The new photodetectors for the LHCb RICH upgrade and their FE design

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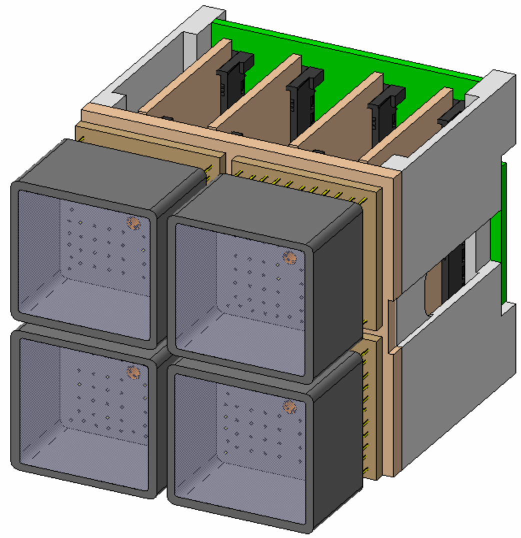
LHCb RICH Upgrade

- Upgrade goal:

Increase luminosity from 4 x 10^{32} cm^{-2} s^{-1} to 2 x 10^{33} cm^{-2} s^{-1} making the detector able to operate at 40 MHz read-out rate. The upgrade is planned to be installed during the LS2 (2018-2019).

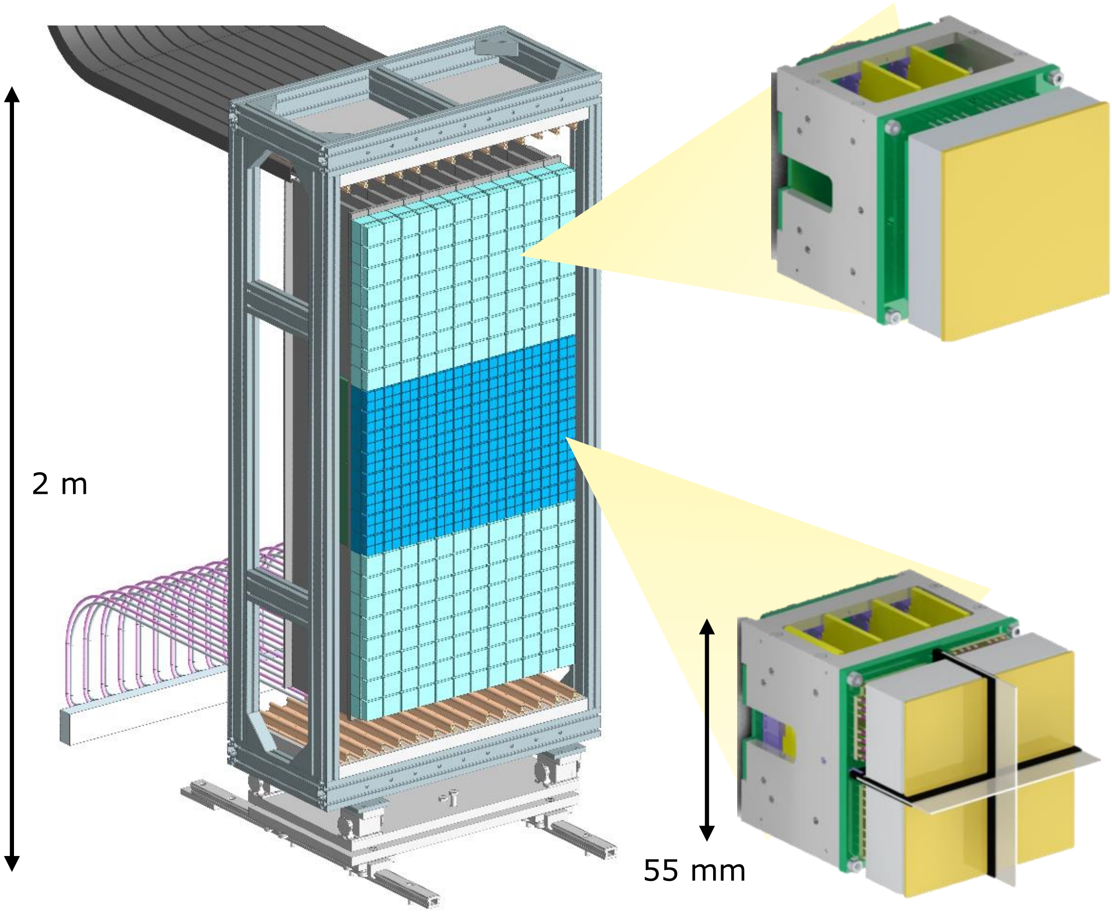
In the RICHs:

- Overall detector strucure unchanged
- Removal of the Aerogel radiator (already removed in RUN-II, see A. Papanestis’s Talk).
- Optical layout of RICH1 adjusted to lower the occupancy to 25% max.
- HPDs replaced with MaPMTs (~ 3000 devices).
- New electronic chain designed for the MaPMT readout



For further details, see S.Easo’s presentation

MaPMT panel



Photosensitive plane of the RICH-2 detector

EC-H type: Large MaPMT

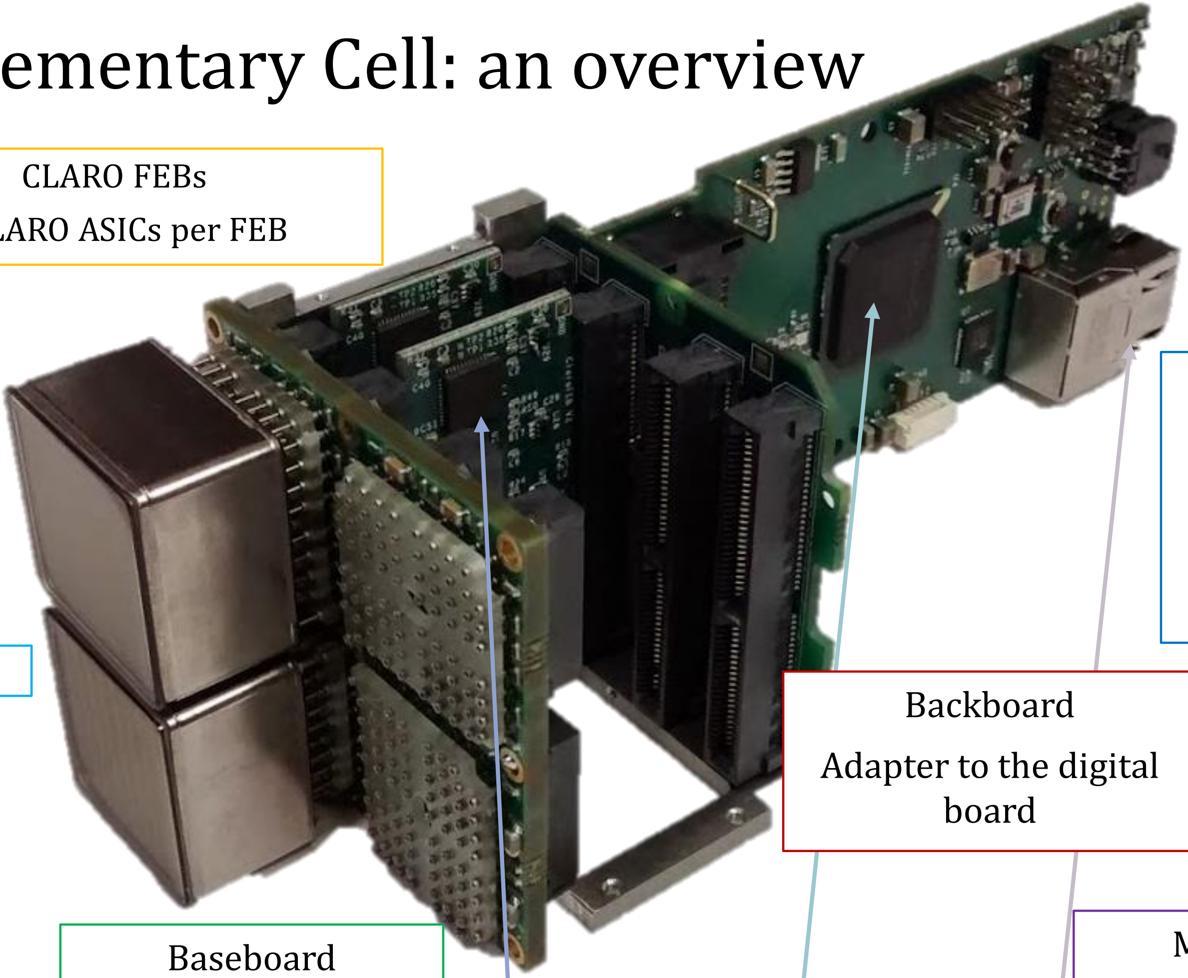
- ~400 modules
- Outer regions of RICH-2
- One R13743 MaPMT (larger model, 2x2 inches) per EC

EC-R type: Small MaPMT

- 2x2 matrix of R13742 MaPMT (smaller model, 1x1 inches) per EC
- ~ 2700 MaPMTs
- ~ 700 modules
- RICH-1 and central regions of RICH-2

Both EC models well operated during the beam tests. For further datails see P. Carniti’s poster

Elementary Cell: an overview



CLARO FEBs

8 CLARO ASICs per FEB

2x2 PMTs

Baseboard

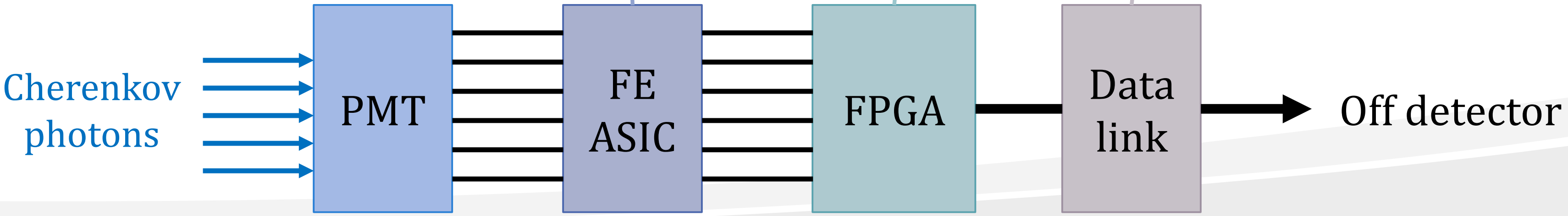
Digital boards

Manage digital signals processing and data transmission.

