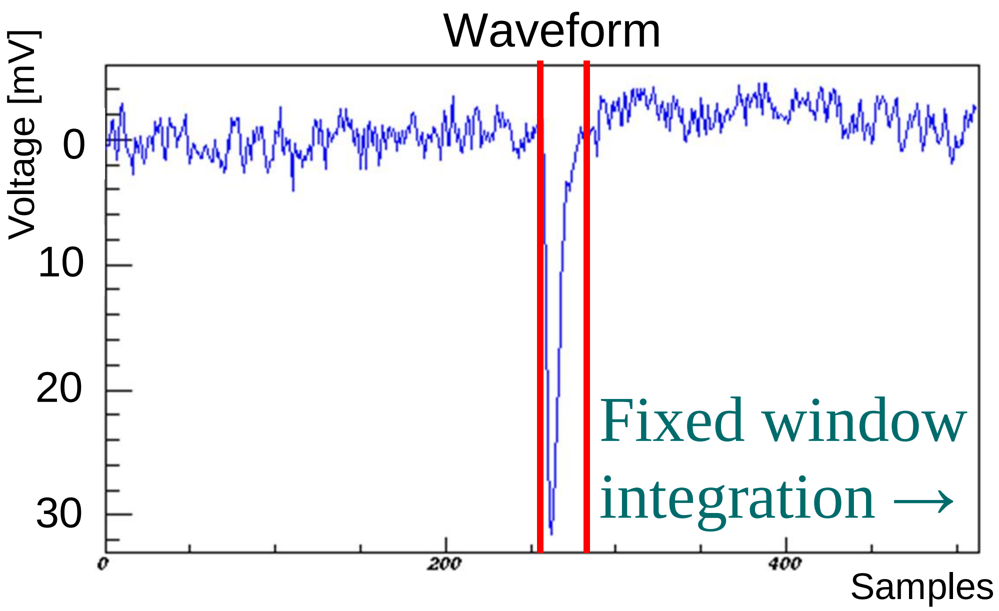

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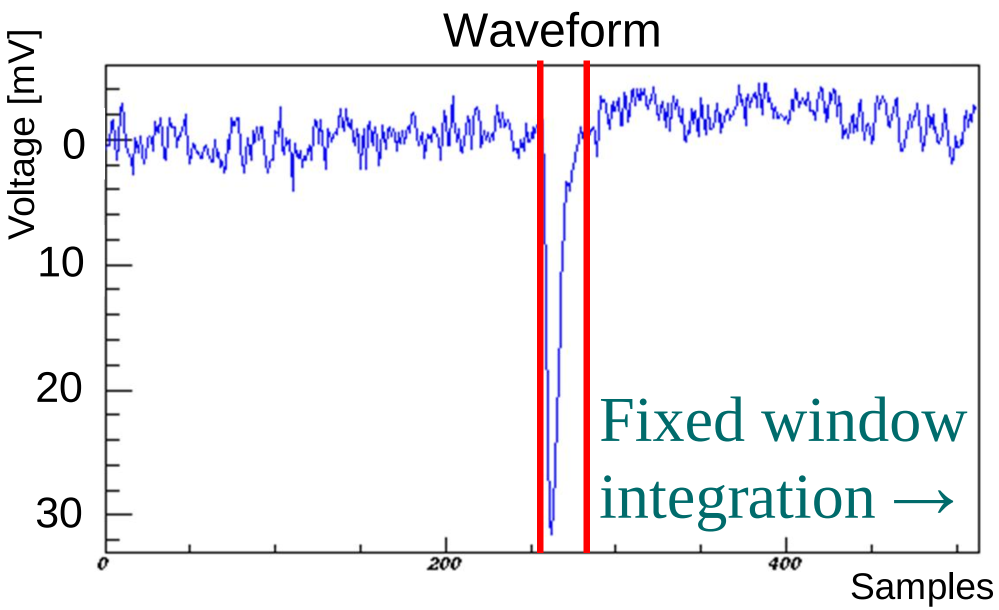

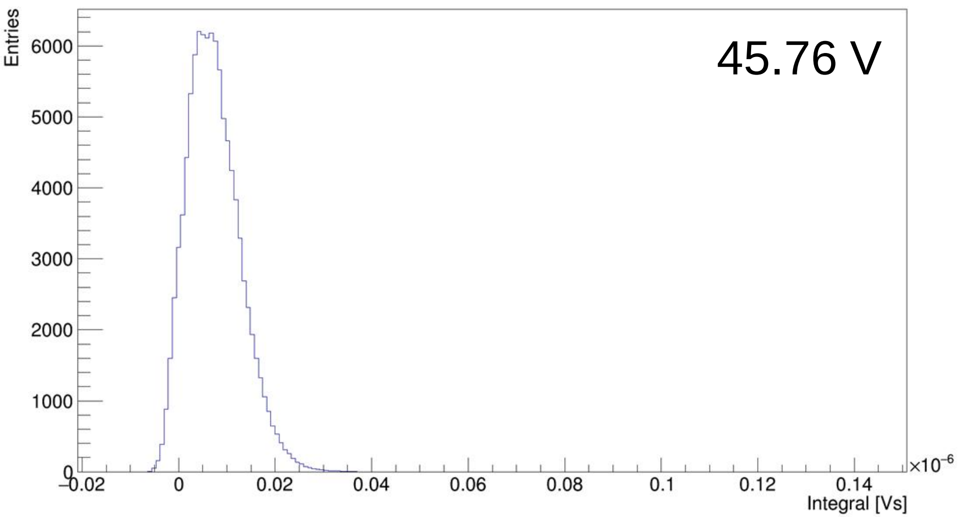

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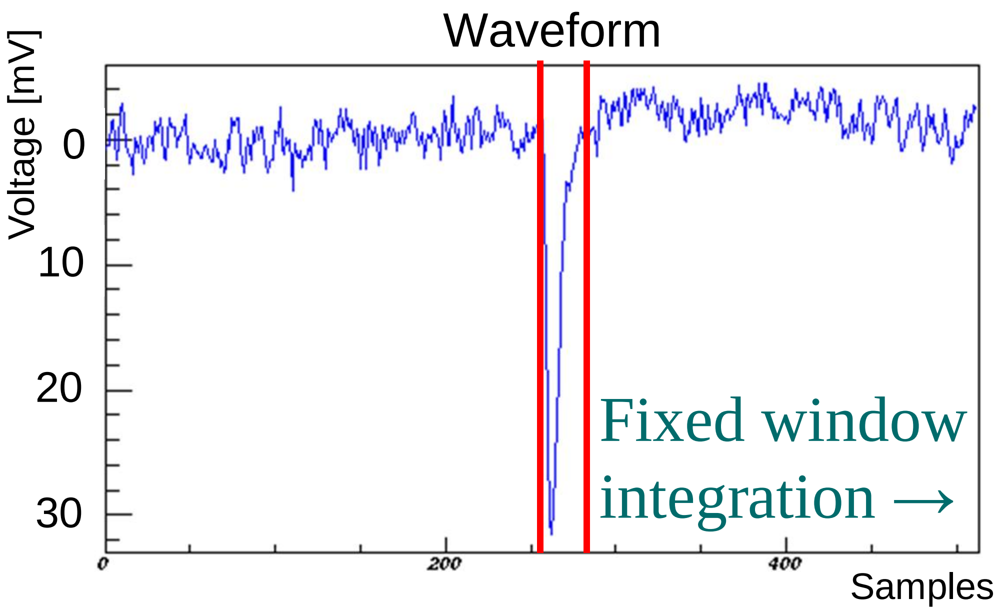

