HKROC:
a modern waveform digitizer for PMT-based experiments

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History

- **HKROC** – an ASIC designed readout chip of the PMT signal
- HKROC was developed as PMT readout chip for Hyper-Kamiokande experiment, however another solution was chosen for main PMT readout

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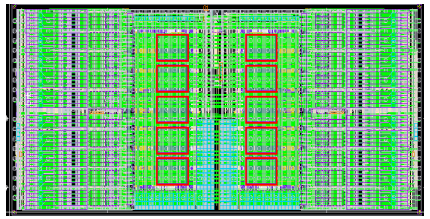
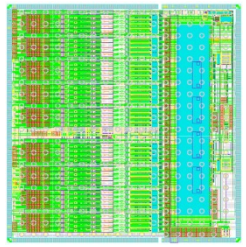
HGCROC



HKROC



Same ASIC structure
Same ADC and TDC
Same readout

New preamplifier
New digital processing
Autotrigger mode

- Derived from the **HGCROC** chip originally designed for the CMS High Granularity Calorimeter

- Designed for HK use chip has extremely high performance characteristics. It can be adapted to different PMT experiments and optimised for different photodetectors

Introduction

Modern PMT-based experiments physics program

Strong requirements on electronics

() in brackets HK requirements are written

Physics constraint	Impact on electronics requirement
Detect synchronous or asynchronous events (e.g. accelerator or solar neutrino)	Self triggering for each channel
No event loss (e.g. crucial for SN neutrino)	High hit rate (e.g. 1 MHz)
Low evergy events detection (e.g. SN or solar neutrino)	Low charge threshold triggering (e.g. <= 1/6 p.e.)
Charge reconstruction from low to high energy physics	Large dynamic charge range $(1 - 1300)$ photoelectrons
Excellent charge reconstruction	High linearity (~ 1 %) and resolution (~1%)
Electronics time resolution < PMT time resolution (1.3 ns)	High timing resolution (e.g. < 0.3 ns)
Low power consumption	~ 1 W/channel

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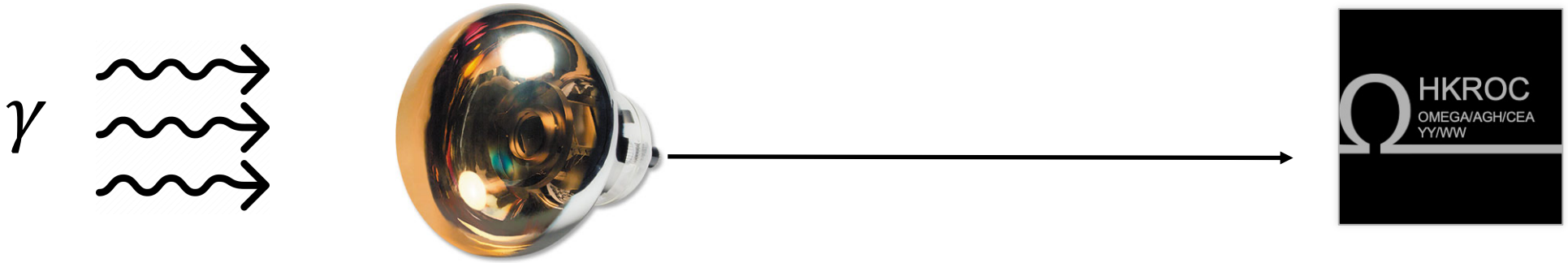
The challenge was taken up

OMEGA, AGH, LLR and CEA present

Advanced ASIC chip for PMT readout

Part I: General description

- HKROC is a waveform **digitizer**: reconstructs the full **shape of the charge-signal** waveform and provides extremely **precise timing measurement**.



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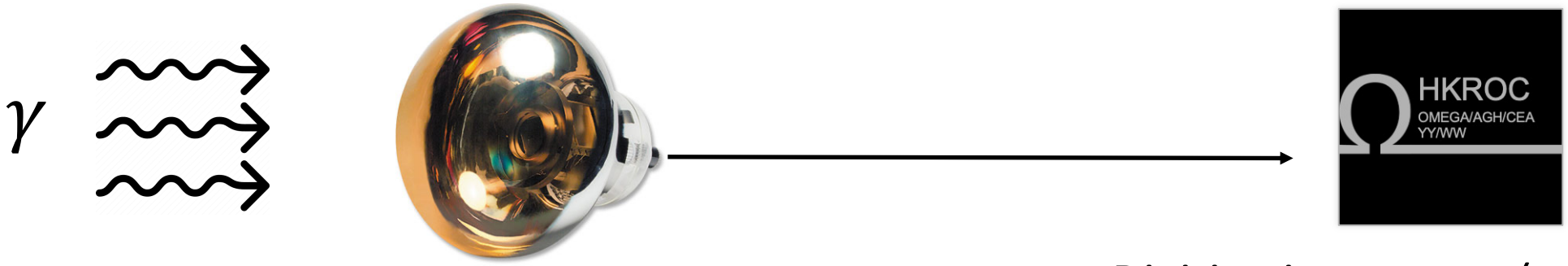
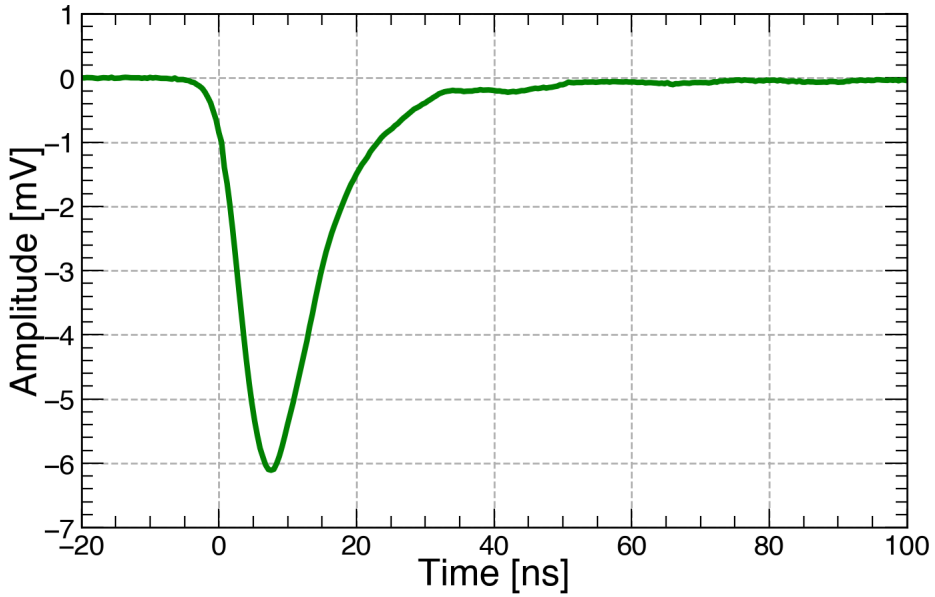
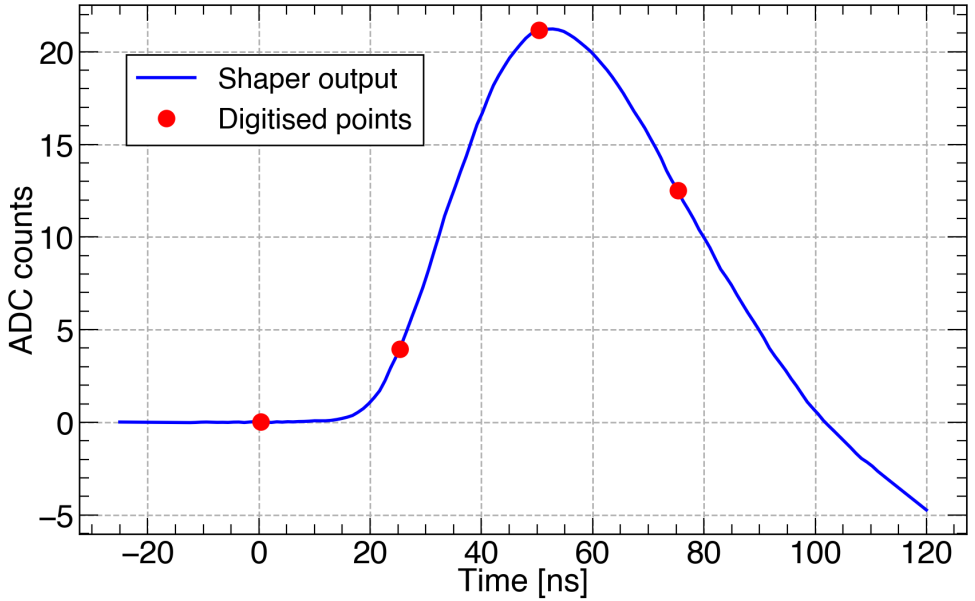


PMT input signal of one photoelectron (p.e.)



Digitisation output (red points)



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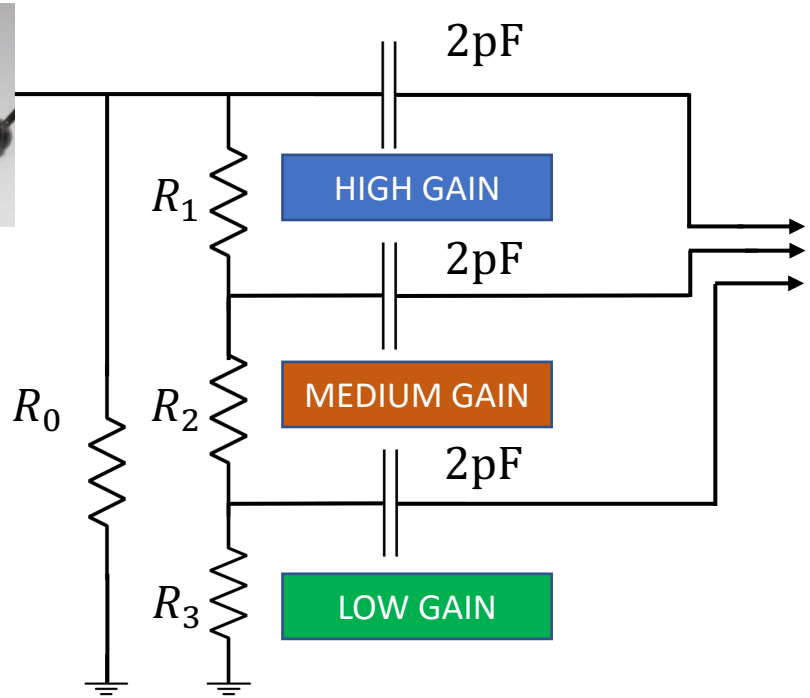

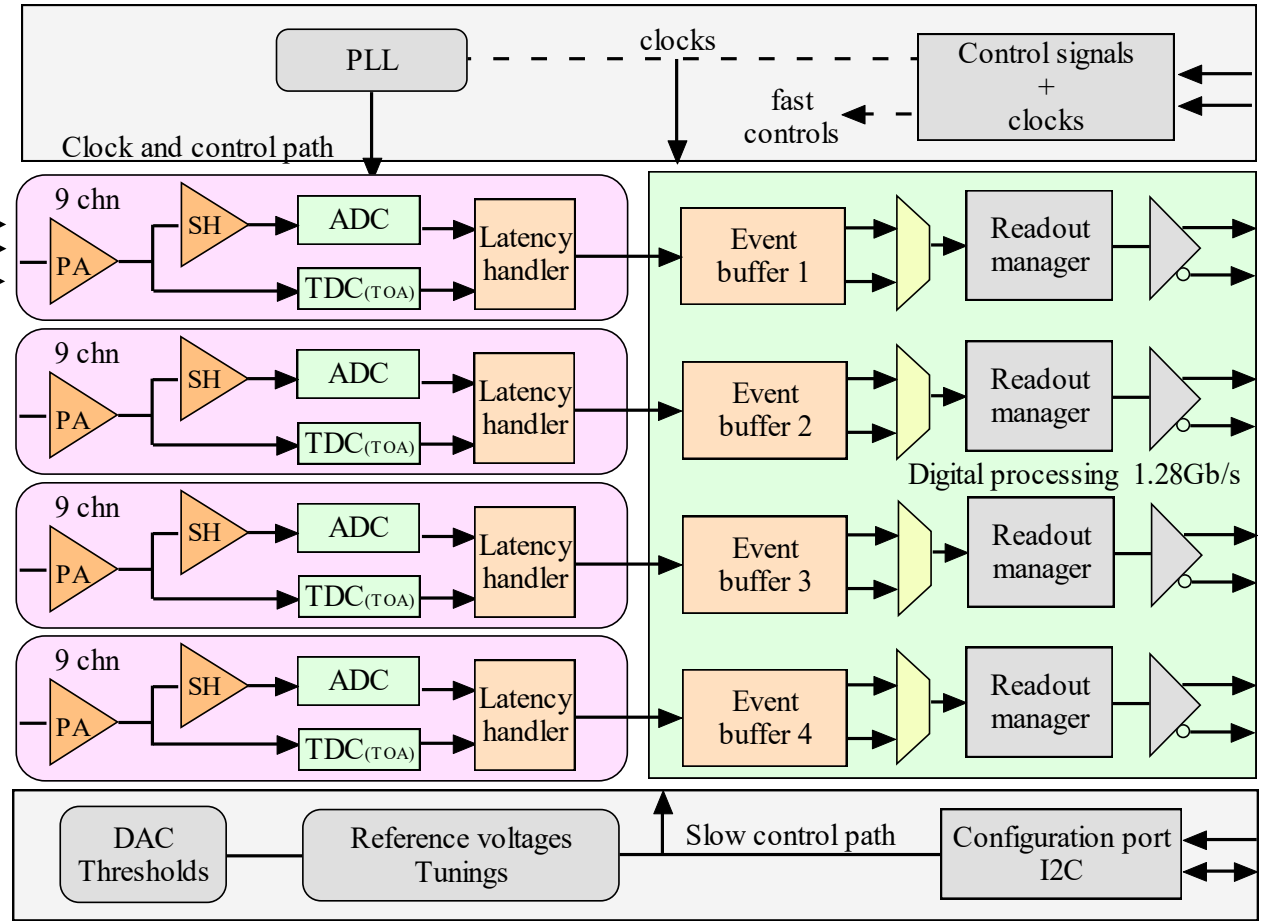

- ASIC in TSMC 130 nm node
- **Low power**: 10 mW per channel
- **Large dynamic range** with 3 gains (**up to 2500 pC**)
- Integrated timing measurements (25 ps binning)
- Readout with high speed links (1,28 Gb/s)
- **HKROC is a waveform digitizer with auto-trigger**

