HGCROC and HKROC

DRD1 meeting CERN 31 jan 2024

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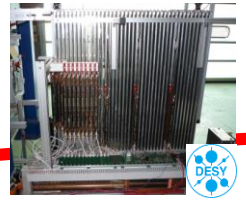
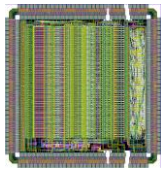
Ecole Polytechnique – CNRS

Organization for Micro-Electronics desiGn and Applications

OMEGA ASICs : overview

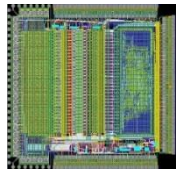


MAROC3

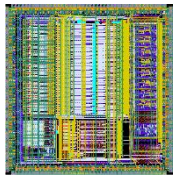


2006

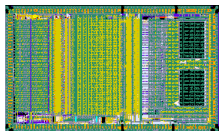
PETIROC



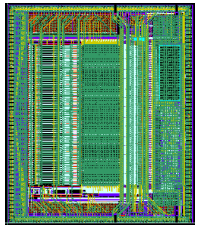
SPACIROC



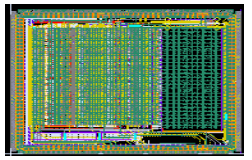
HARDROC



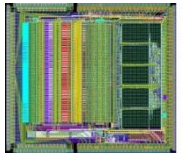
SKIROC



SPIROC



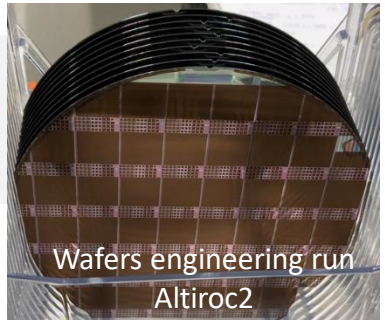
MICROROC



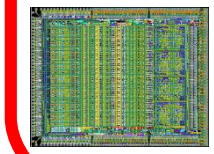
9 engineering runs in 9 years :

AMS SiGe 0,35um 2014, 2016, 2018

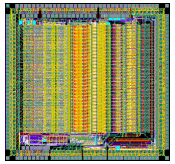
TSMC 130nm: 2019, 2020, 2021, 2022 and 2023 (x2)



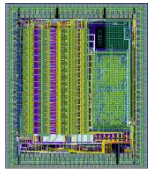
TRIROC



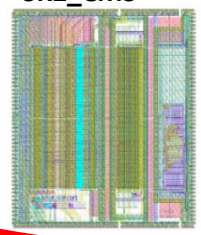
CITIROC



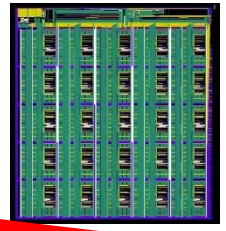
CATIROC



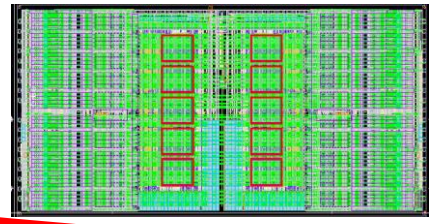
SK2_CMS



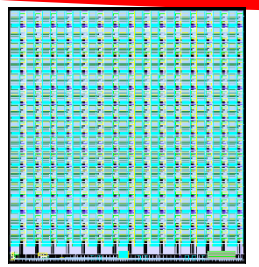
ALTIROC1



HGCROC

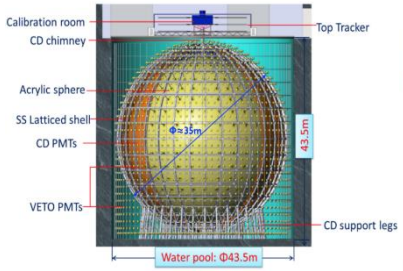


ALTIROC2



HKROC

2023



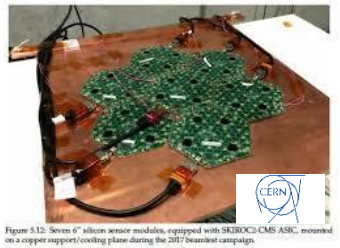
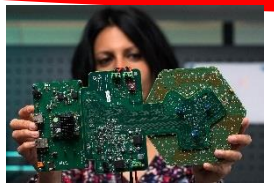
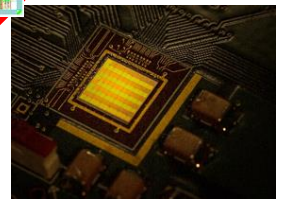


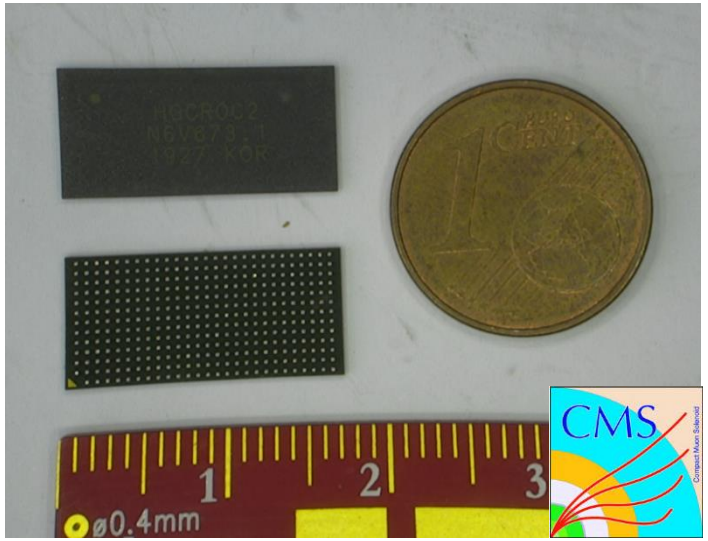
Figure 5.12: Seven 6" silicon sensor modules, equipped with SKIROC2-CMS ASIC, mounted on a copper support/cooling plane during the 2017 beamtest campaign.



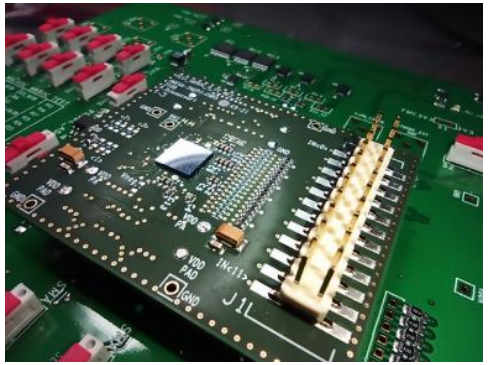


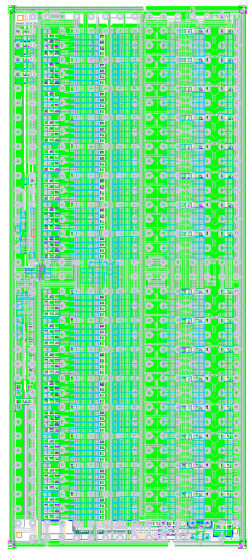
Recent PMT/SiPM chips

- Omega strongly involved in LHC ATLAS & CMS upgrades
- HGCROC/H2GCROC : High Granularity Calorimeter Read Out Chip
  - 78 channels of Si/SiPM readout for calorimetry
  - ADC + TOT + TOA
  - Collaboration : AGH, CEA, CERN, Imperial, OMEGA



- HKROC : PMT readout for PM tubes
  - 3*12 to 36 channels (tri-gain or mono gain)
  - ADC + TOA
  - Collaboration : AGH, CEA, CERN, Imperial, OMEGA



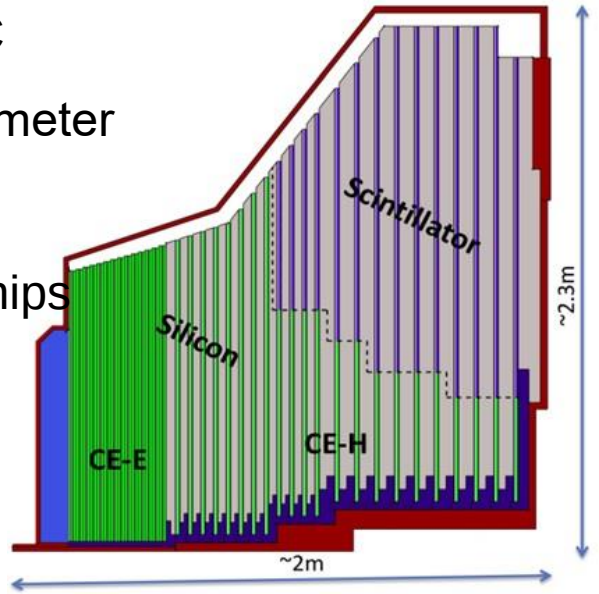


- LIROC : ATTRACT project for space based LIDAR
  - 64 high speed (GHz) amplifiers/discriminators « à la petiroc »
  - 3 ns double pulse resolution on single photons
  - Collaboration OMEGA-WEEROC

- CMOS 130 nm process rad hard up to 300 MRad

CMS High Granularity Calorimeter (HGCAL)

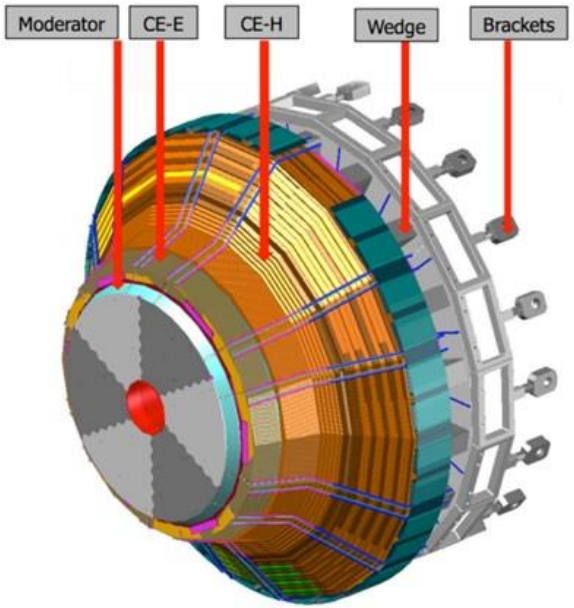
- **Upgrade of CMS at HL-LHC**
  - New “5D” imaging calorimeter
  - Si and SiPM sensors
  - HGCROC/H2GCROC chips



	CE-E Silicon	CE-H Silicon	CE-H Scintillator	Total
HGCROC	60 324	31 596	8 496	100 416
Motherboards	5 004	2 556	384	7 944
Bidirectional data/control links	5 004	2 556	384	7 944
Trigger links	4 020	2 556	768	7 344

Requirement: Use very similar FE electronics for the readout of both detectors

- Si (~ 4 fC / MIP)
- SiPM-on-tile (~ 1.7 pC / MIP)



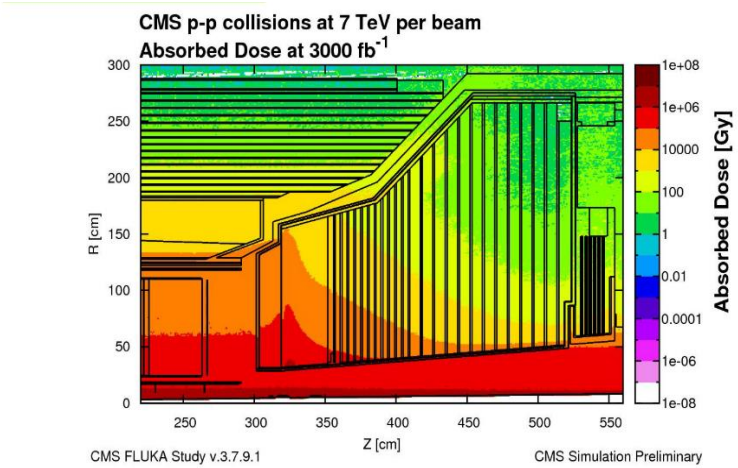
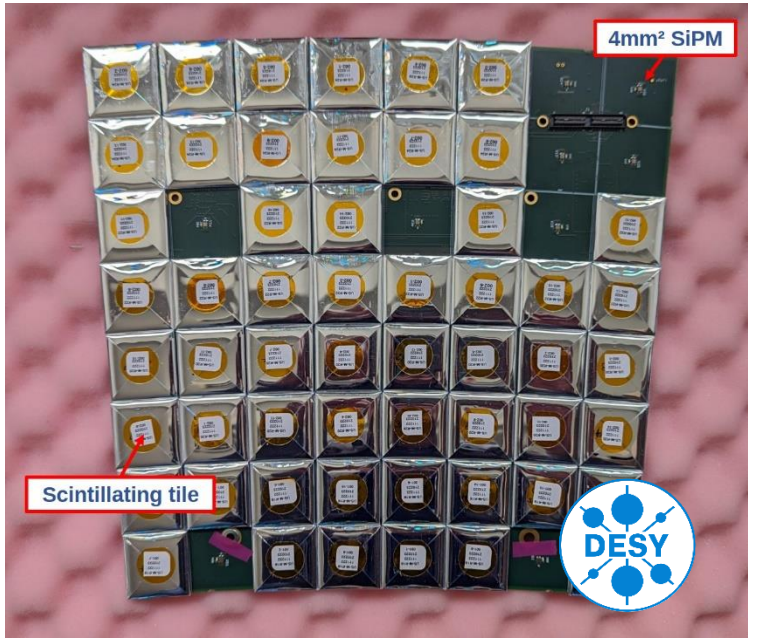


Figure 1.1: Dose of ionizing radiation accumulated in HGCAL after an integrated luminosity of3000 fb^{-1}, simulated using the FLUKA program, and shown as a two-dimensional map in the radial and longitudinal coordinates, r and z.



HGCROC3: Architectural overview

Overall chip divided in two symmetrical parts

- **1 half is made of:**
  - 39 channels: 18 ch, CM0, Calib, CM1, 18 ch
  - Bandgap, voltage reference close to the edge
  - Bias, ADC reference, Master TDC in the middle
  - Main digital block and 3 differential outputs (2x Trigger, 1x Data)

Two data flows

- **DAQ path**
  - 512 depth DRAM (CERN), circular buffer
  - Store the ADC, TOT and TOA data
  - 2 DAQ 1.28 Gbps links
- **Trigger path**
  - Sum of 4 (9) channels, linearization, compression over 7 bits
  - 4 Trigger 1.28 Gbps links

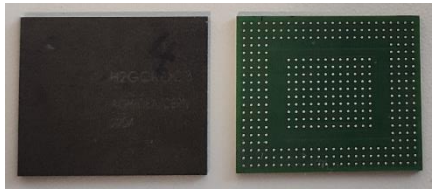
Control

- **Fast commands**
  - 320 MHz clock and 320 MHz commands
  - A 40 MHz extracted, 5 implemented fast commands
- **I2C protocol for slow control**

Ancillary blocks

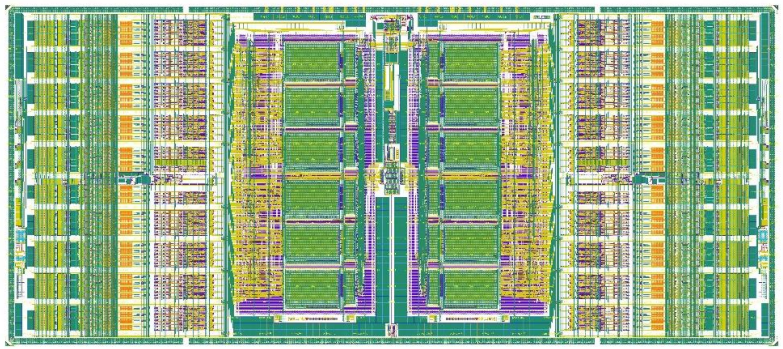
- Bandgap (CERN)
- 10-bits DAC for reference setting
- 11-bits Calibration DAC for characterization and calibration
- PLL (IRFU)
- Adjustable phase for mixed domain

HGCROC3
High density



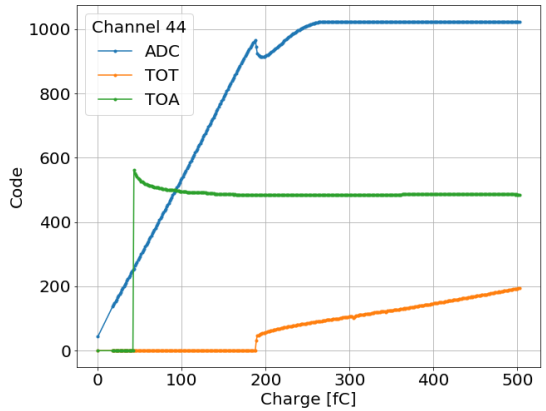
H2GCROC3
Low density

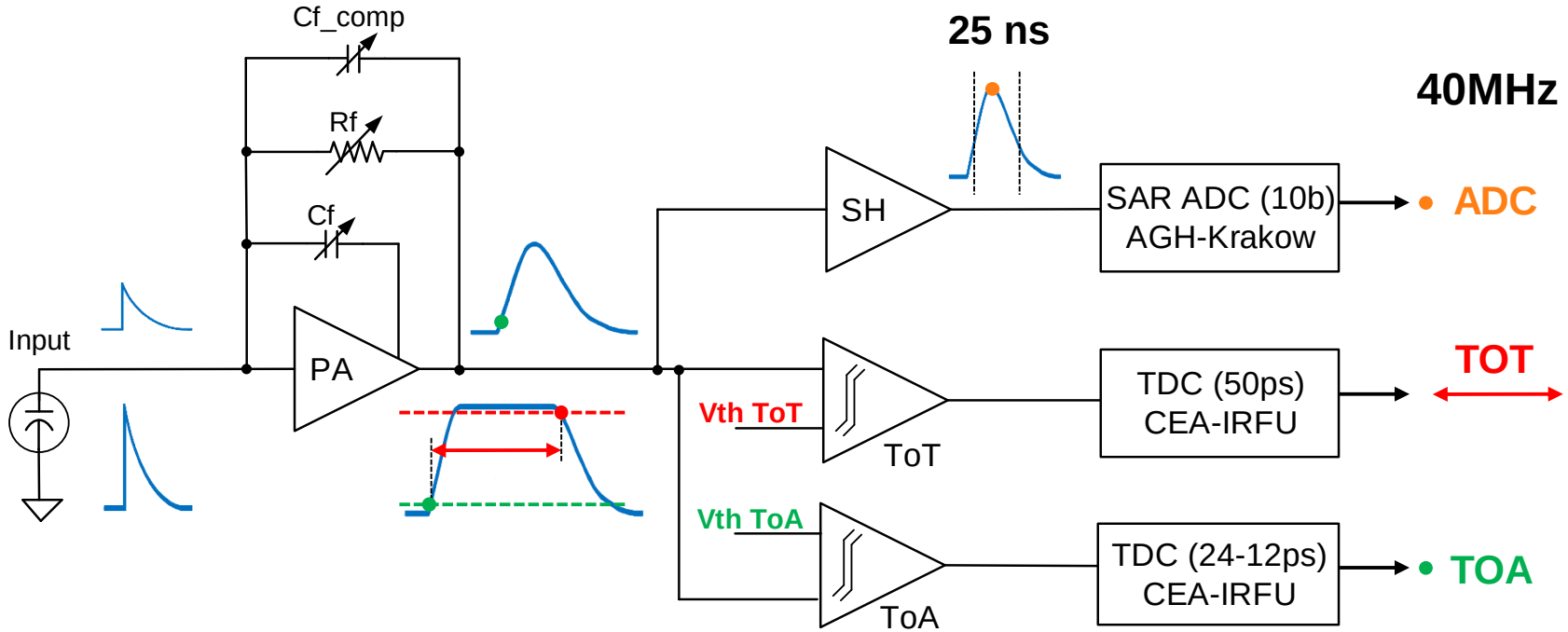
HGCROC3 Layout:



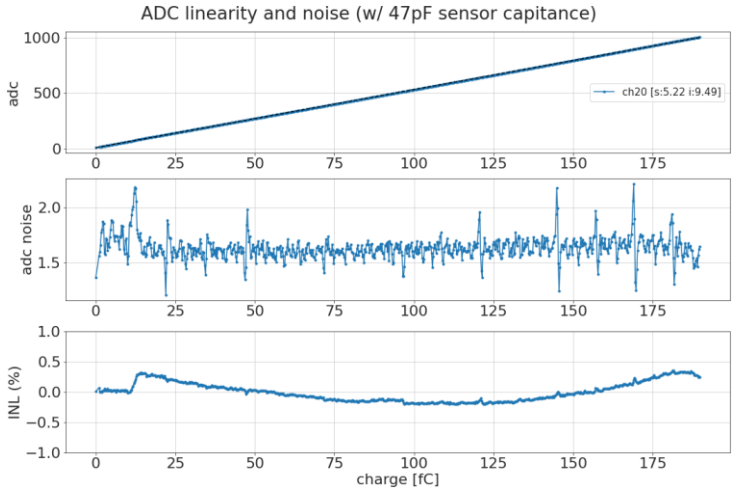
HGCROC3: Analog channel overview

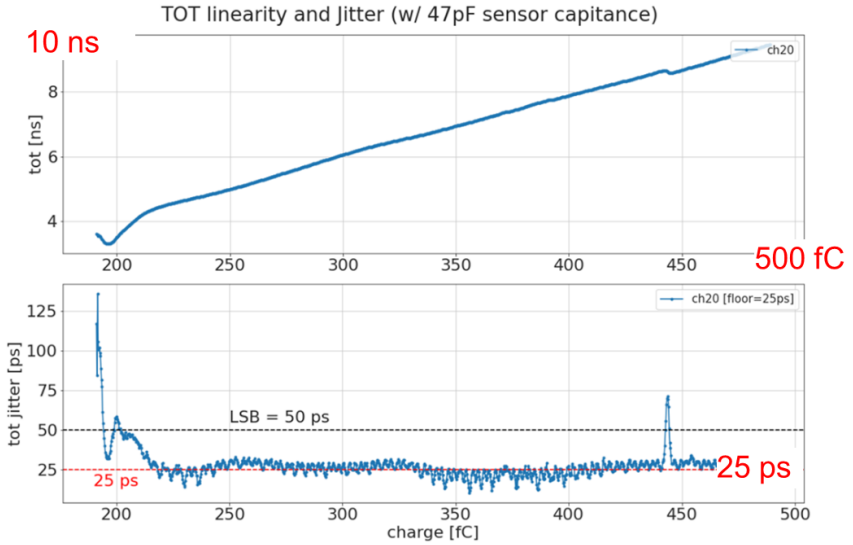
- **Calibration pulser**, 0.5pF and 10 pF calibration cap.
- **Preamp :** adjustable gains for 80, 160 and 320 fC ranges
- **Tunable TOT** over 5 bits
- **Sallen Key shaper RC4**, tp<25 ns,
  tunable (~20%) with 2 bits, BX+1/BX<0.2
- Temperature stabilization to < 0.5 mV/K
- **10 bit ADC from Krakow AGH**
- **TOT and TOA TDCs from CEA-IRFU**

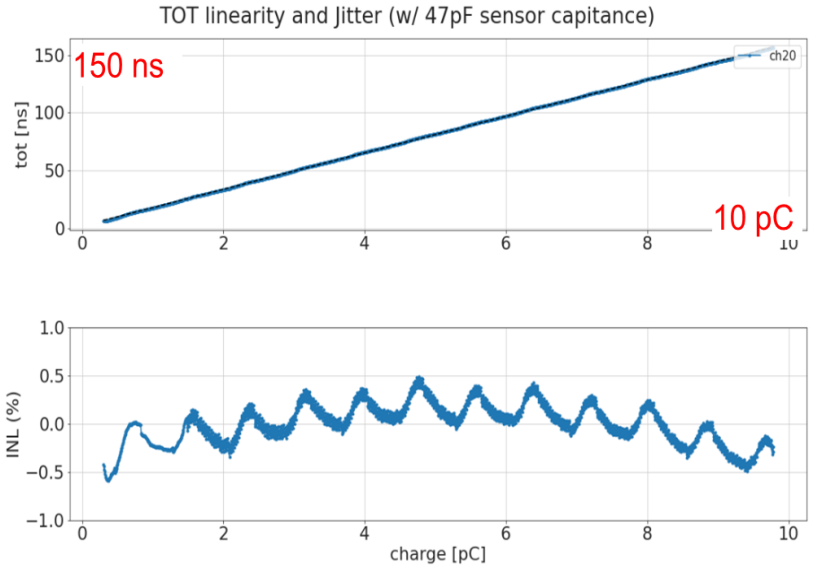


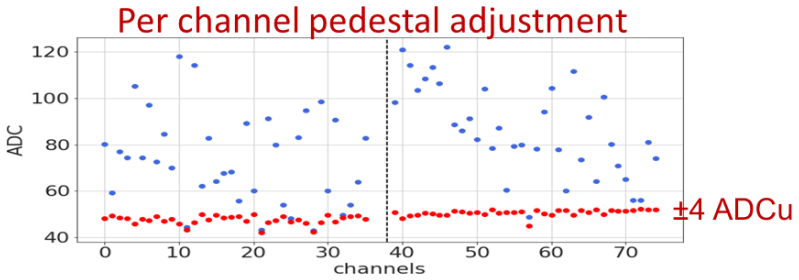


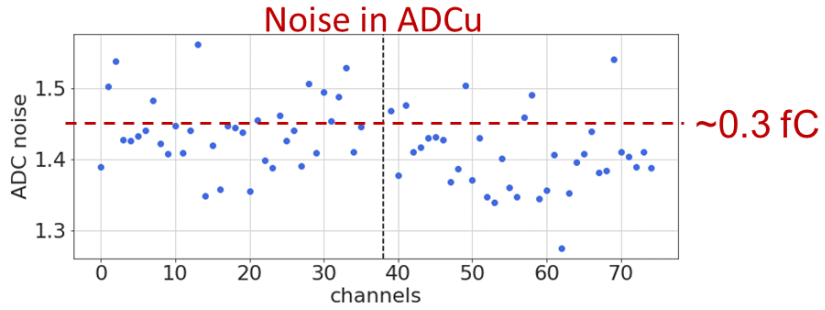
HGCROC3 performance

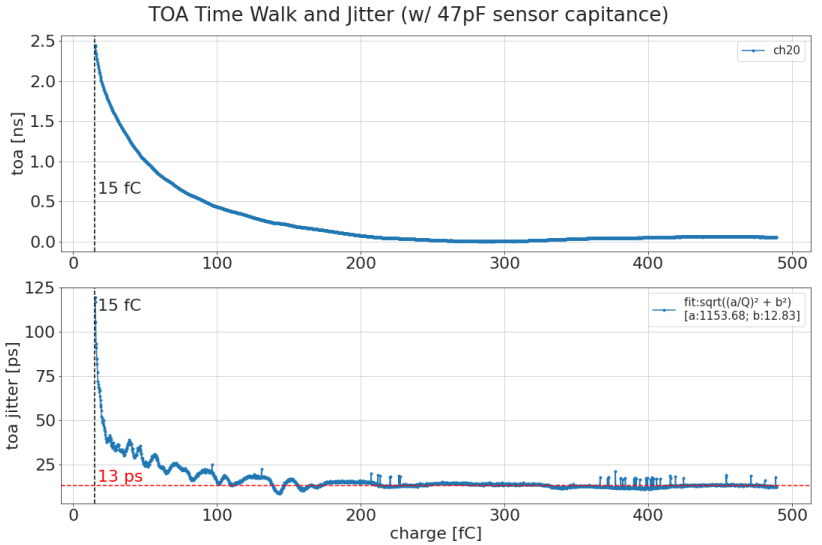








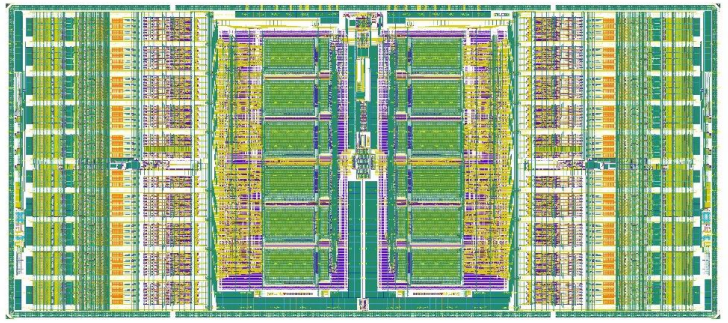


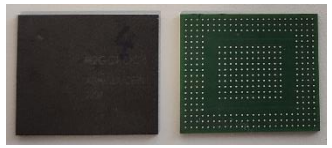


H2GCROC: SiPM version. Requirements

Requirements for H2GCROC (The SiPM version of the ASIC):

- Charge dynamic range : **160 fC to 320 pC**
- Timing accuracy **< 100ps for pulses above 3 MIPs (4.5pC)** for a $C_{det} = 100pF$
- Compensation of the leakage current up to **1mA**
- Radiation resistance up to **300 kRad**
- **Input DAC** to tune the overvoltage

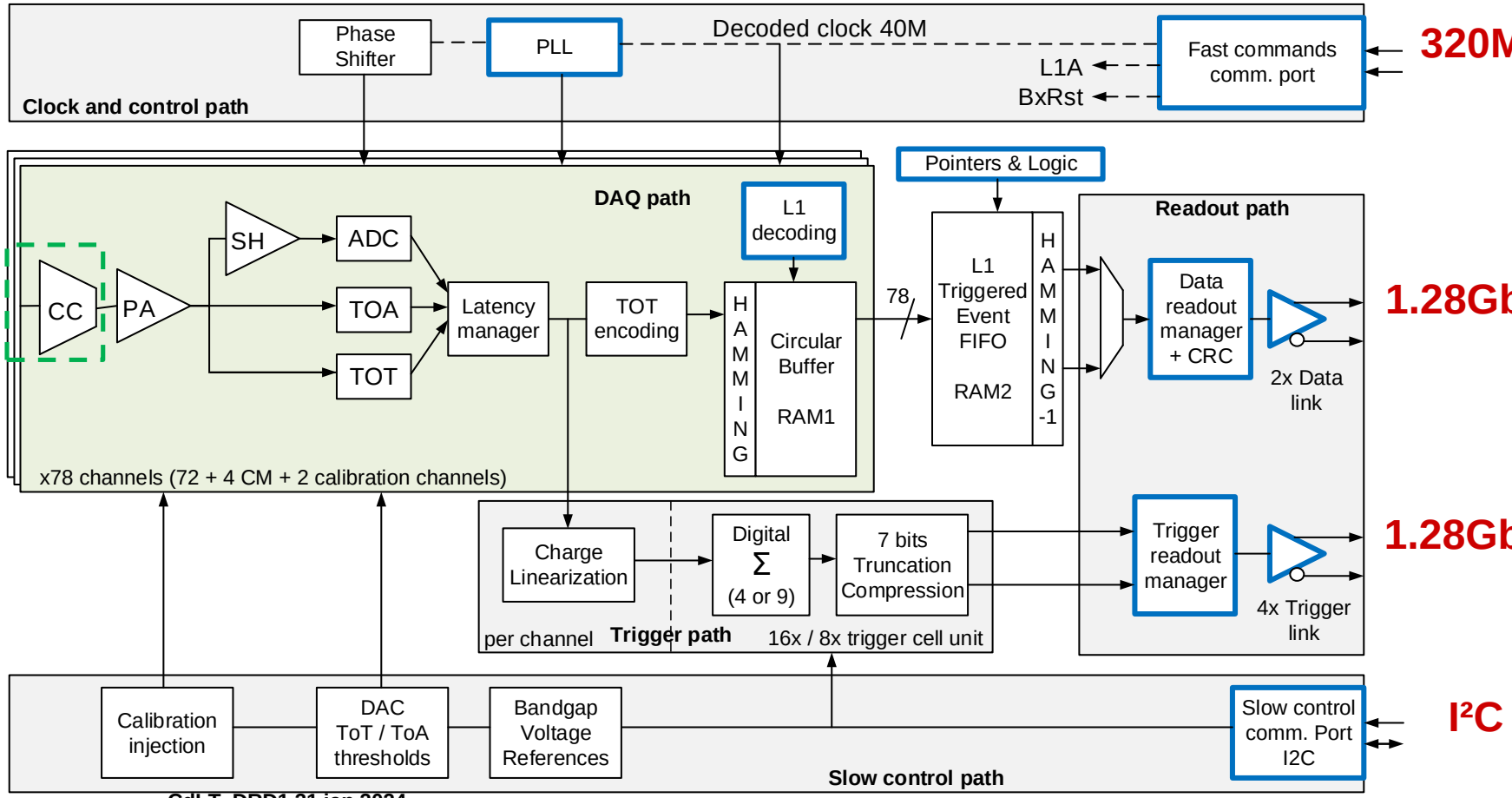




Current Conveyor based on KLAUS chip from Heidelberg UNI.

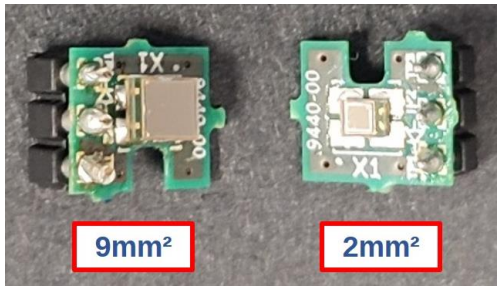
Attenuates the current at the input with 4 bits.

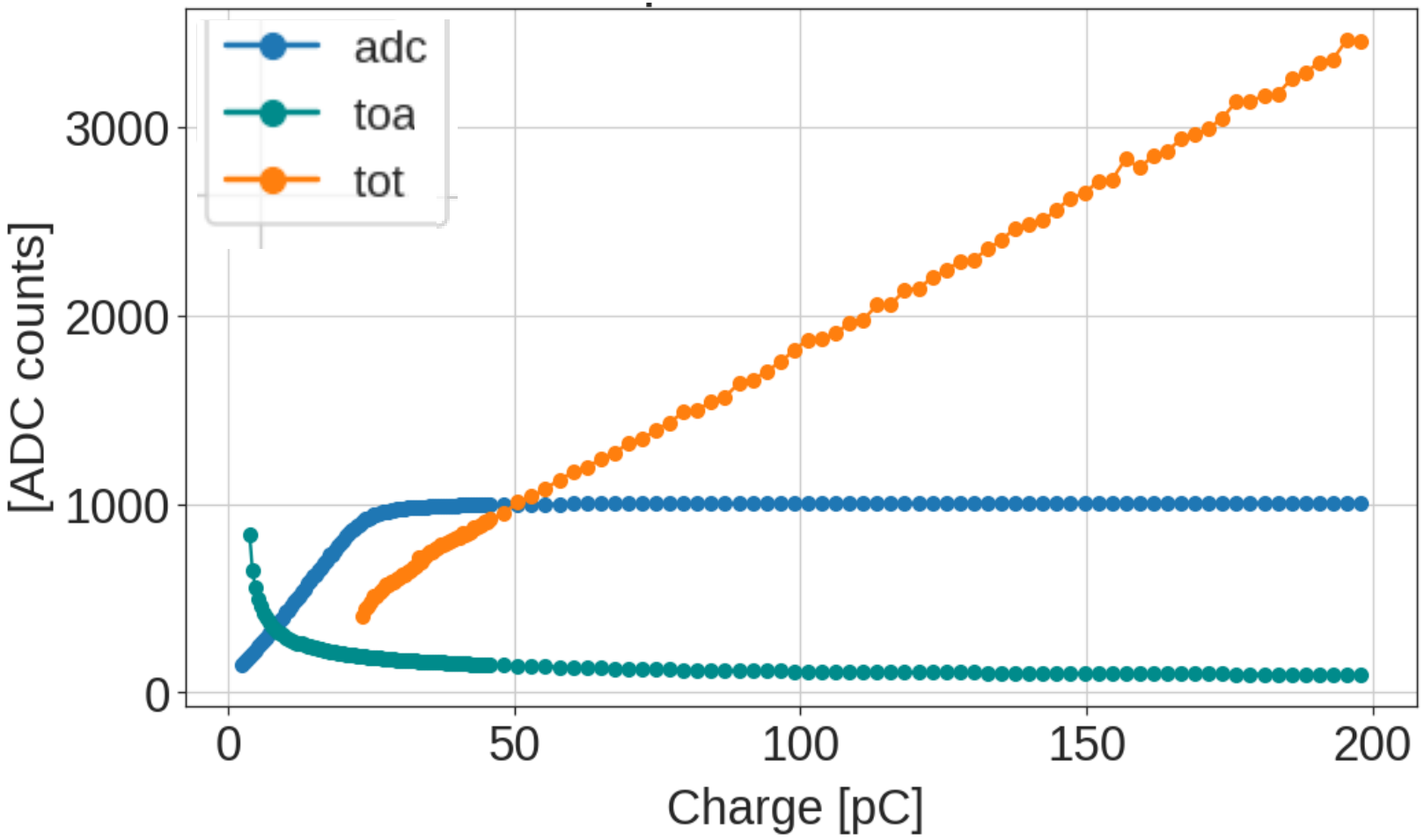
CC gain:
0.025 to 0.375
(step 0.025)



ADC and TOT readout

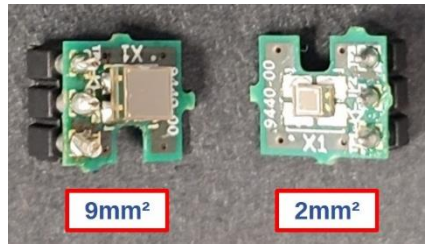
- 16bit dynamic range split in 10 bit ADC and 12 bit ToT
- Tests with 2 sizes of SiPM : 2mm² (120 pF) and 9 mm² (560 pF)



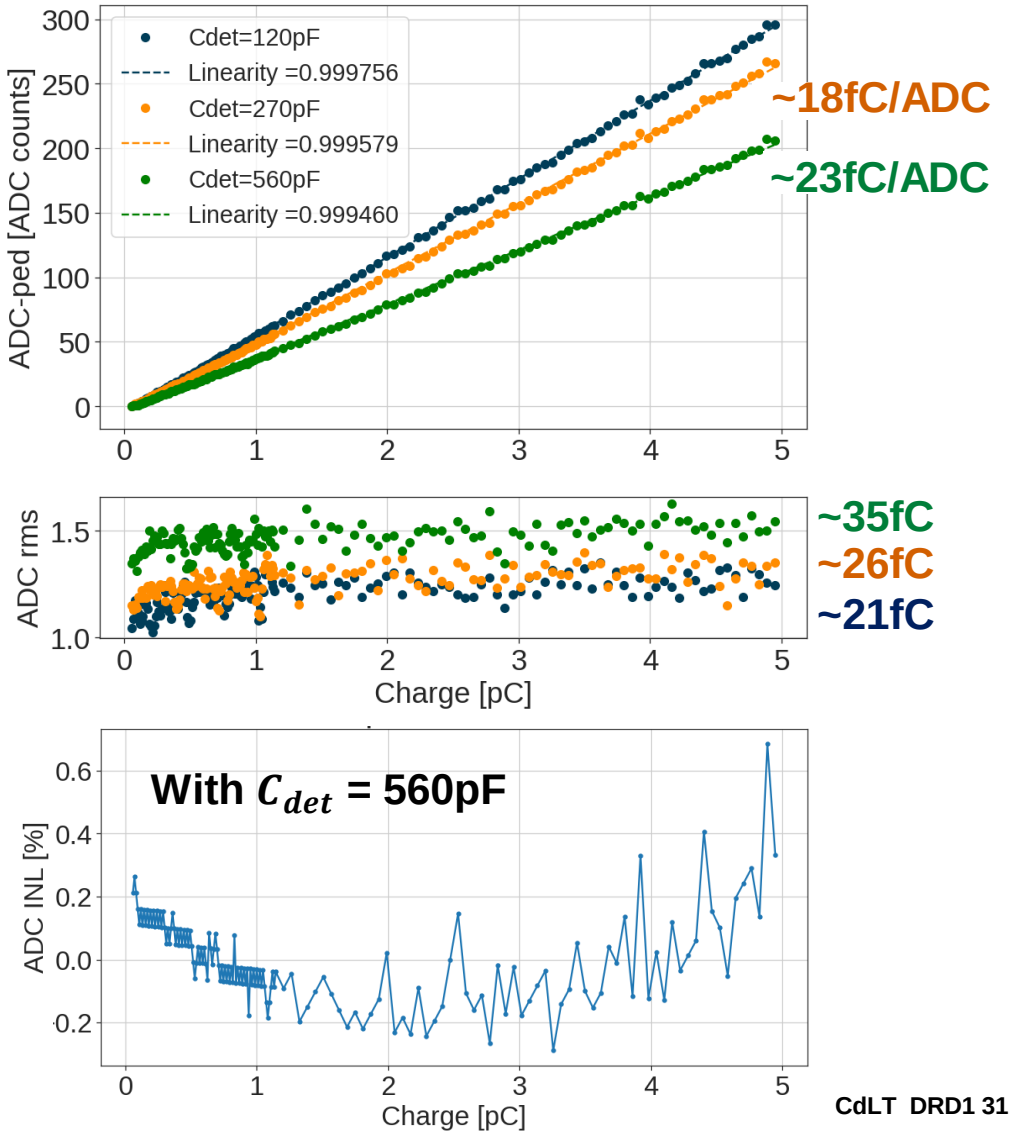


Physics mode : test pulse injection

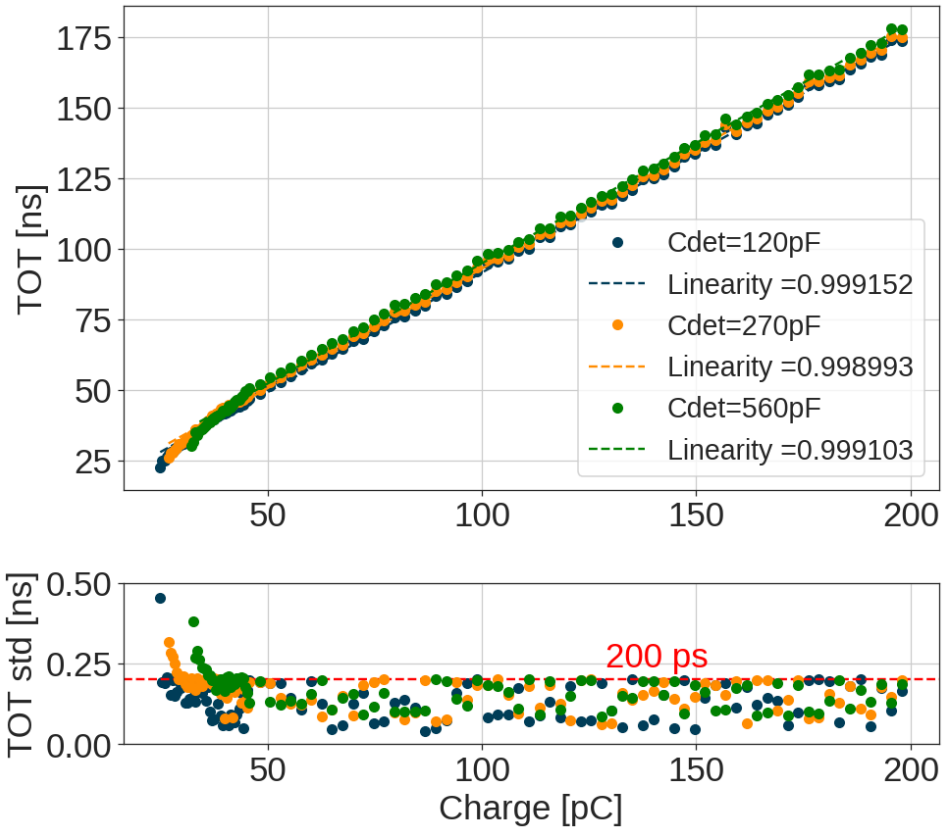
- ~ 60 fC minimum detectable charge efficiently, up to 320pC