Backboard

Adapter to the digital board

Mechanics and cooling



Cherenkov photons

PMT

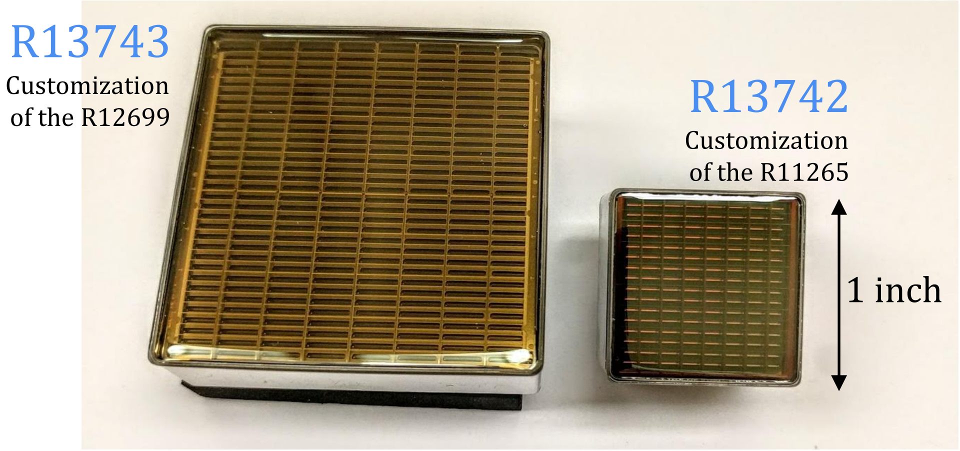
FE ASIC

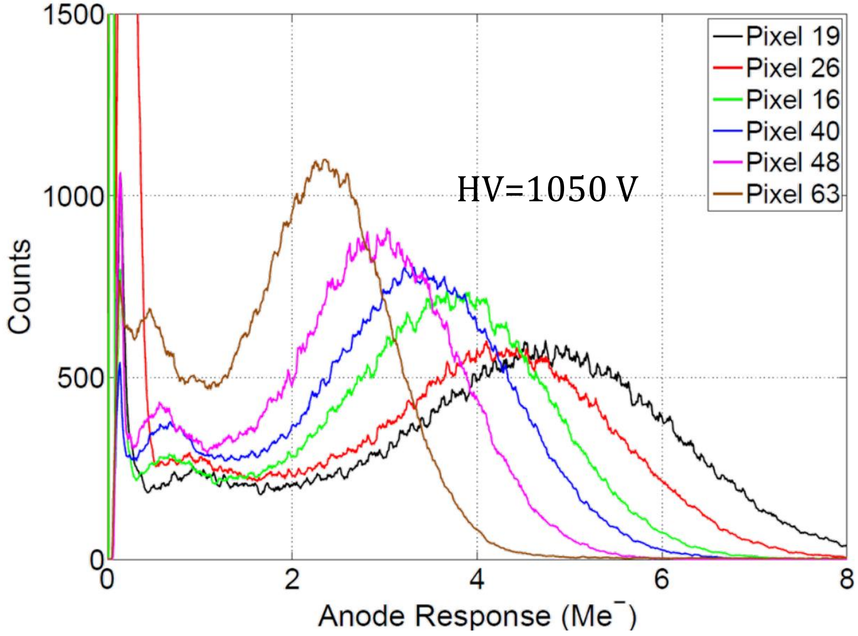
FPGA

Data link

Off detector

MaPMT: anode uniformity





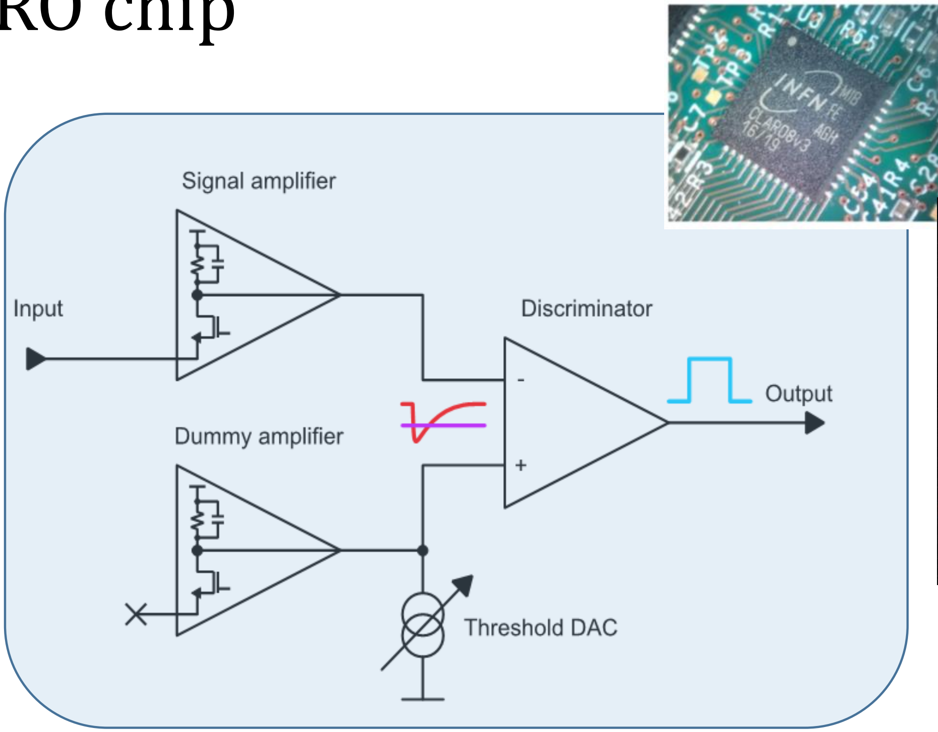
Main tested features:

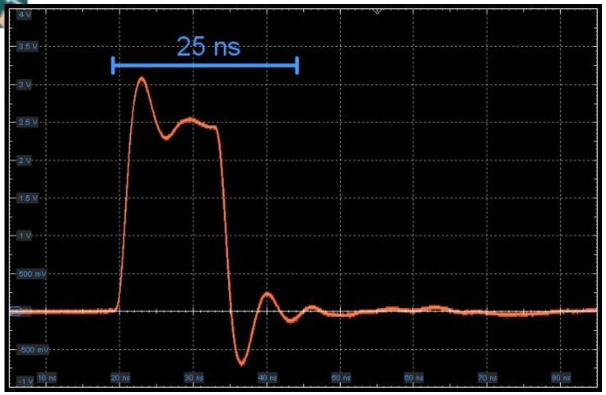
- Single photon detection capability
- Large active area (>80 %)
- Good time response (see F. Keizer's and M. P. Blago's Poster)
- Low dark count rate
- Adequate cross-talk
- Adequate QE (see. S. Gambetta's poster)
- Magnetic field tolerance (see. S. Gambetta's poster)
- Capability to sustain long period of operation

The typical gain spread among the pixels amounts at maximum to 3-4
(in agreement with the Hamamatsu datasheet).

It is compensated by the read-out electronics

CLARO chip





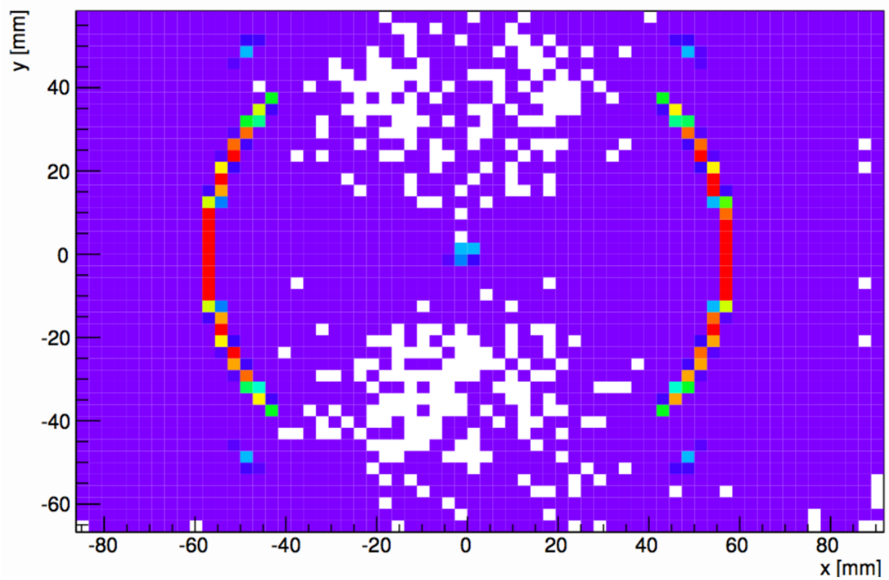
CLARO output signal

The CLARO is a 8 channel integrated circuit designed for **single photon counting** with MaPMTs.

Main features

- **$0.35\ \mu m$ CMOS** technology from AMS → Low cost, high yield, long lifespan
- **Counts at 40 MHz** → Recovery time ~ 25 ns
- **Low power consumption** → ≤ 1 mW/channel at 2.5 V power supply
- **Settable gain** (2 bits) → 4 gain configurations
- **Settable threshold** (6 bits) → 64 threshold levels available
- **Radiation tolerant** (see M.Fiorini's poster) → high reliability in the LHCb envirmonment

Cherenkov ring detection



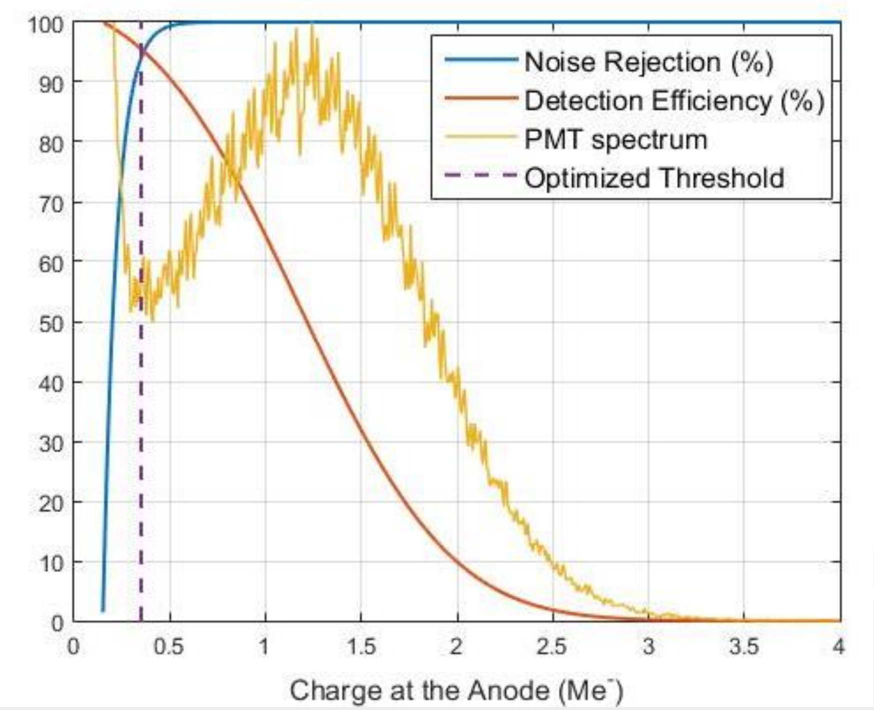
The EC is able to provide a digital information

Each pulse is interpreted as a incident photon

We need to set the trigger threshold in order to:

- ➢ Maximize the Detection efficiency ($\epsilon \geq 95\%$)
- ➢ Maximize the rejection of the spurious counts ($N \geq 95\%$)

Fine adjust of the trigger threshold in each channel required



MaPMT noise: Dark counts

At room temperature, dark event rate of $\sim 60\ Hz/cm^2$.

↓

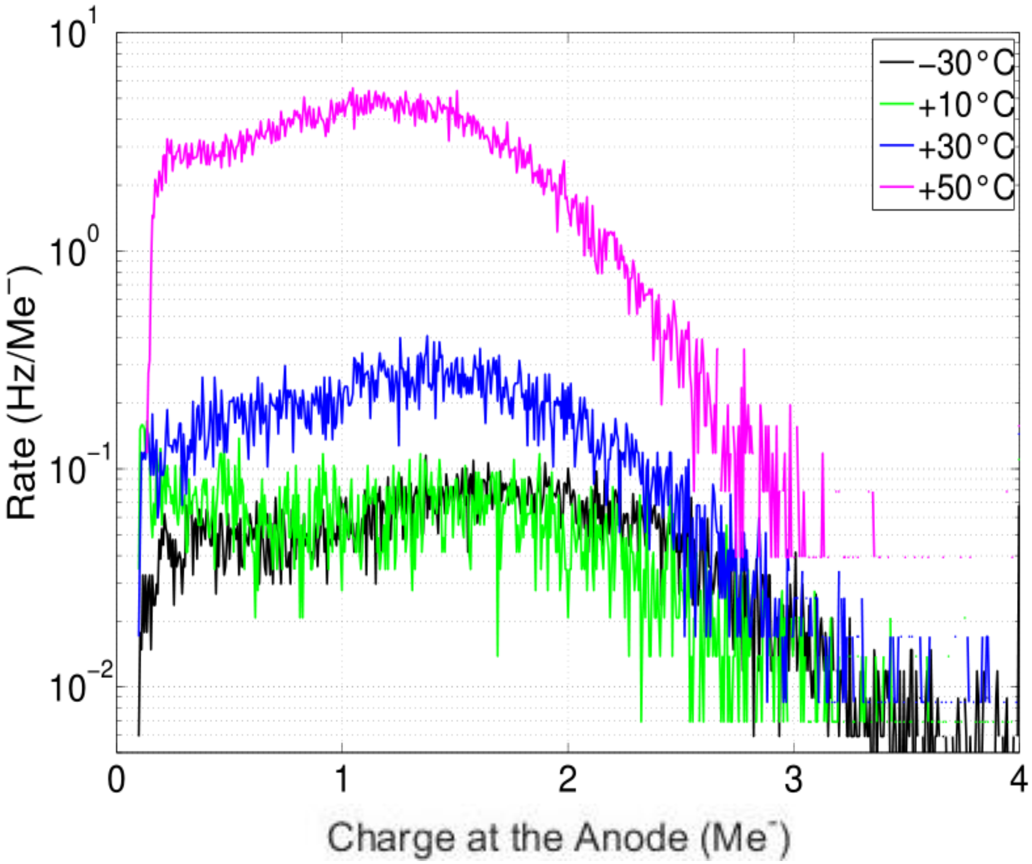
Negligible with respect to signal rate ($\sim MHz$)