1 HKROC = 36 channels = 12 PMT

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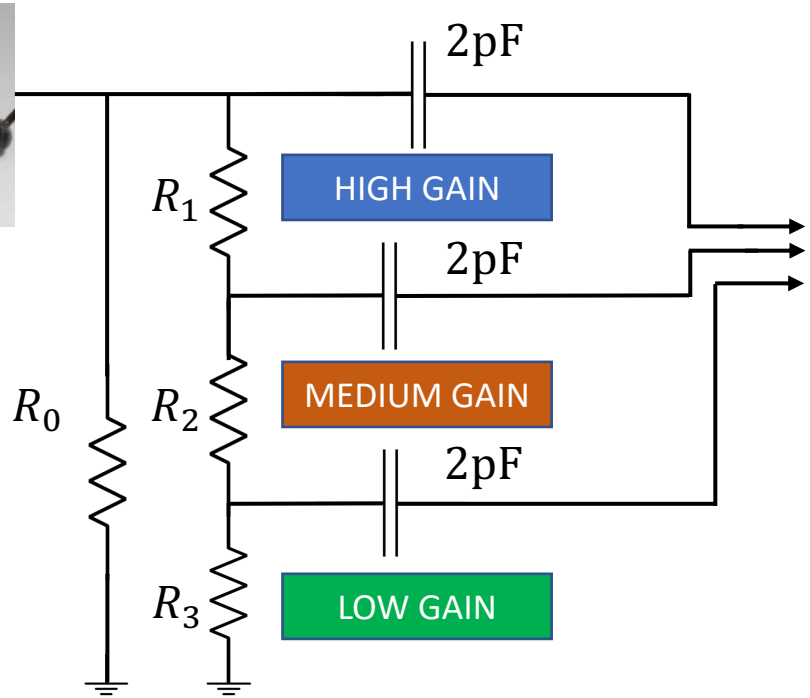

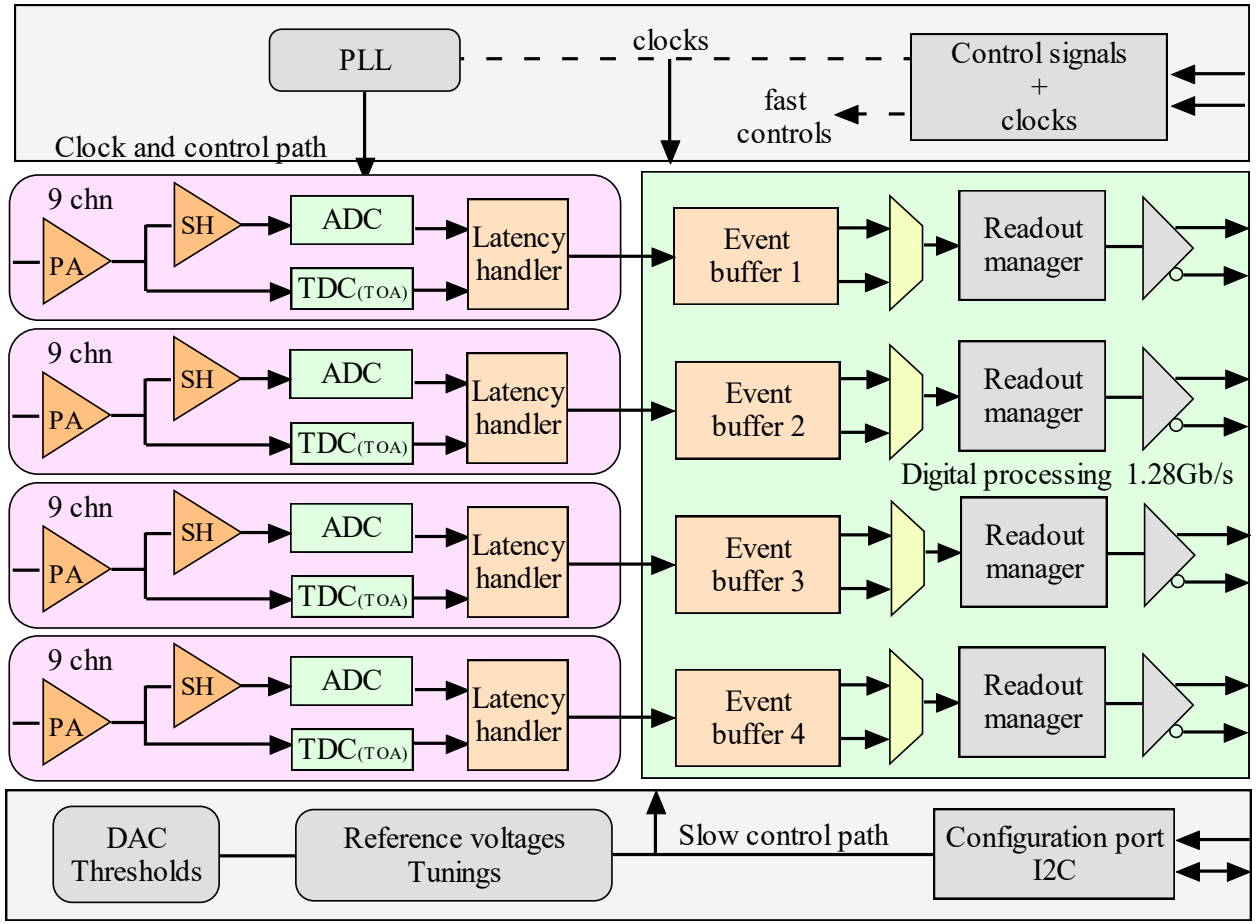

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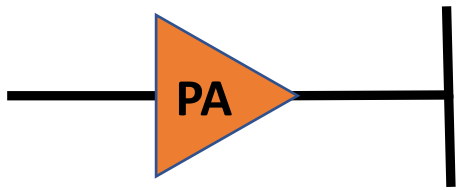
Details on charge and timing performance see on the next slides

Operating principle

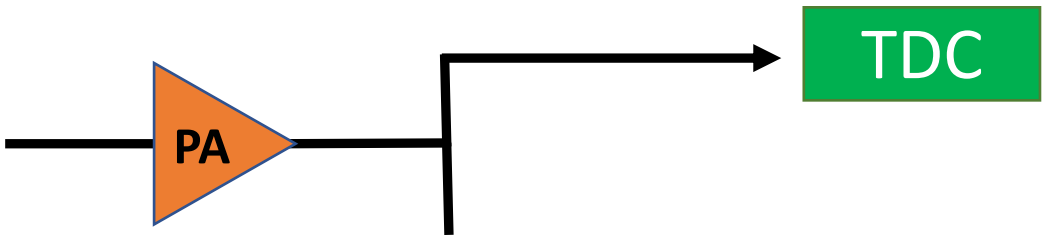
After preamplification signal follows two paths:

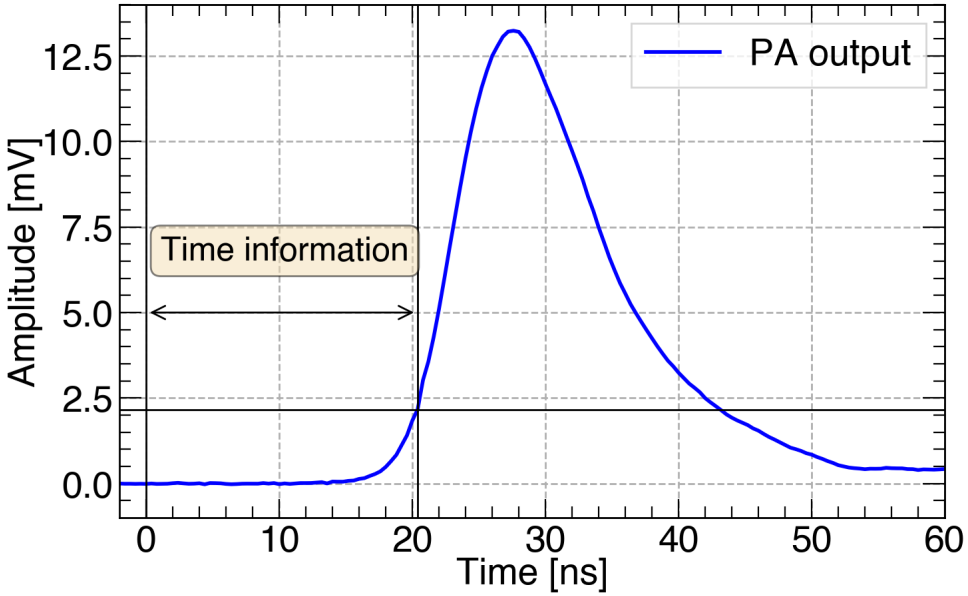


Operating principle

After preamplification signal follows two paths:

- A fast path with a discriminator connected to the TDC for time measurement (dead time 30 ns)





Part I: General description

The PA signal is sent to a discriminator which allows to auto trigger on the signal above a set threshold.

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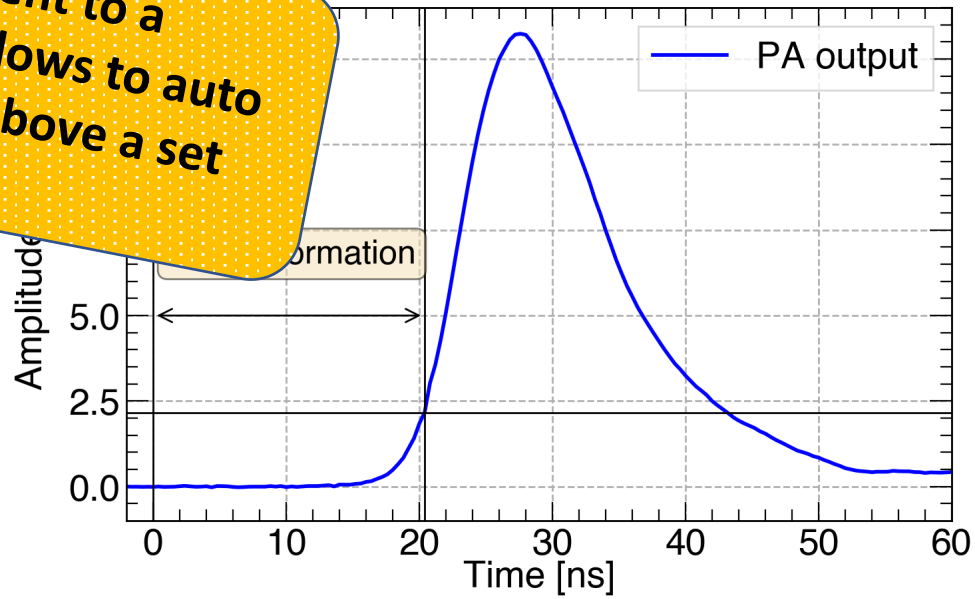

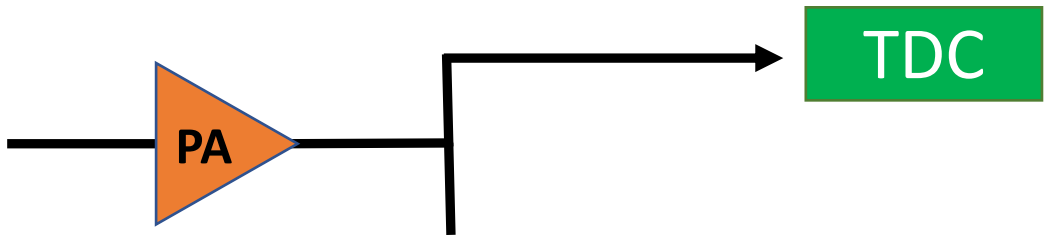

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The PA signal is sent to a low offset discriminator which allows to auto trigger on the signal above a set threshold.