Low range injection (ADC):



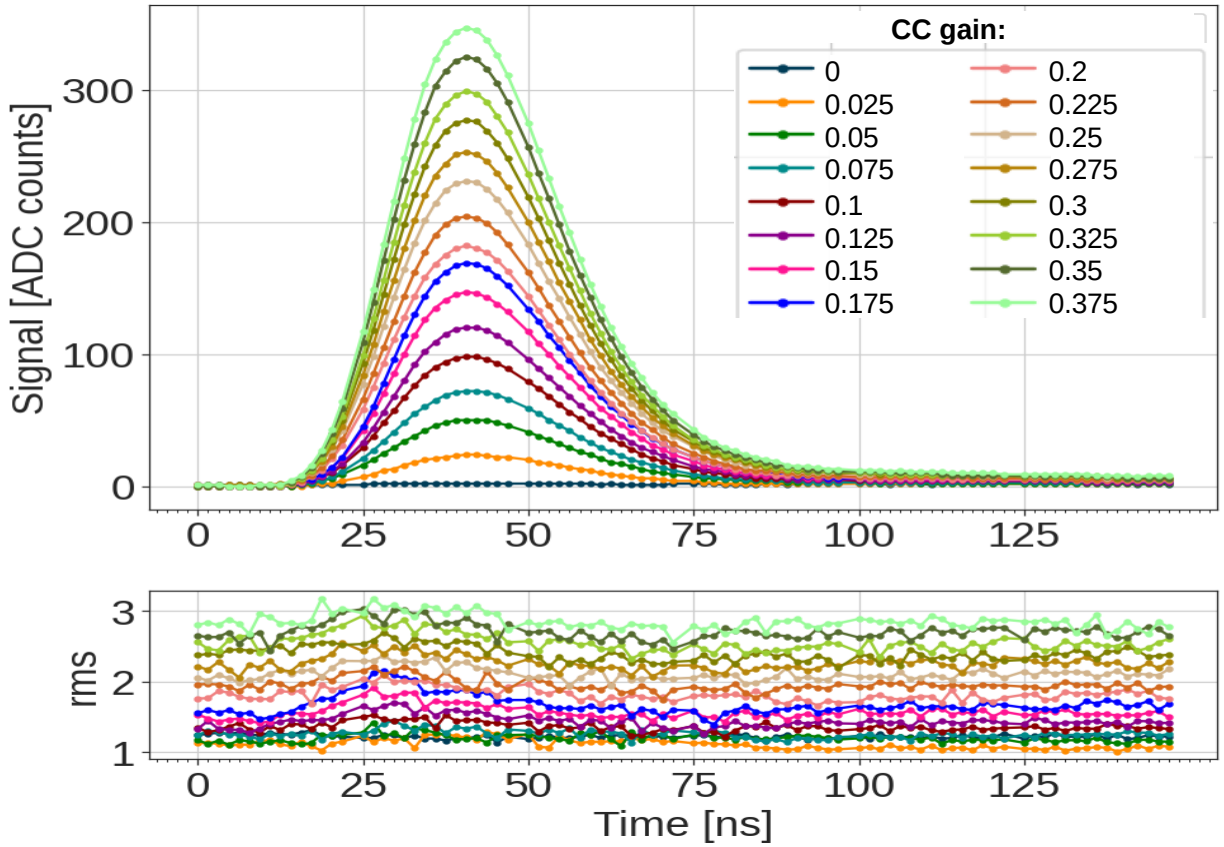
High range injection (TOT):



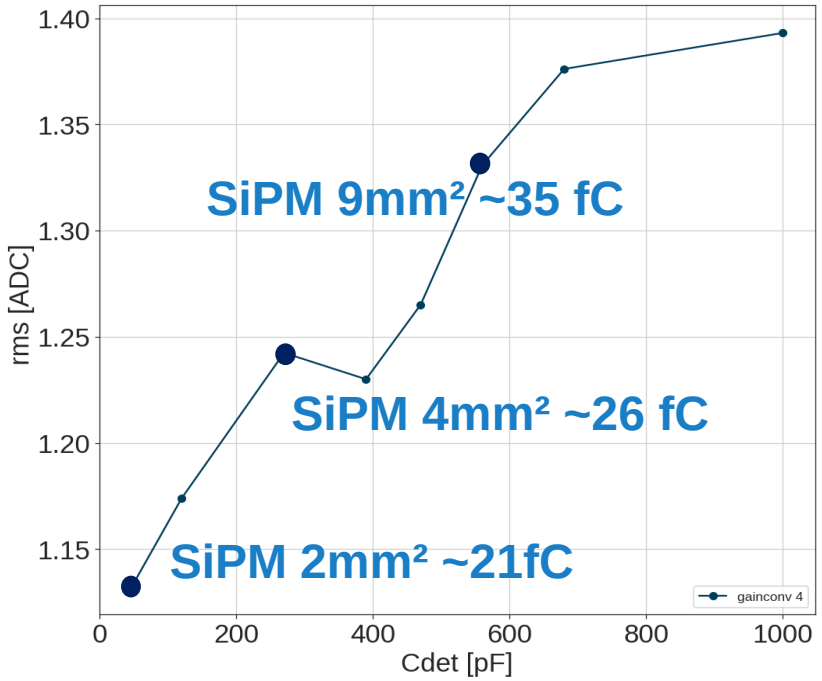
Physics mode : variable gain

- The CC gain has good performance in linearity.
- The increment in noise is due to the gain configuration and the detector capacitance of the SiPM.

CC gain scan:

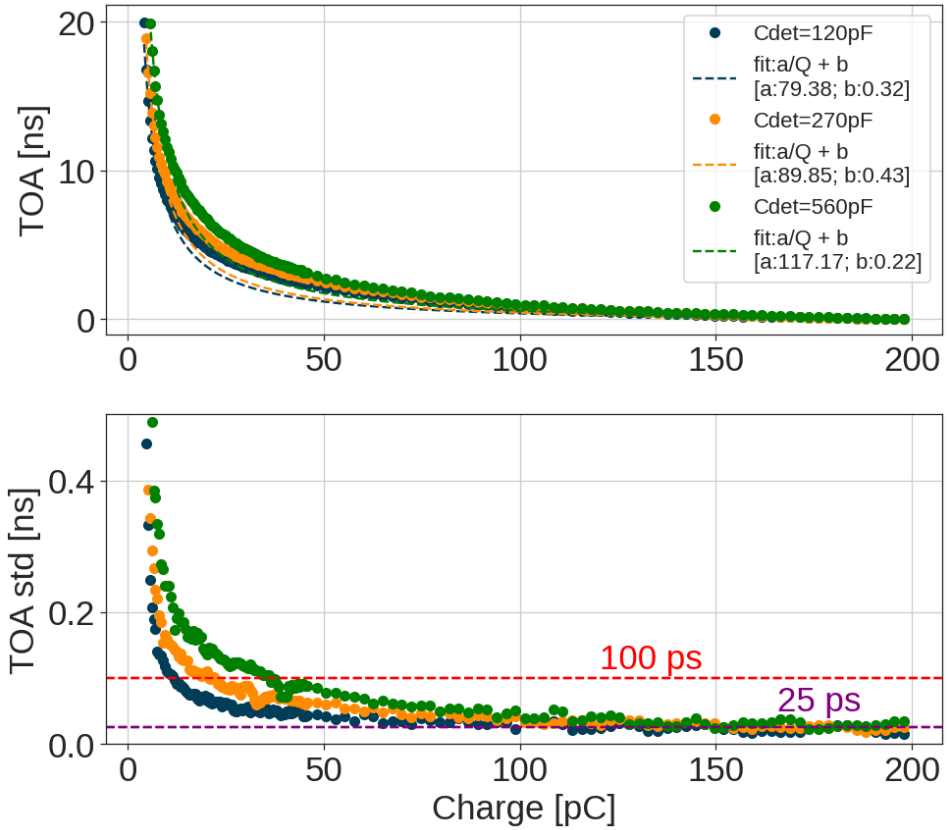


Noise vs C_{det}:



Physics mode : ToA

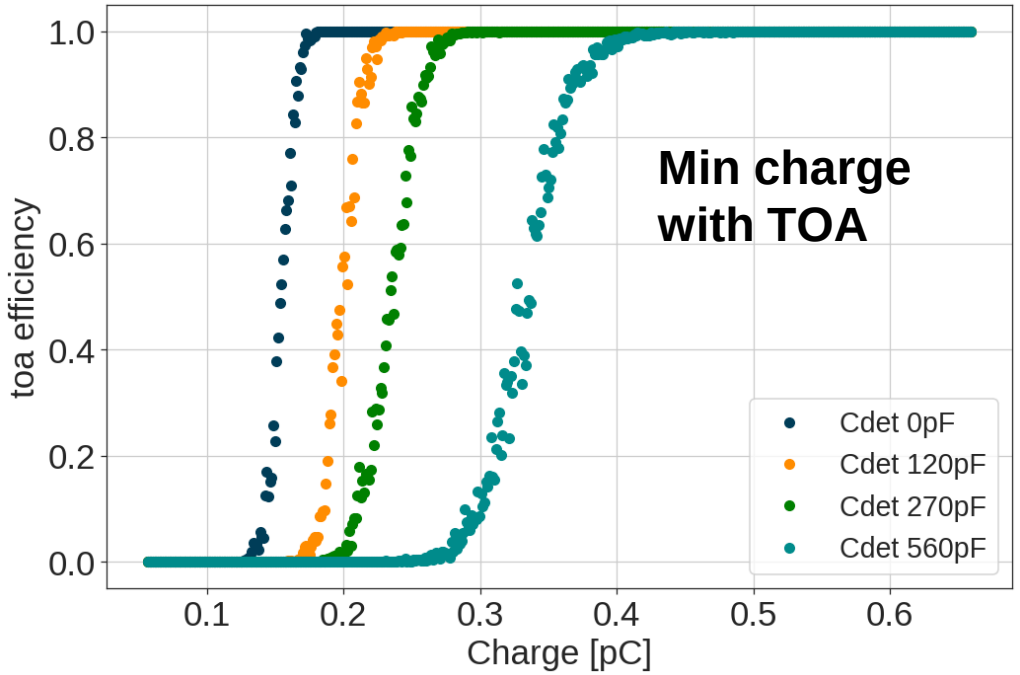
Time of Arrival (TOA) :



- The increase in noise due to larger C_{det} shifts the minimum charge associated with TOA data.
- The thresholds can be adjusted channel-wise for a uniform performance.

Effect of C_{det} on TOA:

- Larger C_{det} produce larger time walk due to the duration of the signal.
- Increasing C_{det} delayed the achievement of a 100ps resolution in charge injection.



Calibration mode: Single-photon-spectrum

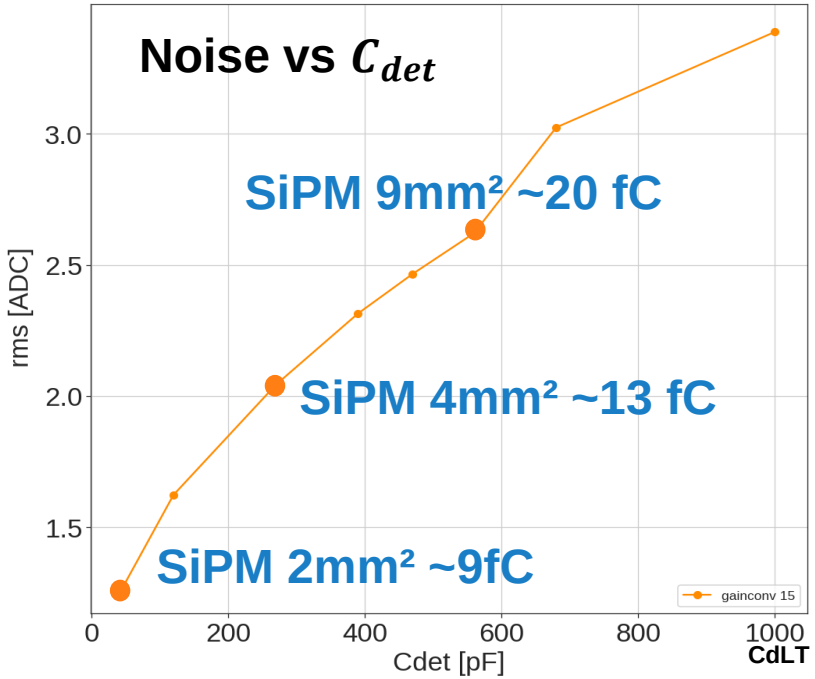
Also a different configuration of the ASIC is necessary to increase the SNR.

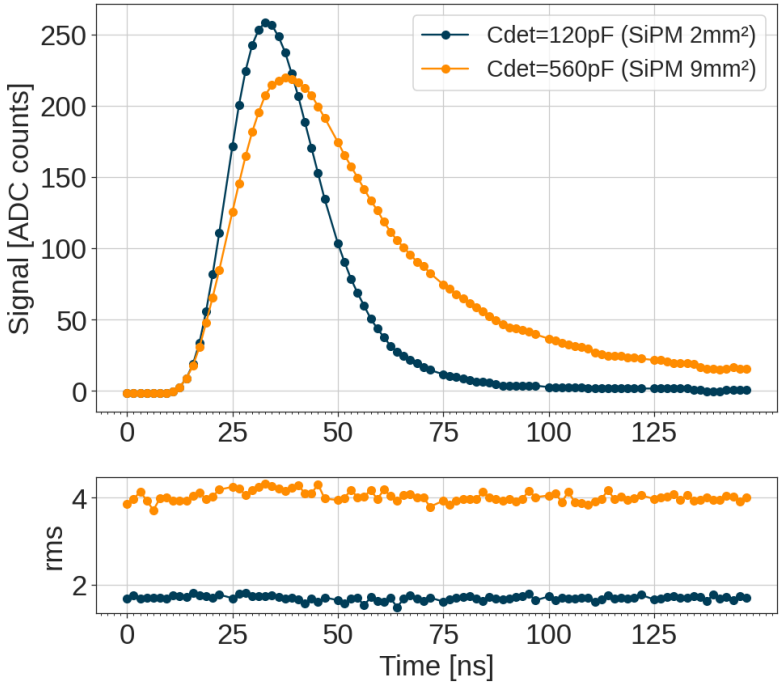
2mm²:

- CC gain attenuation = **0.3**
- $R_f = 16.6\,k\Omega$
- $C_{f\_total} = 600fF\ (C_f + C_{fcomp})$

9mm²:

- CC gain attenuation = **0.375**
- $R_f = 16.6\,k\Omega$
- $C_{f\_total} = \mathbf{300fF}$ (To make the pulse shorter)



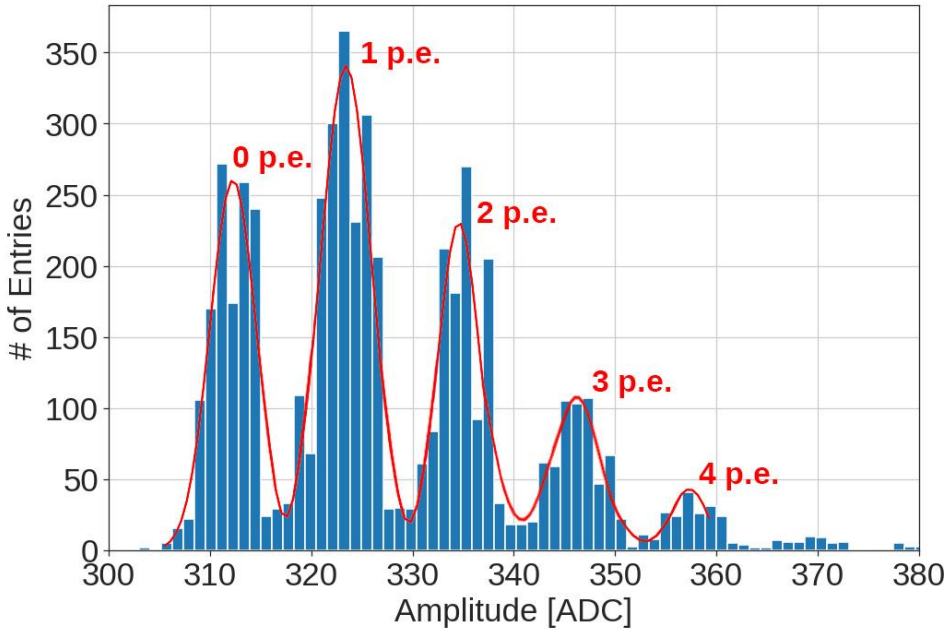


*Noise measured with the same configuration parameters for all C_{det}.

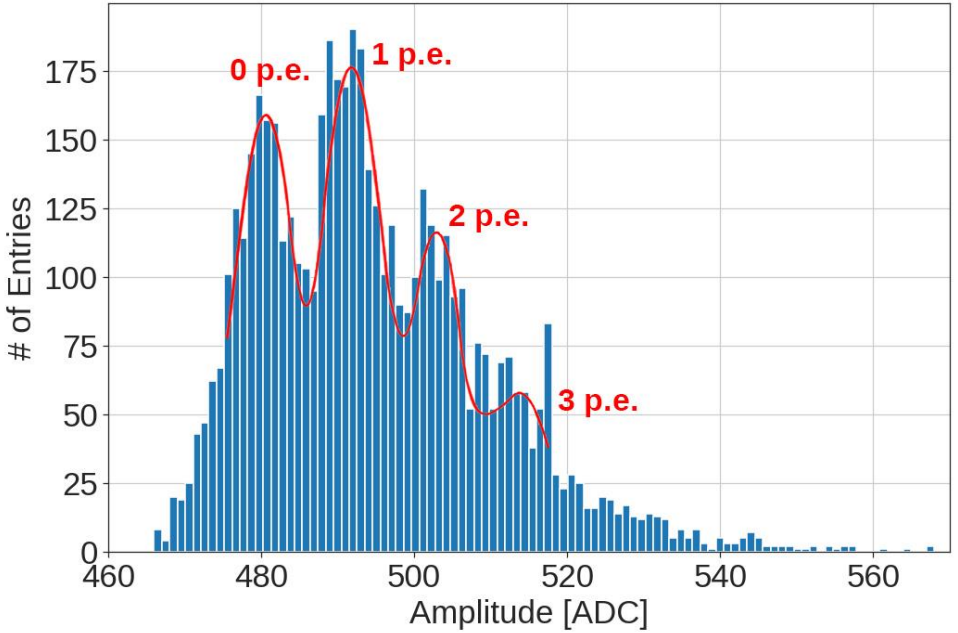
- The increment in noise is due to the detector capacitance of the SiPM.
- SNR can be improved with the gain configuration.

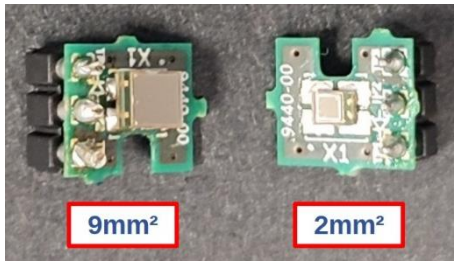
Calibration mode: Single-photon-spectrum

- **2mm²:**



- **9mm²:**



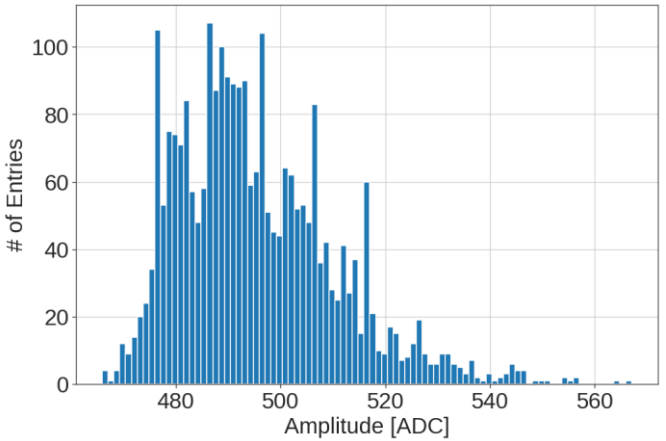


***Extra step for 9mm² SiPM calibration:**

The large C_{det} of the 9mm² SiPM produce an increment of DNL and make it harder to see the photon separation.