Dark count rate increases exponentially with temperature

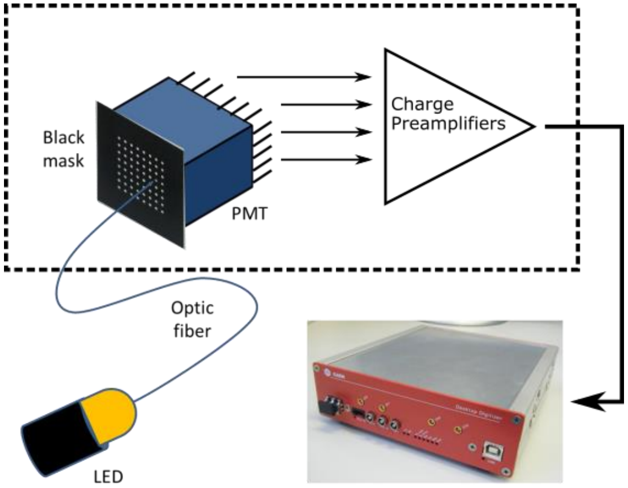
↓

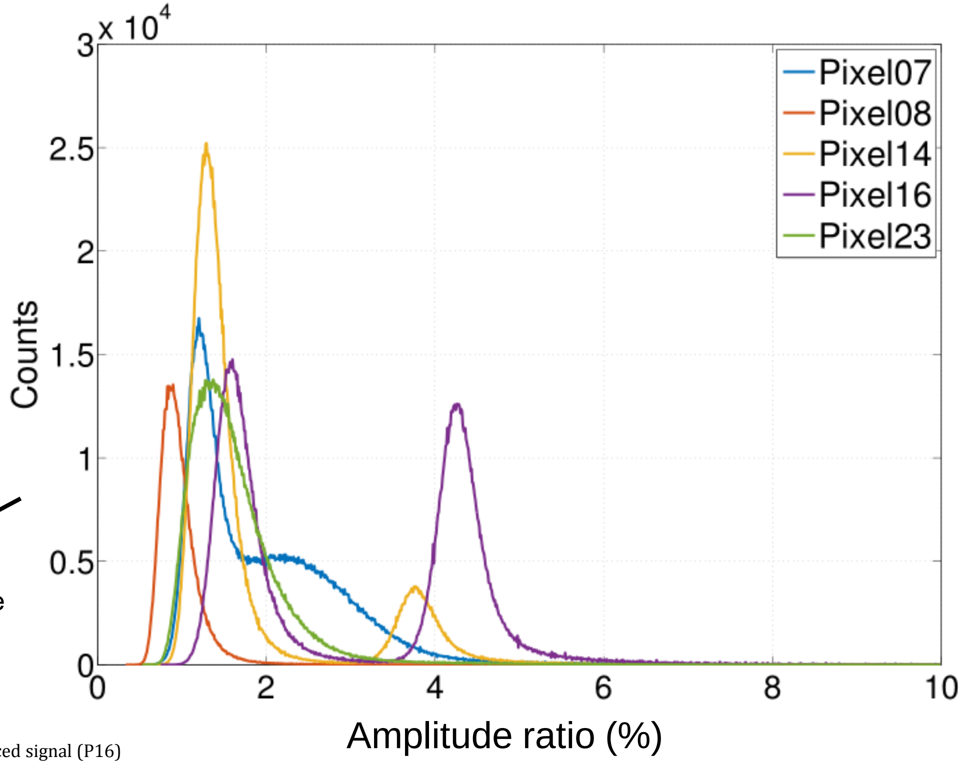
Baseboard provides a thermal mass for the MaPMT thermalization.

CLARO designed to minimize the power consumption

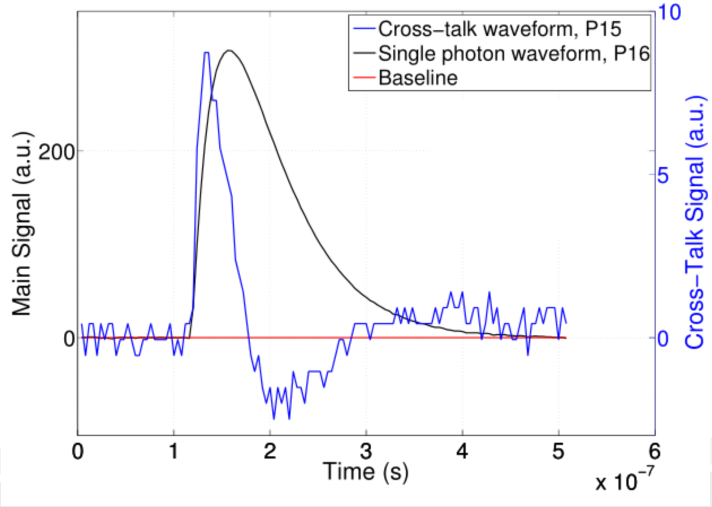


MaPMT noise: amplitude ratio





Capacitive coupling

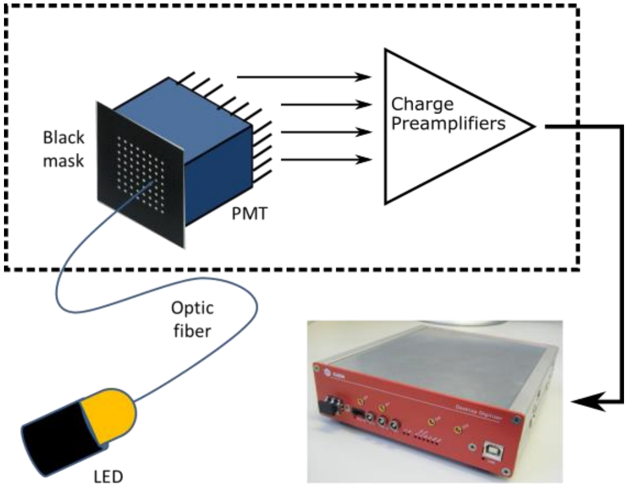


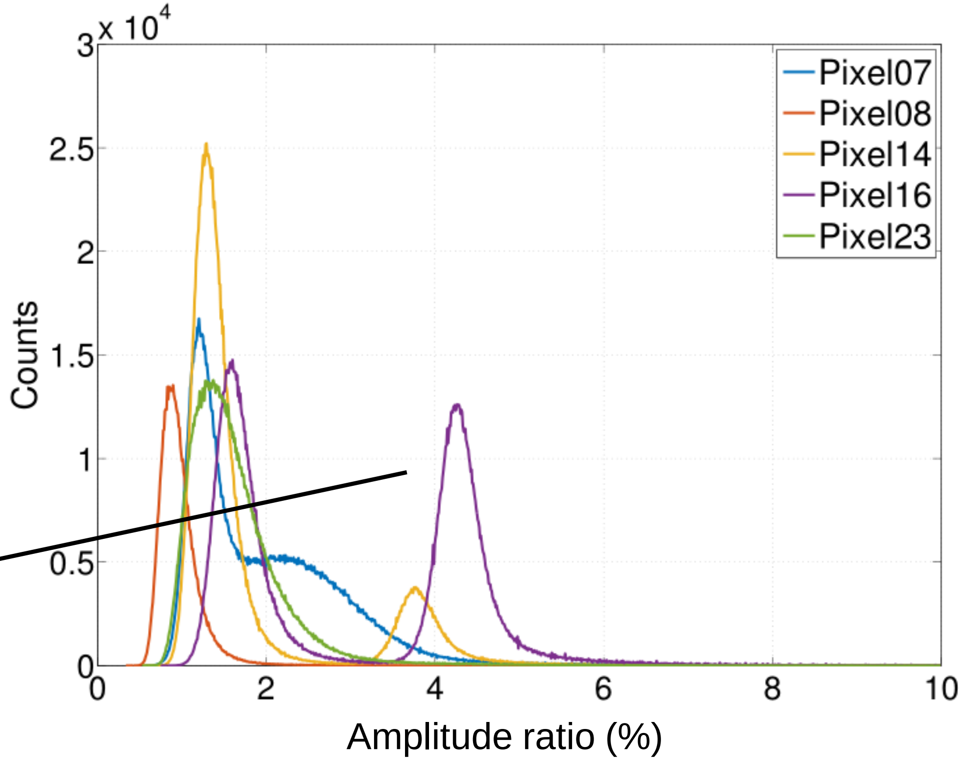
Induced signal (P16)
Inducing signal (P15)
Baseline

The signal amplitude ratio between neighbouring pixels amounts to $\leq 5\%$

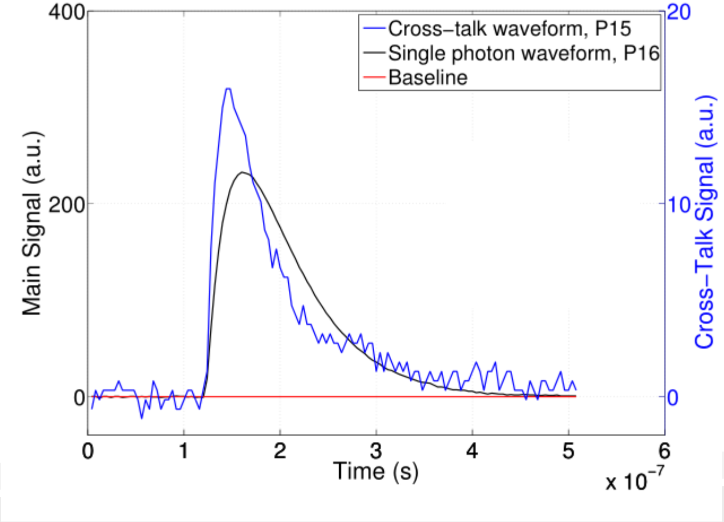
- Capacitive coupling: fast, bipolar, low amplitude signal.

MaPMT noise: amplitude ratio





Charge sharing



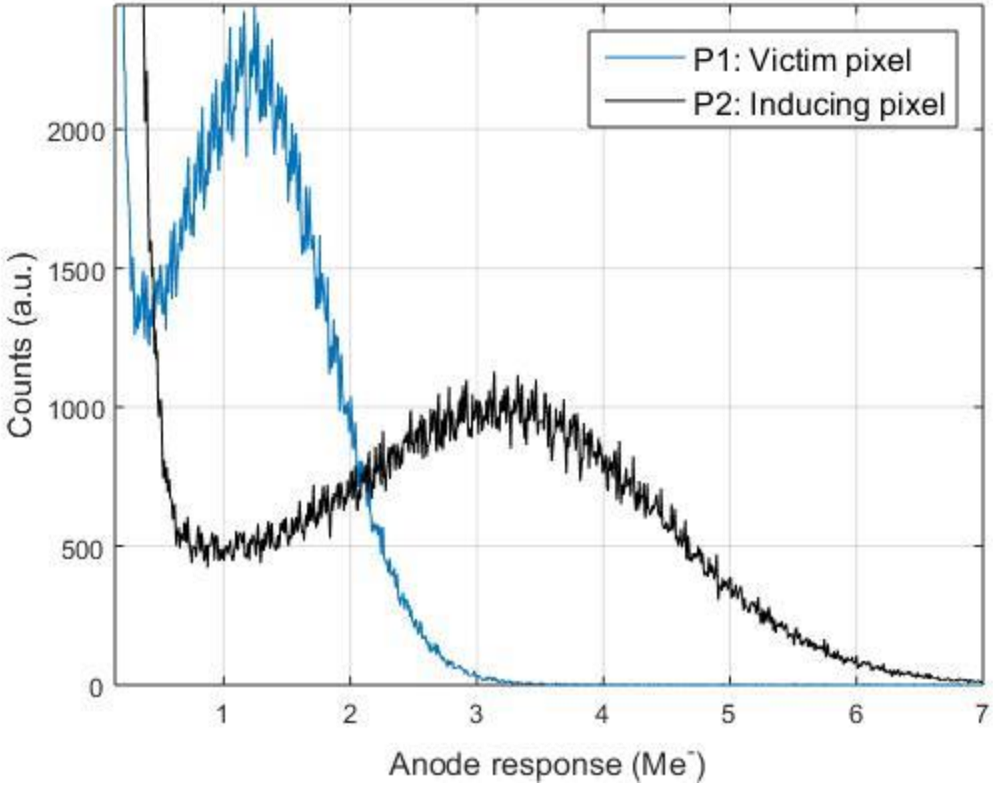
The signal amplitude ratio between neighbouring pixels amounts to $\leq 5\%$