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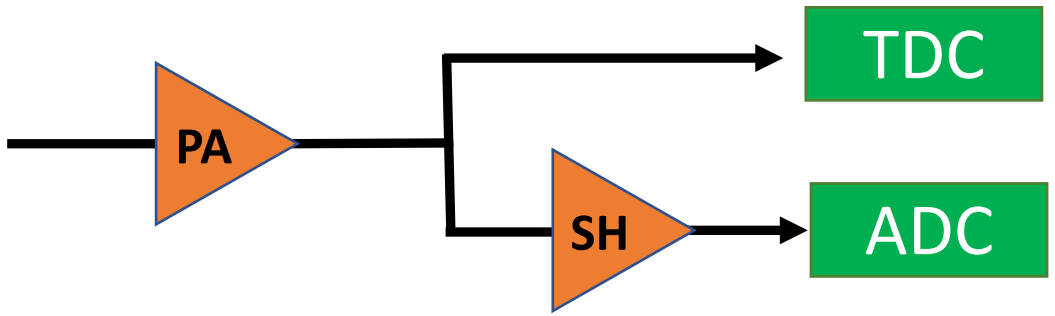
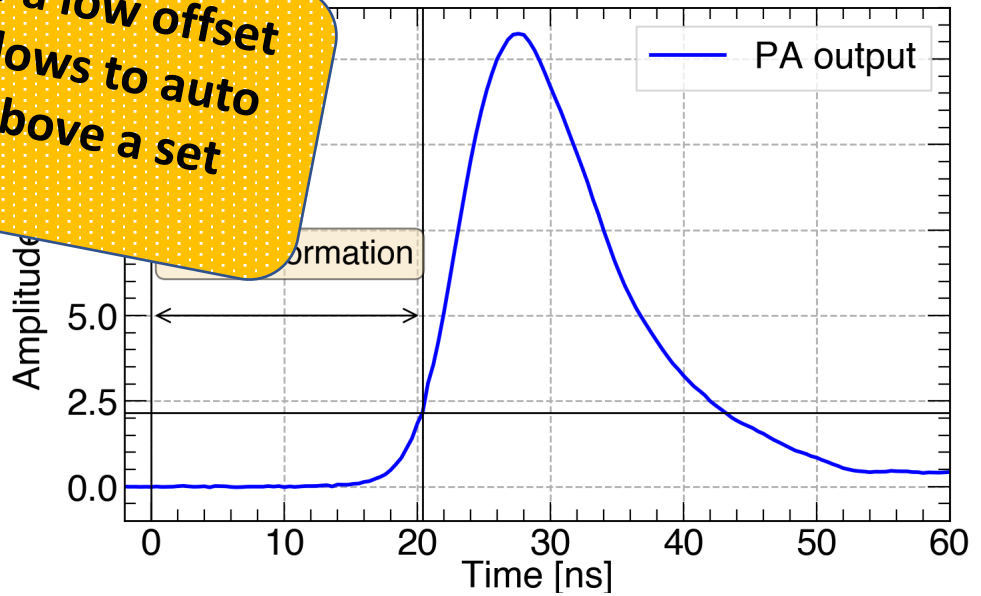
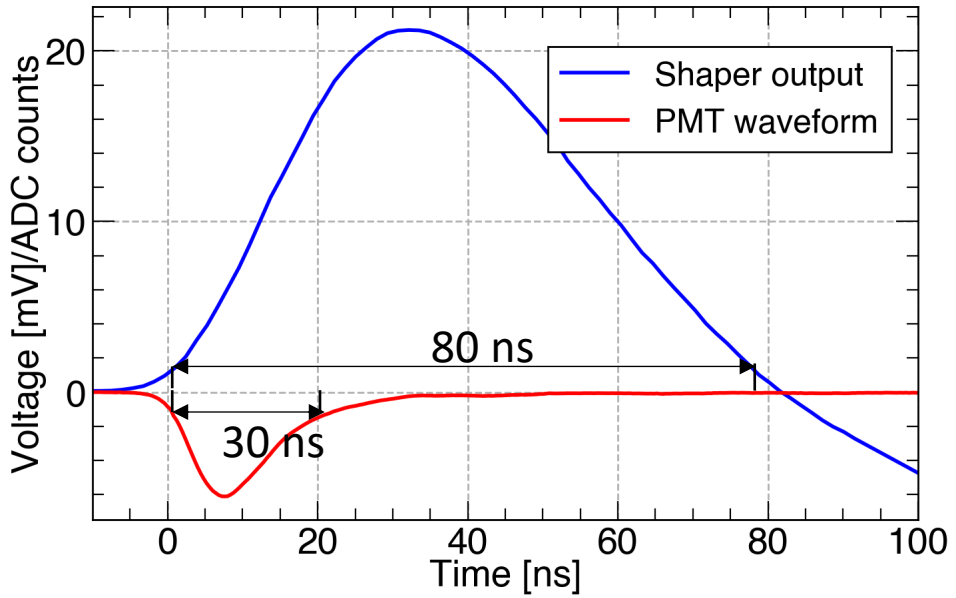
- A slow path with shapers connected to the ADC for charge measurement







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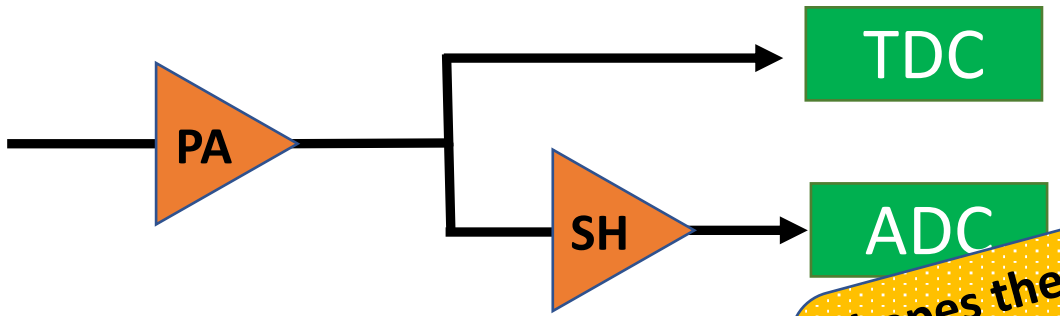
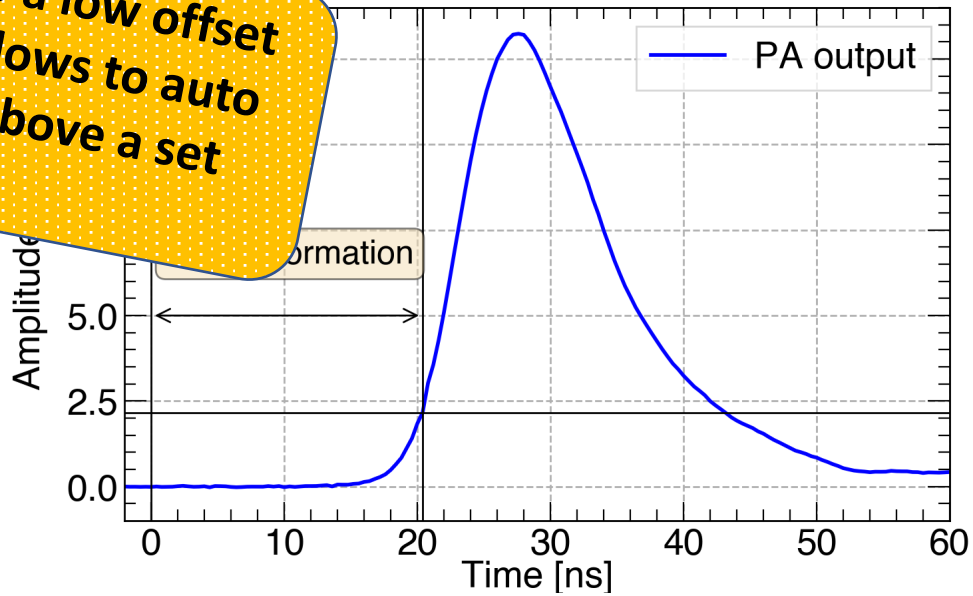
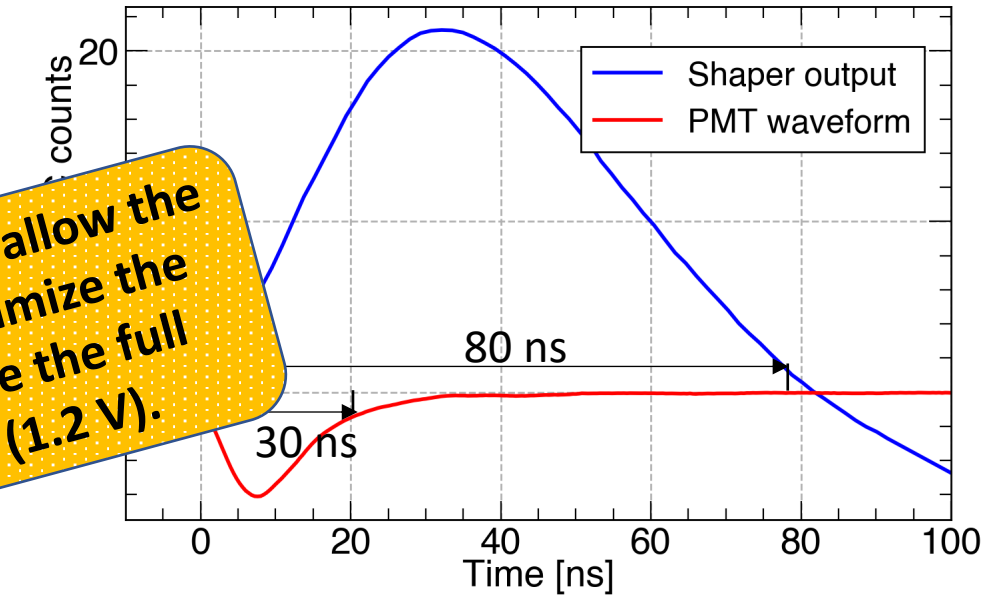
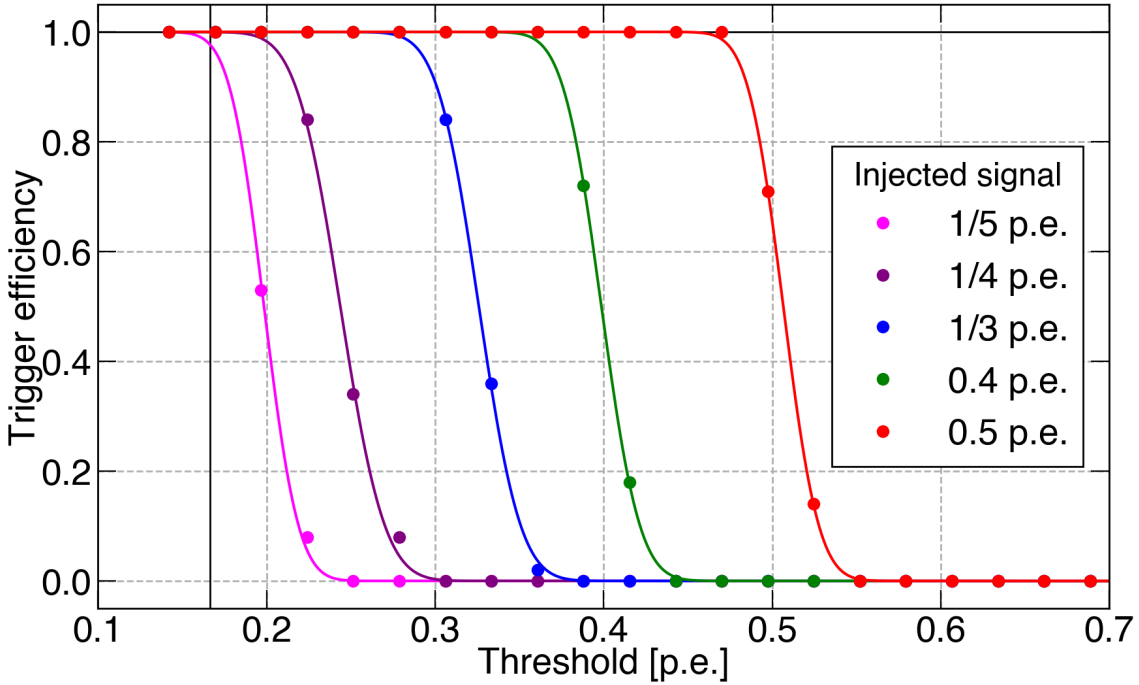


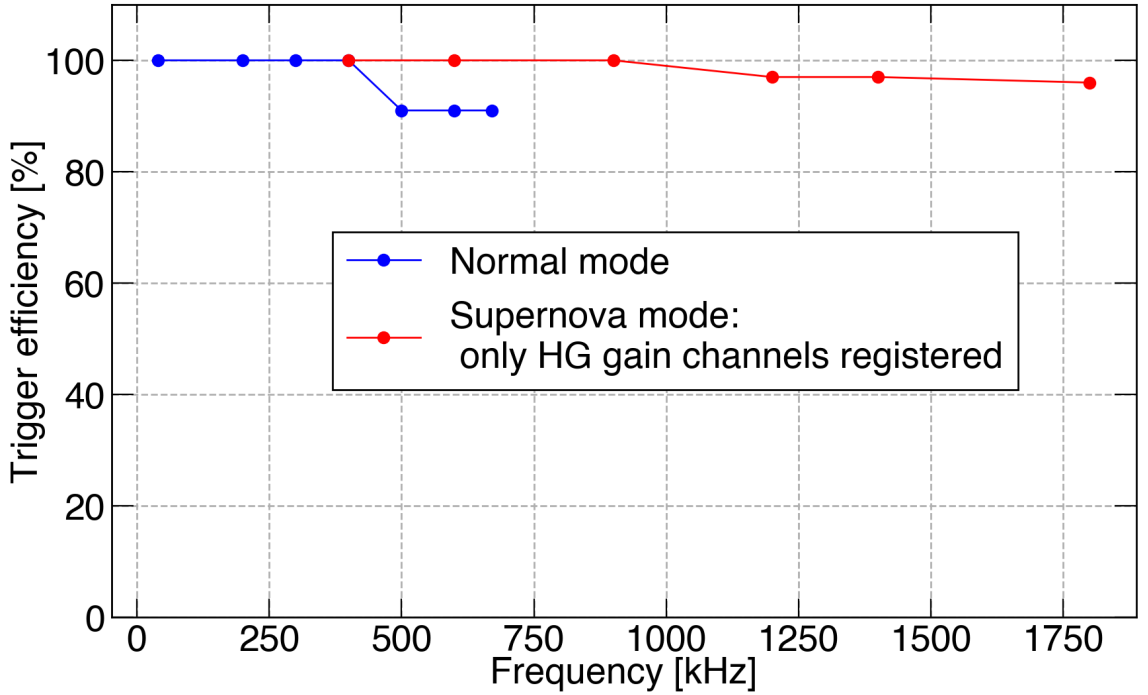




Shapes the PA output signal to allow the charge measurement, to optimize the signal-to-noise ratio and use the full available dynamic range (1.2 V).