The DNL can be mitigated taking data with different pedestal levels using the ASIC to move the pedestals (*Trim_inv* parameter). SPS is clearer after aligning the data.

Without DNL correction:



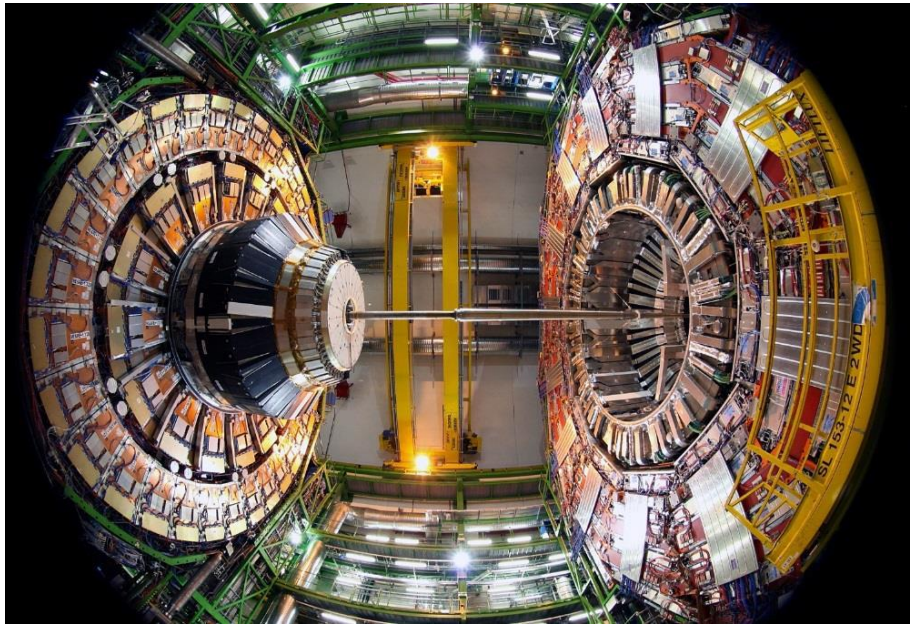
From HL-LHC to the HKROC ASIC

HGCROC for the endcap calorimeter – Phase II

6M of Silicon channels
(+ 240k of SiPM)

Radhard (200 Mrad)
Low Power (15 mW per chn)
Precise timing (25 ps)

Total of 150k ASICs needed
Pre-prod this year
Project started in **2017**



HKROC was developed in
6 months

Same ASIC structure (floorplan)
Same ADC and TDC
Same readout

New preamplifier
New digital processing

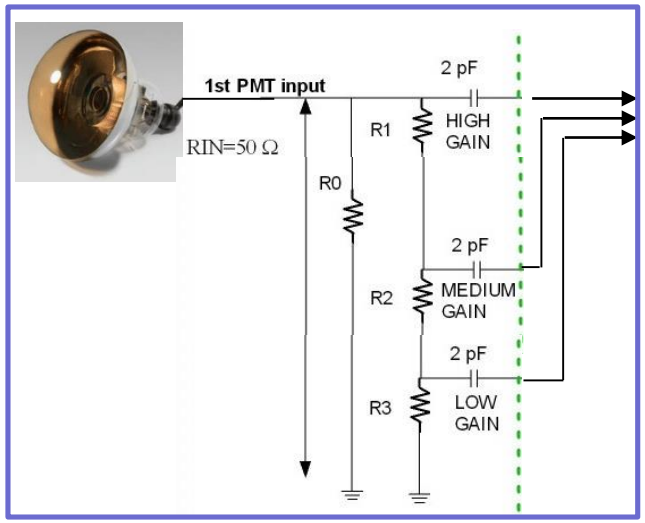
HEP trend => imaging calorimetry

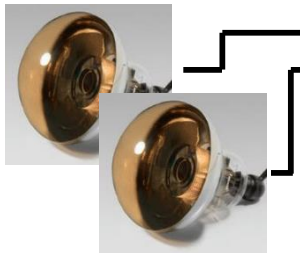
- ❑ High number of channels
- ❑ Charge and precise timing (<50 ps)
- ❑ Low power + System-On-Chip

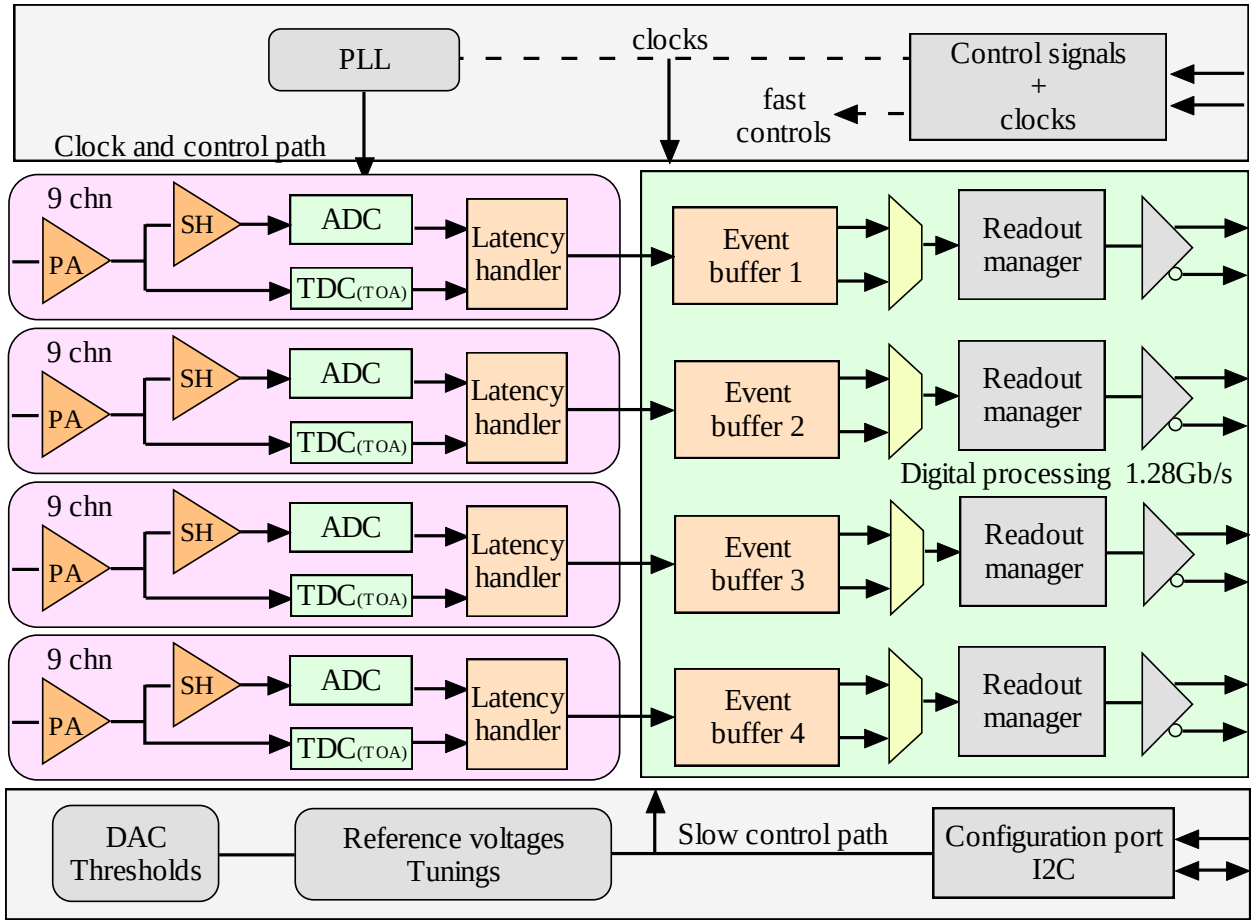
Based on HGCROC, originally aimed at HK, HKROC-based electronics can provide a versatile, low-power and fully integrated solution for large neutrino experiments

HKROC main features

- HKROC is 36 channels: 12 PMTs with High, Medium and Low gain
  - Or 36 PMTs with one gain



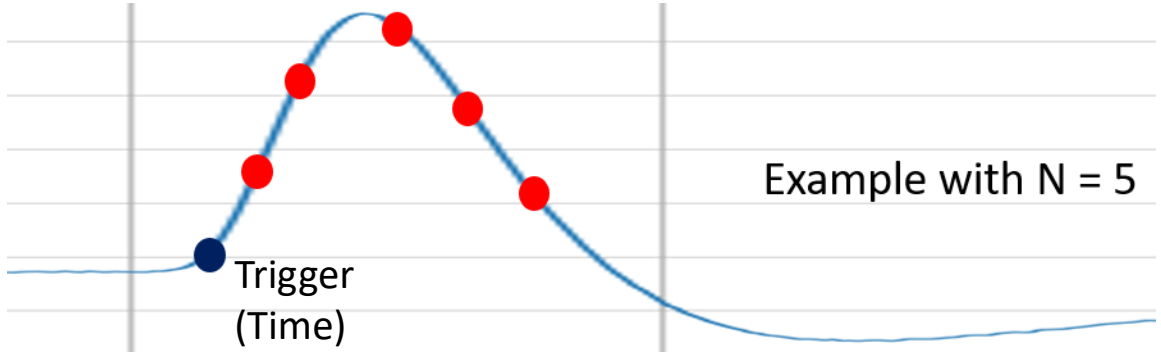




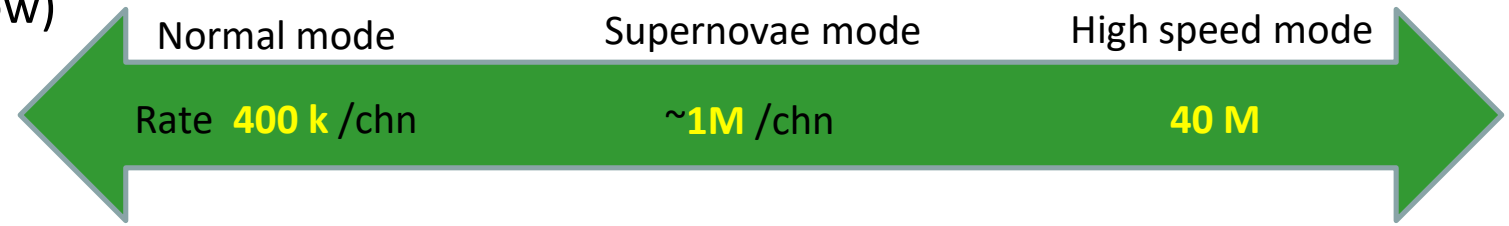
- ASIC in TSMC 130 nm node
- Low power: 10 mW per channel
- Large charge measurement with 3 gains (up to 2500 pC)
- Integrated timing measurements (25 ps binning)
- Readout with high speed links (1,28 Gb/s)
- HKROC is a waveform digitizer with auto-trigger

HKROC: waveform digitizer with auto-trigger

- HKROC is waveform digitizer working @ 40 MHz
  - Number of charge sampling points from 1 to 7
  - Fast channel for precise timing (25 ps binning)
  - Charge reconstruction algorithm in FPGA
    - 5% resources of a modern XILINX FPGA



- When using 3 gains / PMT (high, medium, low)
  - Hit rate capability up to 400 kHz / PMT
  - Increased up up to 1 MHz by focusing on high gain
    - Dynamic selectable by the user
  - Average values only limited by readout speed



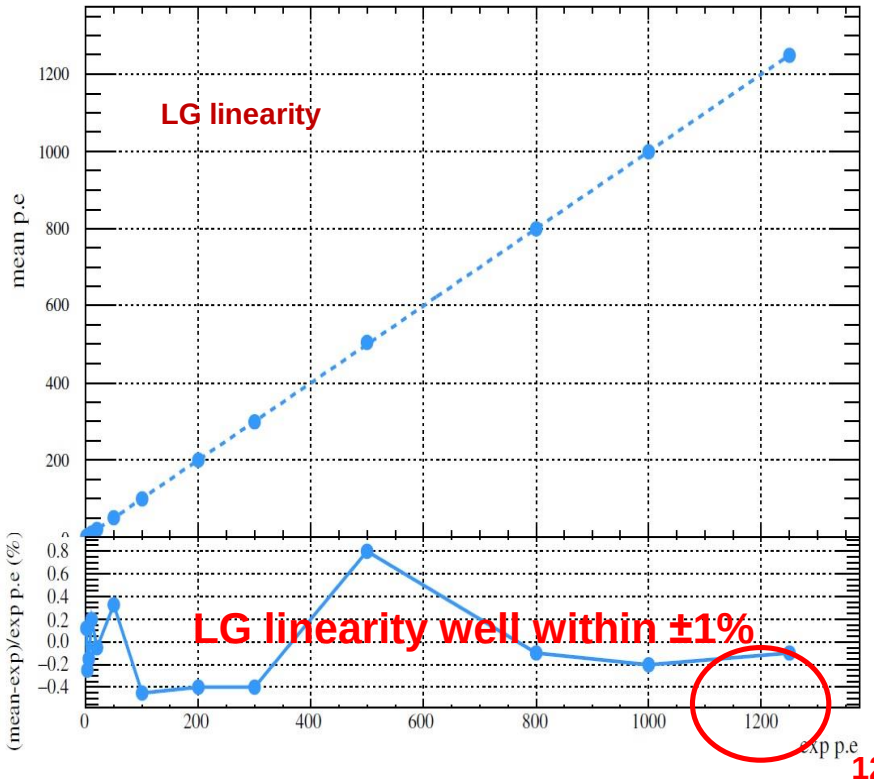
HKROC can accept consecutive events (separated by ~30 ns)

Internal HKROC memory writing is without dead time

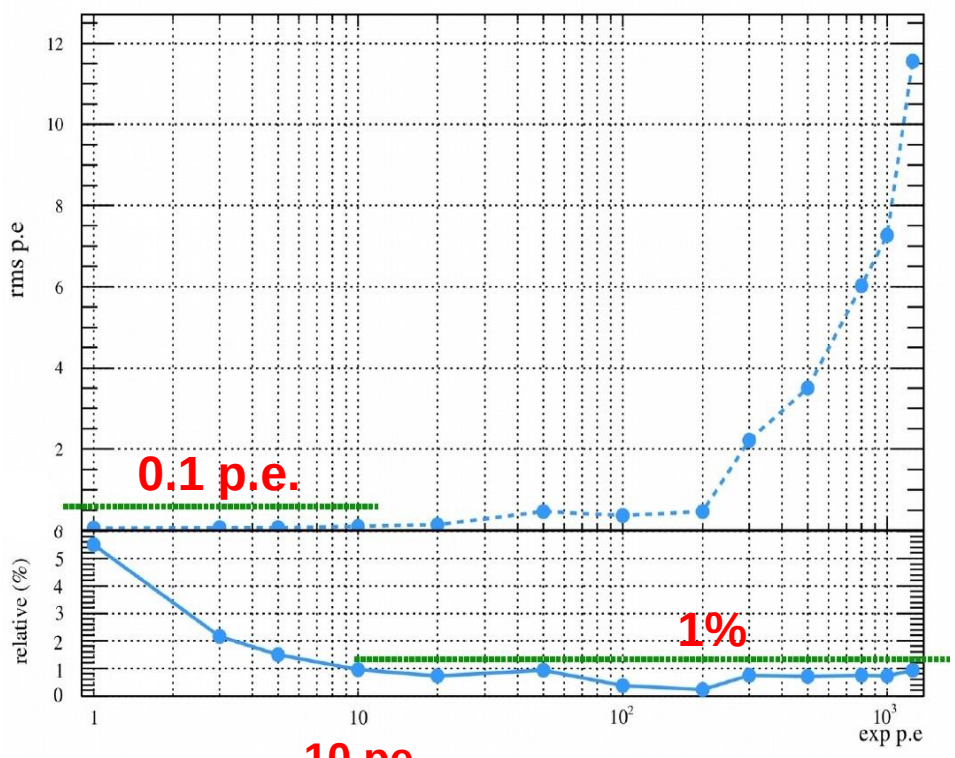
Readout speed is only limited by serial link bandwidth (average values above)

HKROC0 Charge measurements

The **whole** acquisition **chain** is tested:
The signal is **amplified**, **auto-triggered** and **converted** by the internal **ADC**.



1250 p.e. = 2500 pC



10 pe

1250 pe

HG, MG and LG tested!!

Charge linearity < **±1%** from 1 to **1250 p.e. (2500 pC)**

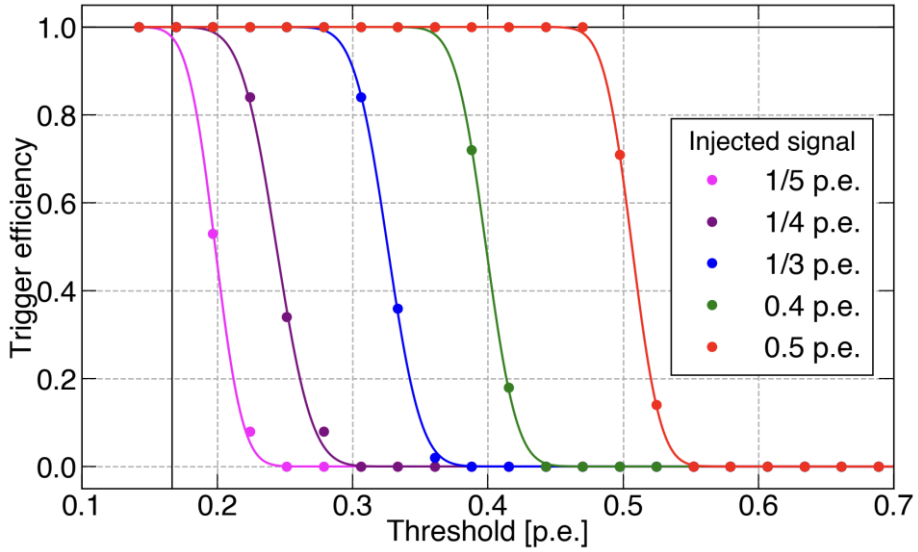
Charge resolution :

< **0.1 p.e (200 fC)** at ≤ 10 p.e

< 1 % otherwise

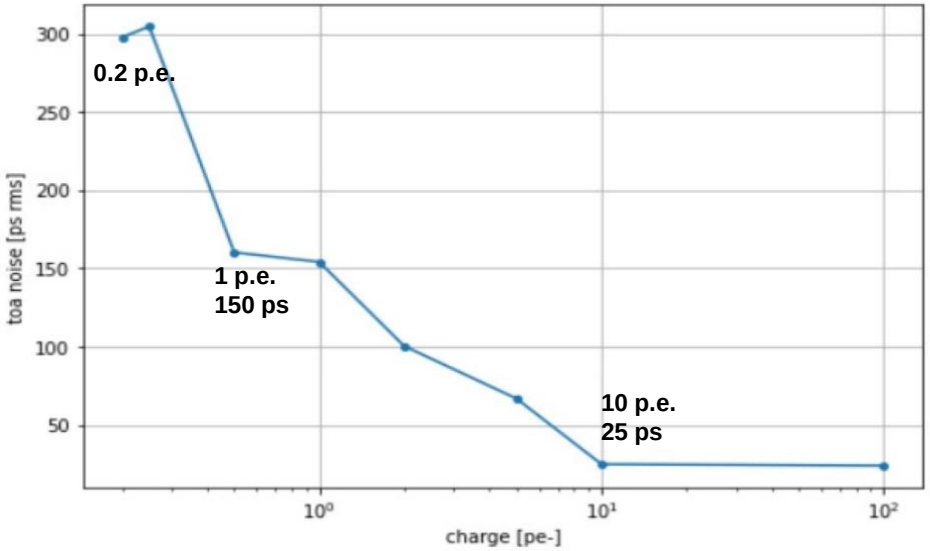
HKROC0 Trigger measurements

The HyperK specifications require the trigger **threshold** to be set at **1/6 p.e (330 fC)**



- **Hit efficiency : 90 % for 1/5 p.e events (400fC)**

  ~100 % if ≥ 1/4 p.e
- Extracted **threshold** value corresponding at **1/6 p.e**
- **Very low noise** : < 1 Hz **(0 noise hit in 10s @ 1/6 of p.e.)**



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

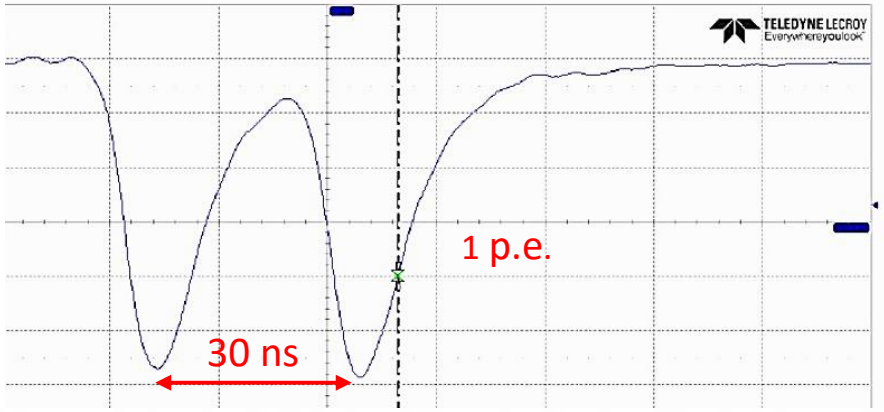
TDC resolution :