- Capacitive coupling: fast, bipolar, low amplitude signal.
- Charge sharing: single polar, larger amplitude signal induced by photons hitting near the pixel edge in the consecutive pixel

MaPMT noise: cross-talk example

Let’s see an example of how the signal induced from one pixel to the neighbouring one can affect the EC operation

Considering single photon spectra from neighbouring channels with a worst-case gain spread of ~3



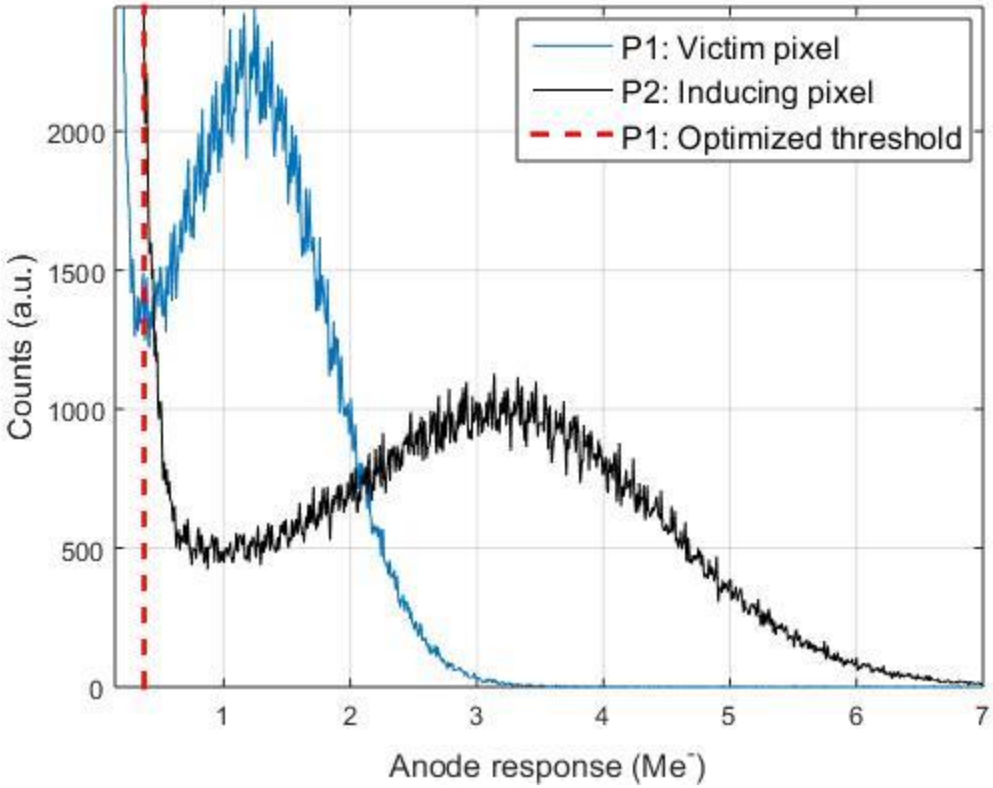
MaPMT noise: cross-talk example

Let's see an example of how the signal induced from one pixel to the neighbouring one can affect the EC operation

Considering single photon spectra from neighbouring channels with a worst-case gain spread of ~3

The red line represents the optimized threshold of the victim pixel P1.

Only signals above that line triggers a count in that channel and mixed up with that due to incident photons

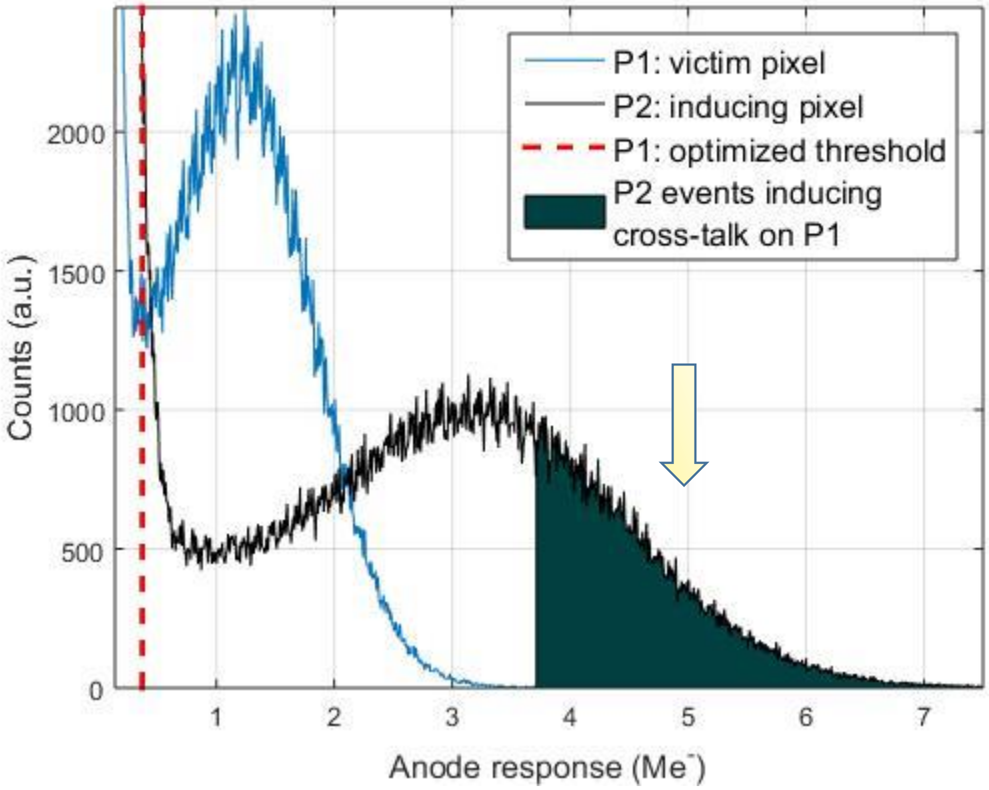


MaPMT noise: cross-talk example

Capacitive coupling or charge sharing between neighbouring pixels can cause spurios counts correlated with the signal.

If the amplitude of the induced signal is 10% of that of the inducing signal

>30% of the events on the inducing pixel trigger an event on the adjacent channel

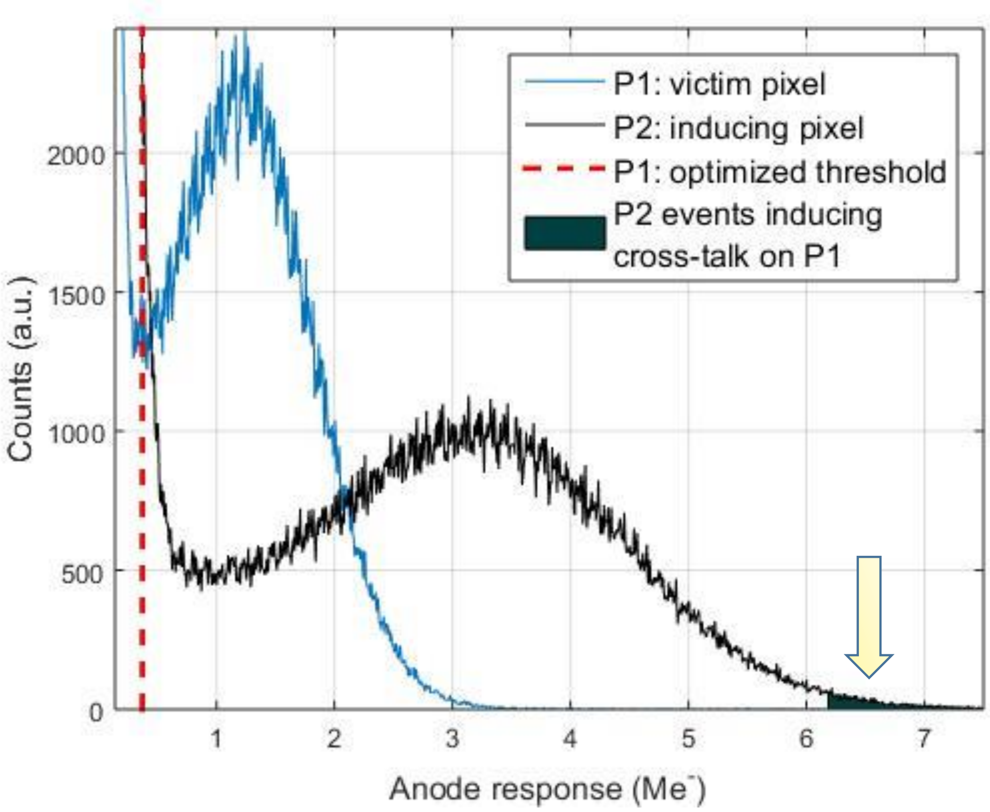


MaPMT noise: cross-talk example

Capacitive coupling or charge sharing between neighbouring pixels can cause spurios counts correlated with the signal.

If the amplitude of the induced signal is 6% of that of the inducing signal

<2% of the events on the inducing pixel trigger an event on the adjacent channel



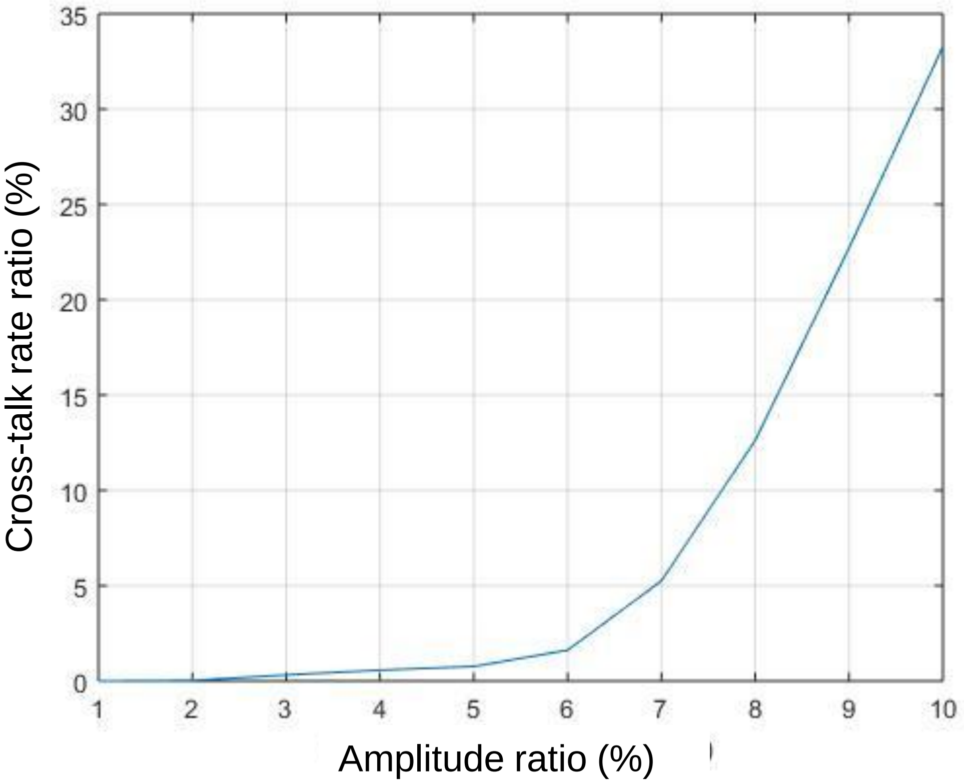
MaPMT noise: cross-talk

Capacitive coupling or charge sharing between neighbouring pixels can cause spurios counts correlated with the signal.