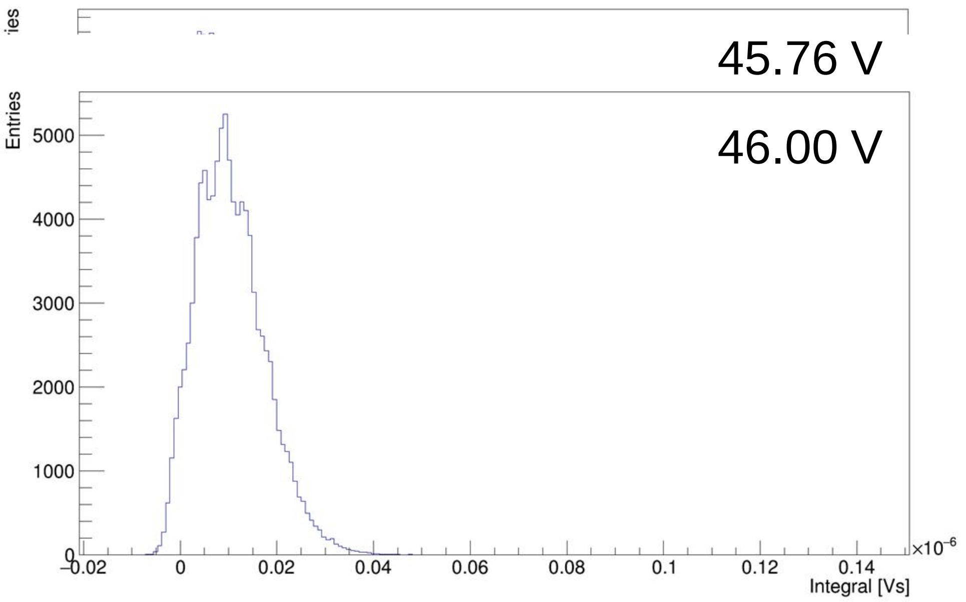

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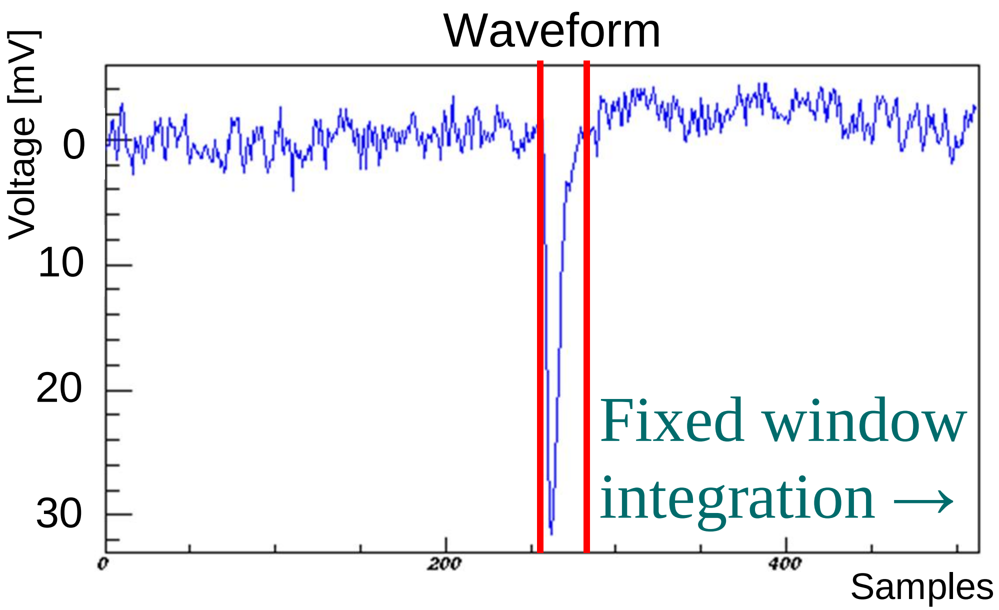
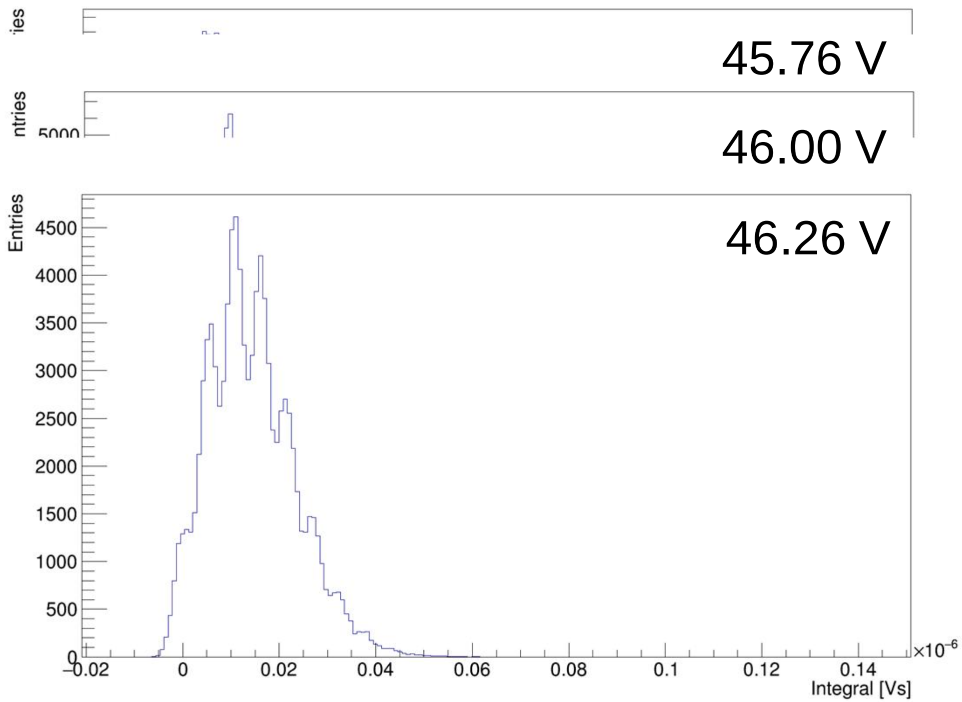
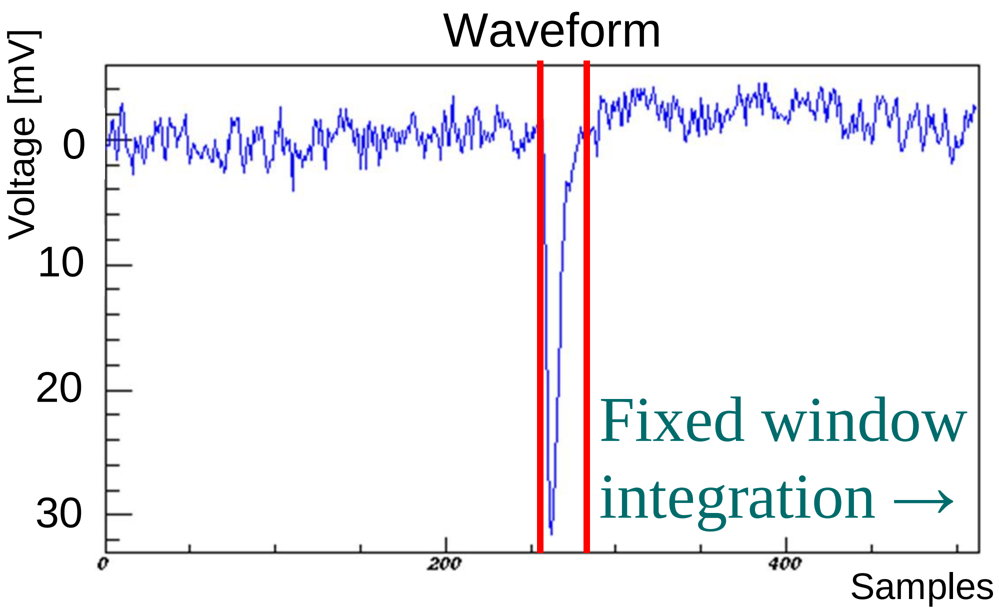
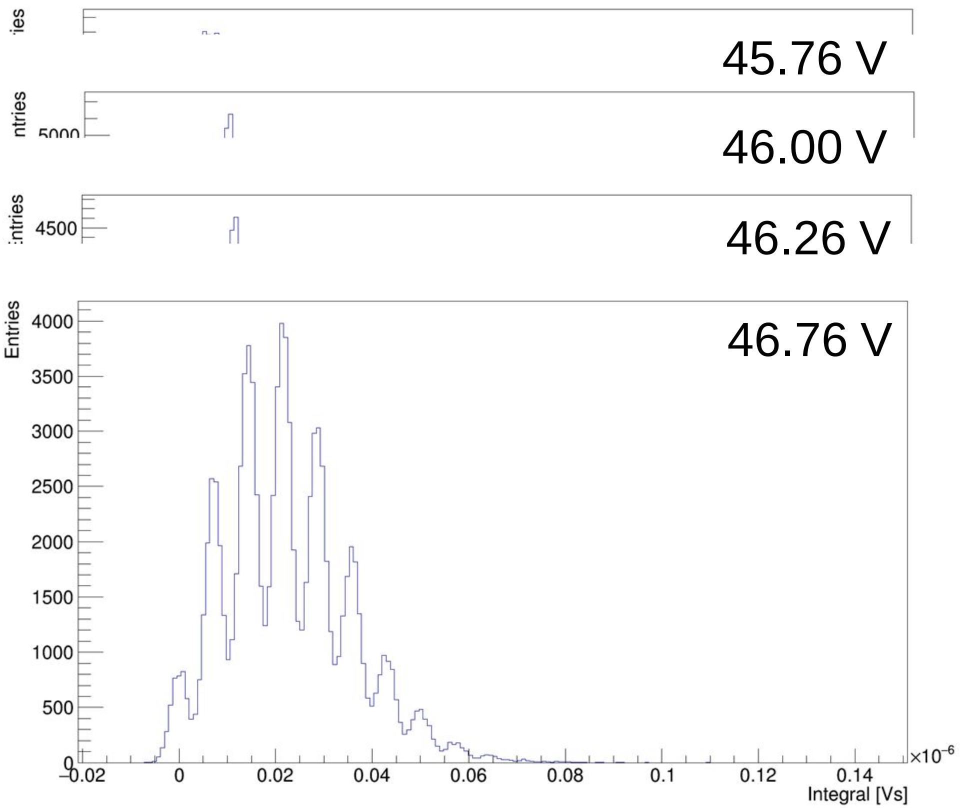
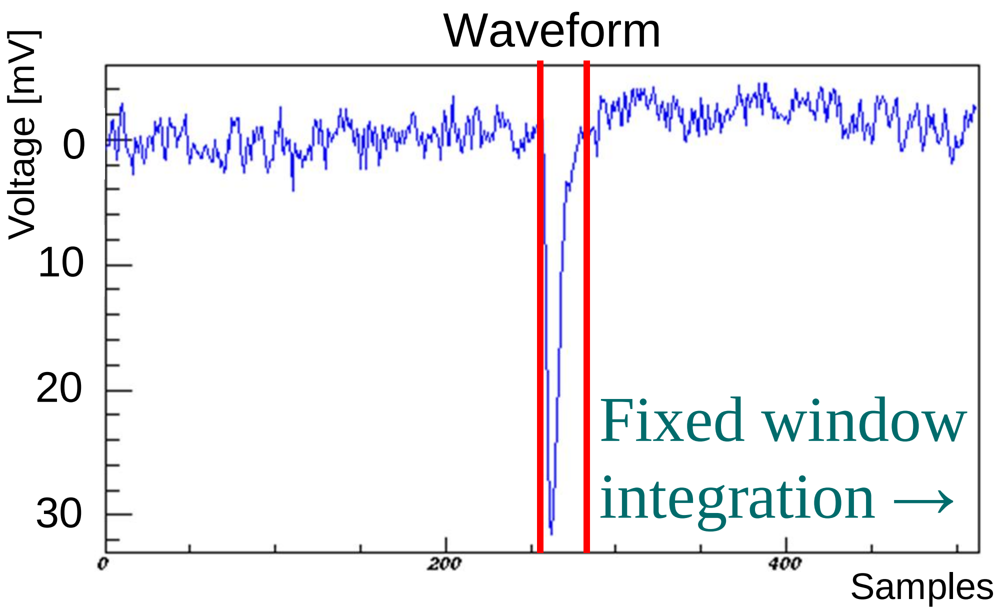