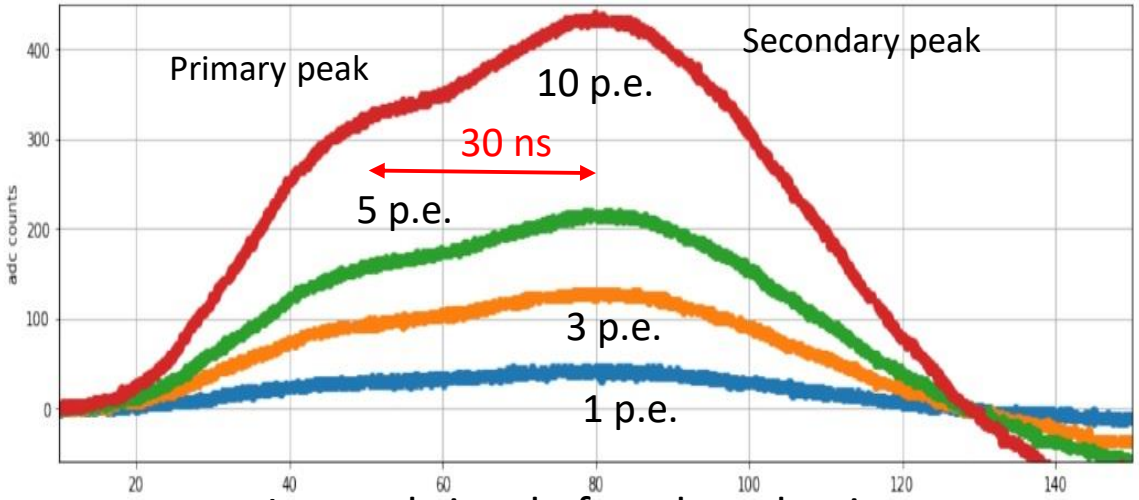
150 ps rms @ 1 p.e [300 ps required]

≤ 25 ps rms @ 10 p.e [200 ps required]

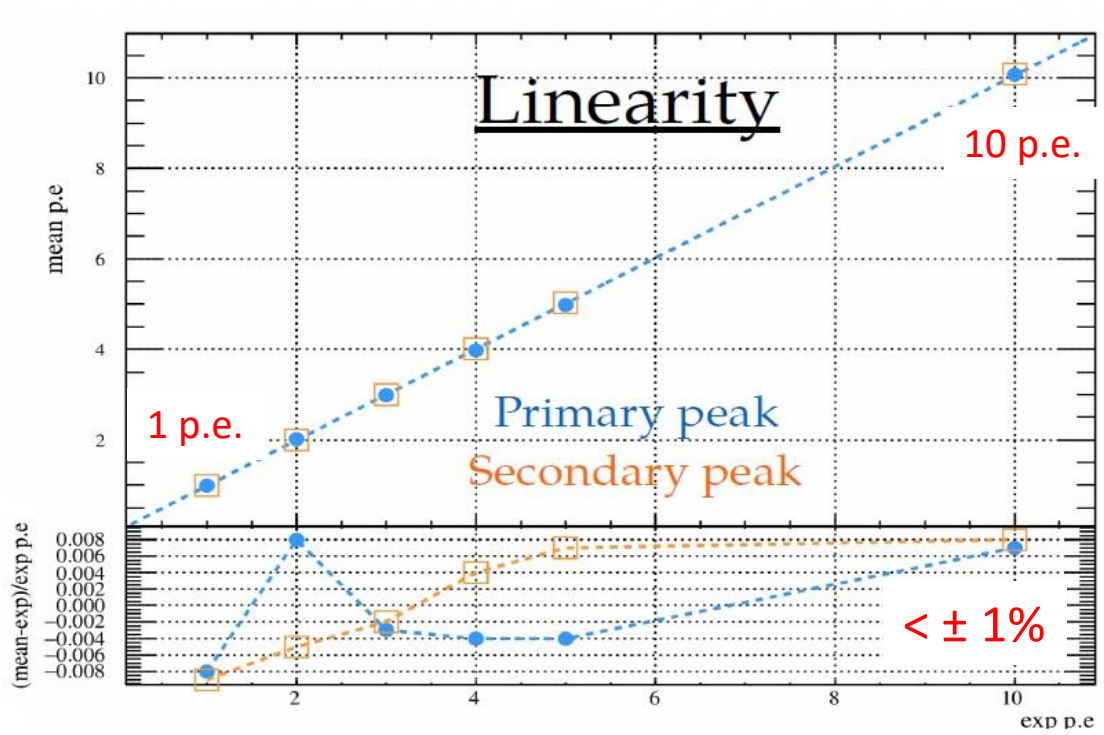
Main experimental results with HKROC0 - Pile-up

- Measurement with 2 events separated by ~30 ns (full chain: analog, digital and reconstruction)
  - Signals auto-triggered (internal prommagble threshold)





Internal signal after slow shaping



Charge reconstruction algorithm of the two peaks

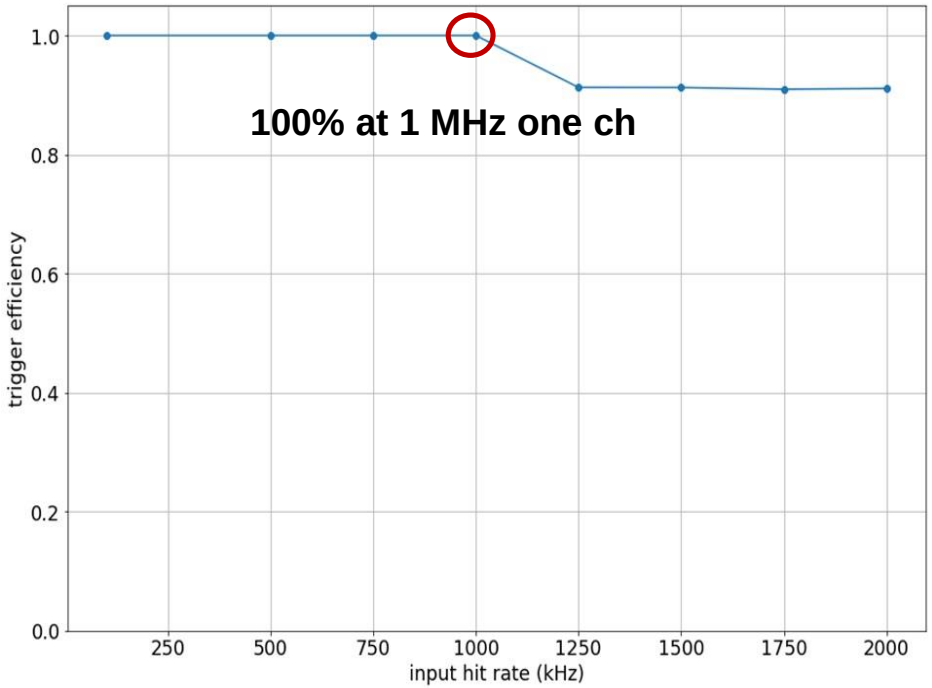
Good linearity of reconstructed pile-up events

We can reconstruct both peaks properly !

HKROC Trigger rate measurements

FAST hit rate (~ 1MHz) required for close Supernova signals (~ 1 p.e.)

Normal mode:

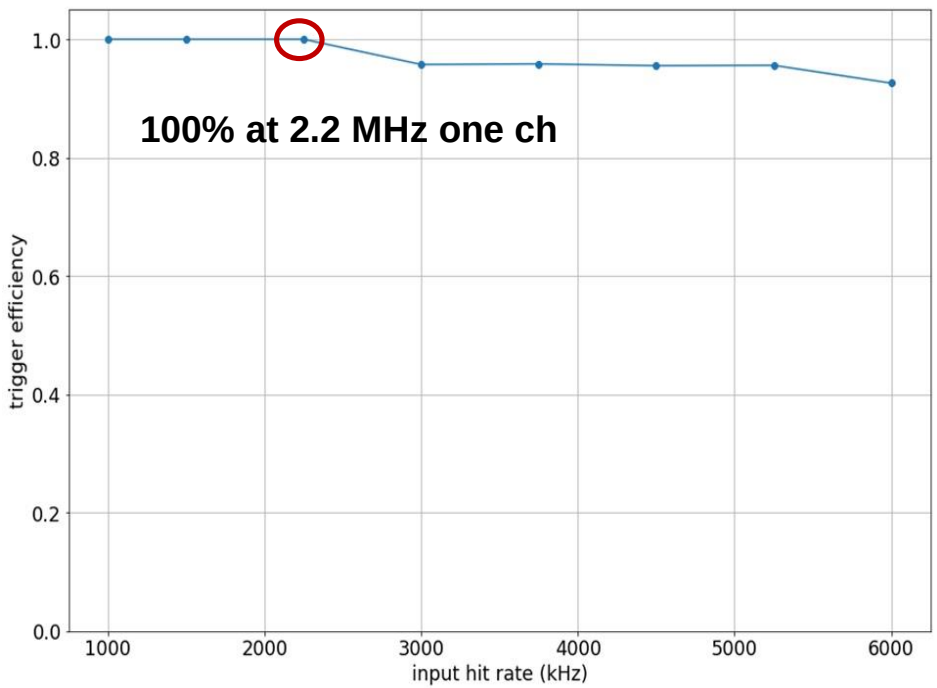


1 PMT channel →

3 HKROC channels tested in Normal Mode:

100% Trigger efficiency up to **415 kHz 3 chs**

Super Nova mode



1 PMT channel →

3 HKROC channels tested in SuperNova Mode:

100% Trigger efficiency up to **950 kHz 3 chs**

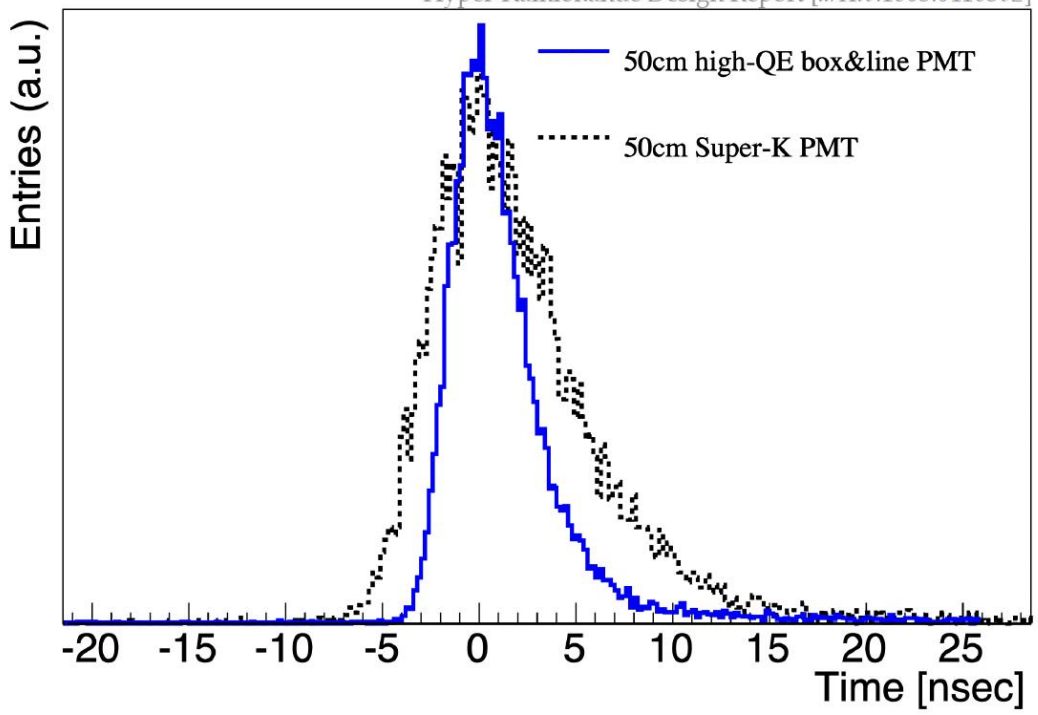
The HKROC saturation naturally appears when the chip internal memory is full. The chip has one independent memory for each read-out link at 1.28 Gb/s, which gather 3 PMTs.

PMT measurements

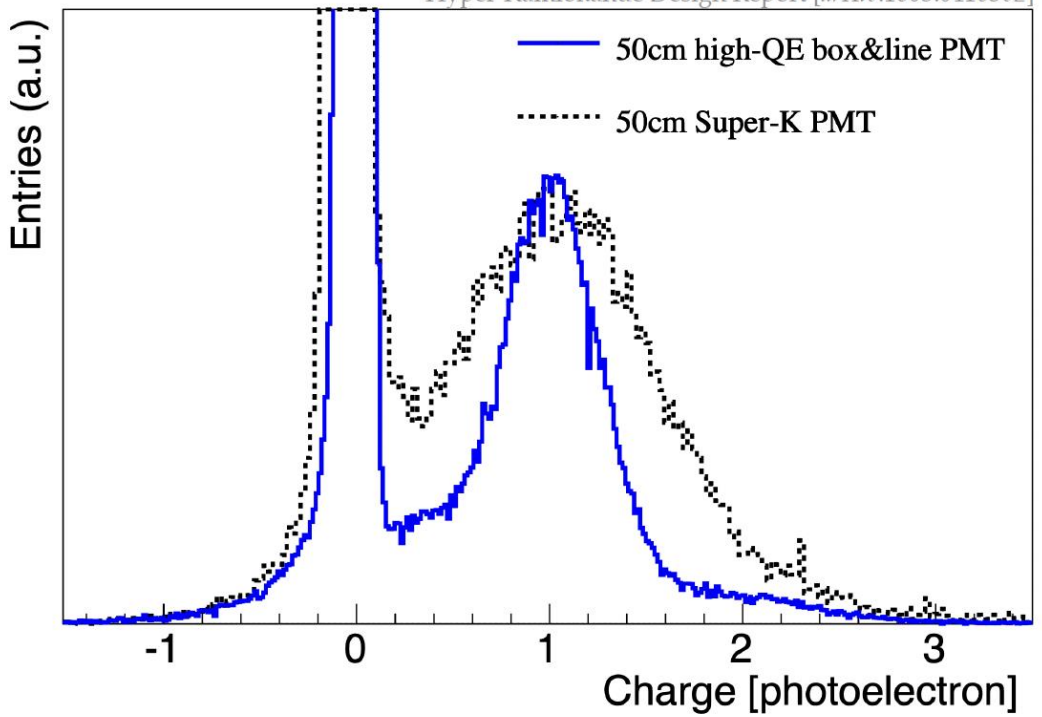
Trigger time distribution for events having charge ≤ 1.5 p.e : FWHM of **2.6 ns**

- **Excellent agreement with the 2.8 ns found for the PMT only**
- Digitizer does not degrade the PMT time resolution !

Time resolution
(TTS for 1 p.e.)
≈ 6.7 ns (σ ≈ 3.4 ns) → ≈ 2.6 ns (σ ≈ 1.3 ns)
Hyper-Kamiokande Design Report [*arXiv:1805.04163v2*]

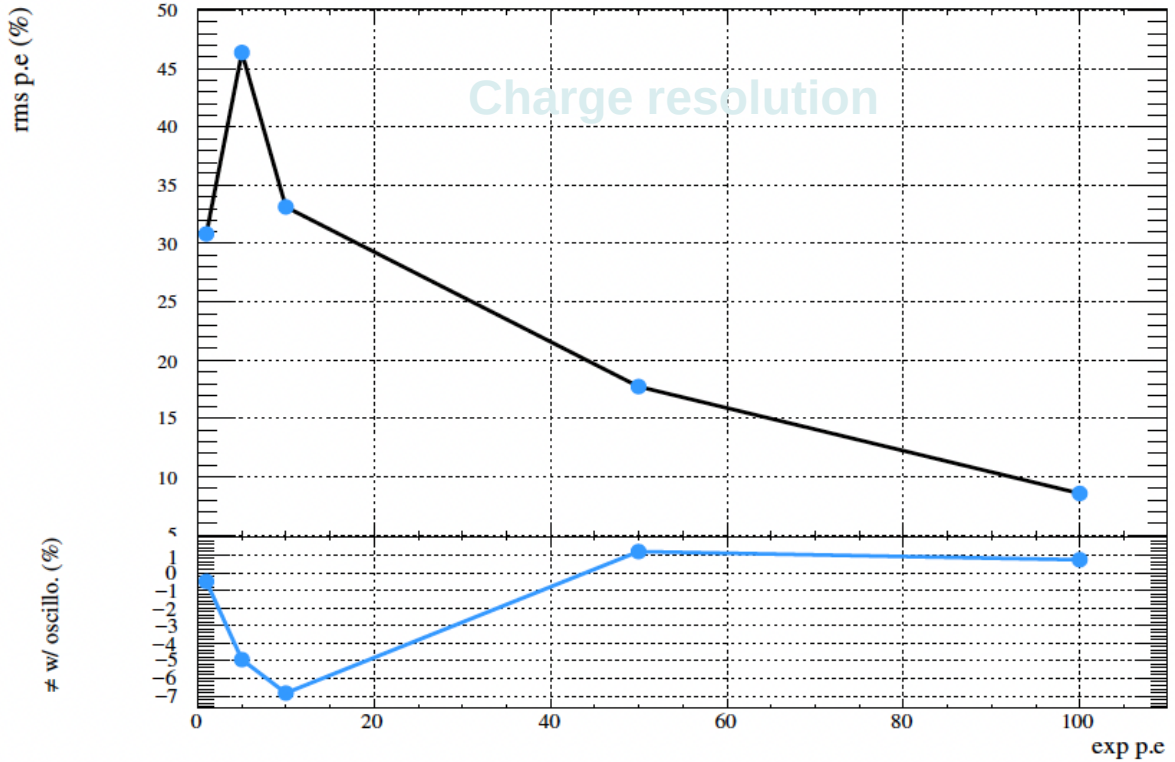


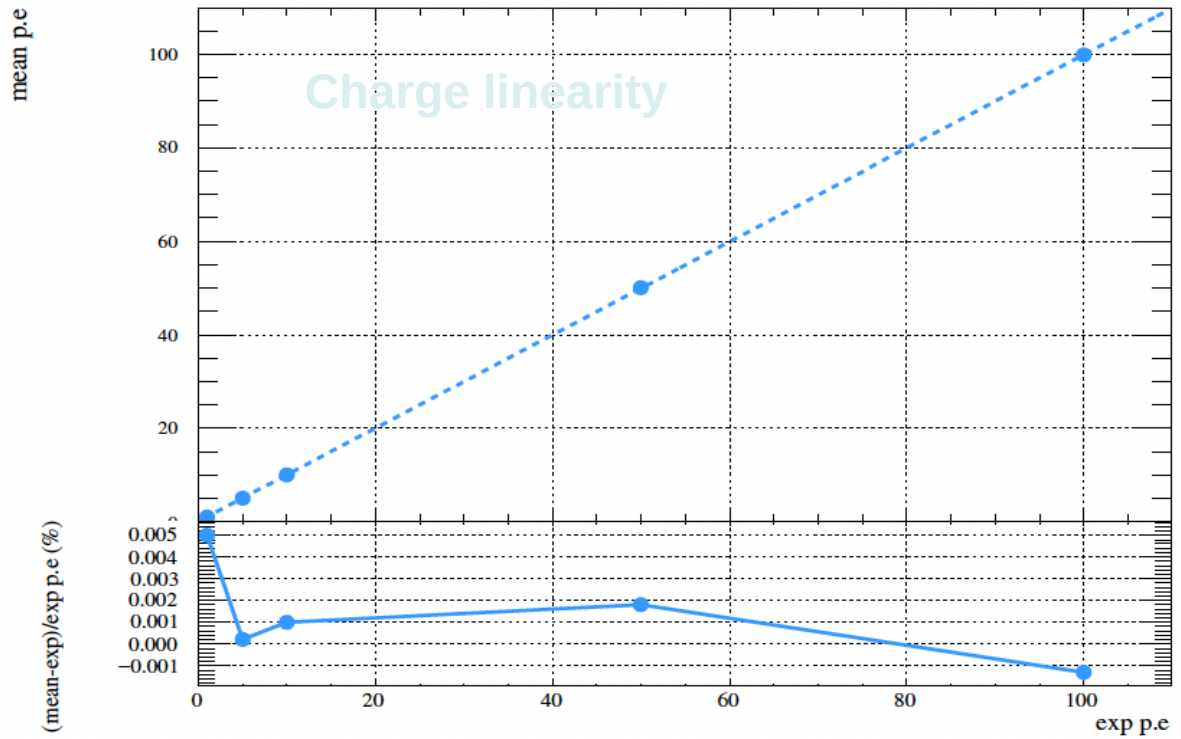
Charge resolution
≈ 60% → ≈ 31%
Hyper-Kamiokande Design Report [*arXiv:1805.04163v2*]