The signal amplitude ratio between

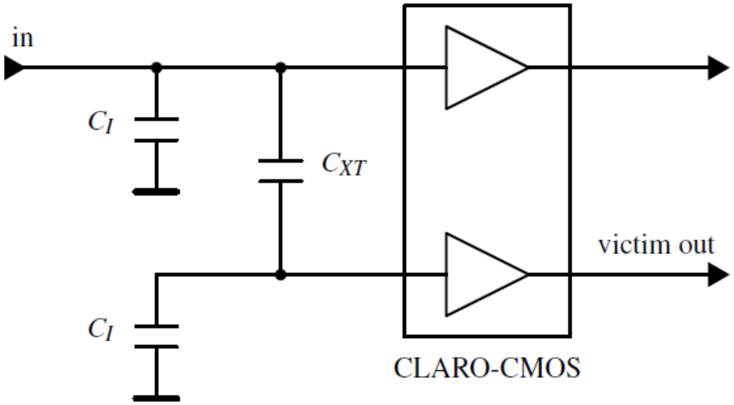
neighbouring pixels amounts to ≤ 5%

Expected cross-talk rate ratio due to MaPMT ~ 1%



Electronic layout: cross-talk and noise

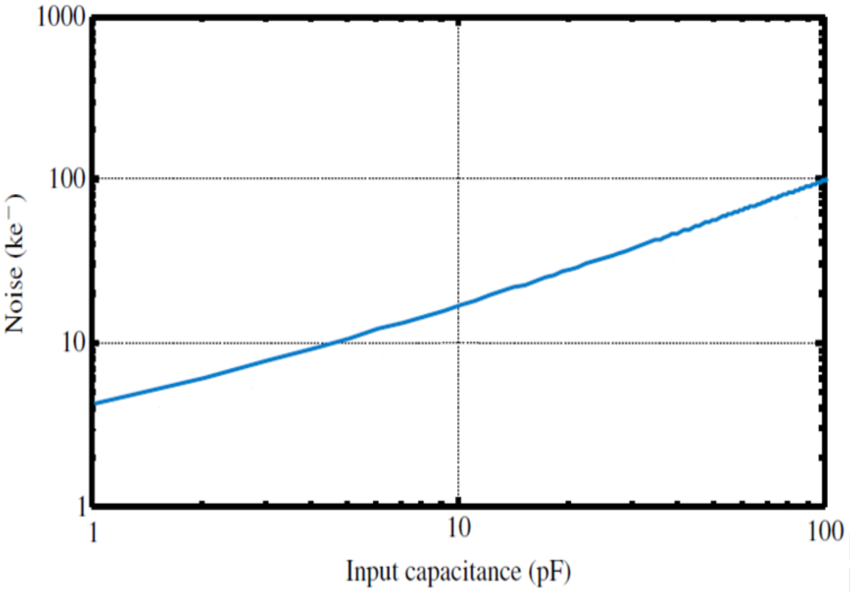
- The noise increases with the input capacitance to ground (C_I)
- The cross-talk increases with the input capacitance between neighbouring pixels



The minimization of input capacitance guides the layout of the CLARO, FEBs and Baseboard (BsB). Combined with the low input impedance of the CLARO, this minimises cross-talk

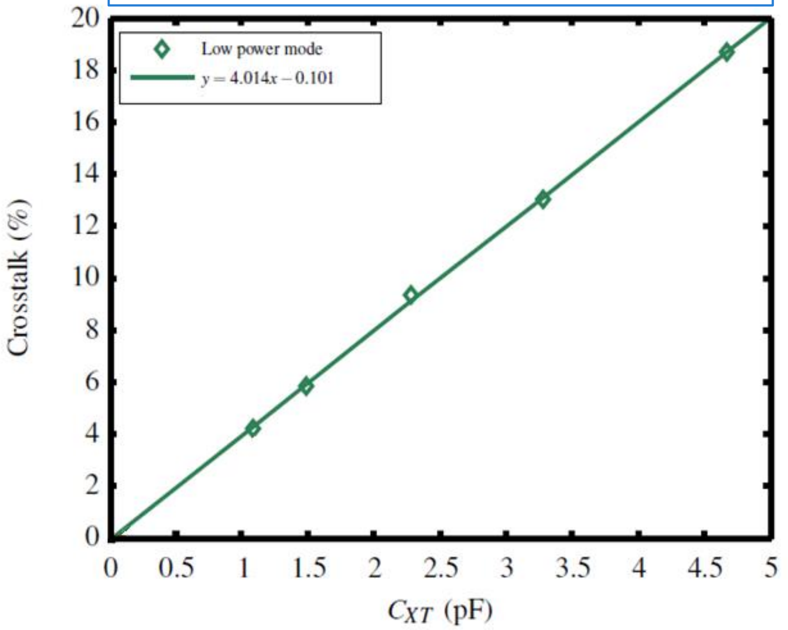
$C_I \simeq 10$ pF

(due to the BsB, FEB and CLARO, ~ 3 pF each)



$C_{XT} \simeq 0.5$ pF

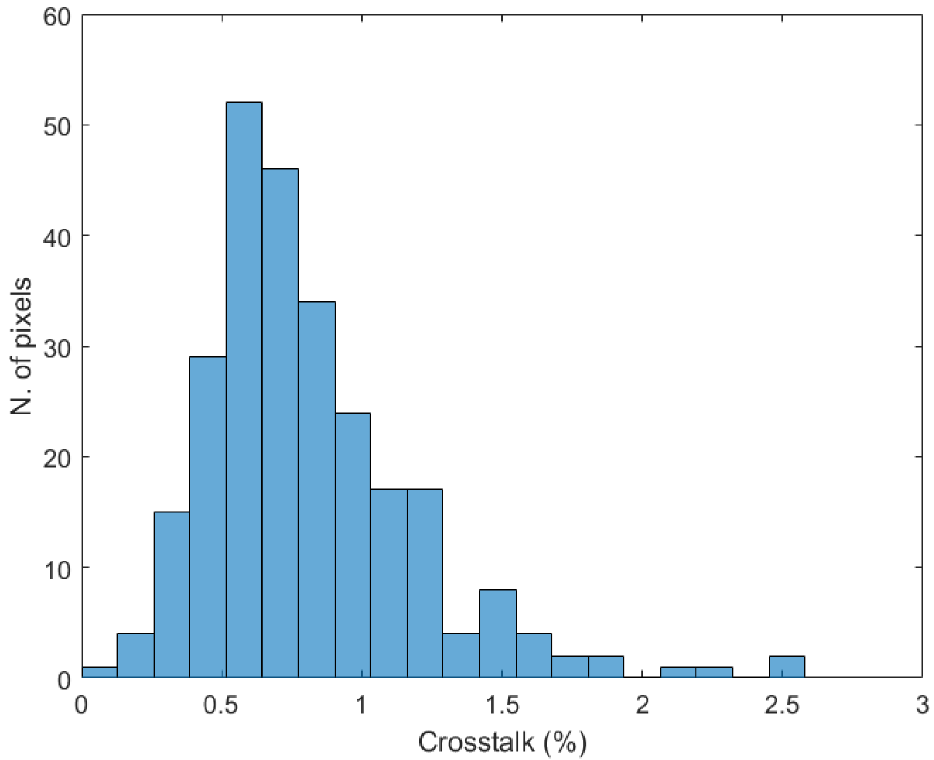
(due to the BsB and FEB, ~ 0.2 pF each)



Full Elementary Cell: cross-talk

Cross-talk extracted from real data taken with the full EC

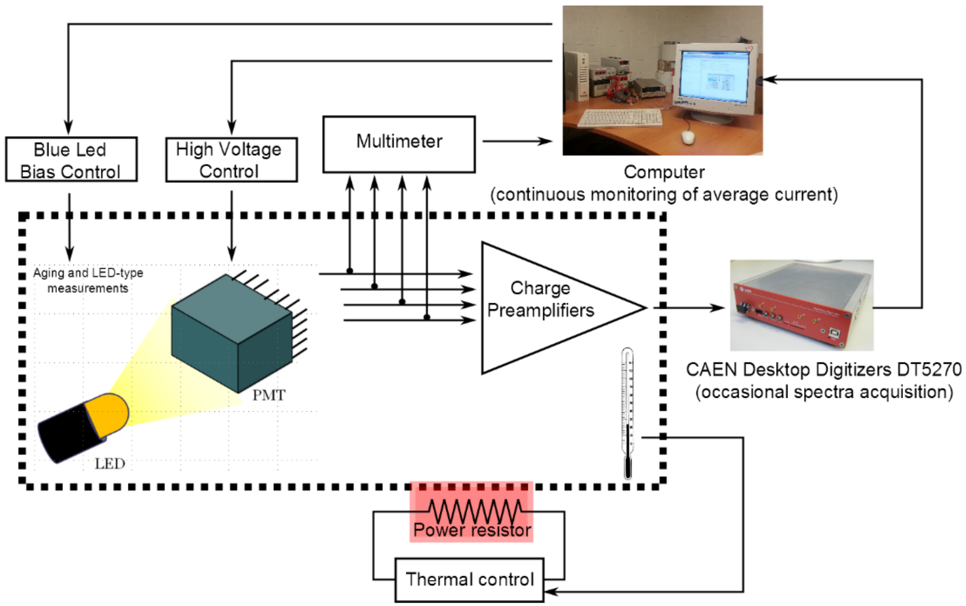
- Threshold on all channels set in the valley between pedestal and single photon peak
- Cross-talk estimated by counting coincidences of dark events between neighbouring pixels
- The cross-talk rate distribution has a mean value of 0.81%

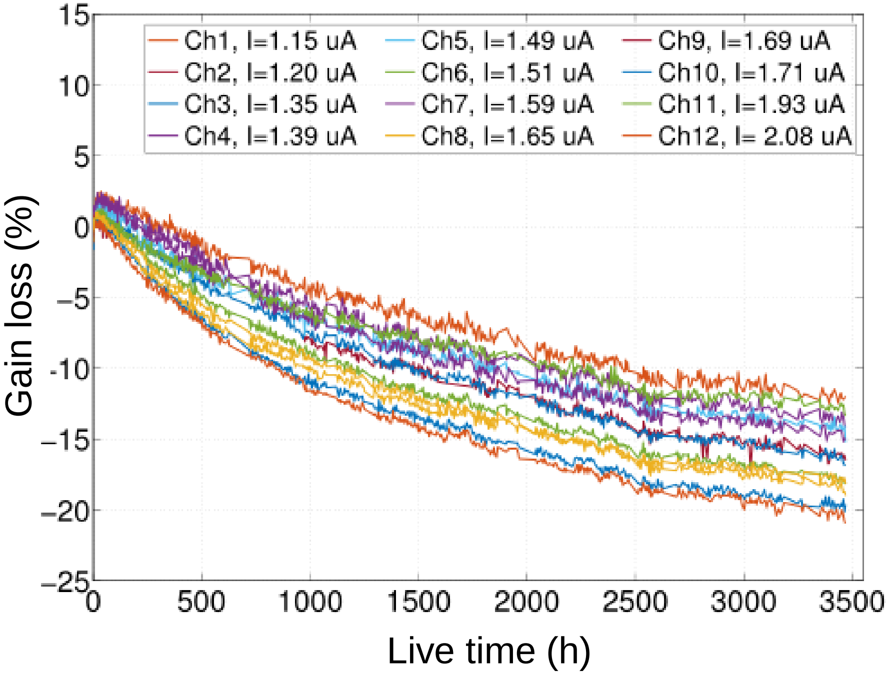


The measured
cross-talk rate ratio is ≤ 1 %.

- ➢ Main contribution due to MaPMT
- ➢ Negligible contribution of the electronics

MaPTM: Gain loss





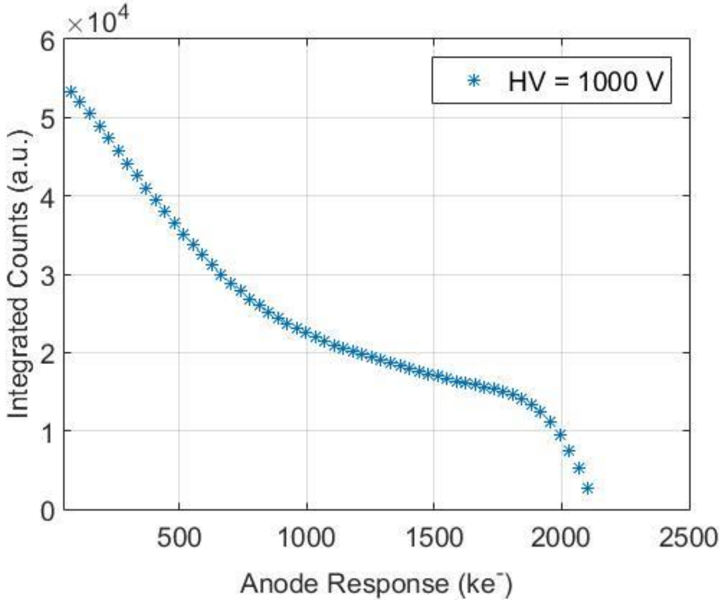
Long period of intense illumination causes a gain variation $\Delta G \simeq \pm 10 - 15\ \%$ due to the wear of the dynodes.

- Even in most critical pixels, the separation between the pedestal and the single photon peak is more than adequate if compared to the front-end resolution.
- A high voltage adjustement of few tens of volts allows to fully compensate the effect.

The MaPMT can operate at the expected level of illumination, but require periodic calibrations.