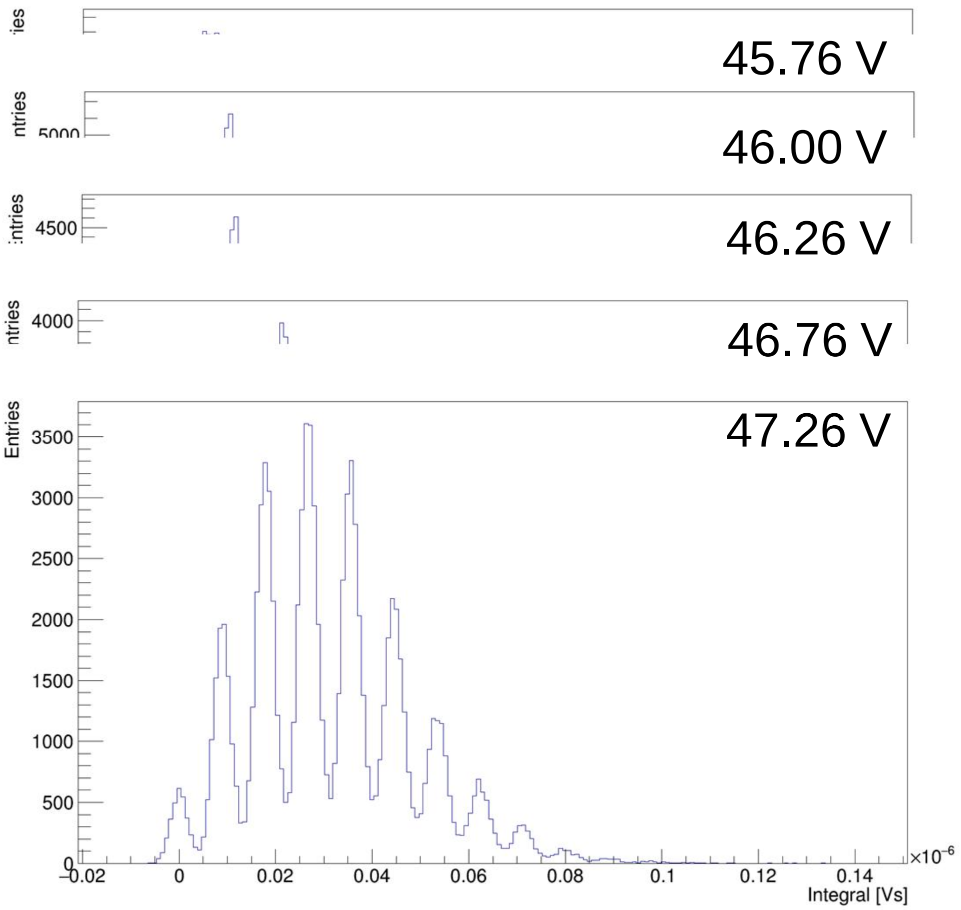



Waveform
Voltage [mV]
0
10
20
30
0
200
400
Samples
Fixed window
integration →

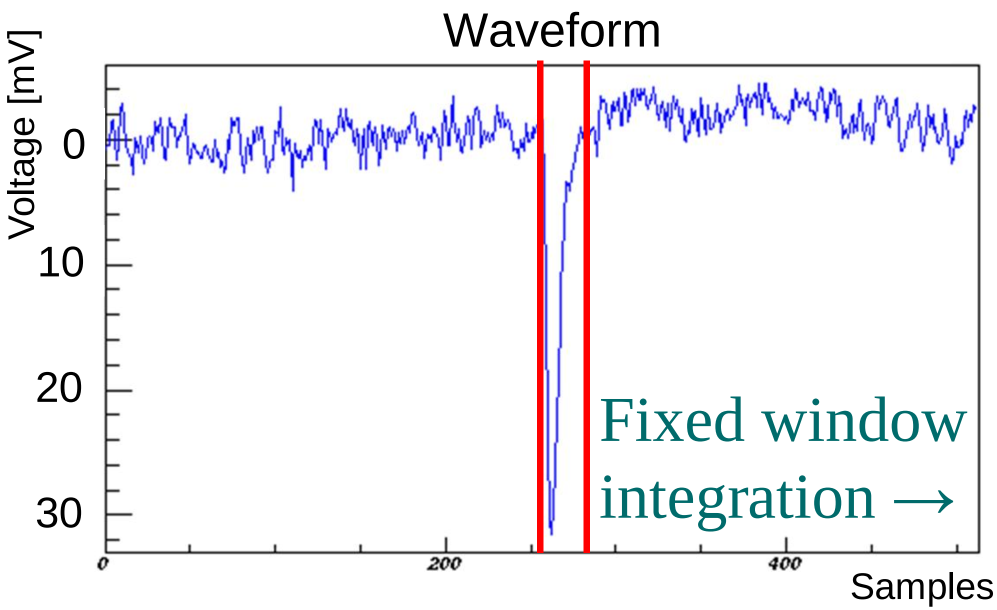

45.76 V
46.00 V
46.26 V
46.76 V
Entries
4000
3500
3000
2500
2000
1500
1000
500
0
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
×10⁻⁶
Integral [Vs]

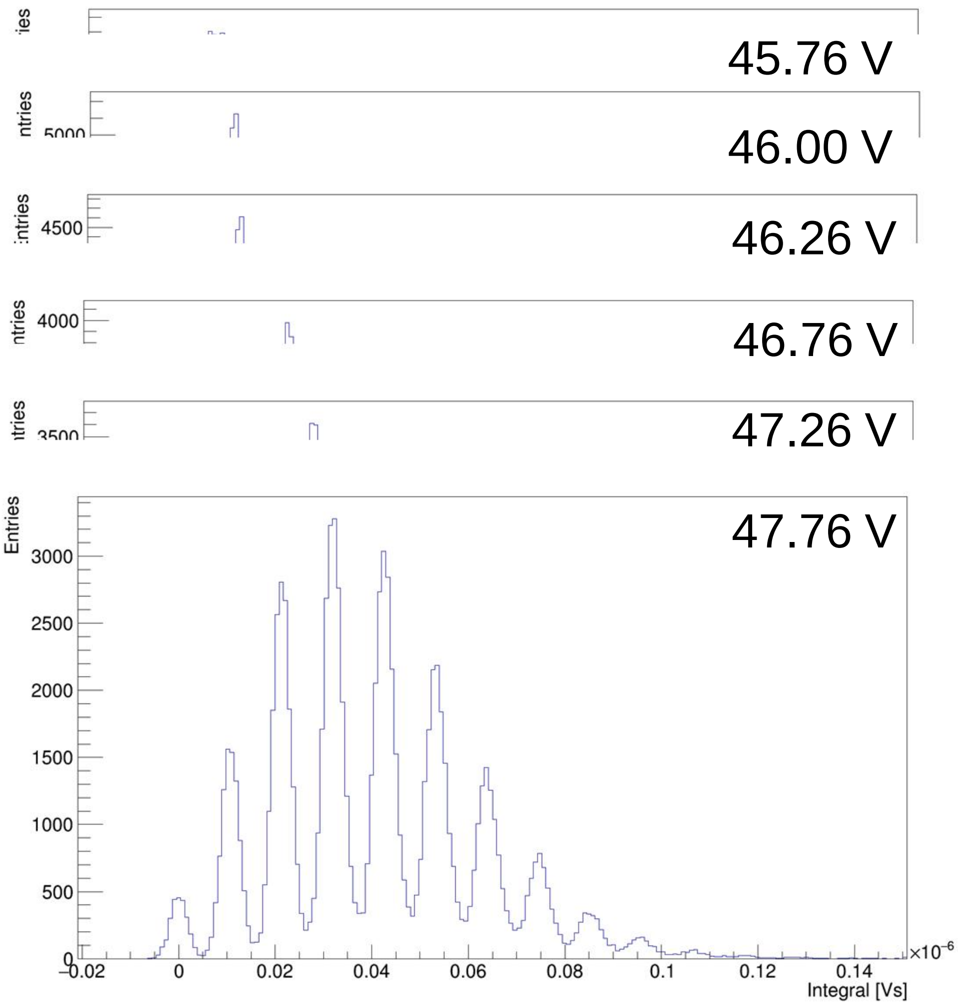
Analysis procedure





Analysis procedure





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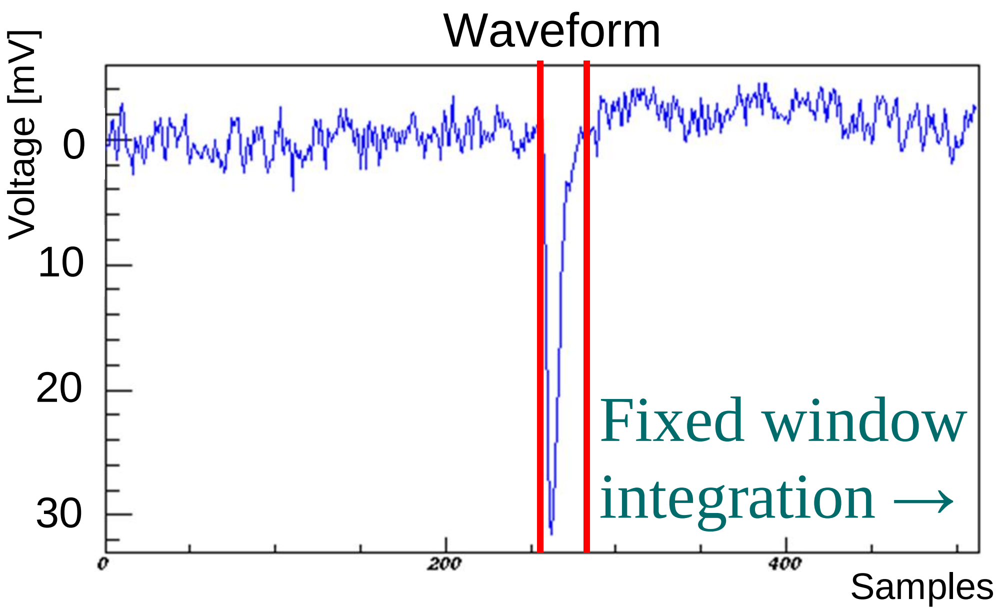