PMT measurements

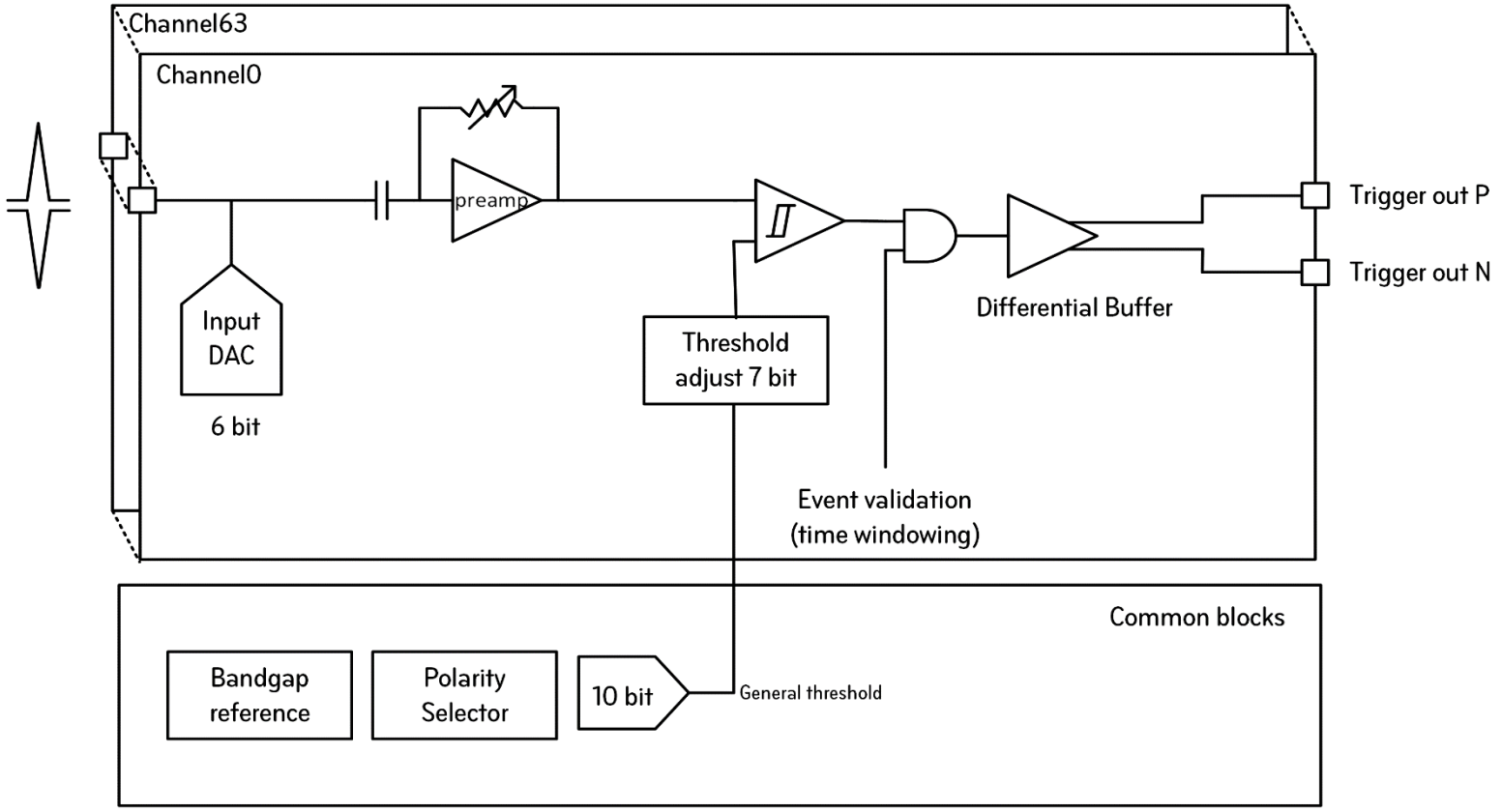
- Charge linearity and resolution
  - Similar with PMT as with pulse generator





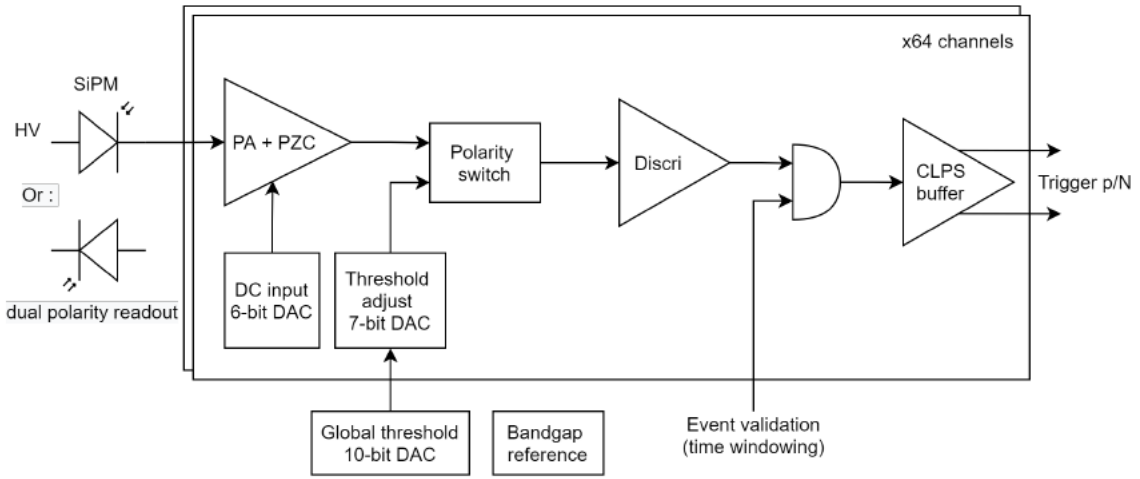
Introducing LIROC : SiPM read-out for Lidar

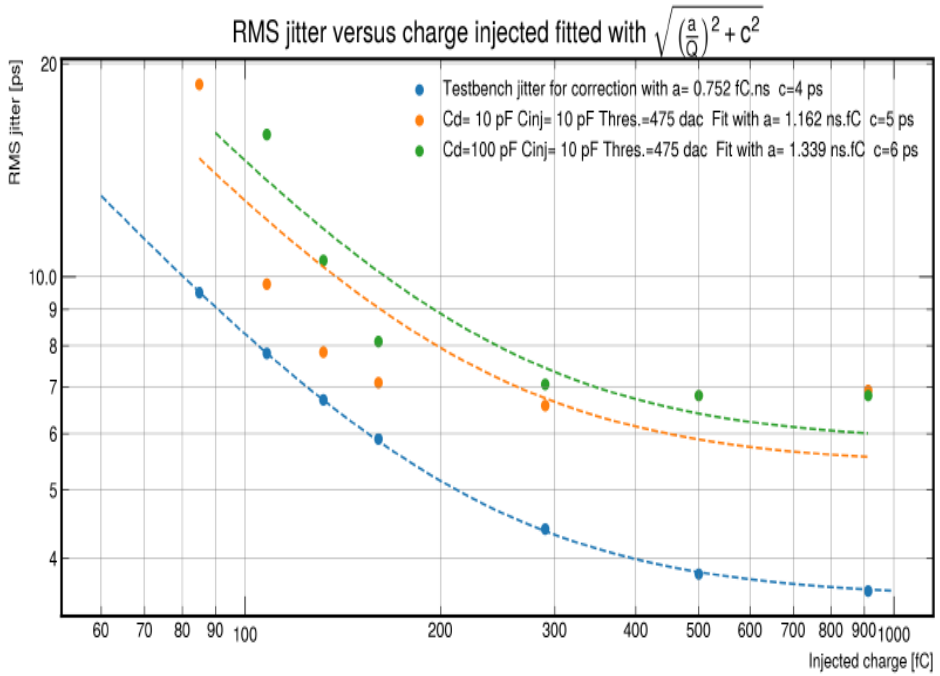
- Evolution of PETIROC (used in CMS RPCs)
- Can connect directly to CERN picoTDC

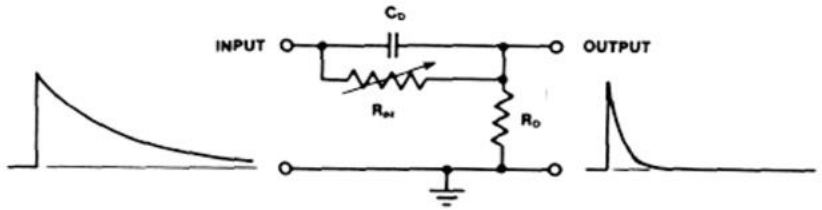


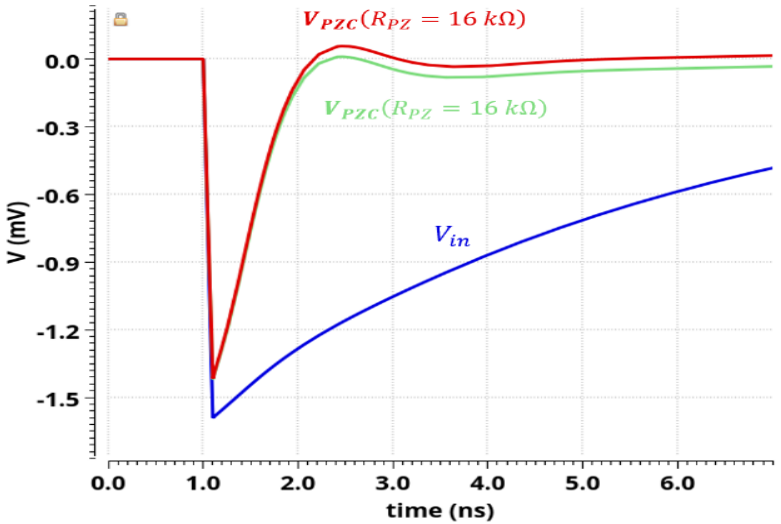
Collaborative design between Weeroc & Omega laboratory that have received Funding from ATTRACT EU H2020 Research & Innovation Program

- LIDAR readout : short double pulse separation
  - 64 channels high speed PA + discri
  - Trigger on 1/3 photoelectron
  - Pole-zero cancellation for 3 ns double pulse separation
  - CLPS discriminator output : couples to picoTDC
  - 3 mW/ch CMOS 130nm









Conclusion

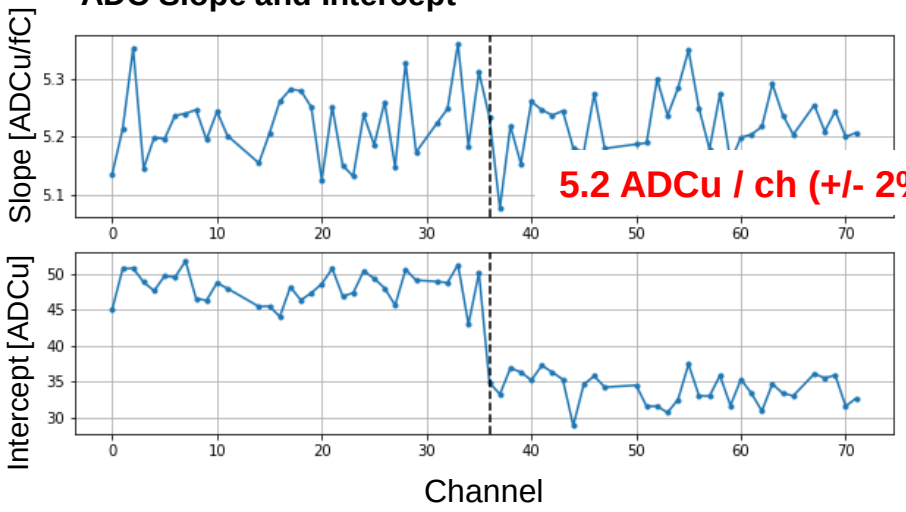
- New generation chips include ADCs and TDCs
- Large dynamic range (15bits)
- Time measurements down to 20 ps
- Low power < 10 mW/ch
- Auto-trigger and streamed data flow
- Radiation tolerant to 100s of Mrad and SEU immune

- H2GCROC, HKROC, LIROC fabricated, used, available !

backup

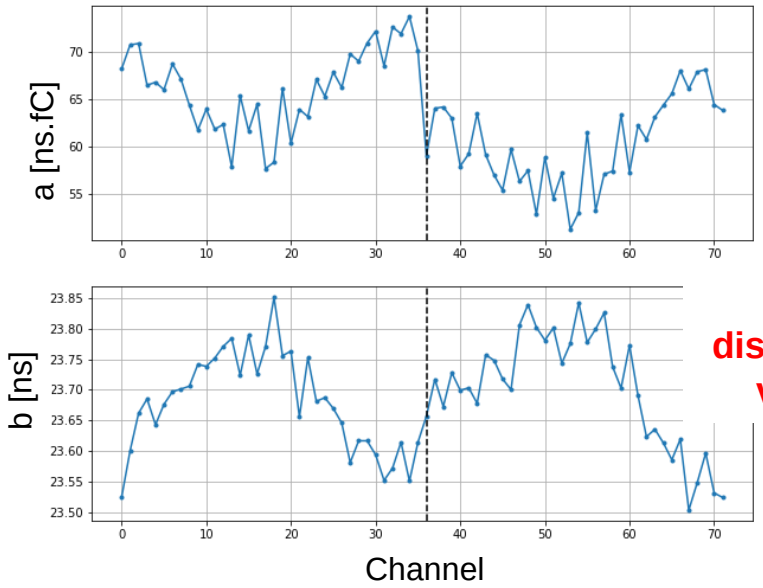
HGCROC3: Charge and time uniformity

ADC Slope and Intercept



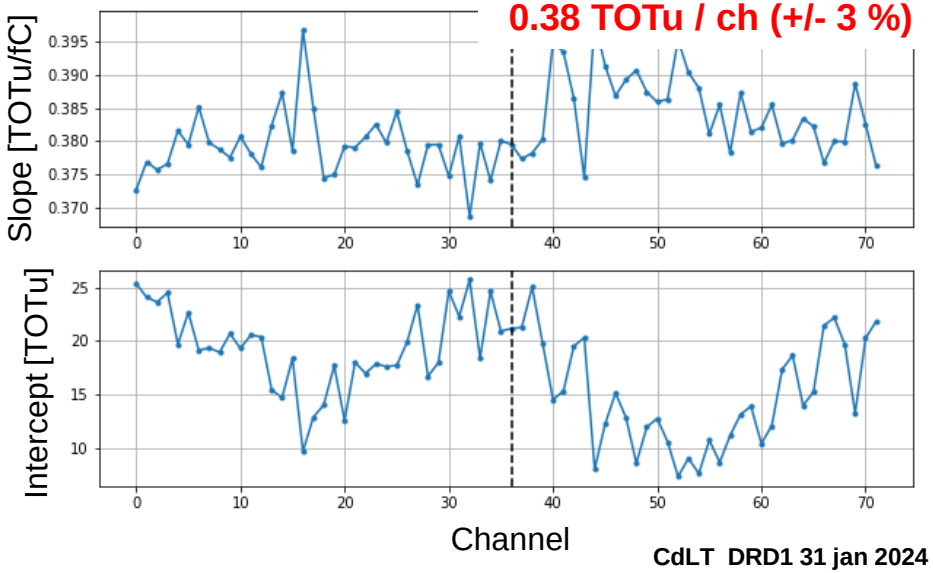
5.2 ADCu / ch (+/- 2%)

TOA Time Walk. a & b parameters of the $a/Q + b$ fit



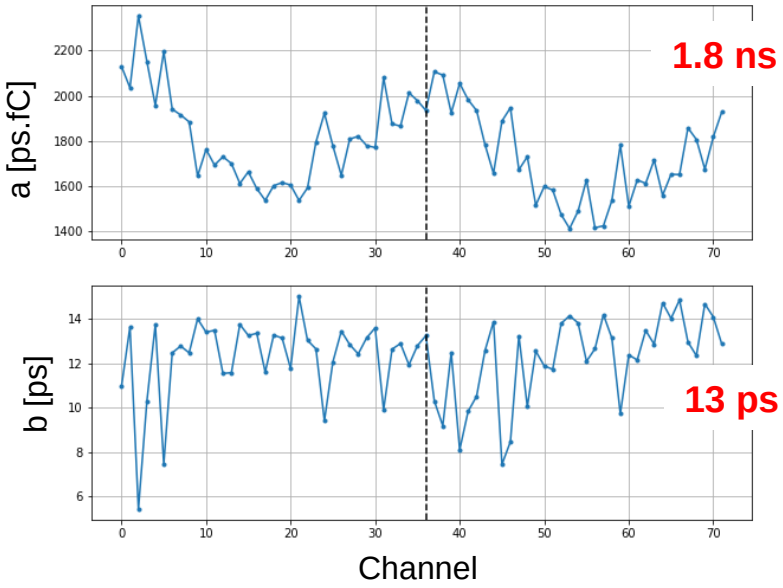
Clock distribution visible

TOT Slope and Intercept



0.38 TOTu / ch (+/- 3 %)

TOA Jitter. a & b parameters of the $\sqrt{(a/Q)^2+b^2}$ fit



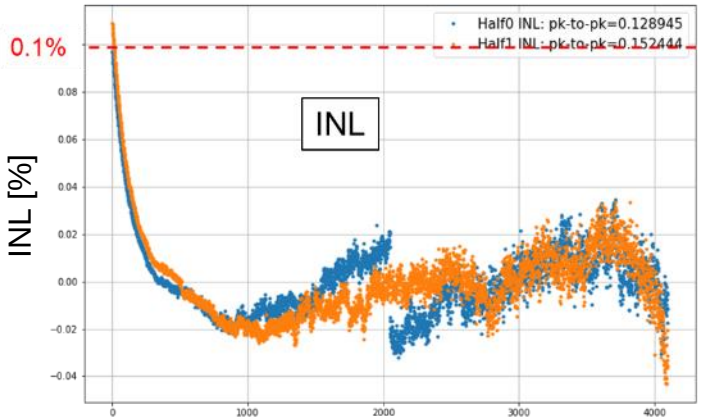
1.8 ns / Q(fC)

13 ps rms

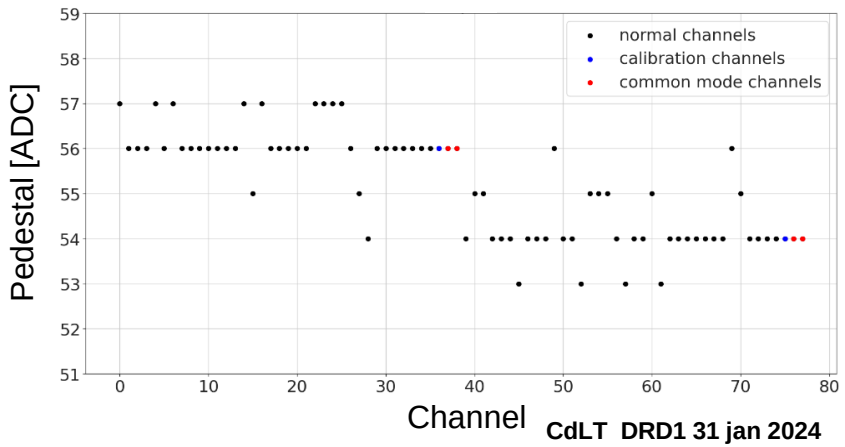
DACs & trimming

- **12 bits calibration DAC**
  - ~ 2-3 mV offset due to leakage current (1 – 1.5 fC)
  - < 0.1 % linearity, temperature sensitivity: 60 ppm/K, stable after 350 Mrad
- **Four 10-bit DACs** to set pedestals, TOA & TOT thresholds + **3 channel-wise 6-bit DACs** to reduce dispersion per channel
  - Pedestals: ~ 1 ADC counts dispersion after trimming
  - TOA & TOT thresholds: 1-2 DAC counts after trimming
- 8-bit input DAC to compensate for the **leakage current** up to **50 µA**
  - Additional noise as expected from simulation

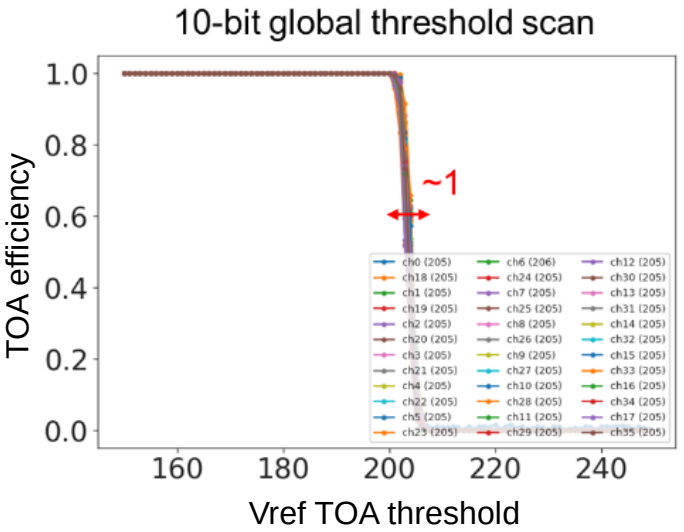
Calibration DAC:



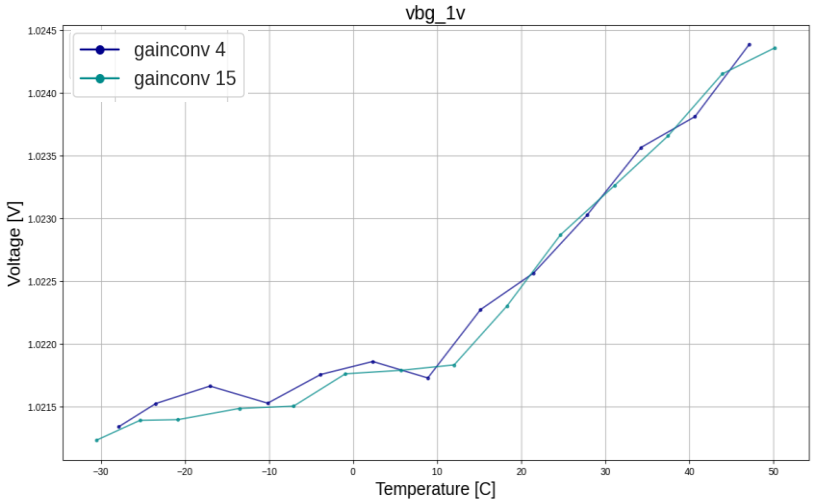
Trimmed pedestals:



Trimmed TOA thresholds:



H2GCROC3: Temperature



Bandgap (Two slopes):

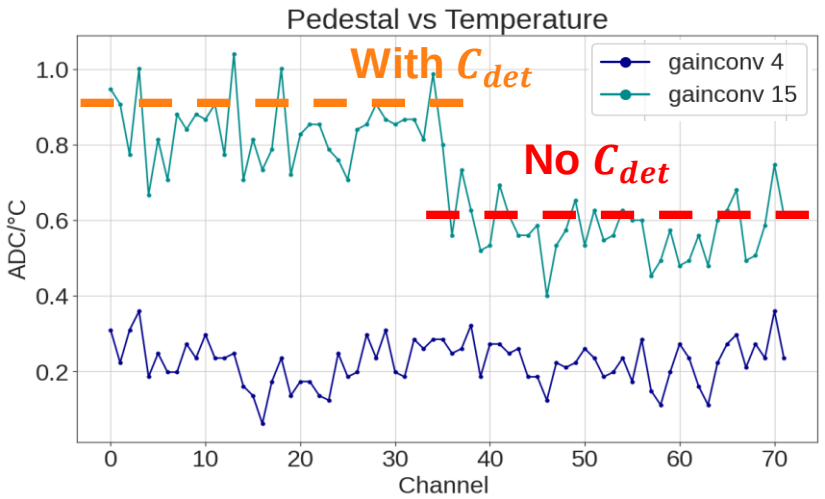
From -30°C to 10°C: ***12.5 µV / °C***

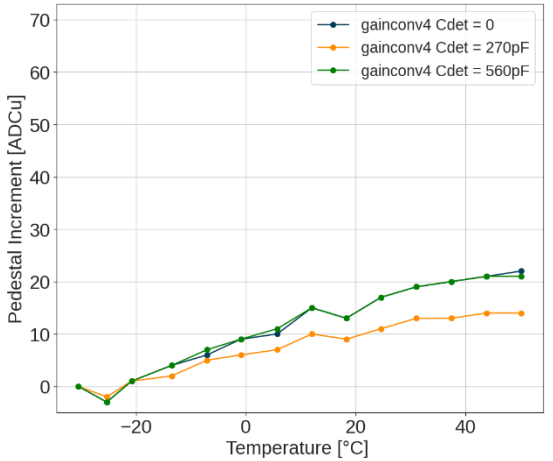
From 10°C to 50°C: ***65 µV / °C***

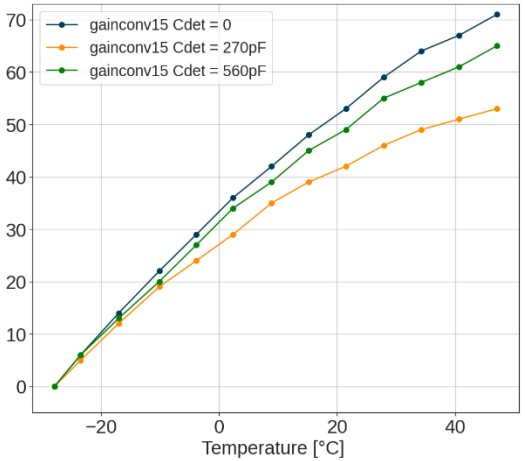
Pedestals:

Physics mode: ***+ 0.3 ADCu / °C***

Calibration mode: ***+ 0.9 ADCu / °C***



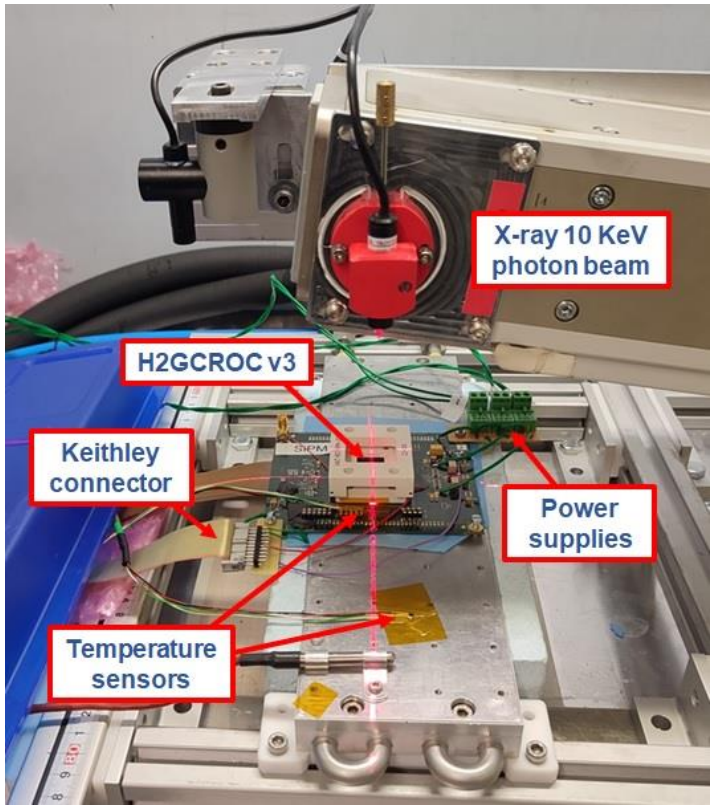




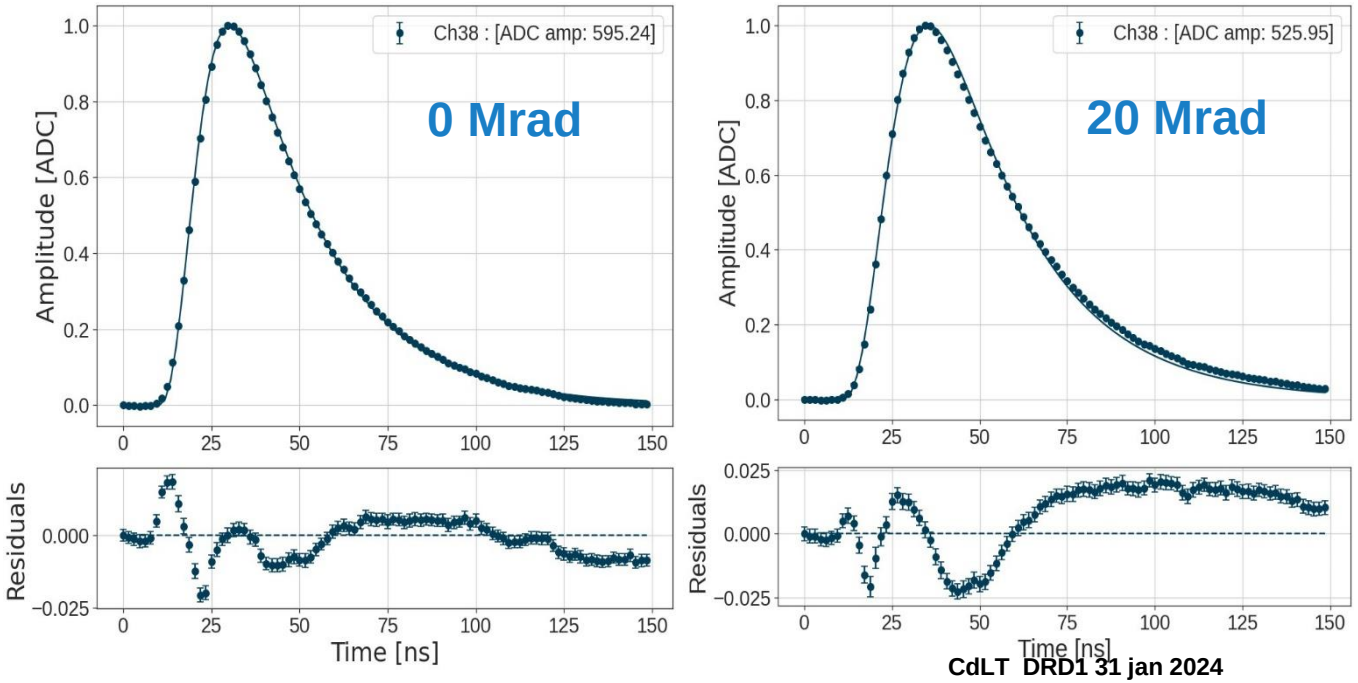
*Noise : almost flat

Irradiation campaigns

- Power consumption, ADC & TDC performance, noise, links stability, etc. tested during irradiation
- **TID irradiation tests in both ASIC versions.**
- **Heavy ion and Proton irradiation in the Si version of the ASIC**
  - Increase on triplicated parts for HGCROC3b



Stability of ADC measurements after 20Mrad:



- **H2GCROCv3** has proven to be **radiation tolerant up to 20 Mrad** at room and -5°C with good ADC, TDC and PLL measurements.

SEE (Single Event Effect) Irradiation Test

- Only tested in **HGCROC Si version** for both Protons and Heavy ions.
- Test the radiation damage induced by a single particle to electronic devices and non-cumulative. It can cause a failure at any moment since the beginning of operation.
- **Three types:**
  - Single Event Upset (**SEU**): bit flip (0 -> 1 or 1 -> 0).
  - Single Event Transient (**SET**): bit shift.
  - Single Event Latchup (**SEL**): permanent damage.

# errors	Counters	Trigger	CRC	Memory	Short SET	**Long SET**
Heavy ions [12]	0	1	2	3	24	**18**
Protons [13]	< 1	38	30	127	85	**190**

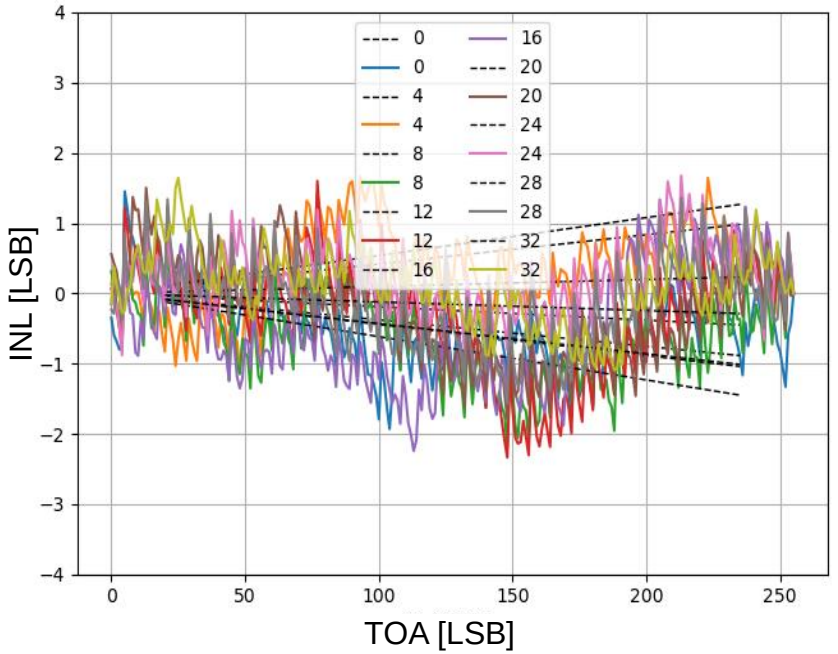
1 link loss / 2.5 years (for each chip on average)

- Very few errors in the not triplicated parts of Trigger and CRC.
- Very few errors in the memory, always detected by the hamming.
- Many errors in the not triplicated part (**PLL**).
  - **Increase in the triplication of the new version of PLL (Tested in EICROC).**

**Analysis by Elena Vernazza*

TDC V3 INL measurements

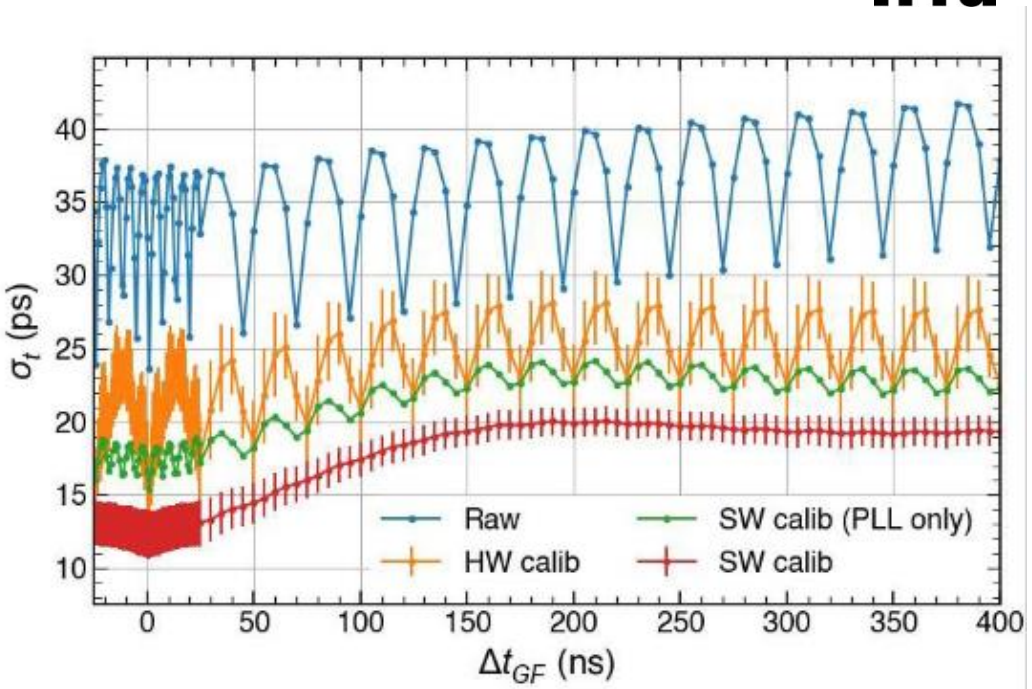
- I2C parameters to tune master and channel-wise DLLs
- Parameters can be optimized thank to the on-chip asynchronous clock generator (ACG) by minimizing the INL.



TDC calibration in 2 steps:

- Master DLL tuning
- Individual channel DLL tuning

After Calibration: INL < ± 2 LSBs, < 16 ps resolution



Resolution of 2 uncorrelated chips given by resolution at large T-delays

- Before calibration (blue): ~ 40 ps resolution
- After calibration (orange): < 30 ps resolution
- (After software correction (cancel FPGA clock jitter): **< 20 ps resolution**)

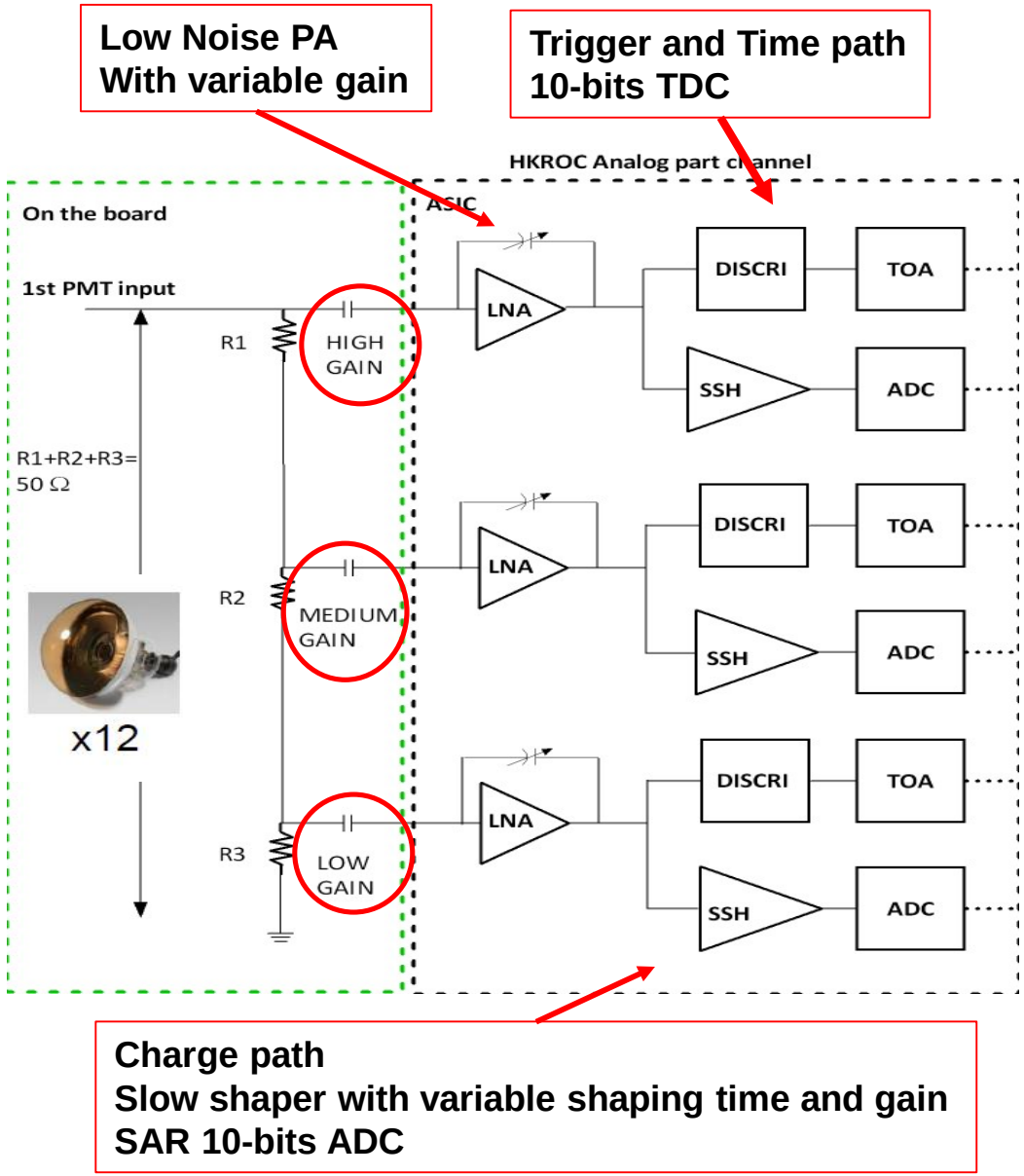
HKROC0 specifications

Min requirements	
Discriminator **threshold**	**1/6 p.e. (0.33 pC)**
Charge linearity	1% for 1 p.e. to **1250 p.e.** (**2 pC to 2500 pC**)
Charge resolution	**0.1 p.e. for < 10 p.e.** (**0.2 pC** for Q< 20 pC) **Better than 1% for >10 p.e.** (1% for 20 pc)
Maximum **hit rate**	**1 MHz/ch** **For close Supernova**
Timing resolution	**300 ps for 1 p.e.**(2 pc) **200 ps for > 6 p.e.** (12 pC)

To extend the charge dynamic range:

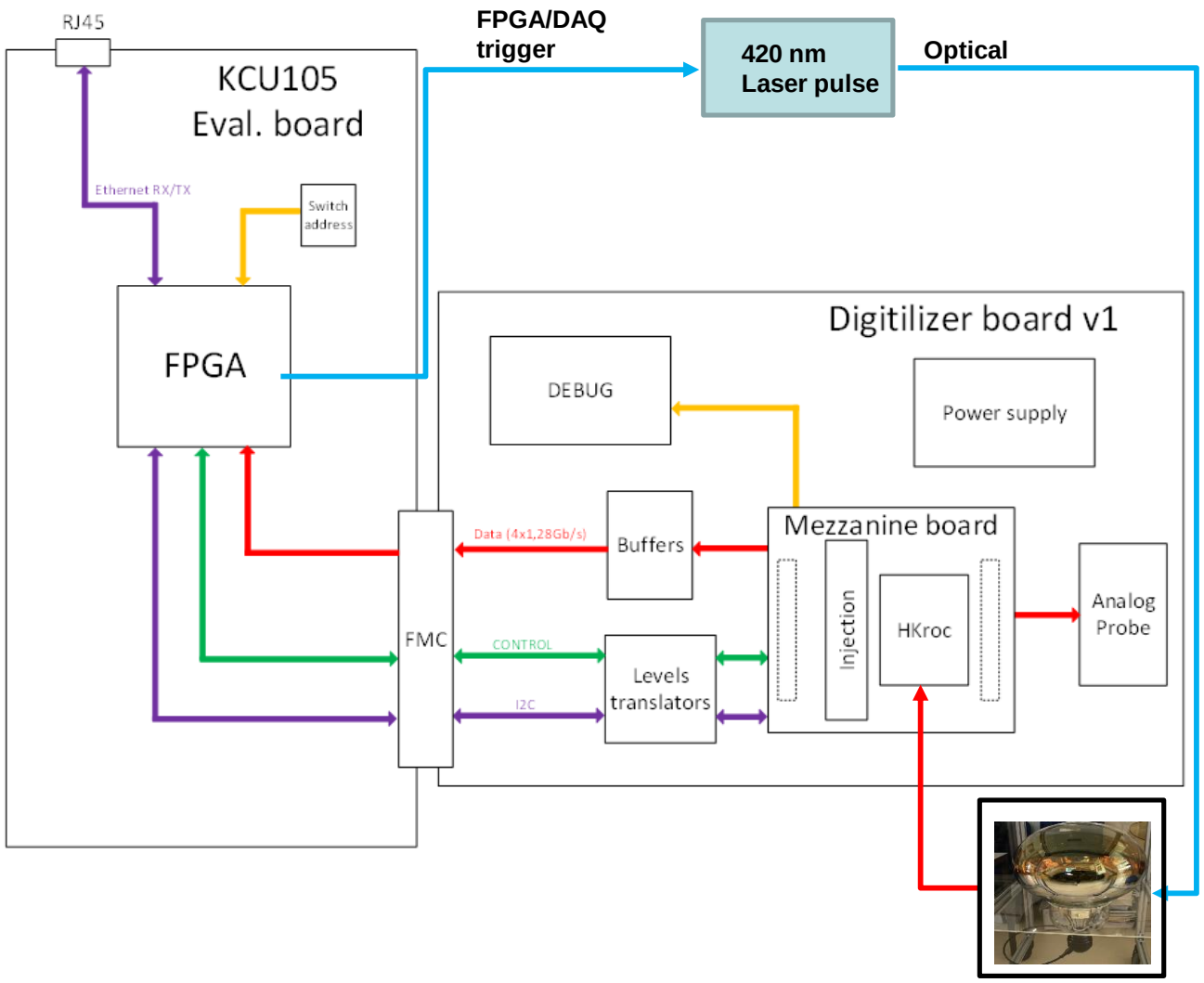
1 PMT channel connected

to **3 HKROC channels**

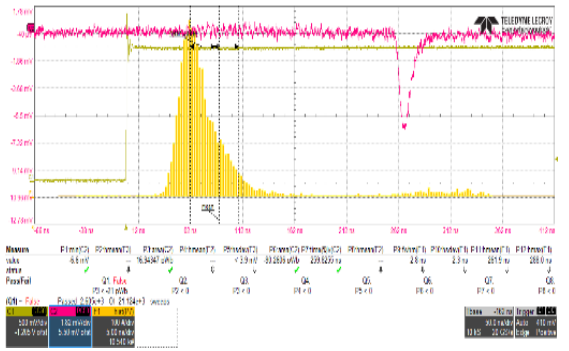


PMT testbench

Connected Hamamatsu R12680 PMT to HKROC illuminated by a PILAS 402 nm laser diode