Part II: Trigger efficiency





Trigger efficiency 100% for threshold 1/6 p.e @ charges >=1/4 p.e.

Noise level: < $\frac{1}{22}$ $p.e$

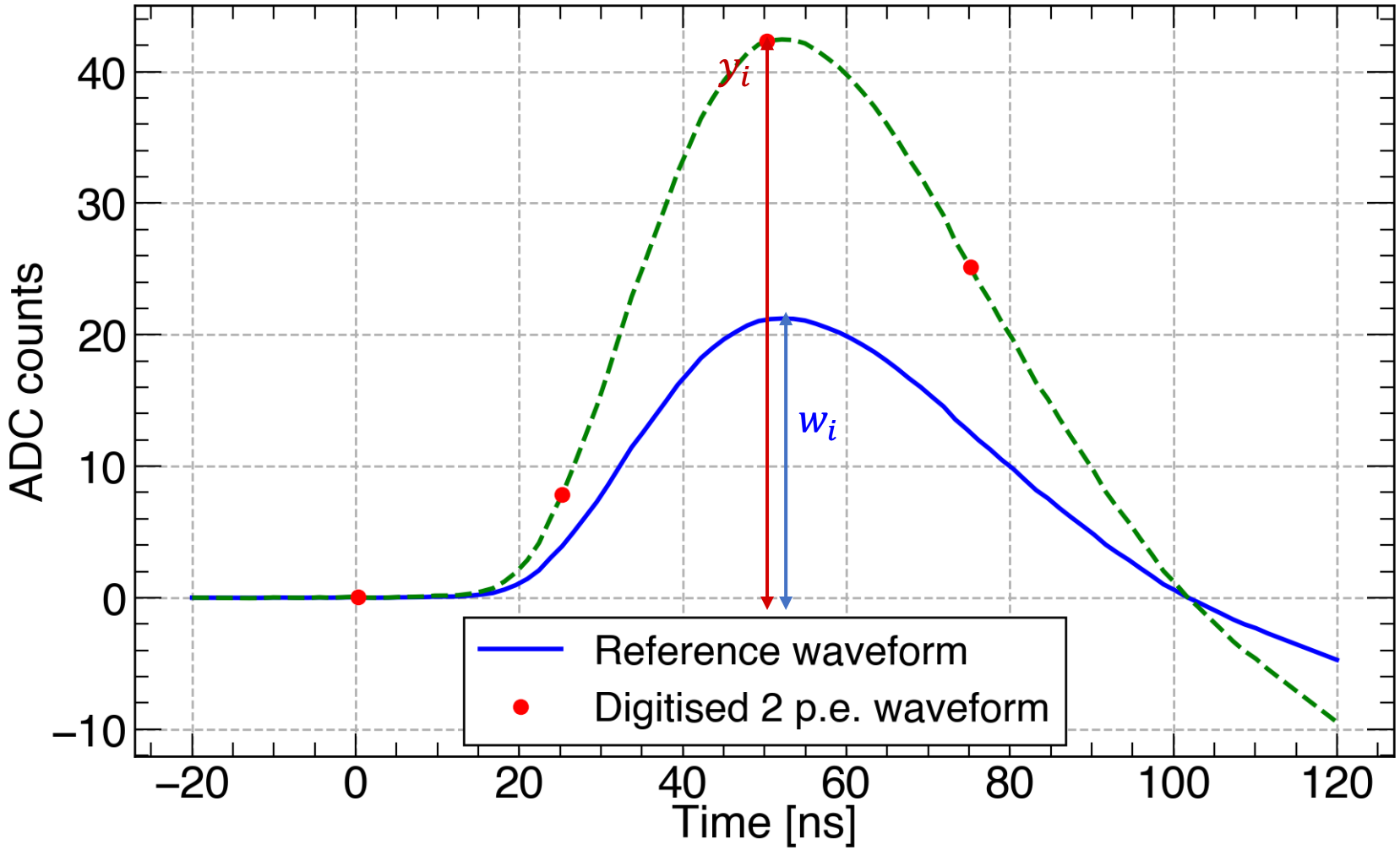
	One channel injection	Multichannel injection
Normal mode	1200 kHz	415 kHz
SN mode	2600 kHz	950 kHz

- The HKROC digitizer saturation naturally appears when the chip internal memory is full.
- The chip has **one** independent memory for each read-out link at 1.28 Gb/s, which gathers **3 PMTs**.

Reconstruction method

Calibrate each channel of the digitizer with one charge – build a **reference waveform**

$$\chi^2(q)$$

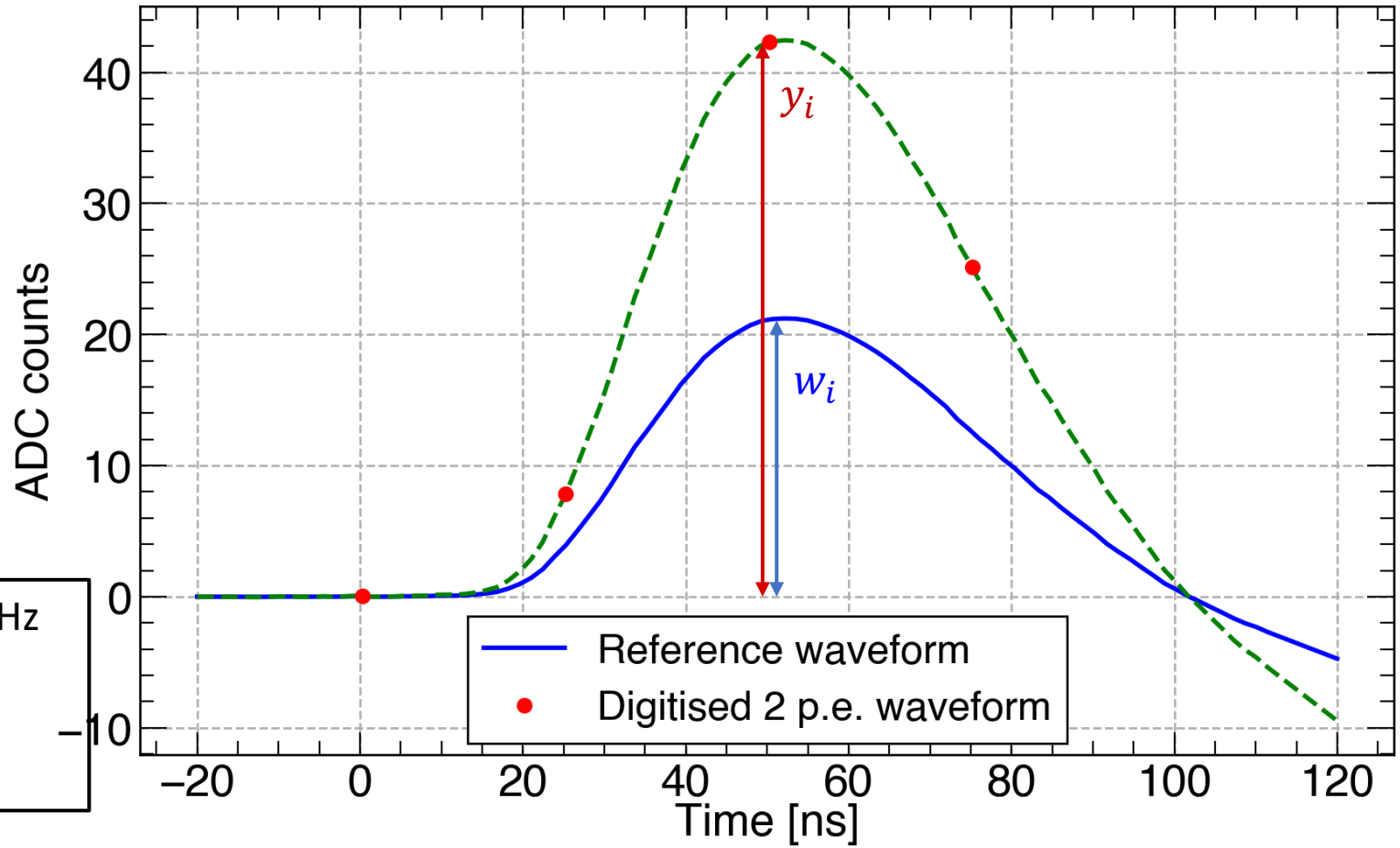


Reconstruction method

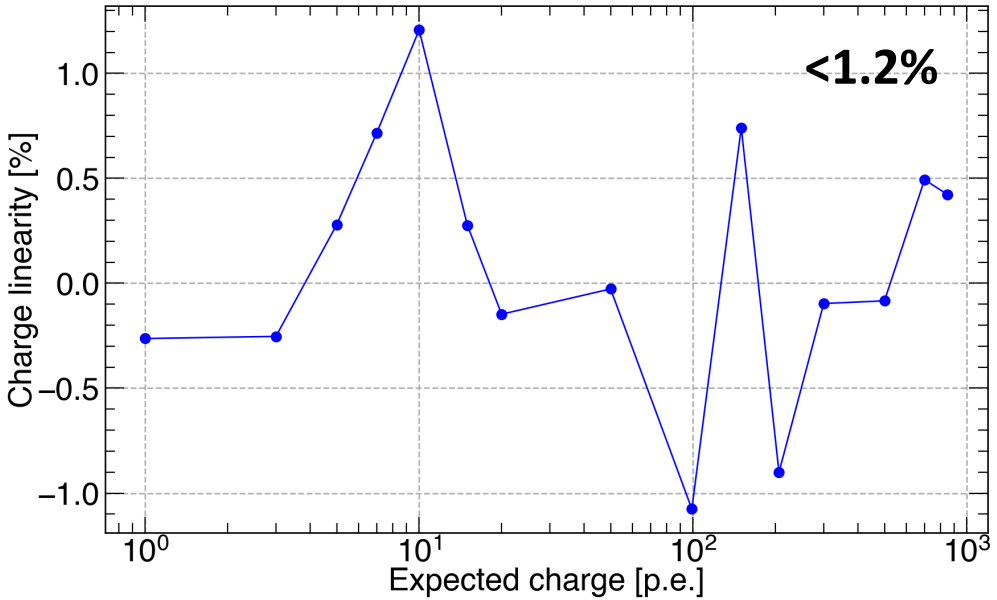
$$\chi^2(q) = \sum_{i=1}^{N} \left(\frac{y_i - q w_i}{\sigma_i} \right)^2$$

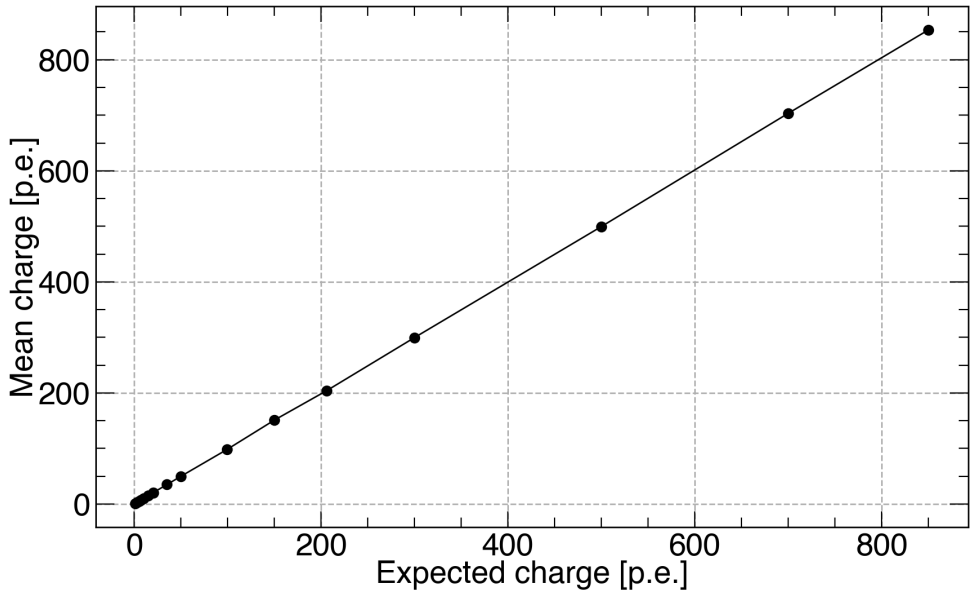
$$q = \frac{\sum_{i=1}^{N} \frac{y_i w_i}{\sigma_i^2}}{\sum_{i=1}^{N} \frac{w_i}{\sigma_i^2}}$$