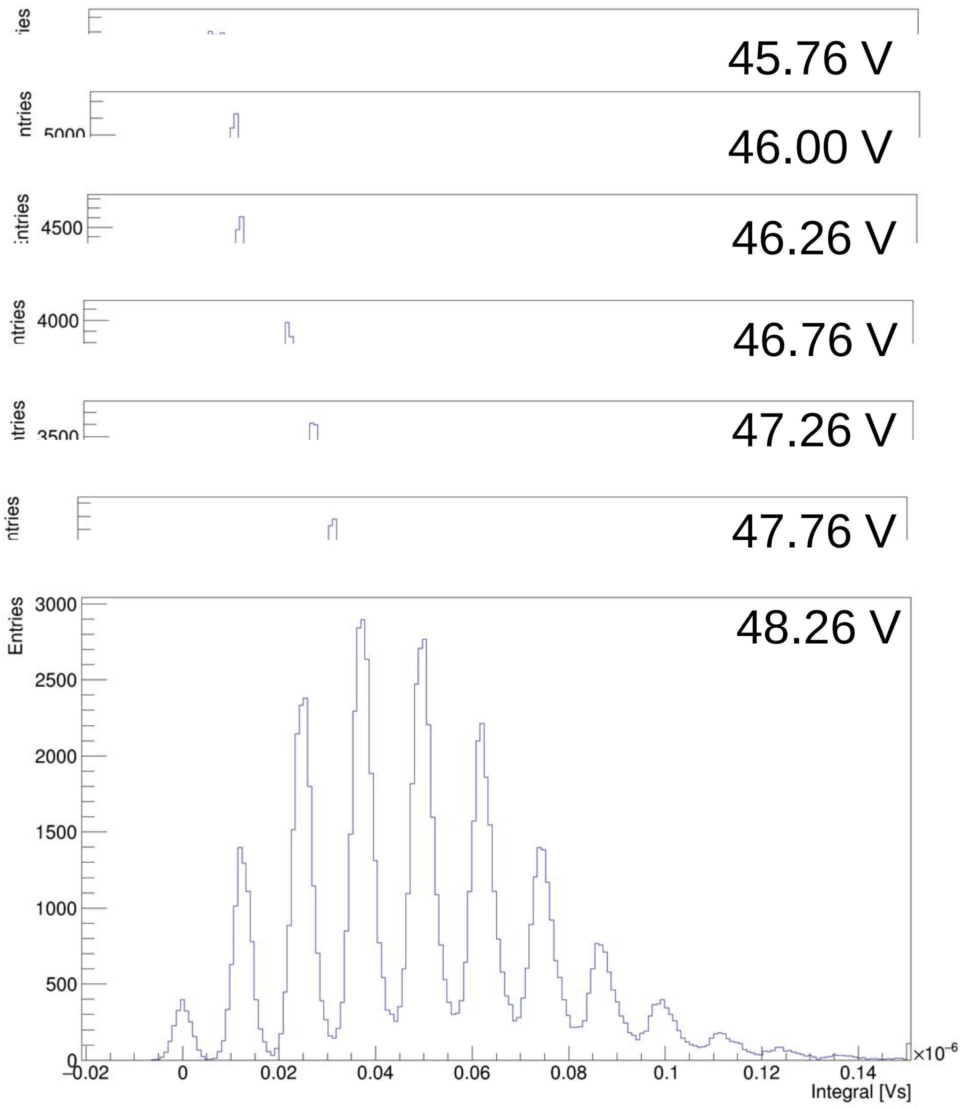

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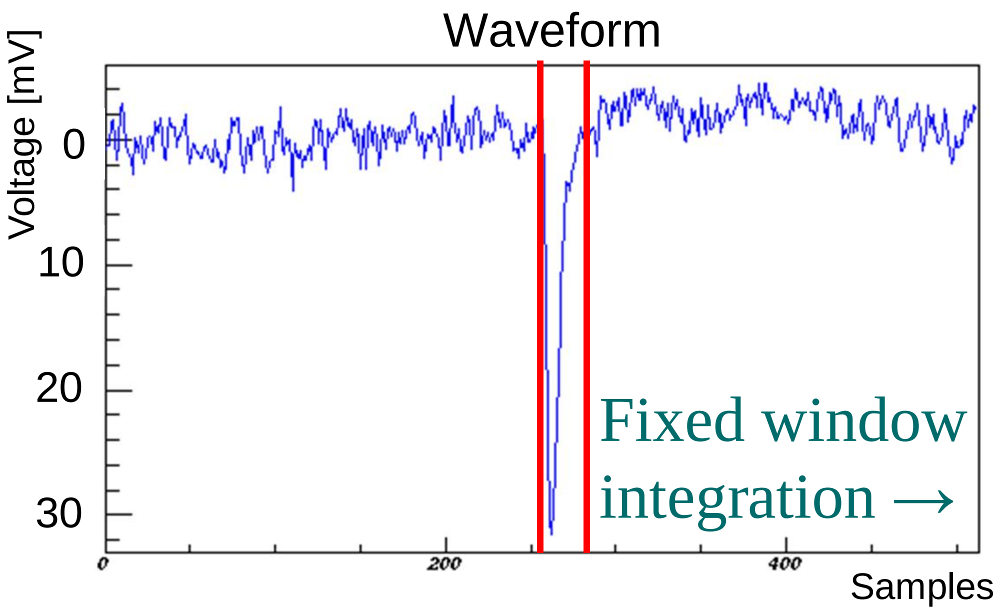