- PMT HV set to have the 1 p.e peak amplitude at -6 mV
- Charge calibrated
- TTS : FWHM= 2.8 ns, σ= 1.2 ns



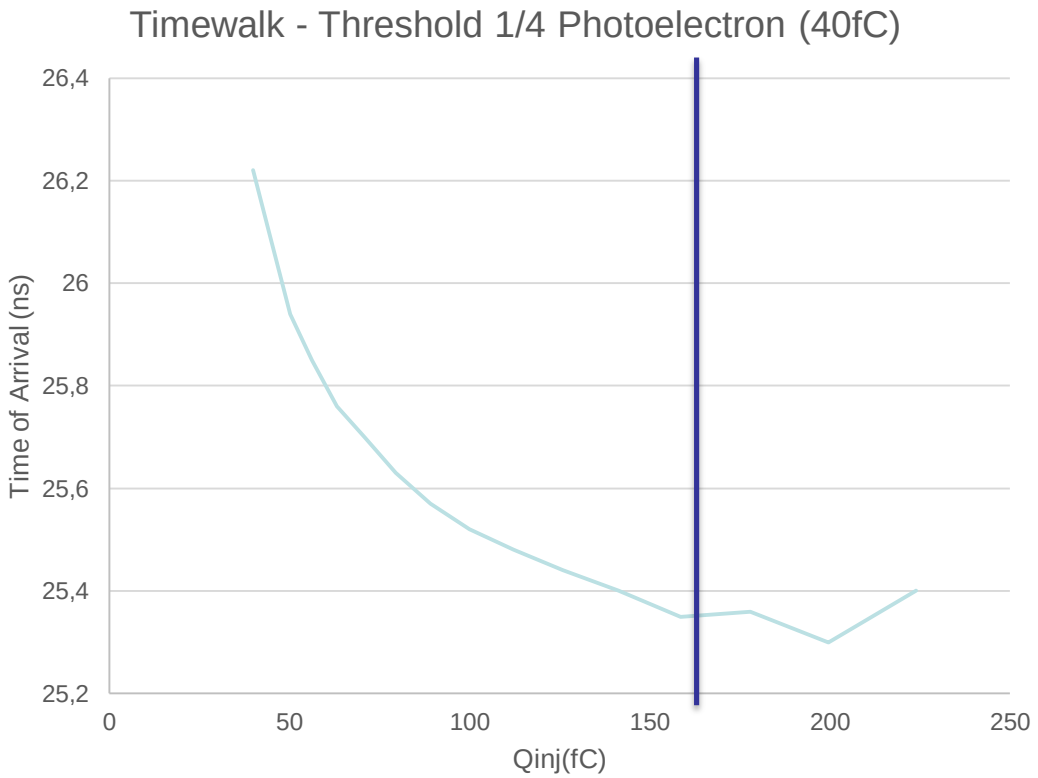
Parameters & Performances

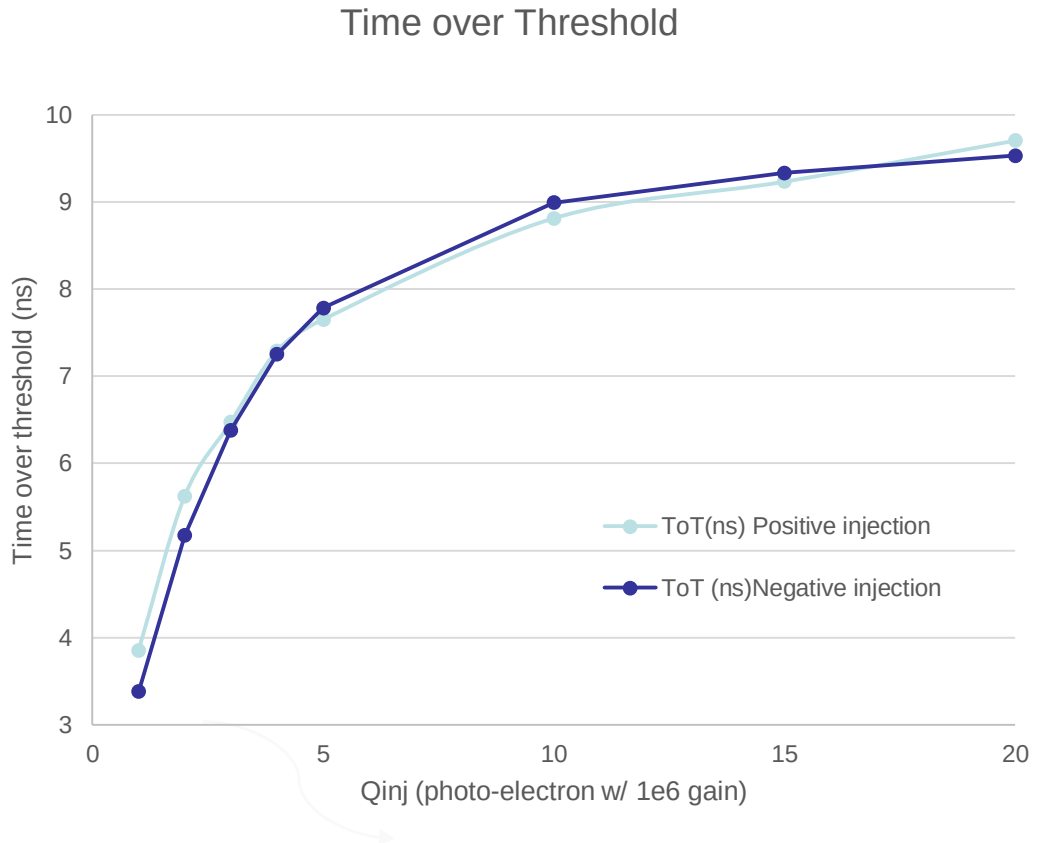
Detector Read-Out	SiPM, SiPM array
Number of Channels	64
Signal Polarity	Positive or Negative (selectable ASIC-wise)
Sensitivity	Trigger on 1/3 of photo-electron
Timing Resolution	Better than 20 ps FWHM on single photo-electron Better than 5ns double-peak separation on single photo-electron
Dynamic Range	Over 100MHz photon counting rate
Packaging & Dimension	BGA 20x20 mm^2 Flip-Chip low inductance packaging technology
Power Consumption	210mW – Supply voltage : 1.2 V
Inputs	64 analogue inputs with independent SiPM HV adjustments
Outputs	64 low-common-mode LVDS triggers (CLPS) – compatible with CERN picoTDC and all LVDS FPGA I/Os
Internal Programmable Features (I^2C)	64 HV adjustment for SiPM (64 x 6 bit), trigger threshold programming (10bits), 64 x 7 bit channel-wise threshold adjustment, ASIC-wise polarity selector, preamp pole-zero cancellation adjustment, individual trigger masking and cell powering.

Technology : TSMC 130nm MS-RF
« CERN qualified » for irradiation

Timewalk and ToT

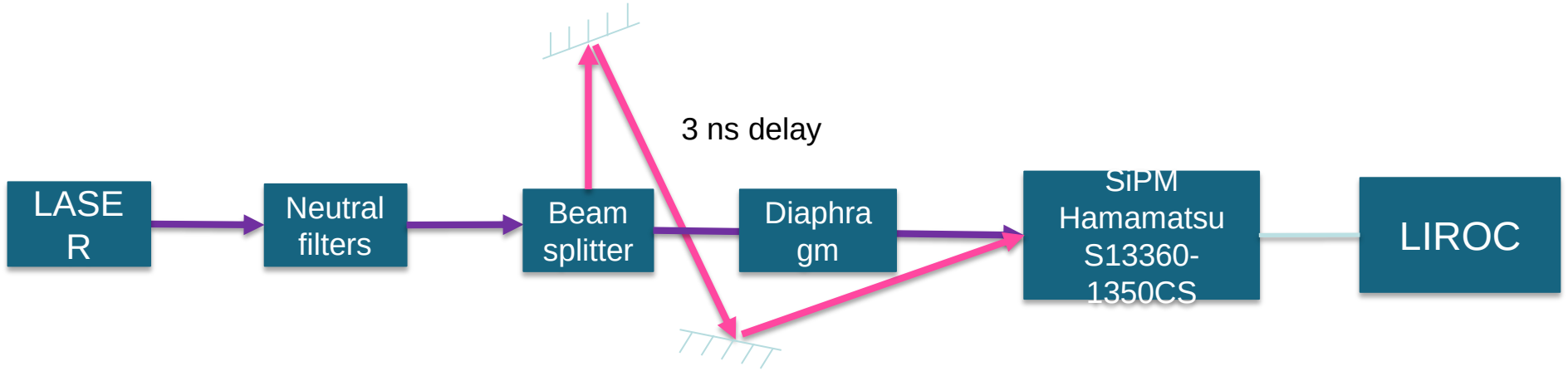
- ToT used to correct timewalk
- Trade-off beetween double peak separation (see consecutive photons) and time over threshold (tuneable).
- Optimized for double-peak separation in that measurement (3ns separation measured)

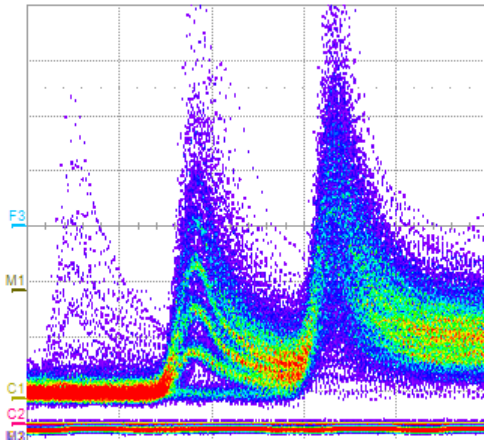




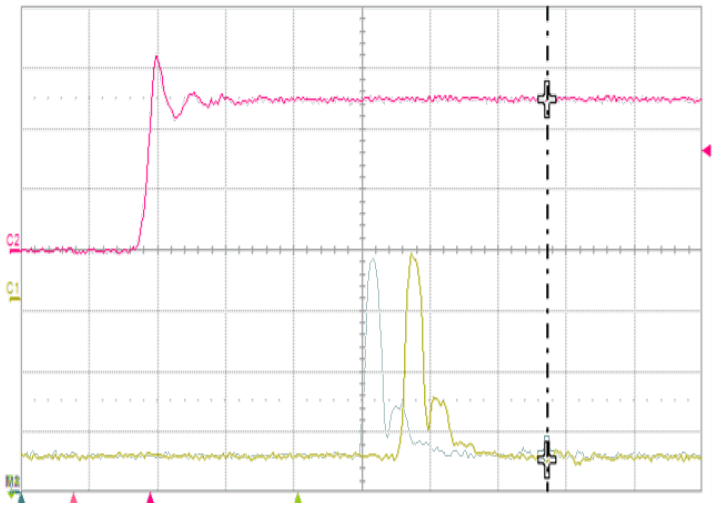
1 photoelectron - Gain 10^6

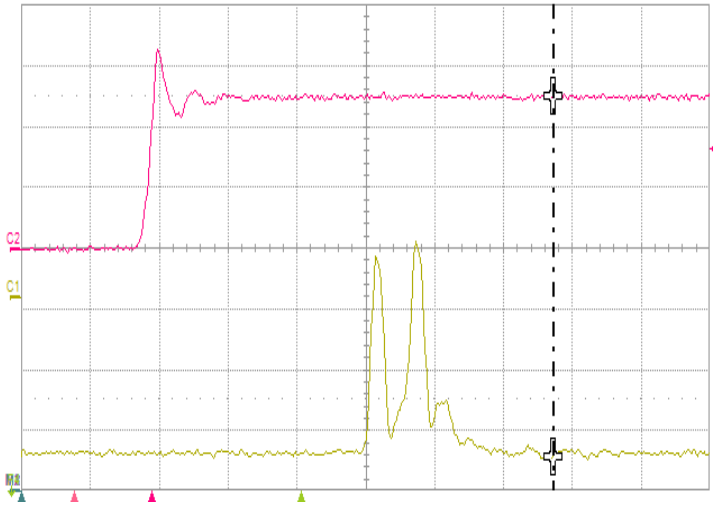
LIROC : double pulse separation



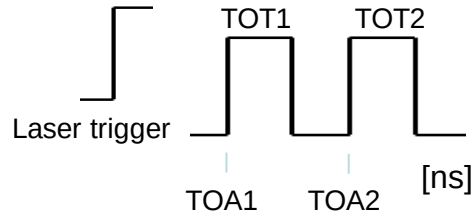


Direct to oscilloscope, 3 ns interval



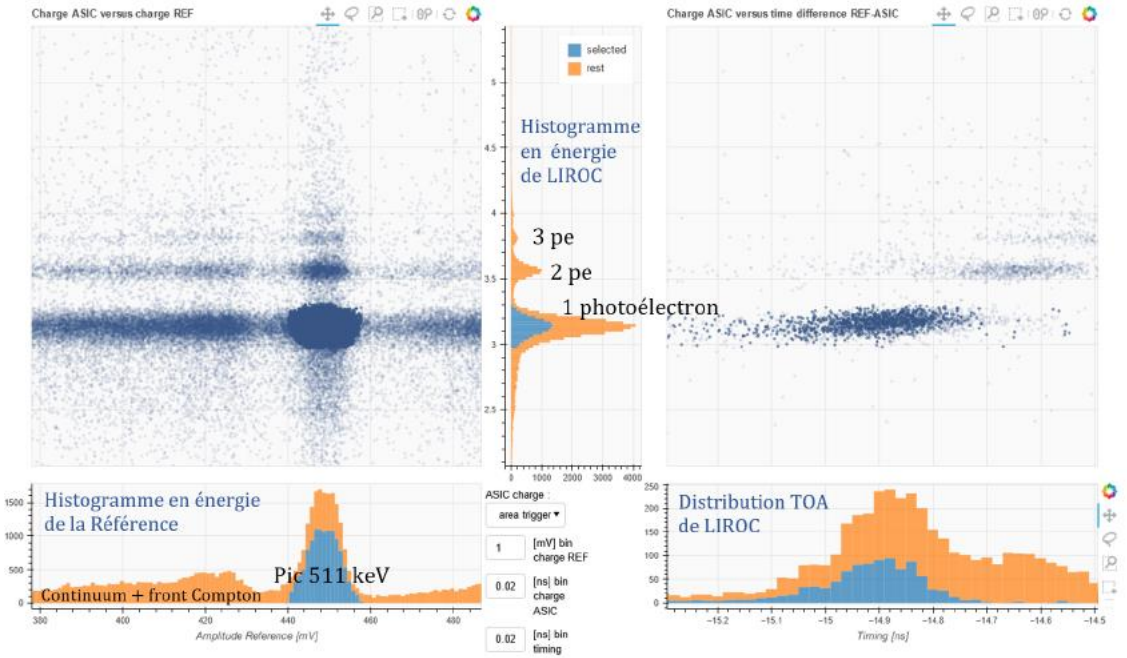


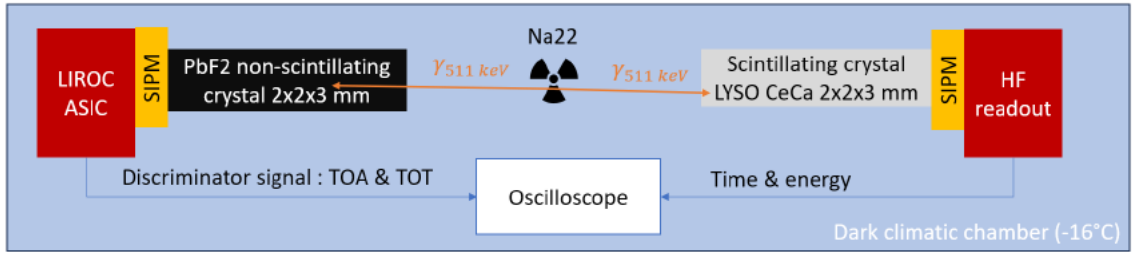
50 mV/div
5 ns /div

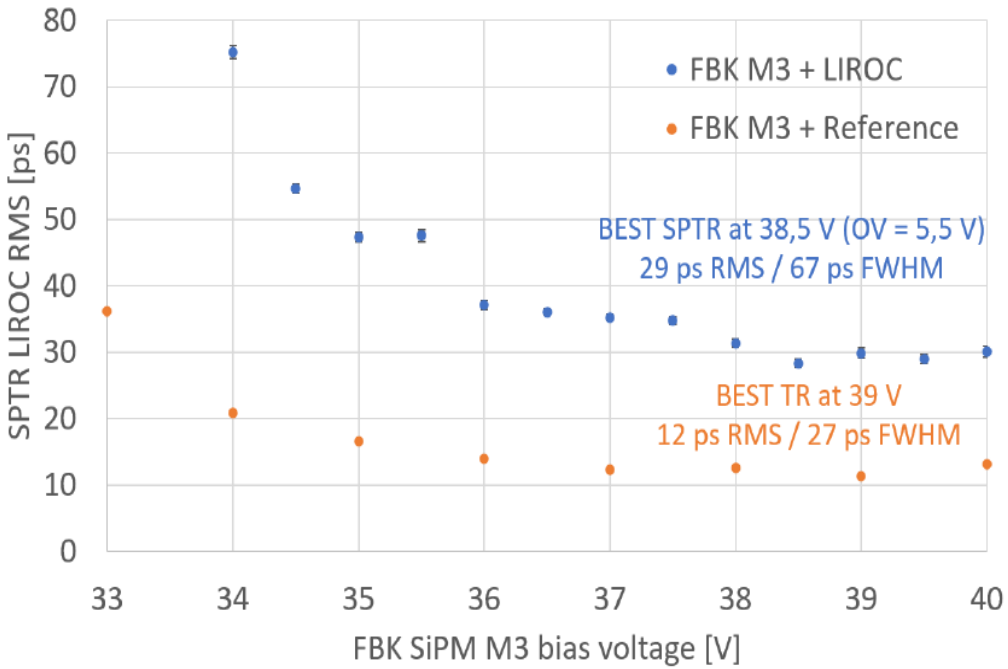


Conclusion : 3 ns double pulse well separated

LIROC SPTR


Charge ASIC versus charge REF
Charge ASIC versus time difference REF-ASIC
selected
rest
Histogramme en énergie de LIROC
3 pe
2 pe
1 photoélectron
Histogramme en énergie de la Référence
Pic 511 keV
Continuum + front Compton
Amplitude Reference [mV]
ASIC charge
area trigger
[mV] bin charge REF
[ns] bin charge ASIC
[ns] bin timing
Distribution TOA de LIROC
Timing [ns]


LIROC ASIC
SIPM
PbF2 non-scintillating crystal 2x2x3 mm
Na22
$\gamma_{511\ keV}$
$\gamma_{511\ keV}$
Scintillating crystal LYSO CeCa 2x2x3 mm
SIPM
HF readout
Discriminator signal : TOA & TOT
Oscilloscope
Time & energy
Dark climatic chamber (-16°C)


SPTR LIROC RMS [ps]
FBK SiPM M3 bias voltage [V]
FBK M3 + LIROC
FBK M3 + Reference
BEST SPTR at 38,5 V (OV = 5,5 V)
29 ps RMS / 67 ps FWHM
BEST TR at 39 V
12 ps RMS / 27 ps FWHM