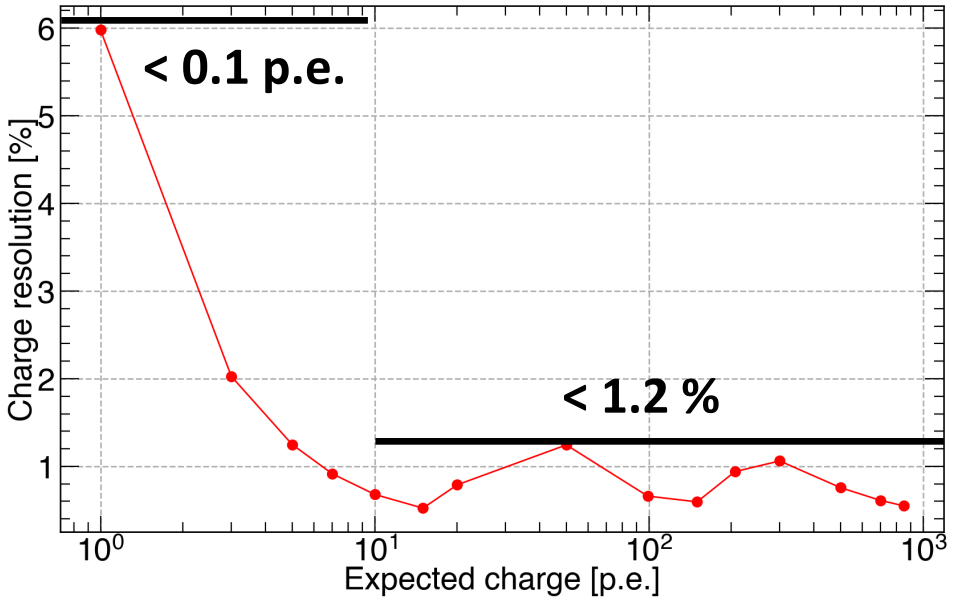
- HKROC is a waveform digitizer working @ 40 MHz
- Number of charge sampling points from 1 to 7
- Charge reconstruction algorithm in FPGA
- 5 % resources of a modern XILINX FPGA



Part III: Charge reconstruction



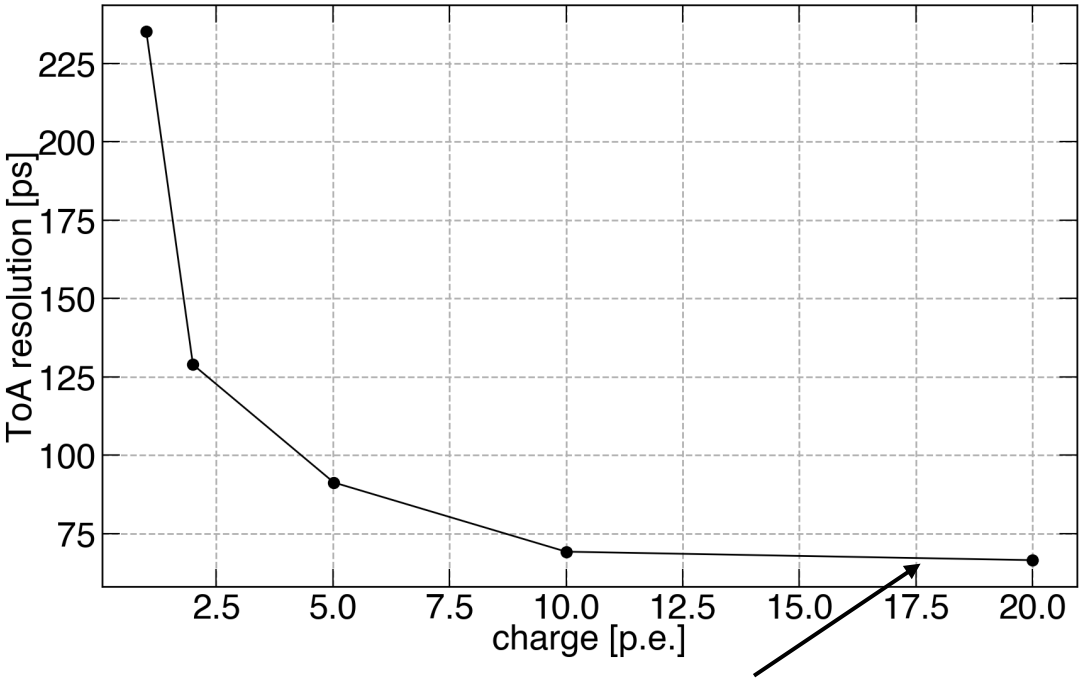




Charge linearity:
< 1.2 % in all charge range

Charge resolution:
< 0.1 p.e. for charge < 10 p.e
< 1.2 % for charges > 10 p.e.

Part IV: Timing performance



saturation because of generator jitter

TDC characterization with **1/6 p.e. threshold**

TDC resolution:

200 ps std @ 1 p.e

≤60ps std @ >10 p.e (intrinsic resolution 25 ps)

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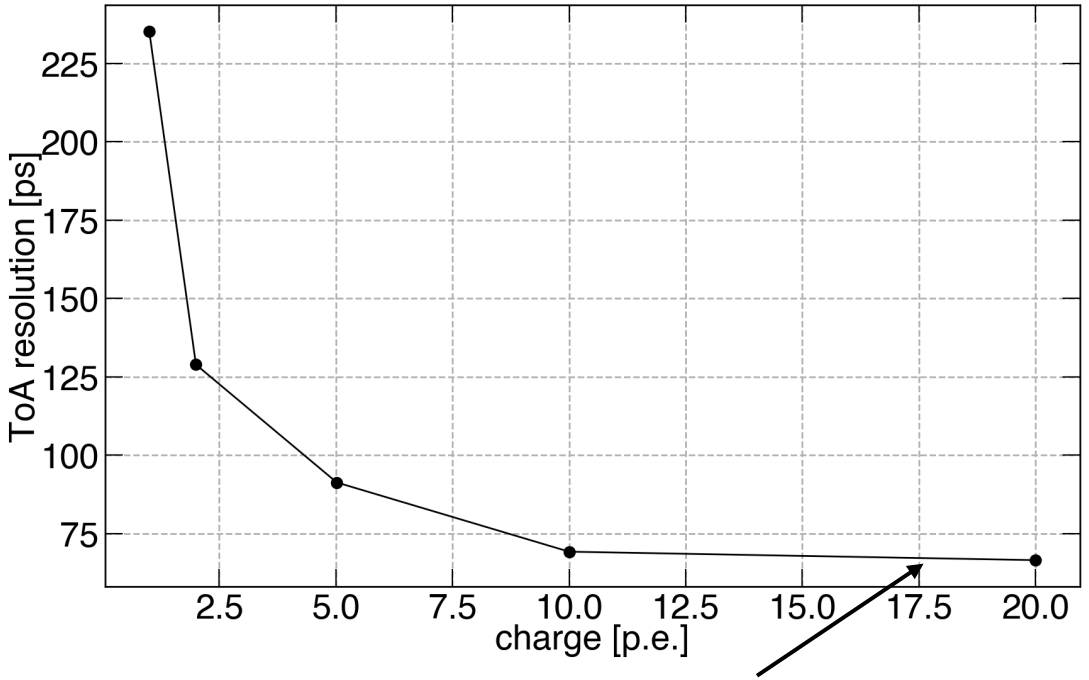

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N.B. PMT time resolution 1.3 ns

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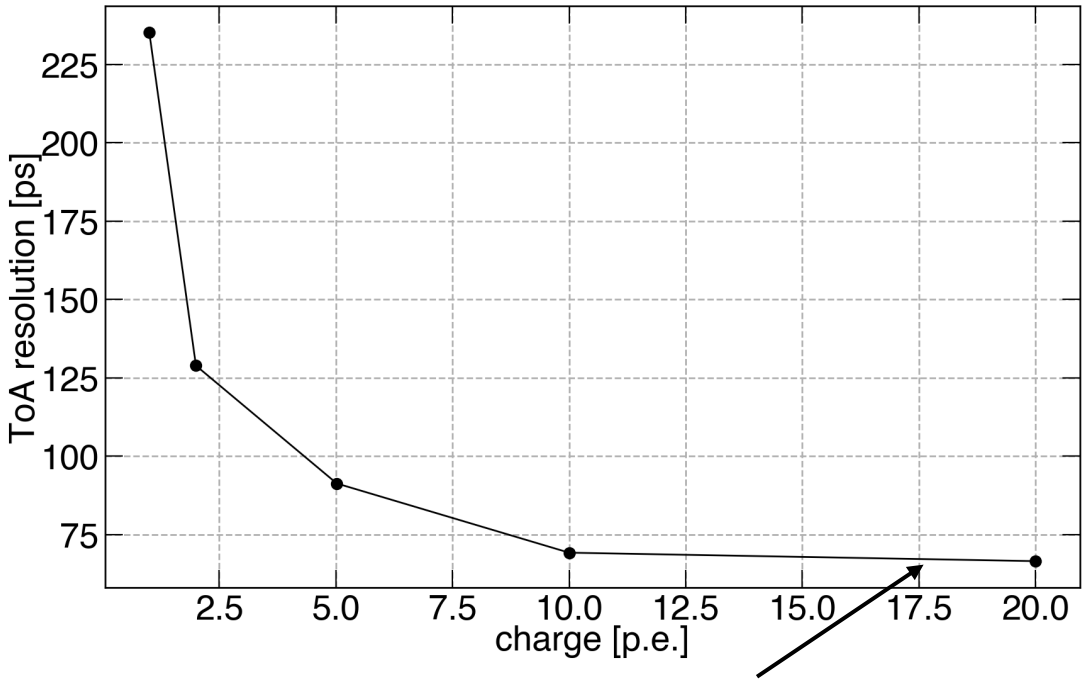

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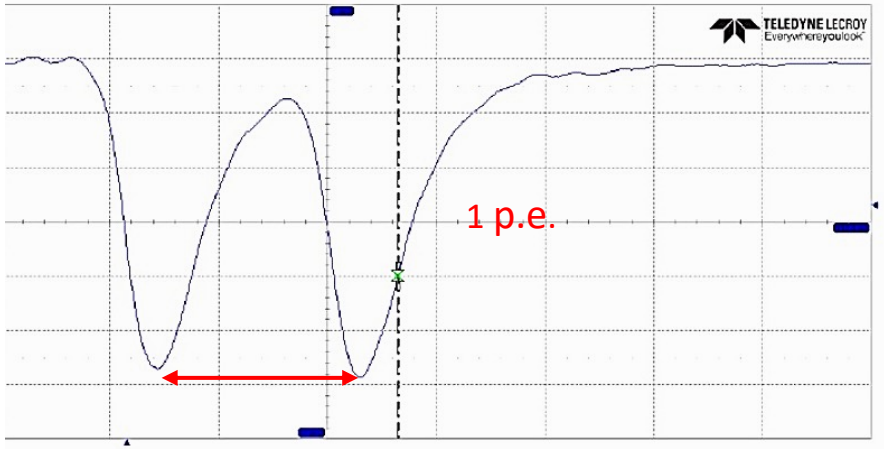

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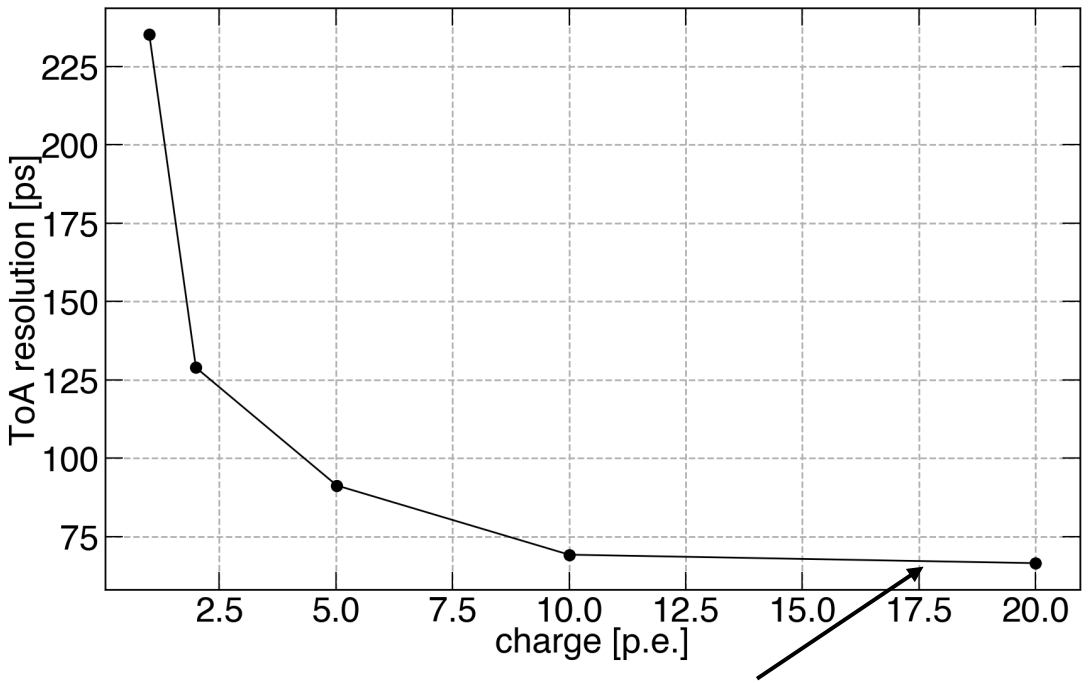