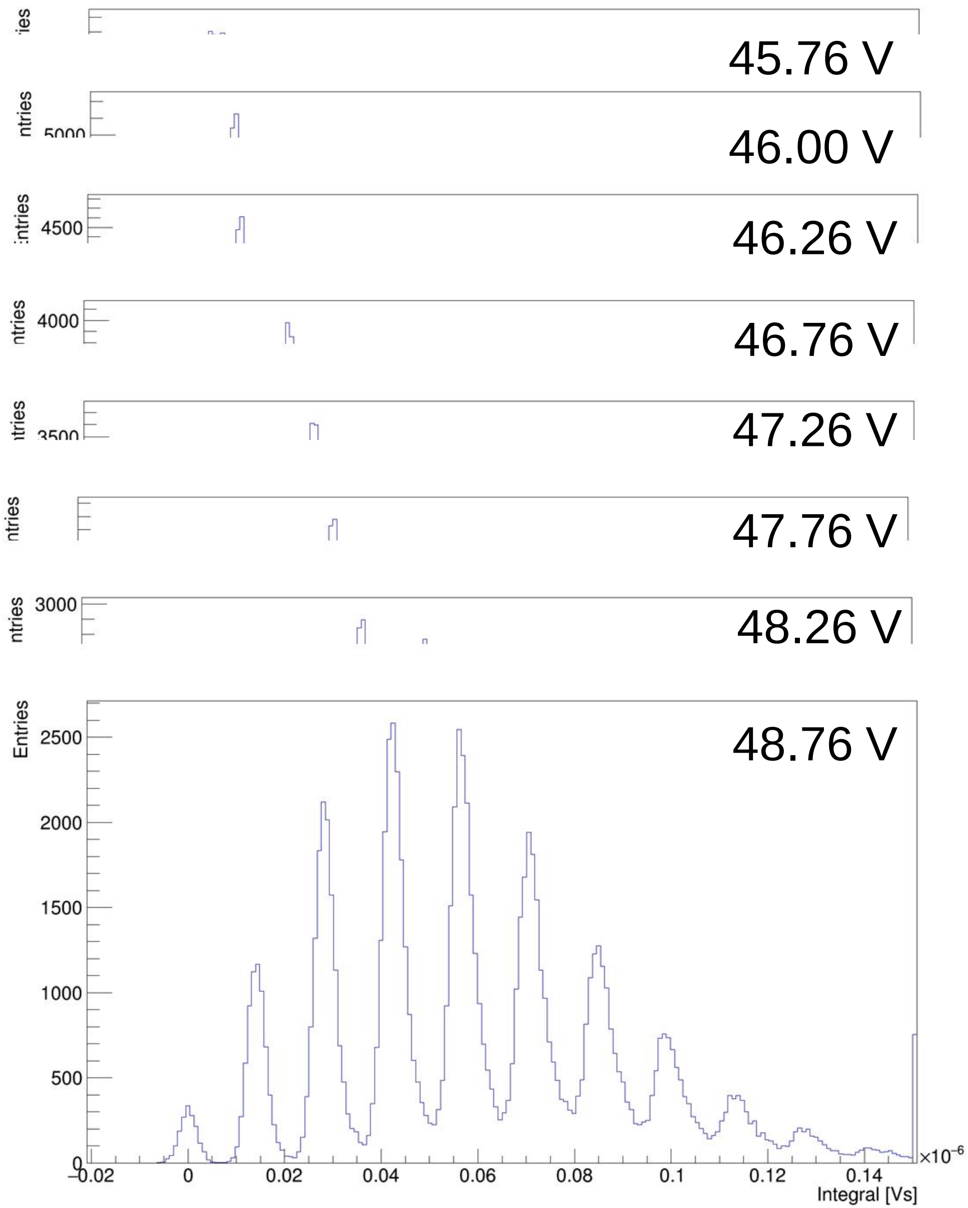

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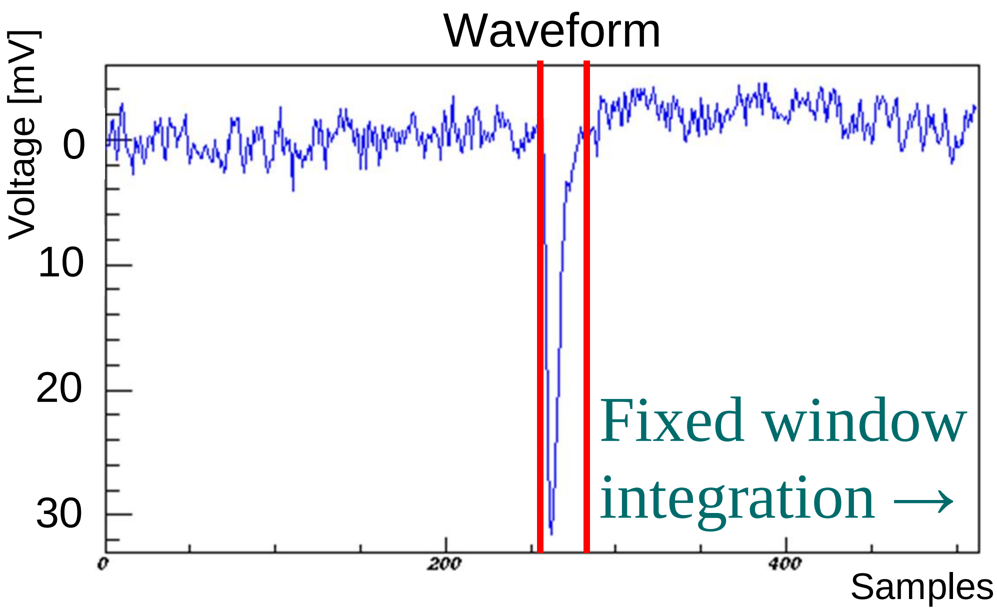
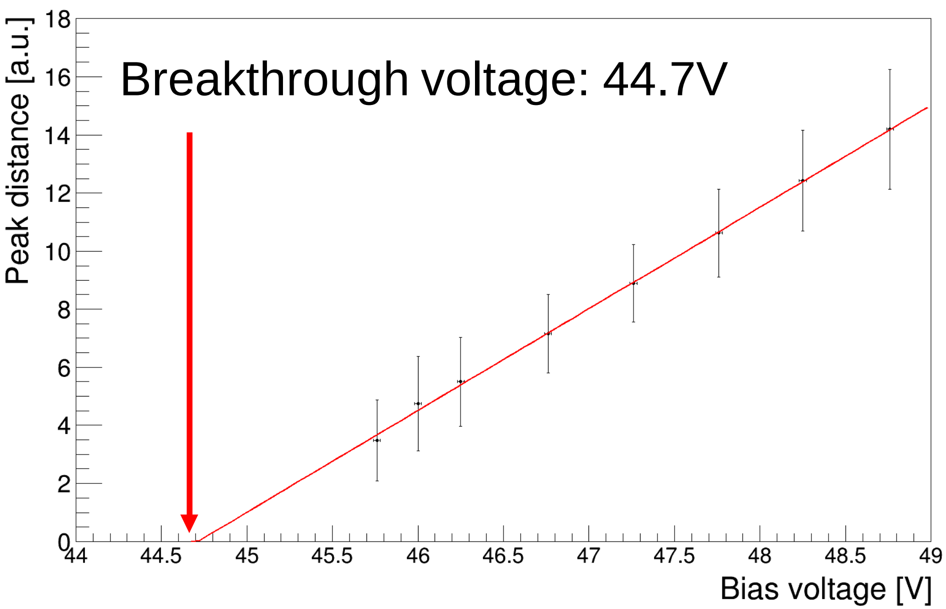
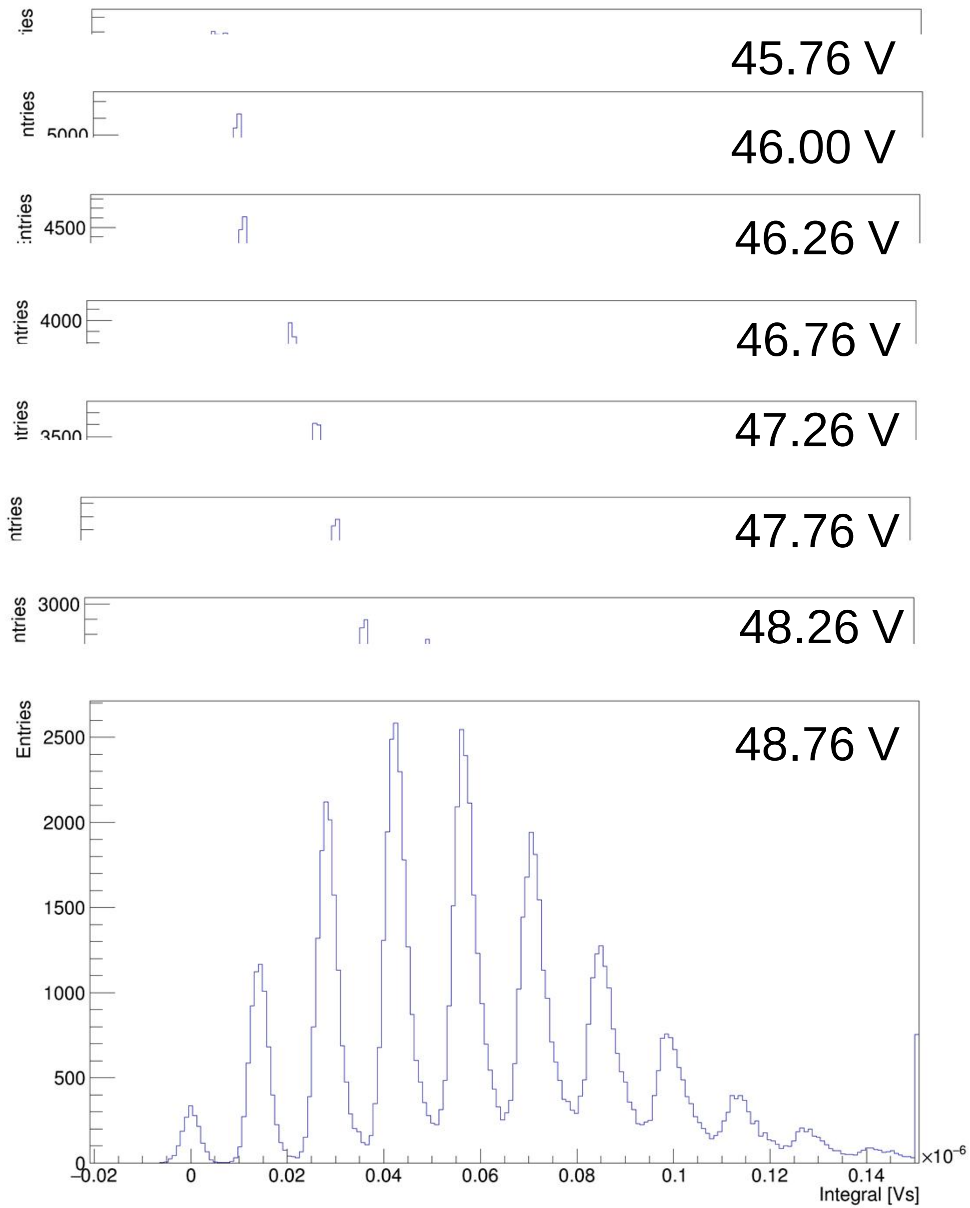
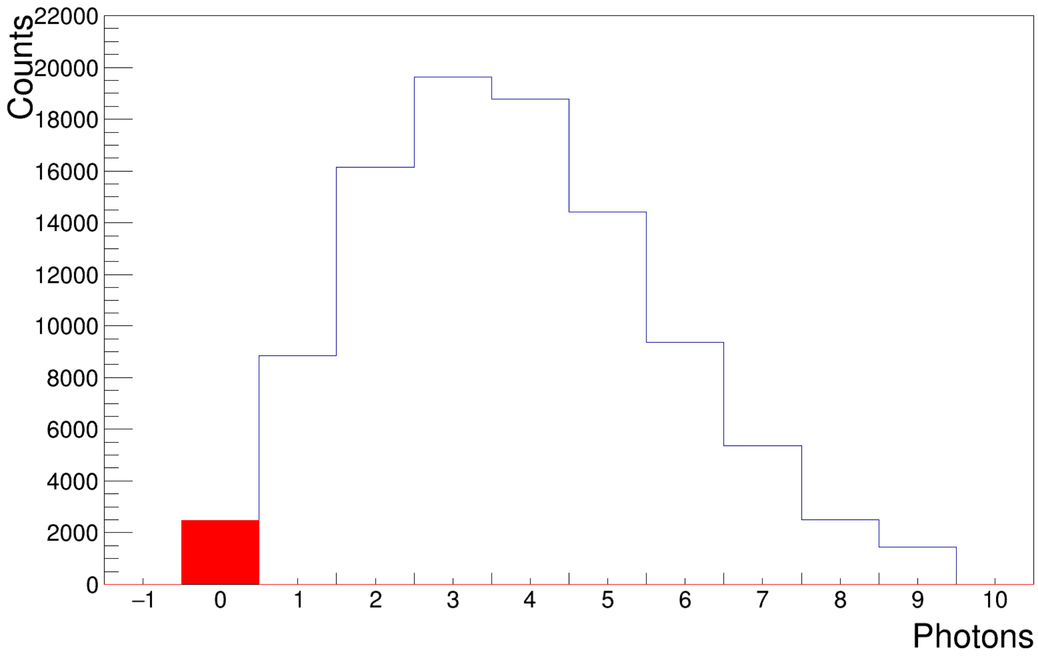






Cross-talk analysis

Photons Poisson distributed,
when no cross-talk occurs



- SiPM data

Cross-talk analysis

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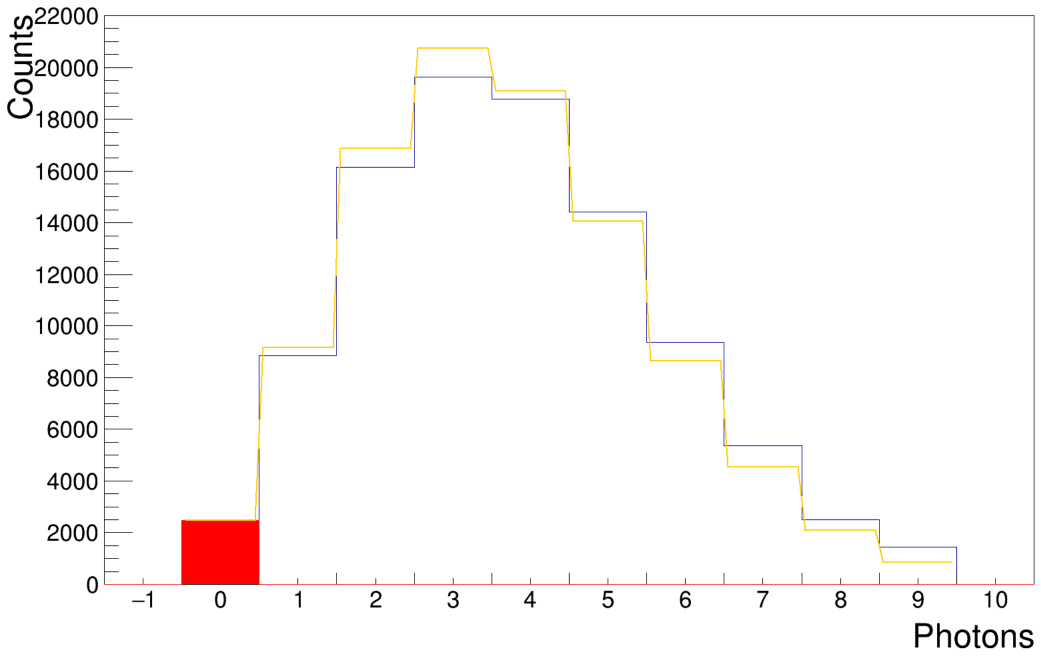