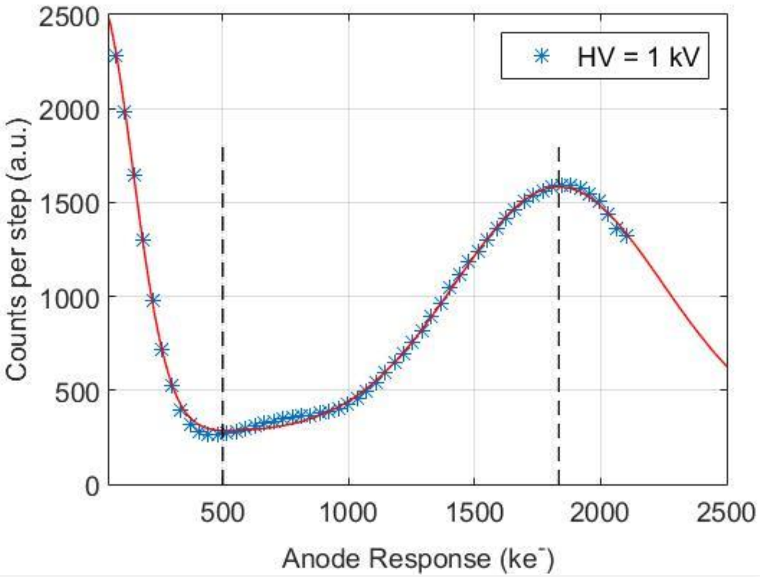
MaPMT calibration – Threshold Scan

Threshold scan: given a stable illumination, measure the hit rate increasing the trigger threshold position.



The derivative of such measure gives the single photon spectrum of the pixel under study.

derivative

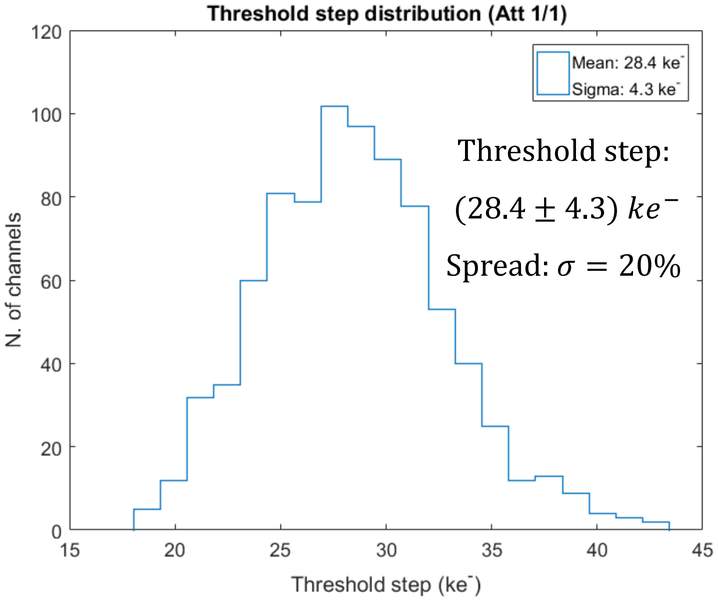


MaPMT characterization

Single photon peak position and pedestal valley can be measured on-line.

This process allows to measure the pixel gain (peak position) and the optimized threshold position.

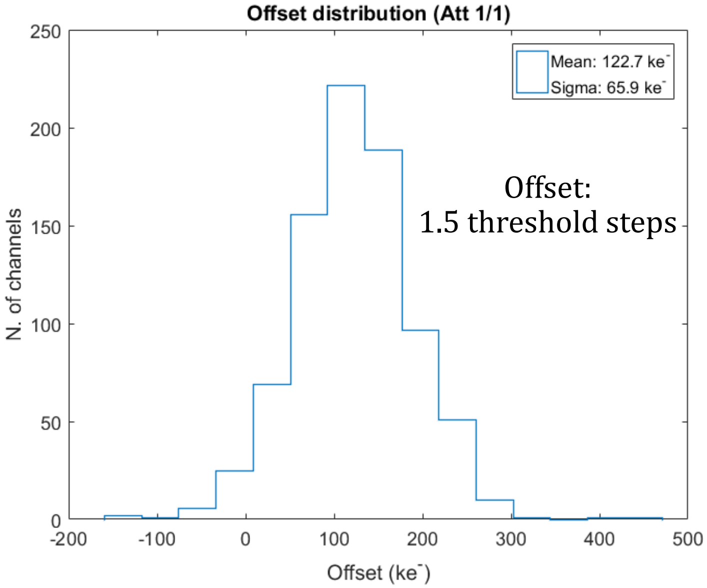
CLARO: spread between channels



Threshold step:

$(28.4 \pm 4.3)\ ke^-$

Spread: $\sigma = 20\%$



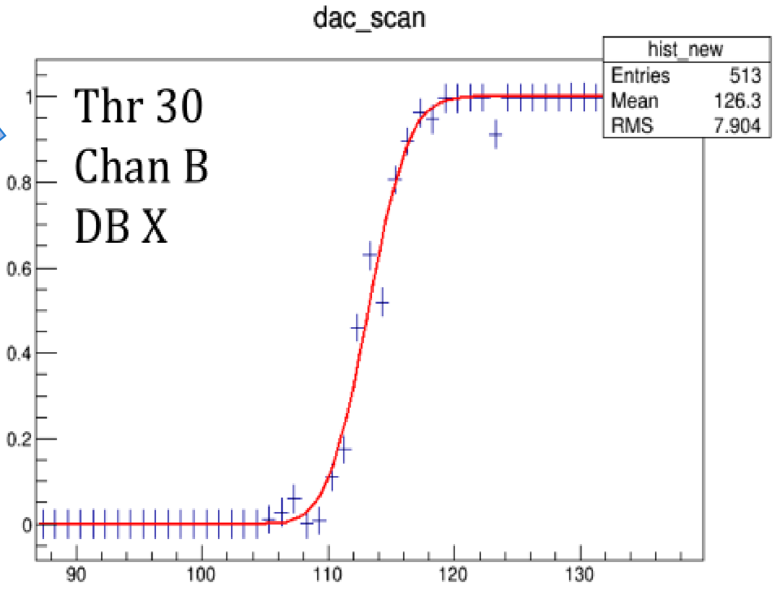
Offset:
1.5 threshold steps

- The offset can be compensated by adjusting the threshold accordingly.
- The spread of the threshold step is much lower than the gain spread expected from MaPMT pixels in a given device (1÷3).
- Radiation damages cause a variation of the nominal threshold value.

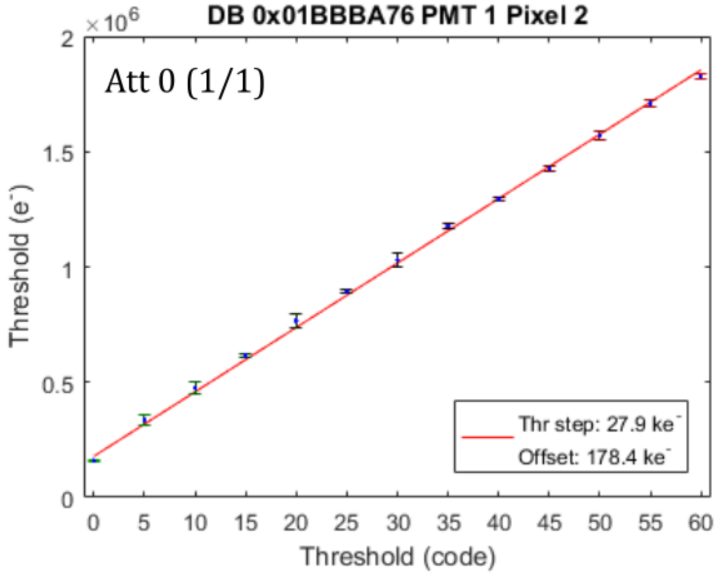
Mismatches between channels can be compensated, but periodic calibrations are required

CLARO calibration – DAC Scan

DAC scan: given a fix threshold value, inject a known signal at the CLARO input. The calibrating signal amplitude spans the whole CLARO dynamic.



A S-curve (fitted with a Erf function) is obtained. The position of the transition gives the threshold equivalent value. The slope gives the noise.



Several DAC scans

CLARO characterization

Acquiring DAC scans at various thresholds, the linear trend relating the threshold equivalent charge and the threshold code can be measured.

The slope gives the threshold step and the CLARO linearity, the intercept gives the zero-code offset.

Conclusions

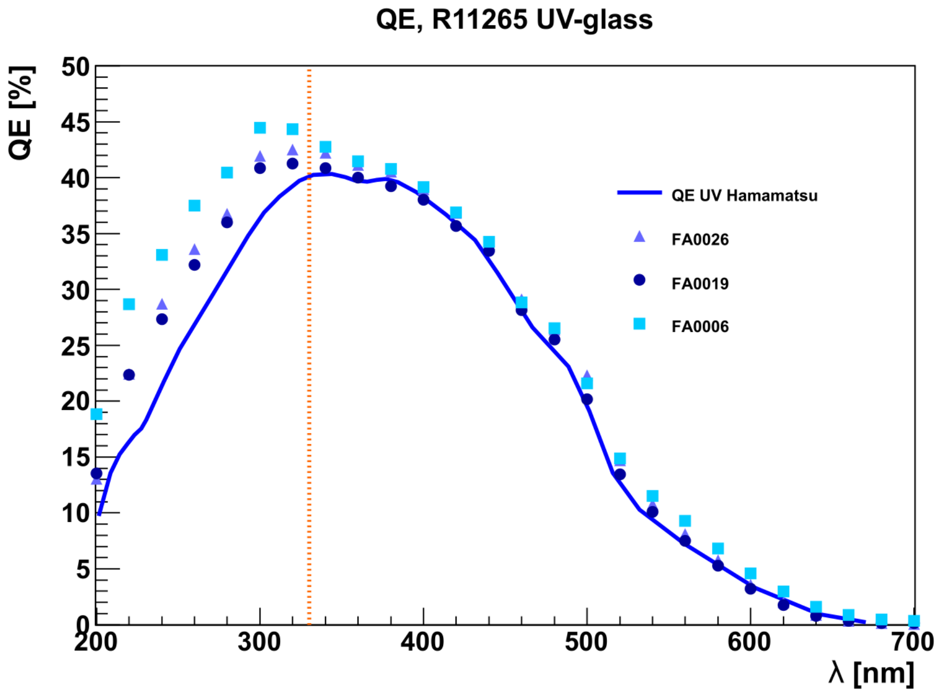
- The Elementary Cell, the minimum autonomous and fully operational module of the LHCb RICH Upgraded detector has been presented.
- The HPD photosensors currently used will be replaced by 2700 1x1 inch MaPMT (R13742) and 400 2x2 inches MaPMT (R13743).
- The CLARO ASIC was specifically designed in 0.35 μm CMOS technology from AMS for the MaPMT read-out. It ensures high bandwidth, low power consumption, radiation tolerance and more than adequate resolution and range.
- The Elementary Cell layout is optimized to minimize the spurious counts due to dark counts and cross-talk
- The non-uniformity of both photosensors and electronics can be compensated with proper calibration procedures.

The end

Thank you for the attention!

MaPMT: quantum efficiency

- Gain uniformity in agreement with the expectations. It is compensated by the readout electronics.
- Gain vs Temperature
- Noise vs Temperature
- Cross-talk
- Quantum efficiency

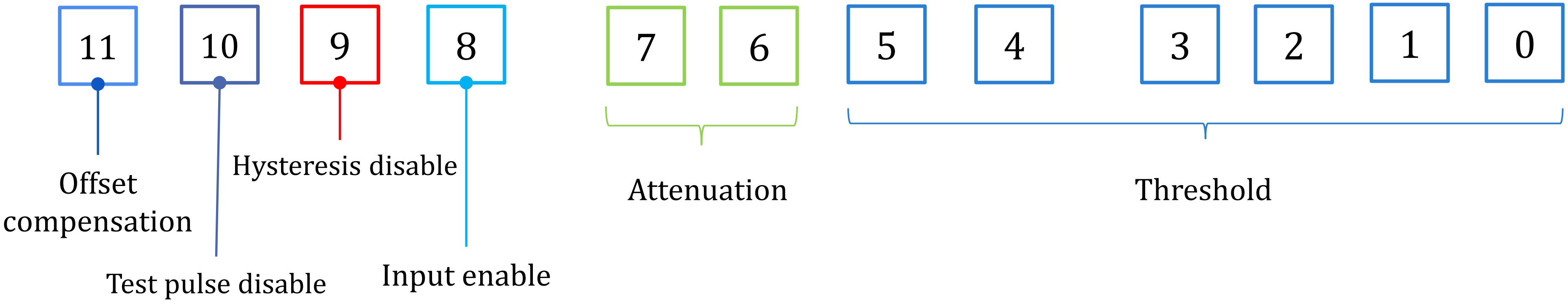


Quantum efficiency is the number of photoelectrons emitted from the photocathode divided by the number of incident photons. It was measured from the current read at the photocathode induced by a known incident photon rate.