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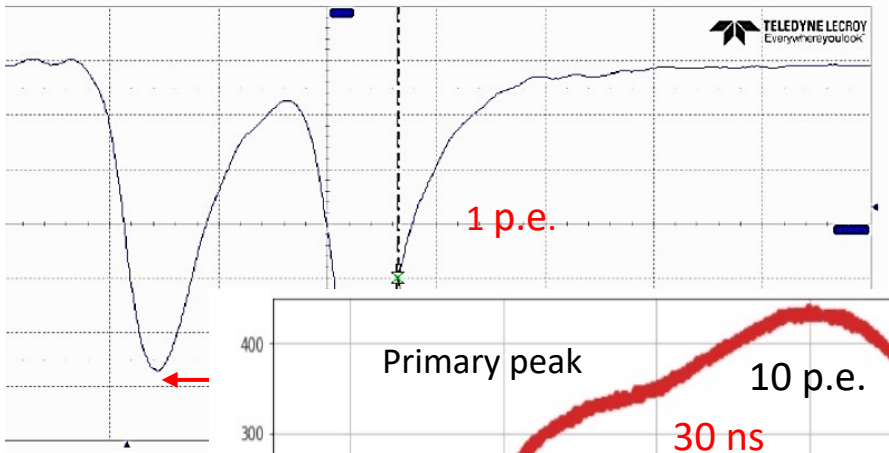

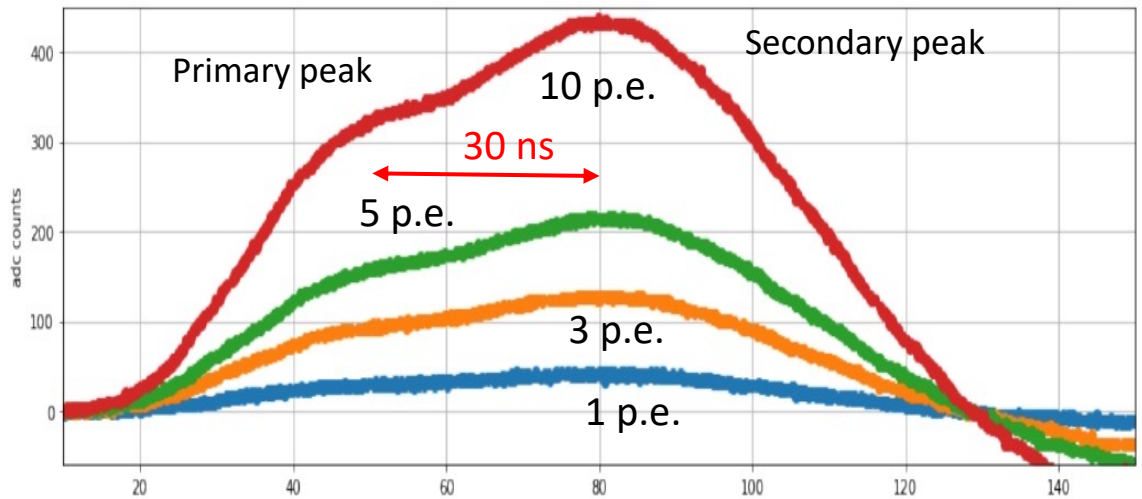

TDC characterization with **1/6 p.e. threshold**

TDC resolution:

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Dead time: 30 ns

Accurate charge reconstruction of pile-up:

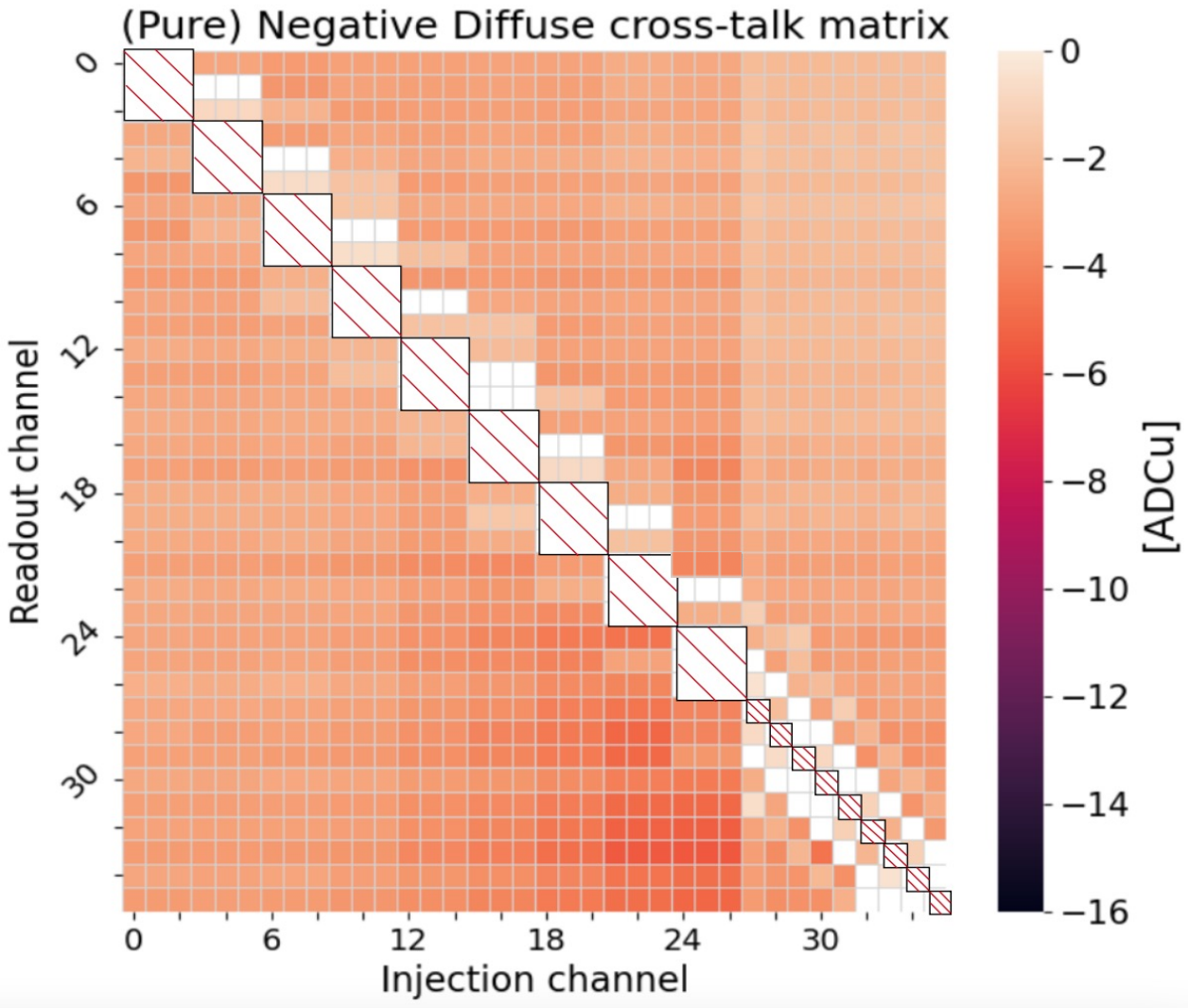
Charge linearity $< \pm 2 - 3\%$

Charge resolution: $< 0.1\,p.e <= 5\,p.e.$

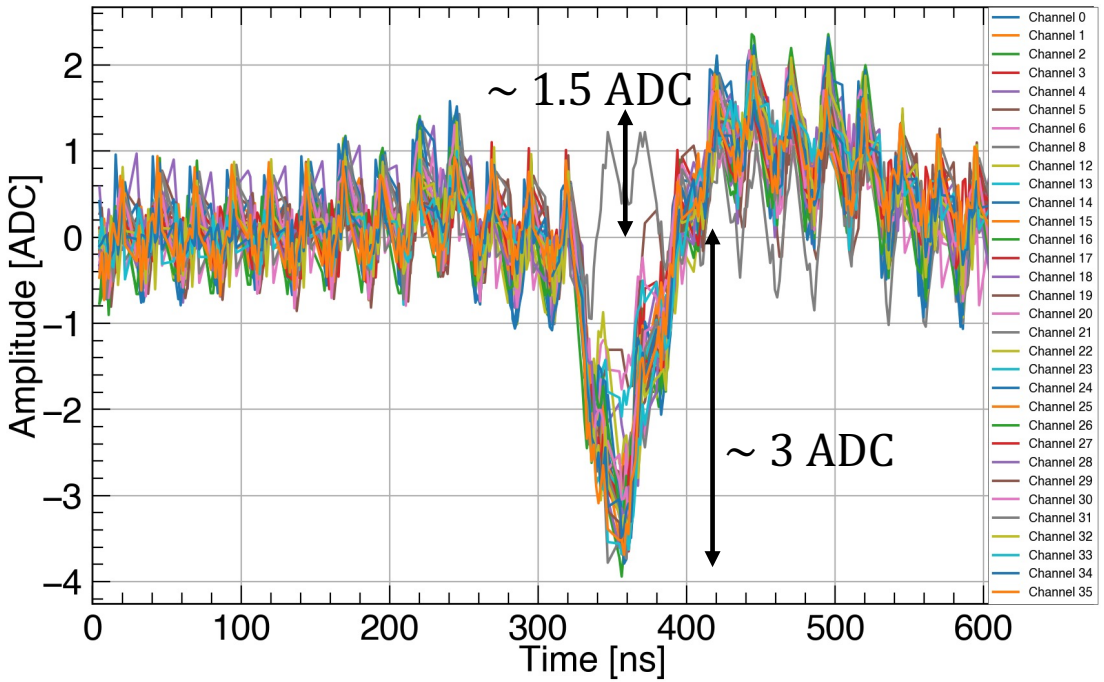
$< 0.17\,p.e.@\,10\,p.e.$

Part V: Cross-talk

Cross-talk induced by high charge 850 p.e.



N.B. ADC for 1 p.e. signal is 22 ADC



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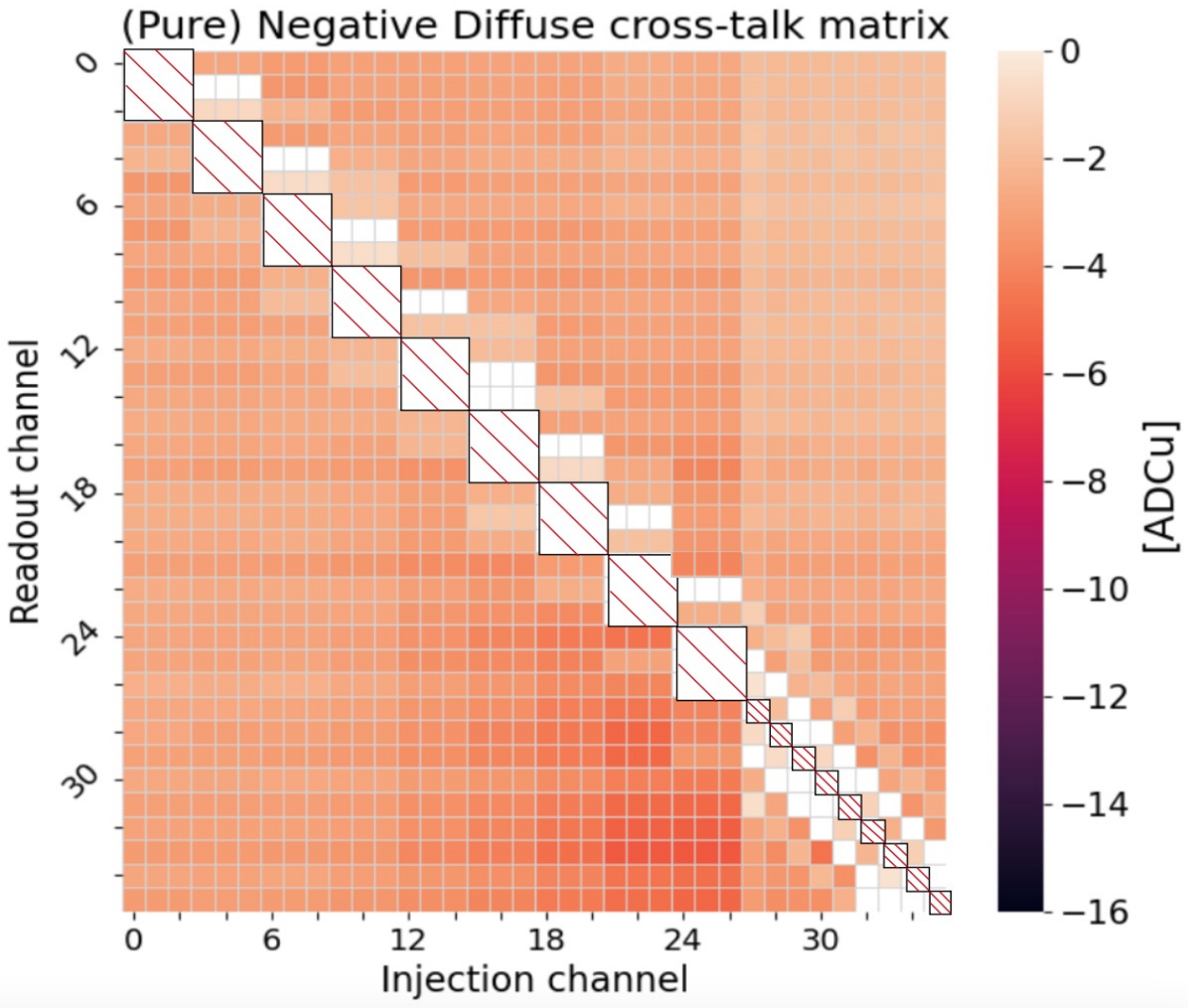