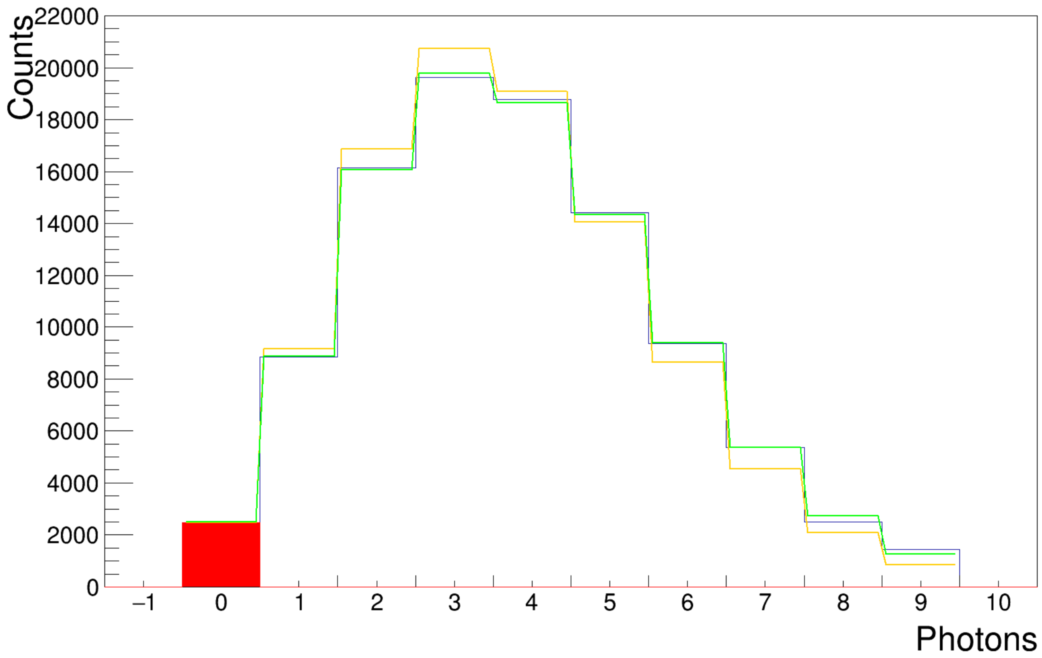
- SiPM data
- Poisson distribution

Poisson distribution:

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Cross-talk shifts events to higher photon numbers.

Photons Poisson distributed, when no cross-talk occurs



- SiPM data
- Poisson distribution
- Generalised Poisson fit

Poisson distribution:

$$P(n, \lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Cross-talk shifts events to higher photon numbers. Use generalised Poison Distribution:

$$P(n, \mu, \lambda) = \frac{\mu \cdot (\mu + n \cdot \lambda)^{n-1} e^{-(\mu + n \cdot \lambda)}}{n!}$$

n: photon number

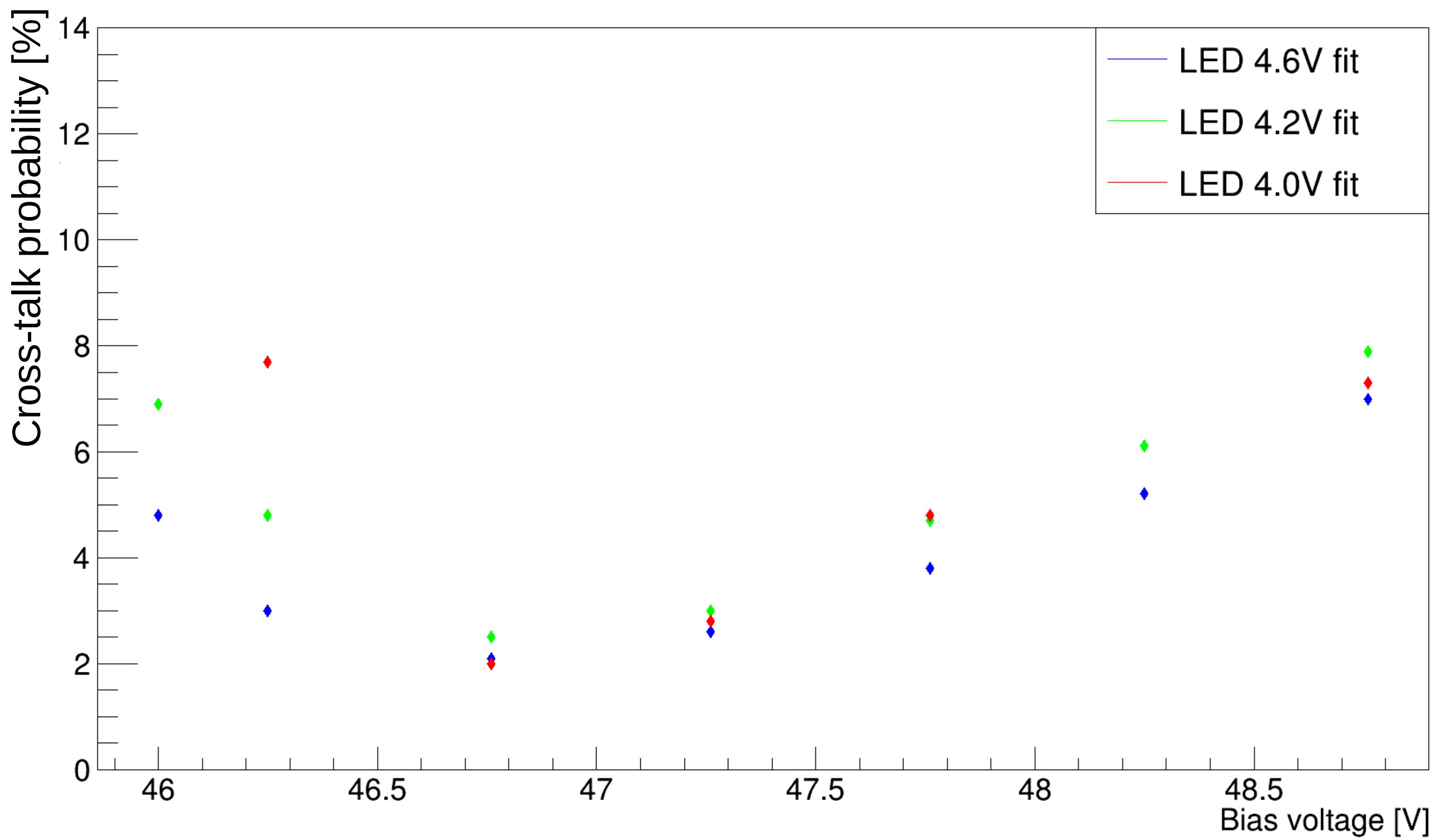
μ: mean of poisson distribution

λ: Borel branching parameter

[S.Vinogradov, Nucl Instrum Meth Phys Res Sec A: Accelerators,Spectrometers, Detectors and Associated Equipment, 1-5, Elsevier (2011)]

JG|U

Cross-talk:
Preliminary cross talk probabilities for different illumination strengths (S13370):