$\mathrm{QE} \simeq 35 - 40\ \%$ at the wavelength of interest

The UV-Glass ensures also better performance in terms of radiation tolerance.

Channel digital register


11 10 9 8 7 6 5 4 3 2 1 0

Offset compensation

Test pulse disable

Hysteresis disable

Input enable

Attenuation

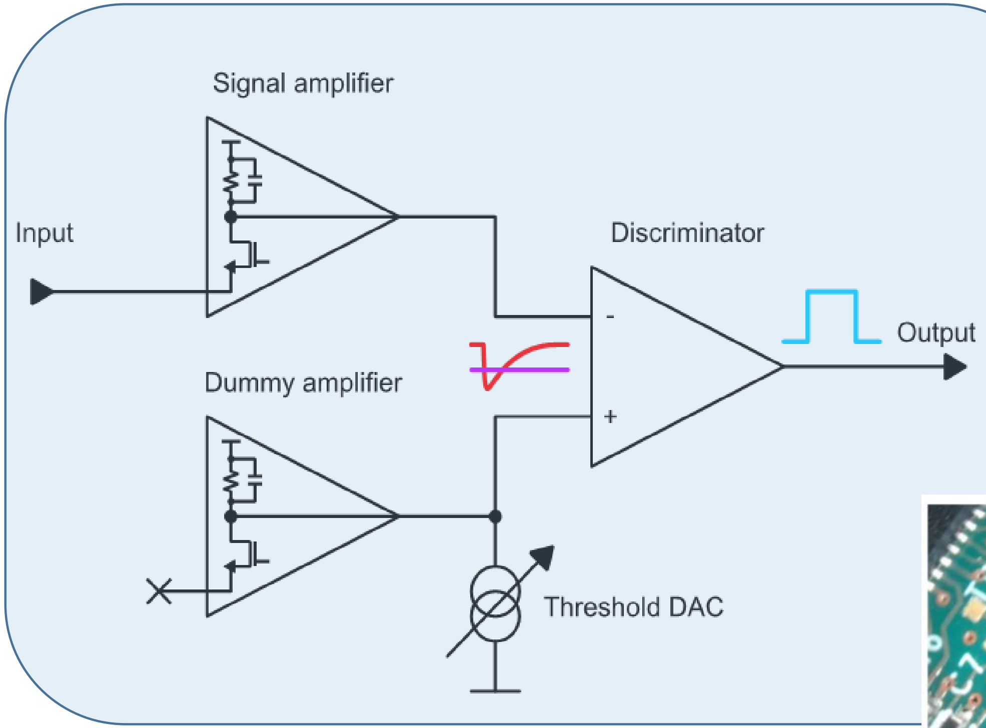
Threshold

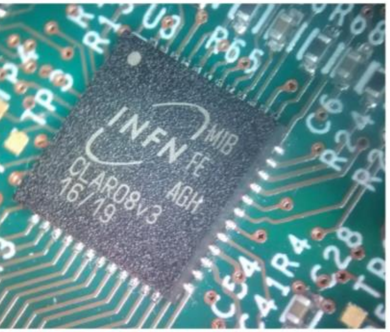
The CLARO is programmable using a SPI bus.
Each channel is equipped with a 12 bits configuration register allowing to configure:

- 64 threshold values. Without attenuation, the typical threshold step is 30 ke^-, and ranges up to 2 Me^-.
- 4 gain values: nominal attenuation of the input signal by a factor 1, 1/2, 1/4, 1/8.
- 1 bit to enable/disable the input.
- 1 bit to enable/disable the hysteresis.
- 1 bit to enable the trigger a test pulse useful for the CLARO calibration.
- Tolerance between the CSA and the dummy components can results in an offset in the threshold levels. Bit11 allows to shift the threshold by half the range to compensate it.

The digital block is synthesized with cells rad hard by design. Using to a Triple Modular Redundancy technique, the CLARO is able to detect, count and self-correct any Single Event Upset (SEU).

CLARO channel



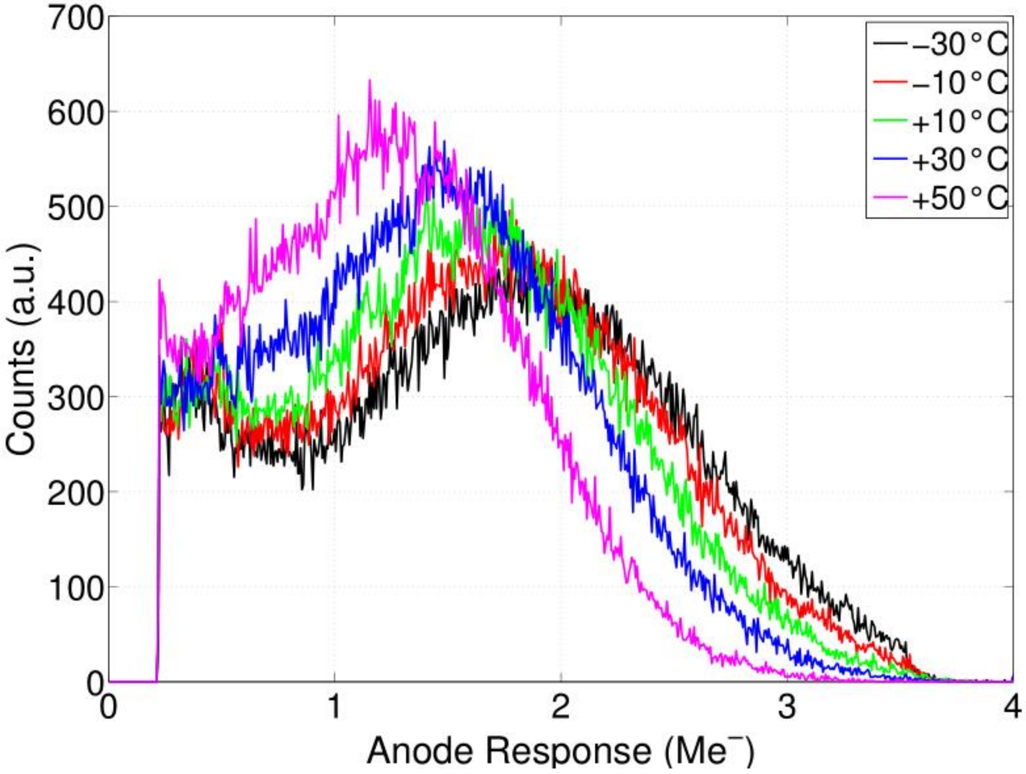


Analogue simplified Scheme

- The CLARO is a 8 channel ASIC.
- A CLARO channel is made by two identical charge sensitive amplifiers, a «signal amplifier» and a «dummy amplifier»
- The «dummy amplifier» improves the PSRR (>40 dB up to 2 MHz)
- The «threshold DAC» sinks a current to offset the output of the «dummy amplifier»
- The amplifier is DC-coupled to the «discriminator» (a voltage comparator)
- The output of the comparator feeds an active output pad

MaPMT: temperature behaviour

- Gain uniformity in agreement with the expectations. It is compensated by the readout electronics.
- Gain vs Temperature

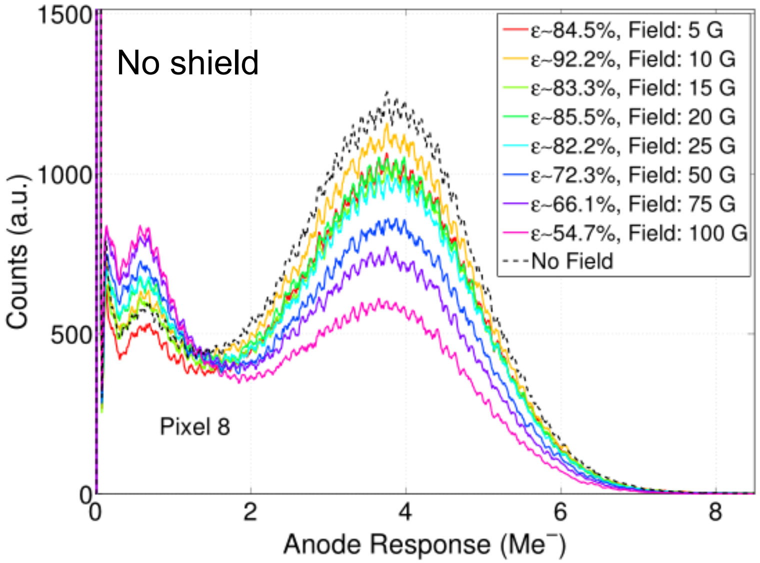


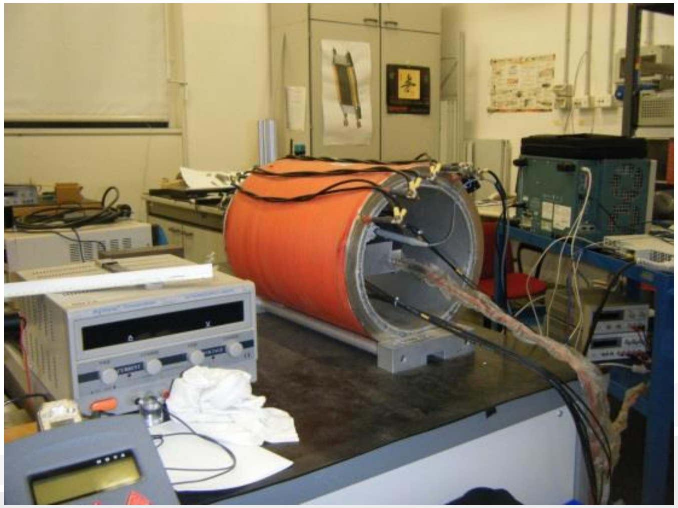
The gain reduces almost linearly by about 0.25 % /°C

MaPMT: behaviour in magnetic field

- Gain uniformity in agreement with the expectations. It is compensated by the readout electronics.
- Gain vs Temperature
- Noise vs Temperature
- Cross-talk
- Quantum efficiency
- Behaviour in magnetic field:
  1. Field orientation
  2. Shielding material
  3. Shielding configuration

Efficiency loss ~ 15% (at 15 G) without shielding the device for peripheral pixels.





