CLARO-CMOS: a Fast, Low Power and Radiation-hard Front-end ASIC for Single-photon Counting in 0.35 μm CMOS Technology

Authors

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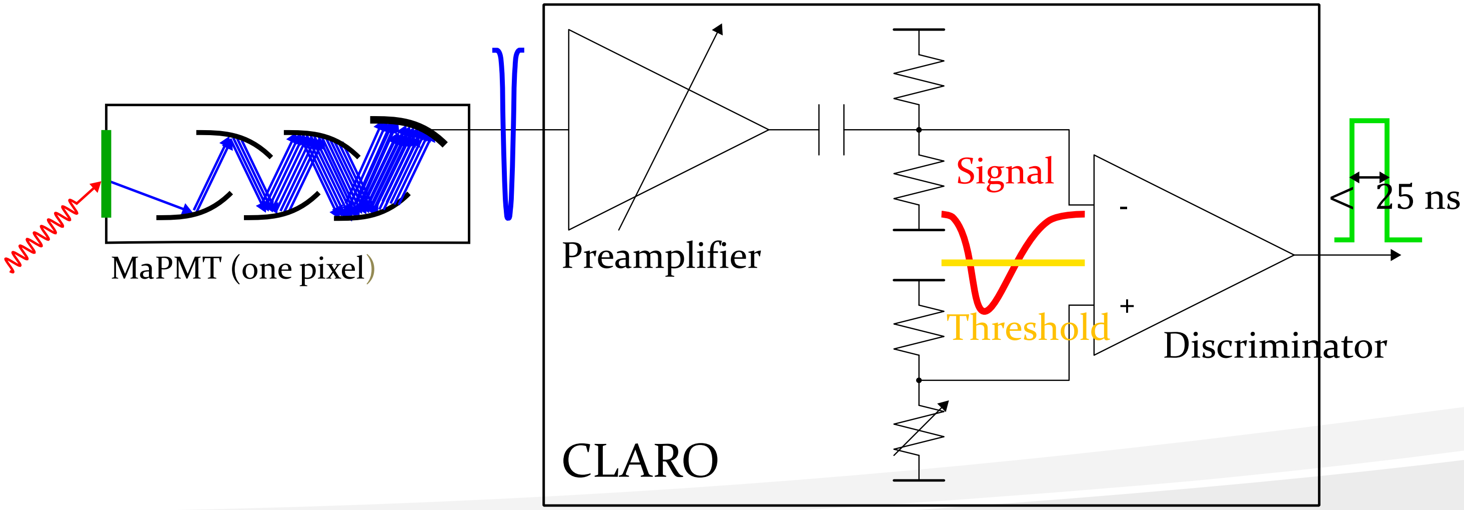
Overview of the CLARO ASIC

The CLARO is an integrated circuit designed for single photon counting with Ma-PMTs.

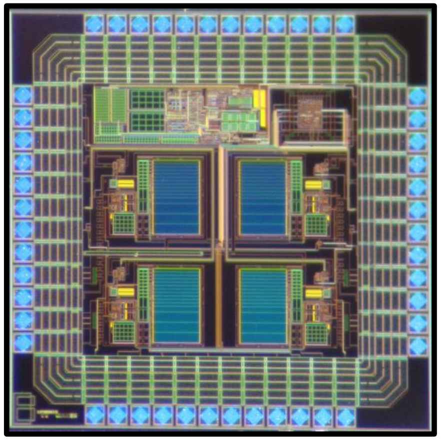
Main features:

- 0.35 µm CMOS technology from AMS → Low cost, high yield, long lifespan
- Photon counting at 40 MHz rate → Recovery time < 25 ns
- Low power consumption → ≤ 1 mW/channel
- Settable gain and threshold → 8 bits per channel

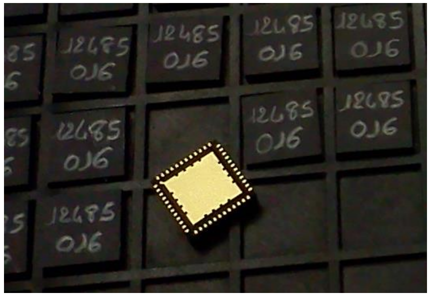


The CLARO timeline

Die photograph



- **2011**:
  - ➡ The **4 channel prototype** «CLARO-CMOS» was designed
- **2012**:
  - ➡ Deep characterization on the test bench
- **2013**:
  - ➡ Radiation hardness tests with neutrons and X-rays
  - ➡ Tests of the CLARO-CMOS with R11265 MaPMTs
  - ➡ **Chosen as the baseline front-end ASIC for the LHCb RICH upgrade**
- **2014**:
  - ➡ Radiation hardness tests with protons
  - ➡ New & improved **8 channels version** «CLARO8*» and an **improved 4 channel version** «CLARO4v1» (both currently under testing)