Cross-talk analysis

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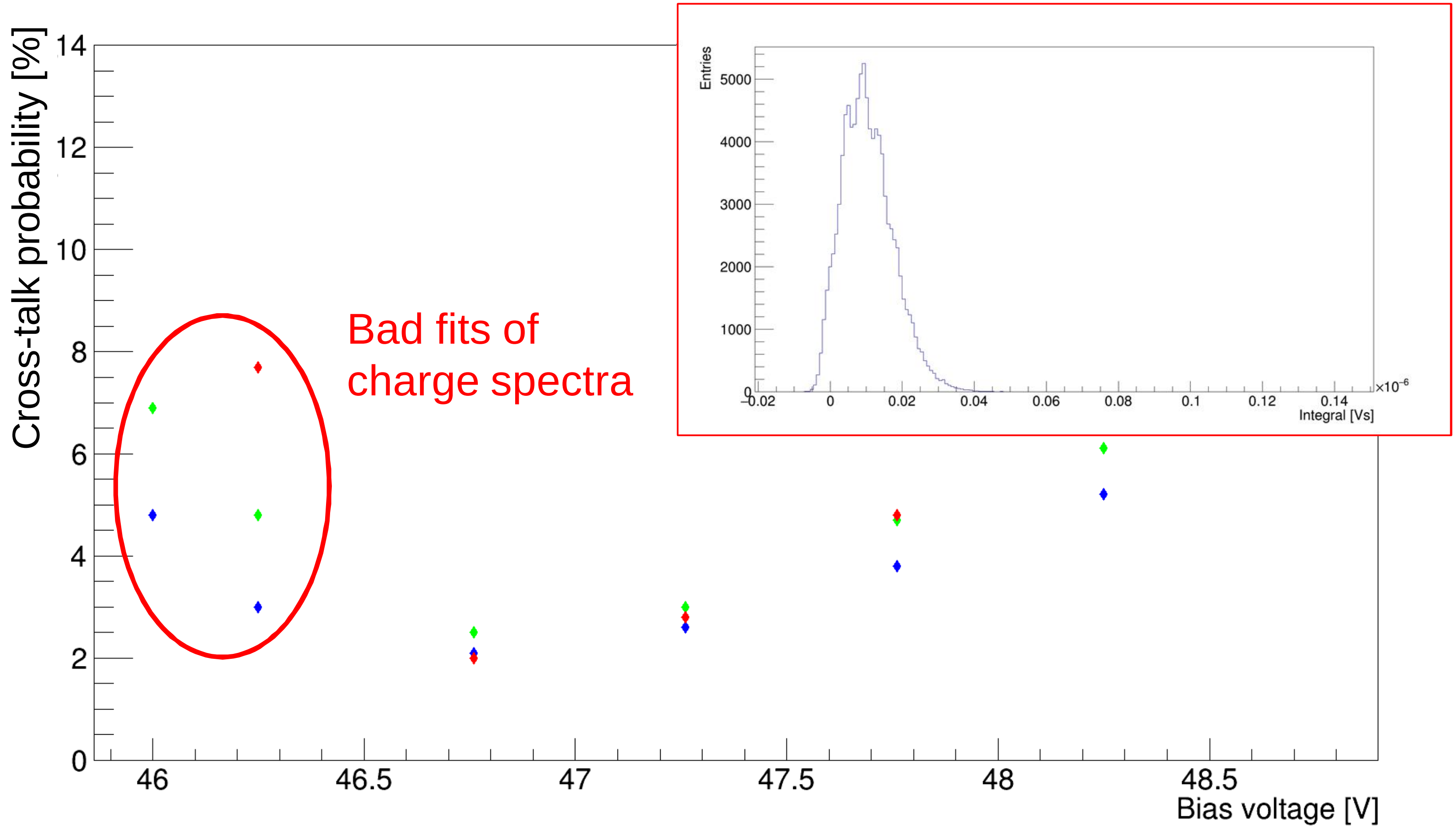
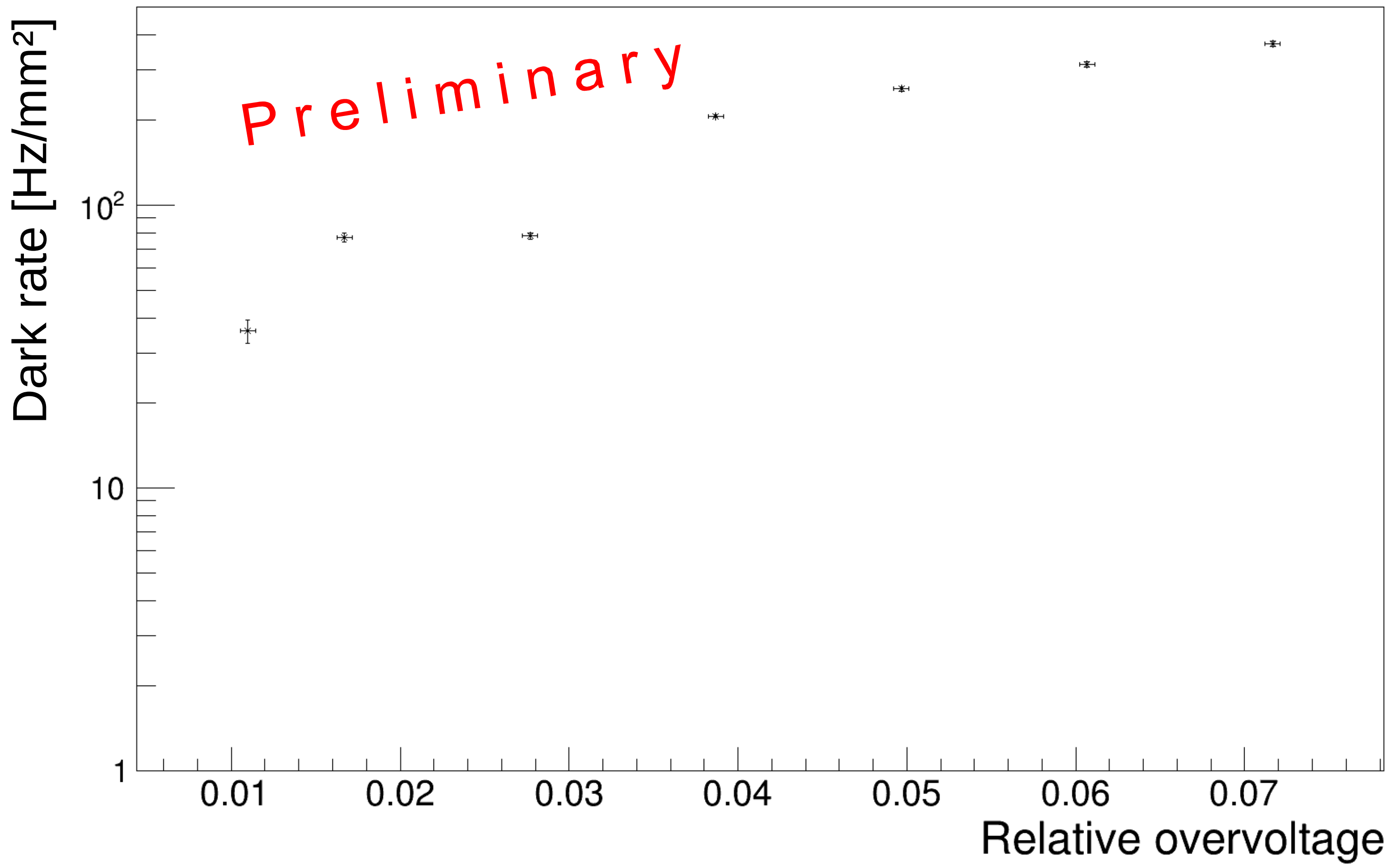


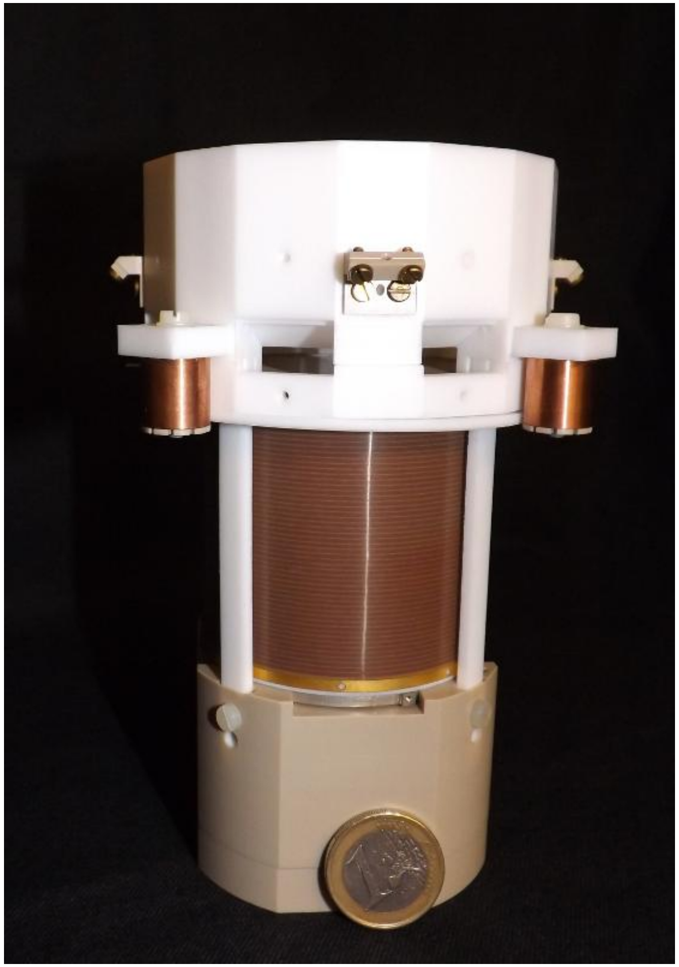
Dark-count rate

Preliminary dark-count measurement for Hamamatsu Gen4:



Application in LXe-TPC

MainzTPC:



Currently position reconstruction is done with APDs
→ no single photon detection

Next Step:
Replace APDs with SiPMs to increase sensitivity

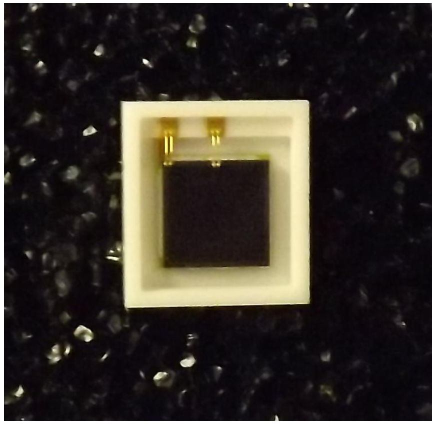
Step after:
Replace PMT with SiPM array

[Bastian Beskers, PhD Thesis, Design and commisioning of a dual-phase xenon time-projection-chamber for studies of the scintillation pulse shape]

Outlook

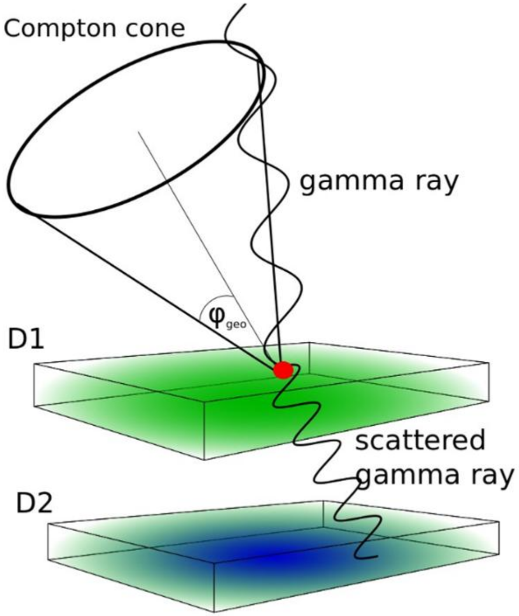
Improvements to test setup:

- improvement of readout electronics
- finalize analysis software
- replace sensors in MainzTPC
- Digital SiPMs



Future Applications:

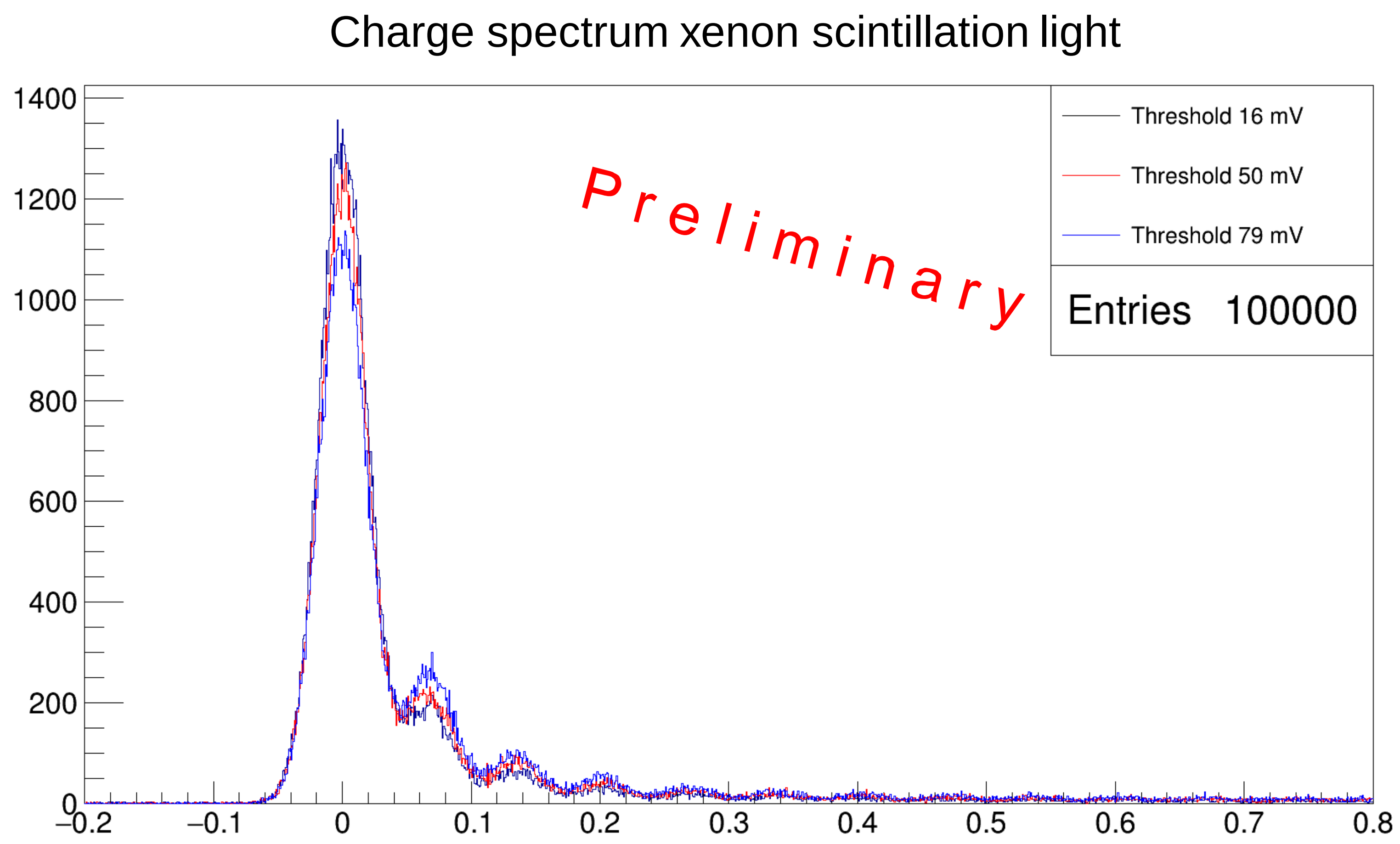
- Compton Camera:
  - medical imaging
  - γ-ray telescope
- DARWIN Dark Matter WIMP search



Thank you!

Thanks to:
Uwe Oberlack
Matteo Alfonsi
Andrea Brogna
Daniel Wenz

Backup



Charge spectrum xenon scintillation light
1400
1200
1000
800
600
400
200
0
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Preliminary
Threshold 16 mV
Threshold 50 mV
Threshold 79 mV
Entries 100000

Backup

Light production mechanisms:
- two processes involving excited Atoms (Xe^*) and ions (Xe^+):

1. $Xe^* + Xe + Xe \longrightarrow Xe^*_2 + Xe$

$$Xe^*_2 \longrightarrow 2Xe + h\upsilon$$

2. $Xe^+ + Xe \longrightarrow Xe^+_2$

$$Xe^+_2 + e^- \longrightarrow Xe^{**} + Xe$$

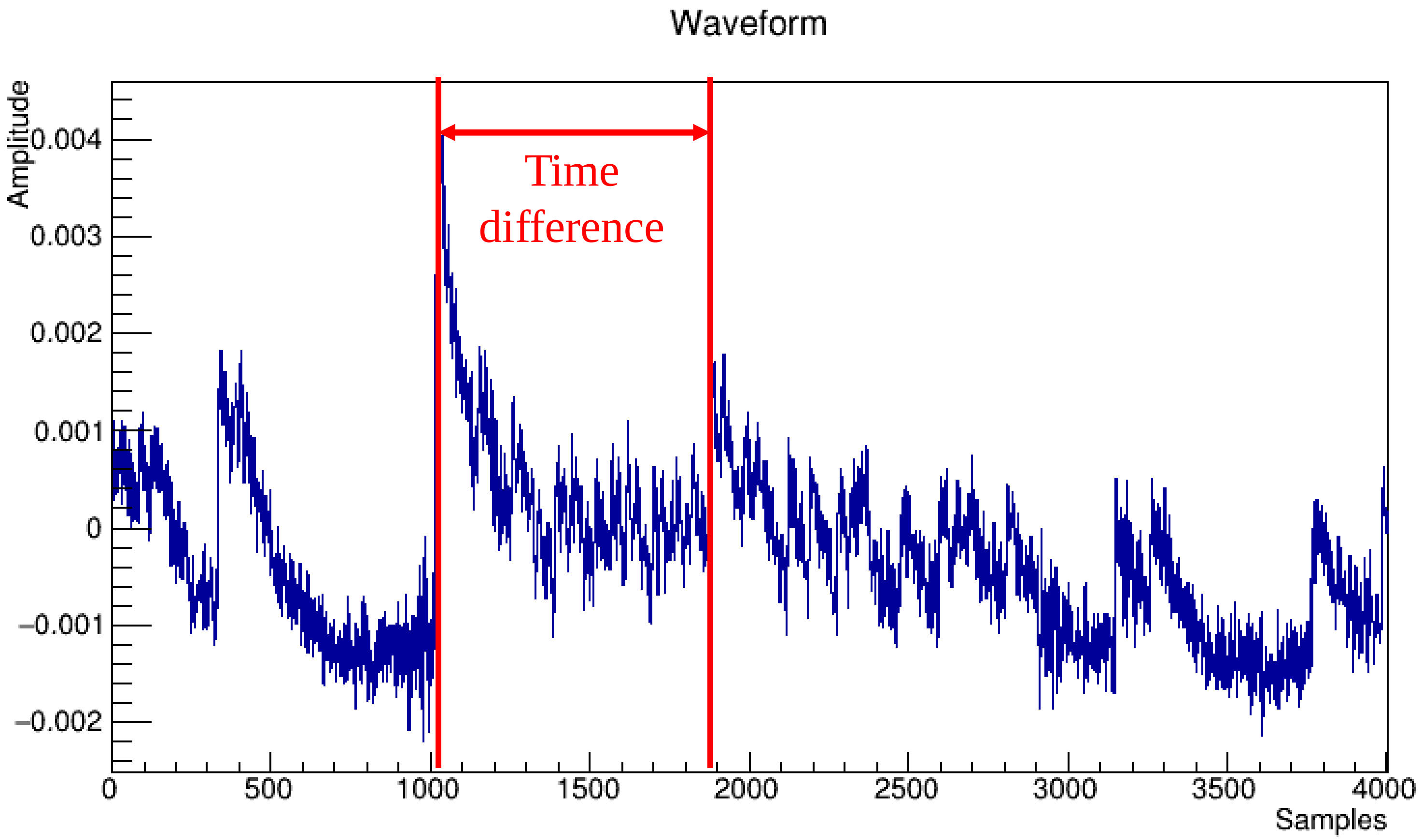
$$Xe^{**} \longrightarrow Xe^* + \text{heat}$$

$$Xe^* + Xe + Xe \longrightarrow Xe^*_2 + Xe$$

$$Xe^*_2 \longrightarrow 2Xe + h\upsilon$$

Afterpulsing:

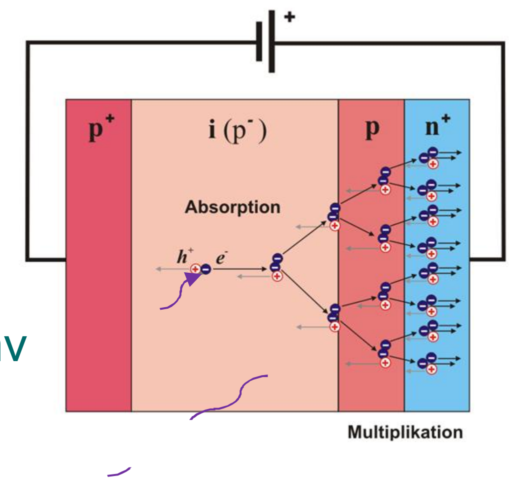
Use time difference between successive signals

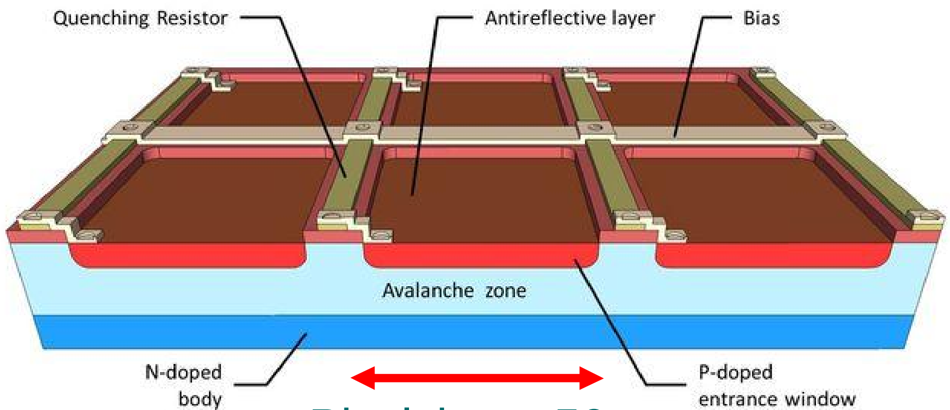


Backup

- Semiconductor sensor using photoelectric effect
- SiPM: multipixel avalanche photodiode (APD)
- Each pixel operating in Geiger-mode
  → Channel insensitive after event
- Output signal is given by sum of all pixels
  → analogue device with quasi-digital signal

E=hv





[Picture: Ketek,
Source: http://www.ketek.net/products/sipm-technology/microcell-construction/]