MaPMT: behaviour in magnetic field

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  1. Field orientation
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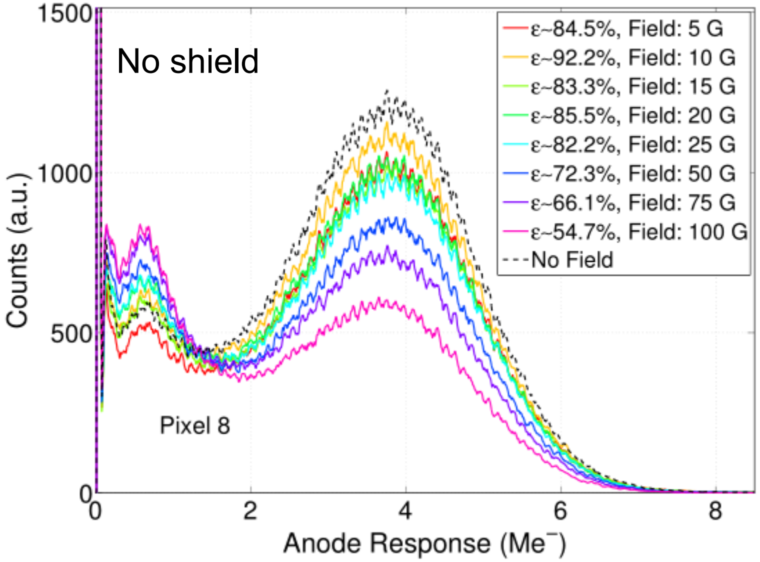
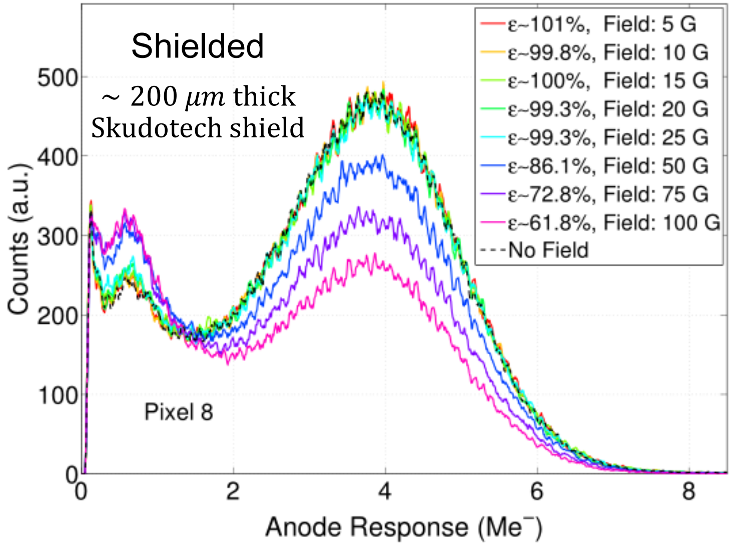
  3. Shielding configuration

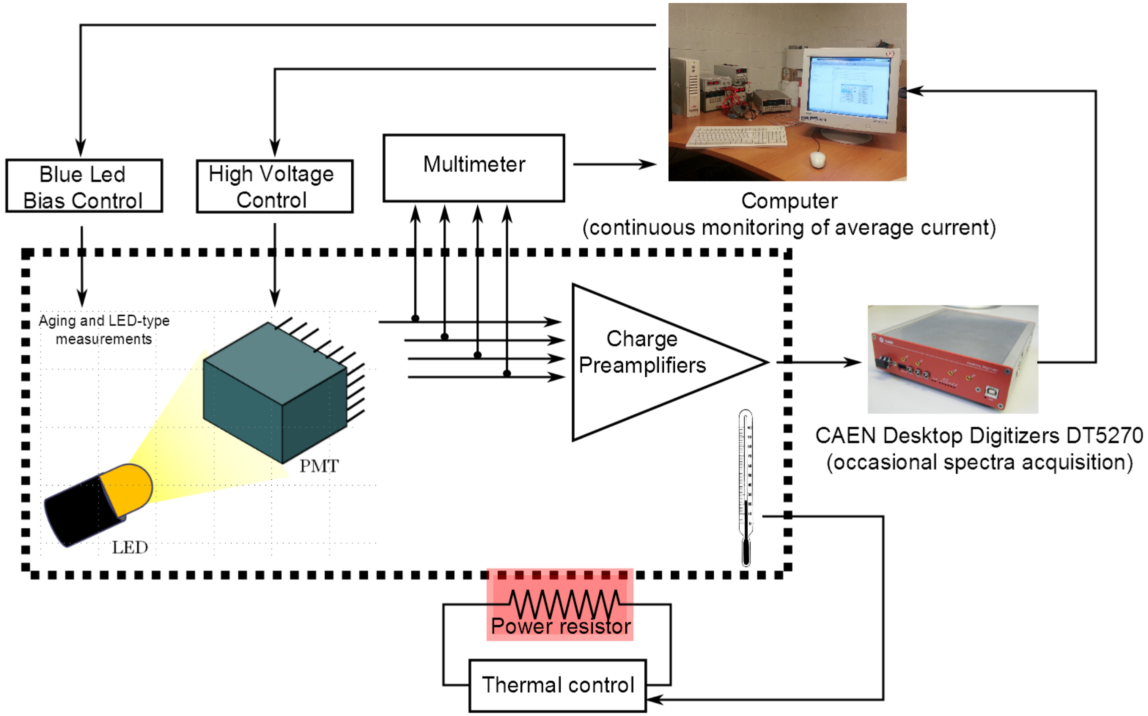
Efficiency loss ~ 15% (at 15 G) without shielding the device for peripheral pixels.
At moderate fields, the full performance can be recovered using a shield made of high permeability material.
Cross-shaped μ-metal shield designed for the EC-R.





MaPMT: aging tests

- Gain uniformity in agreement with the expectations. It is compensated by the readout electronics.
- Gain vs Temperature
- Noise vs Temperature
- Cross-talk
- Quantum efficiency
- Behaviour in magnetic field:
    1. Field orientation
    2. Shielding material
    3. Shielding configuration
- Aging
    1. Gain variation
    2. Efficiency loss
    3. Noise increase



Blue Led Bias Control

High Voltage Control

Multimeter

Computer
(continuous monitoring of average current)

Aging and LED-type measurements

PMT

LED

Charge Preamplifiers

CAEN Desktop Digitizers DT5270
(occasional spectra acquisition)

Power resistor

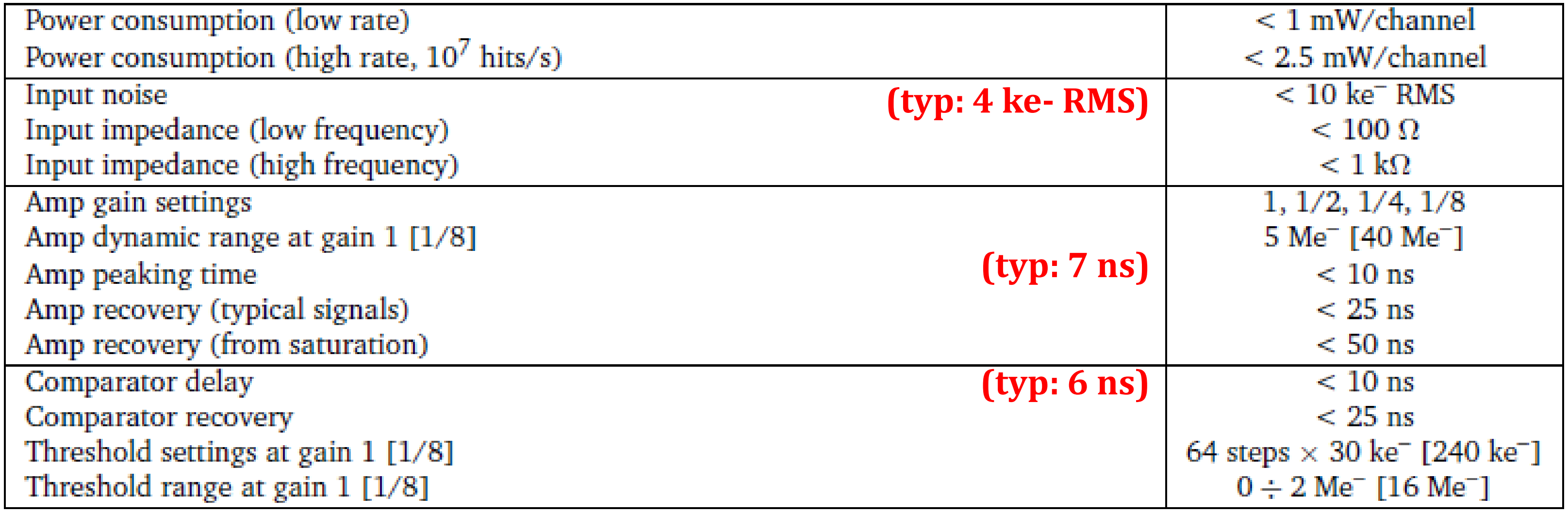
Thermal control

The tests lasted 3000 hours, at stable illumination level and temperature.
Both DC current variation and single photon spectra are acquired.

The most critical parameter is the gain variation due to the wear of the dynodes.

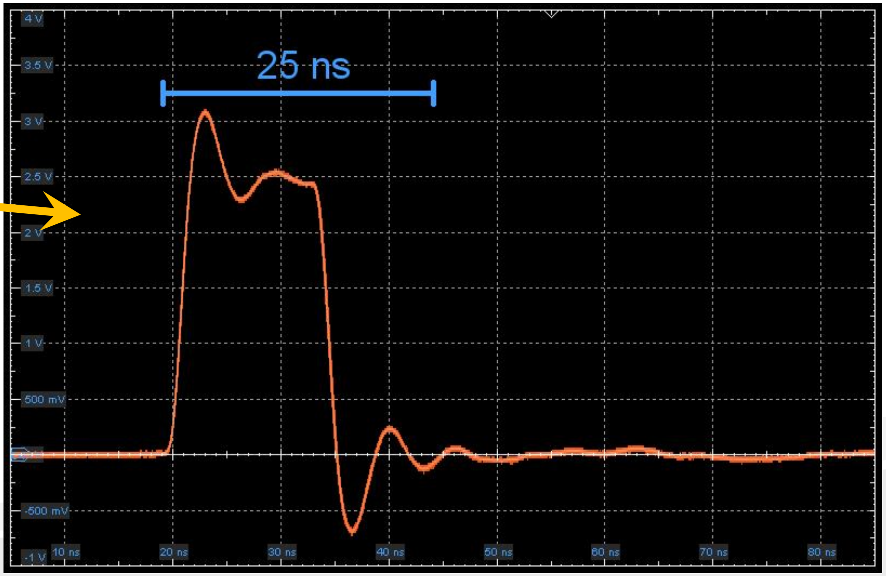
CLARO peformance

Channel specs for 10 pF input load, 30 pF output load (typical values):



Power consumption (low rate)		< 1 mW/channel
Power consumption (high rate, 10^7 hits/s)		< 2.5 mW/channel
Input noise	**(typ: 4 ke- RMS)**	< 10 ke⁻ RMS
Input impedance (low frequency)		< 100 Ω
Input impedance (high frequency)		< 1 kΩ
Amp gain settings		1, 1/2, 1/4, 1/8
Amp dynamic range at gain 1 [1/8]		5 Me⁻ [40 Me⁻]
Amp peaking time	**(typ: 7 ns)**	< 10 ns
Amp recovery (typical signals)		< 25 ns
Amp recovery (from saturation)		< 50 ns
Comparator delay	**(typ: 6 ns)**	< 10 ns
Comparator recovery		< 25 ns
Threshold settings at gain 1 [1/8]		64 steps × 30 ke⁻ [240 ke⁻]
Threshold range at gain 1 [1/8]		0 ÷ 2 Me⁻ [16 Me⁻]

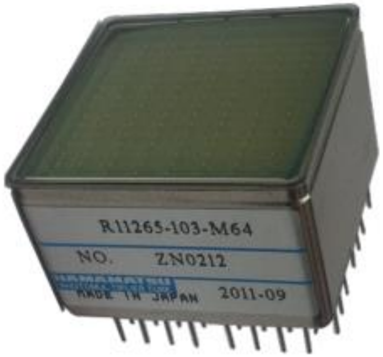
Typical single photon hit at the output of the CLARO



Multi–anode Photomultiplier tube

R13742

Customisation of the R11265 MaPMT



R13743

Customisation of the R12699 MaPMT

Window material / thickness	UV glass / 0.8 mm
Photocathode material	Super Bialkali
Spectral response range	185 – 650 nm
Number of pixels	64
Number of dynodes	12
Maximum supply voltage	−1.1 kV
Typical gain at −1 kV	$> 1 \times 10^6$
Uniformity between pixels	1 ÷ 3
Dark current (average per pixel)	0.4 nA
Rise / transit time	0.6 ns / 5.1 ns

Feature	R11265	R12699
Geometrical dimension	25,4×25,4 mm^2	51×51 mm^2
Photocathode minimum active area	23×23 mm^2 (>80 %)	48.5×48.5 mm^2 (>87 %)
Number of pixel and dimension	64 / 2,9×2,9 mm^2	64 / 6×6 mm^2

See the S. Gambetta poster describing the Quality Assurance Testing of MaPMTs for the LHCb RICH Upgrade

EC components

MaPMT	R13742 and R13743 models, produced by Hamamatsu. They are able to detect single photons.
Baseboard (BsB)	Socket holding the MaPMT. The baseboard hosts the voltage divider biasing the photosensor (P=330 mW). Thermal mass connected to the cooling bar
CLARO	8 channel ASIC for the fast photon counting.
Front-end Board (FEB)	Each FEB hosts 8 CLAROs, 4 per side. Minimized capacitance to reduce noise and cross-talk. Provides the 2.5 V biasing the CLAROs. Leads the output signal towards the DB
Backboard (BkB)	Leads the digital CLARO signal from the FEB to the DB. It hosts a 8-bit DAC useful for calibration a debug.
Digital Board (DB)	Allows to configure the CLAROs and collects its output signal sending it off the detector. Direct contact to the cooling bar to prevent heat injection towards the MaPMT.
External Metalic structure	Give the mechanical support to the EC. It is made of high termal conductance metal to thermalize the baseboard.