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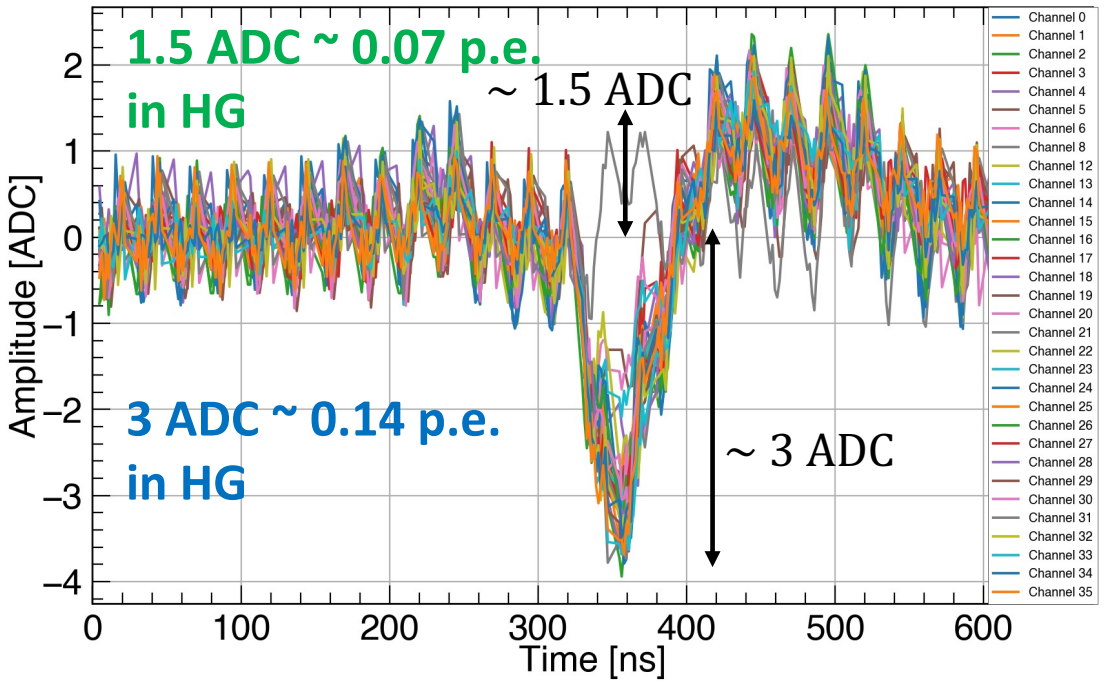

- There is a “diffuse” XT bettween all channels
- Positive amplitude level of XT is about **0.07 p.e.** of injected charge
- Very small, but even next version reduce it by factor of 3

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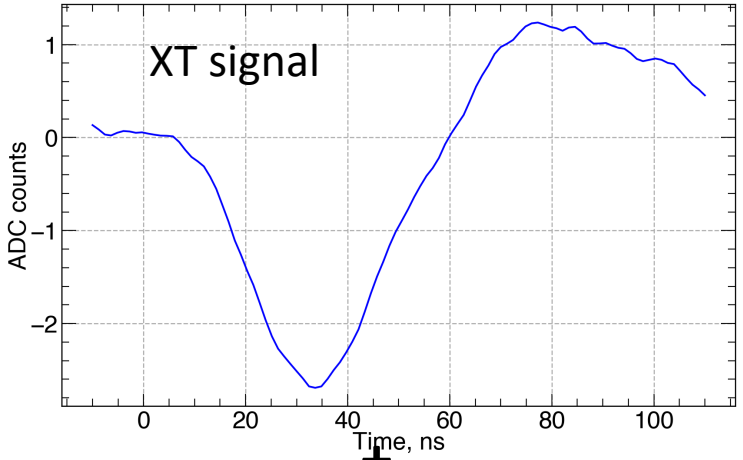

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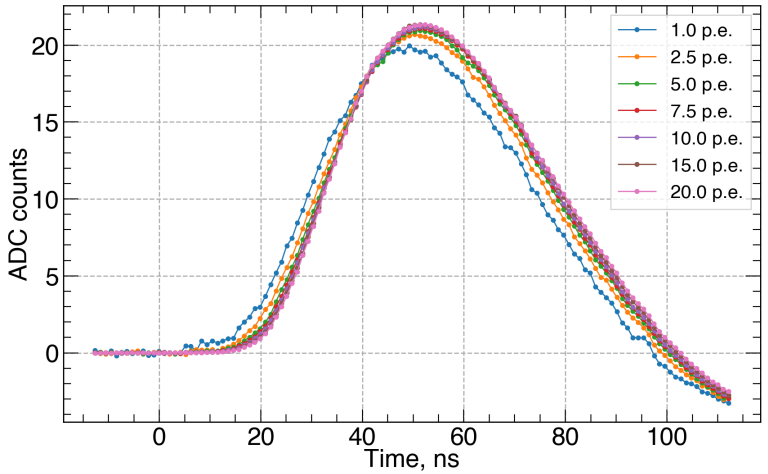
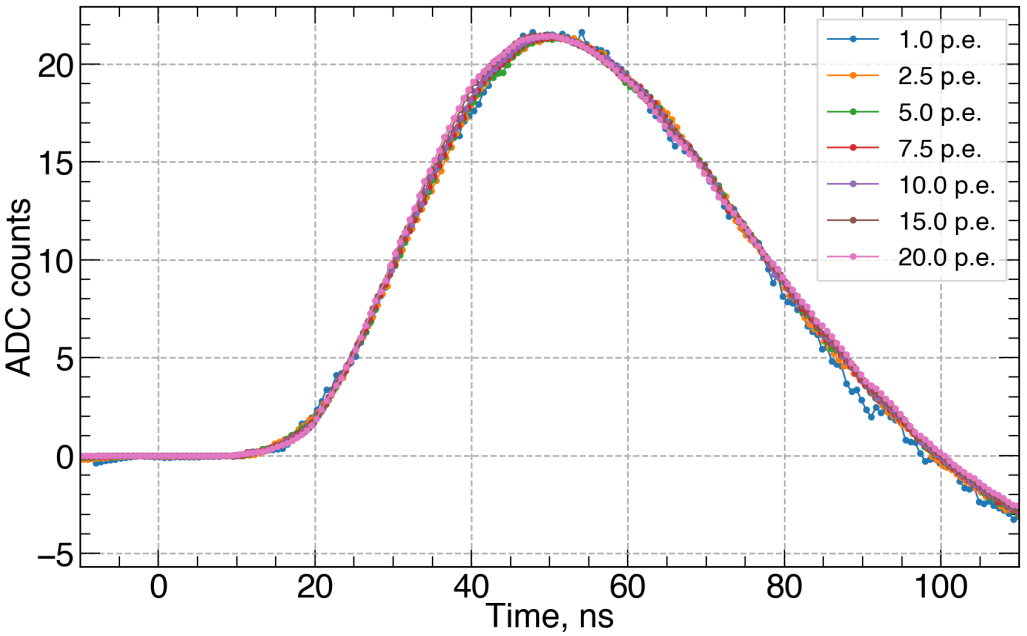
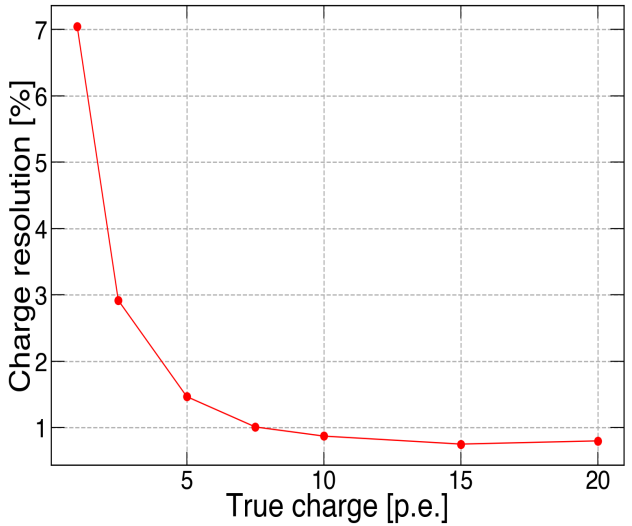
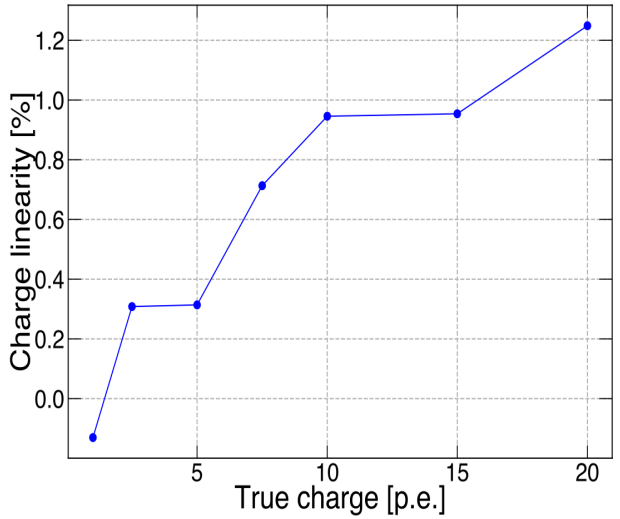
Normalised waveforms - direct measurements



Performing joint fit







- Diffuse XT impact can be removed/corrected thanks to waveform digitizer opportunities
- The same linearity and resolution as without XT

Conclusion

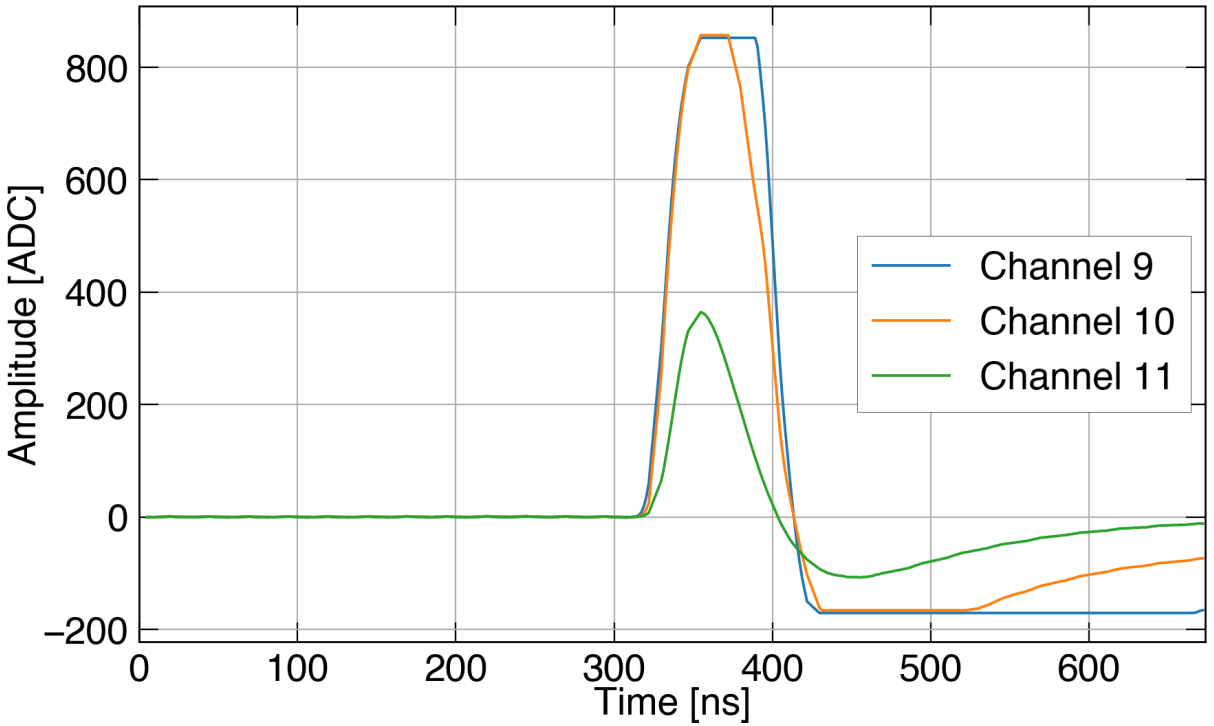
HKROC is an extremely precise digitizer:

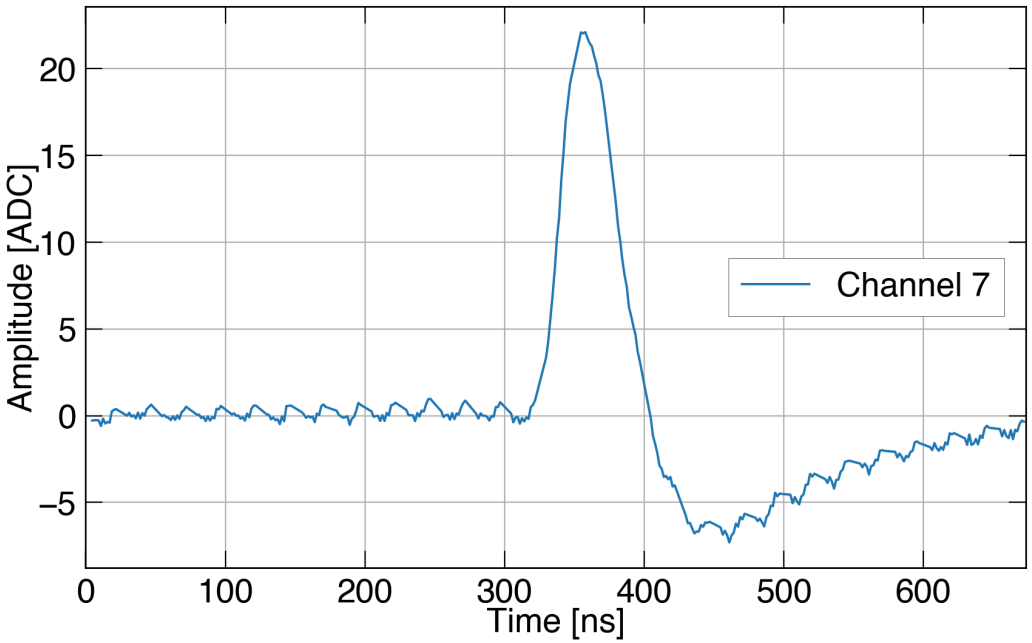
- Autotrigger mode
- Charge linearity: $\sim \pm \mathbf{1}\%$ from 1 to 1250 p.e
- Charge resolution: $< \mathbf{0.1}\ \boldsymbol{p.e}\ @ \leq\ 10\ p.e$ and $\sim \mathbf{1}\%$ for charges $> 10\ p.e$.
- Time resolution: $\mathbf{200}\ \boldsymbol{ps}$ $@1\ p.e.$ and $\leq \mathbf{60}\ \boldsymbol{ps}$ for charges $> 10\ p.e$.
- Hit rate: **950 kHz** in SN mode
- Dead-time: **30 ns**

HKROC-based electronics will provide a versatile, accurate, and fully integrated solution for PMT-based experiments

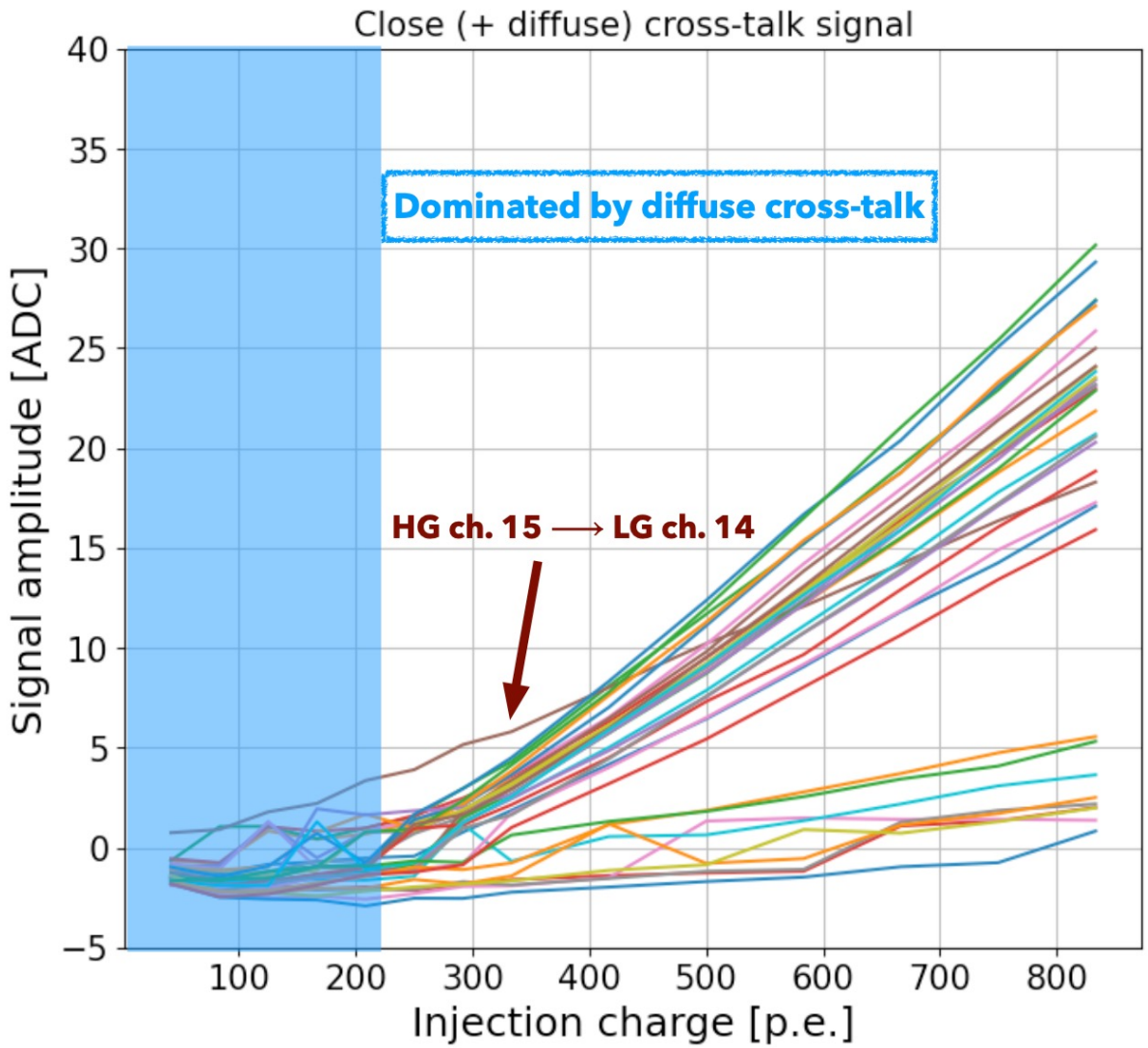
BackUp

Close XT



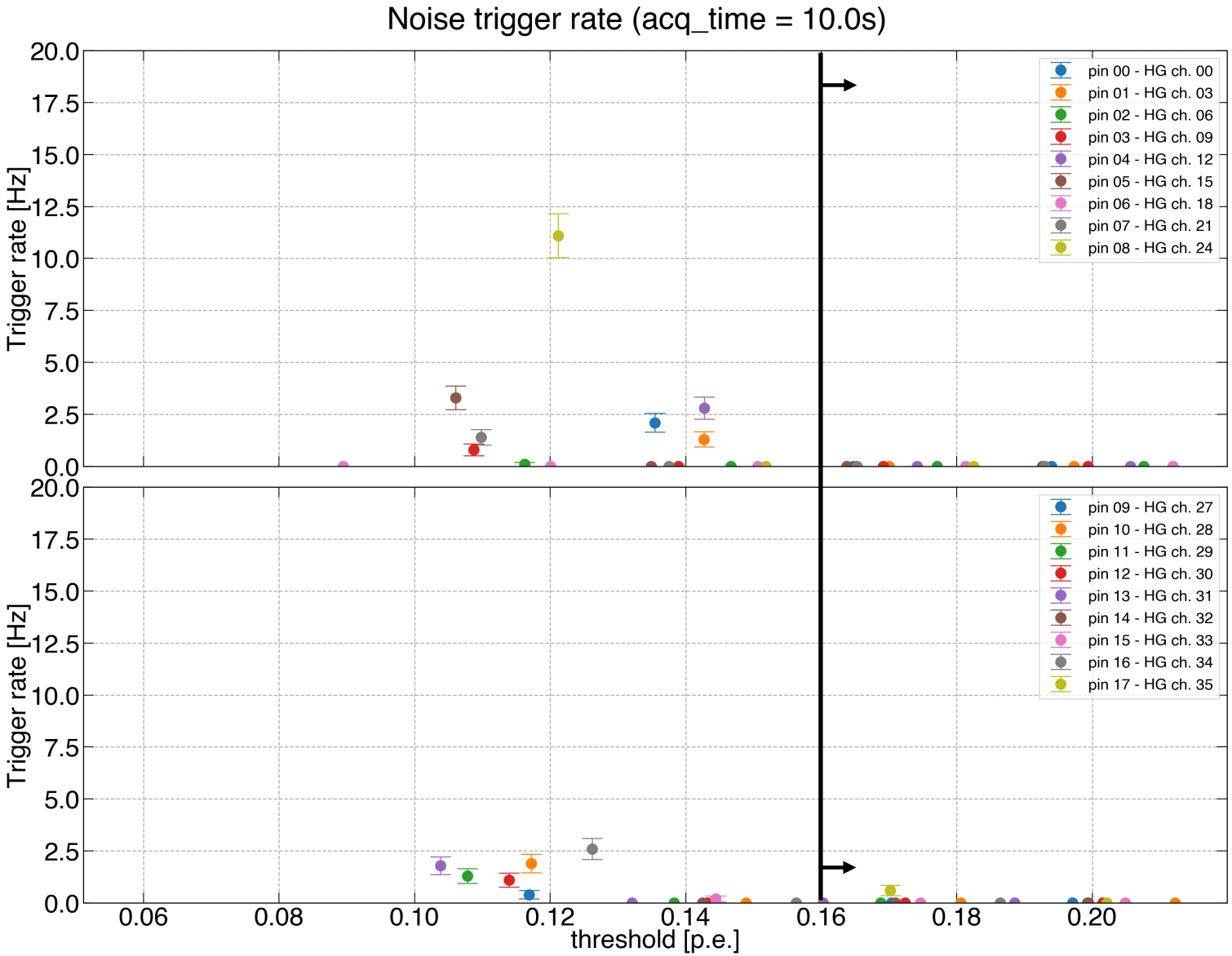


BackUp

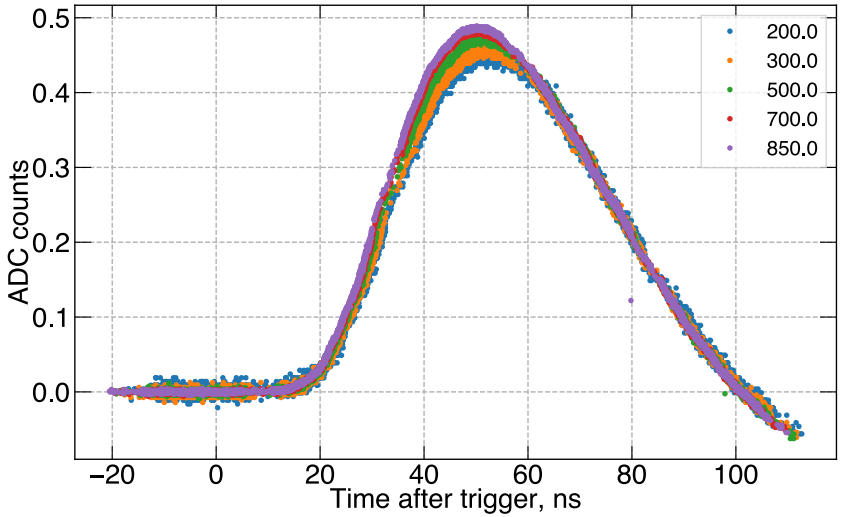


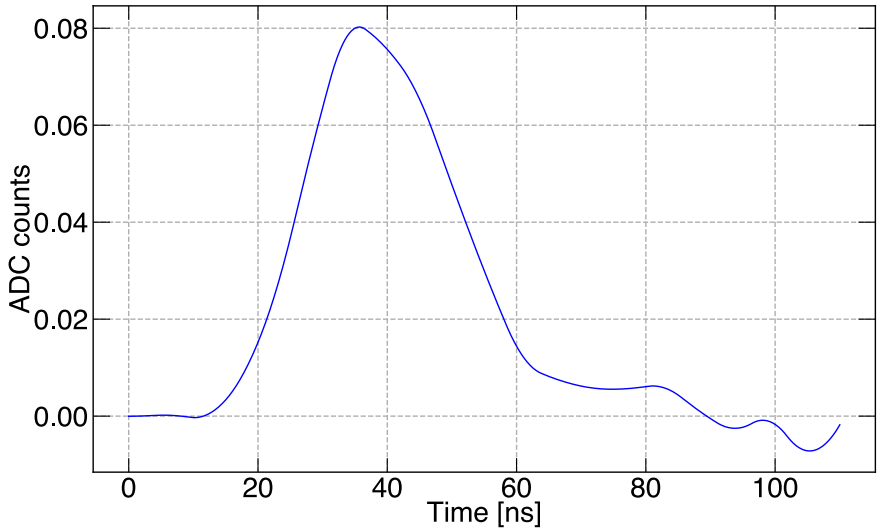
Close XT depending on charge

BackUp


Noise trigger rate (acq_time = 10.0s)
Trigger rate [Hz]
threshold [p.e.]
pin 00 - HG ch. 00
pin 01 - HG ch. 03
pin 02 - HG ch. 06
pin 03 - HG ch. 09
pin 04 - HG ch. 12
pin 05 - HG ch. 15
pin 06 - HG ch. 18
pin 07 - HG ch. 21
pin 08 - HG ch. 24
pin 09 - HG ch. 27
pin 10 - HG ch. 28
pin 11 - HG ch. 29
pin 12 - HG ch. 30
pin 13 - HG ch. 31
pin 14 - HG ch. 32
pin 15 - HG ch. 33
pin 16 - HG ch. 34
pin 17 - HG ch. 35

BackUp





Low Gain