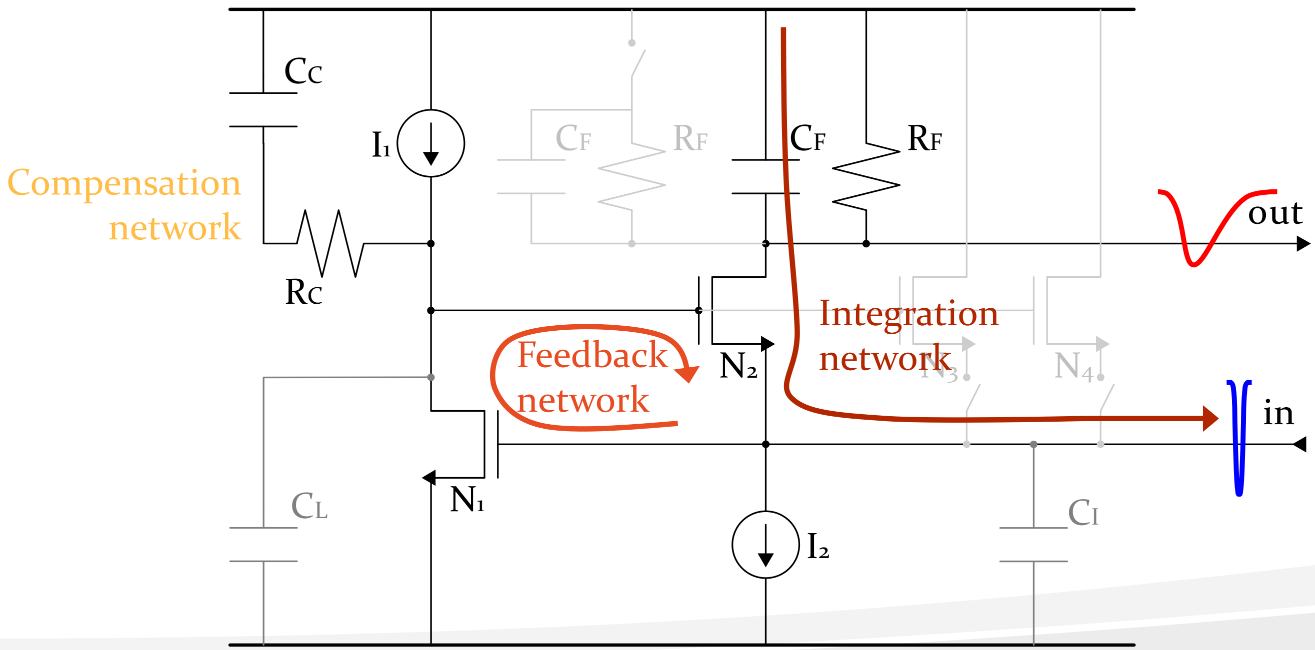


QFN48 package

* in collaboration with M.Baszczyk, P.Dorosz, W.Kucewicz, AGH, Krakow, Poland

CLARO preamplifier schematic

- Active cascode or «super common base» topology (similar to others ASIC)
- The charge signals are integrated and converted to voltage signals on C_F and R_F
- N_1 provides a feedback loop to keep the input impedance of N2 low (about 100 Ω)
- C_C and R_C are needed to keep the feedback loop stable
- (C_I and C_L are the main contributions from parasitics)

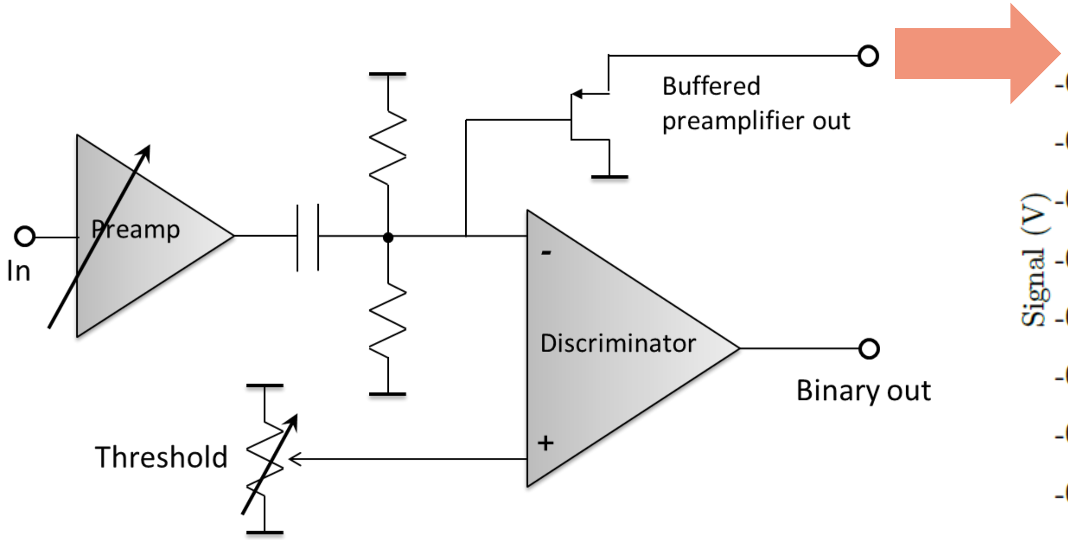


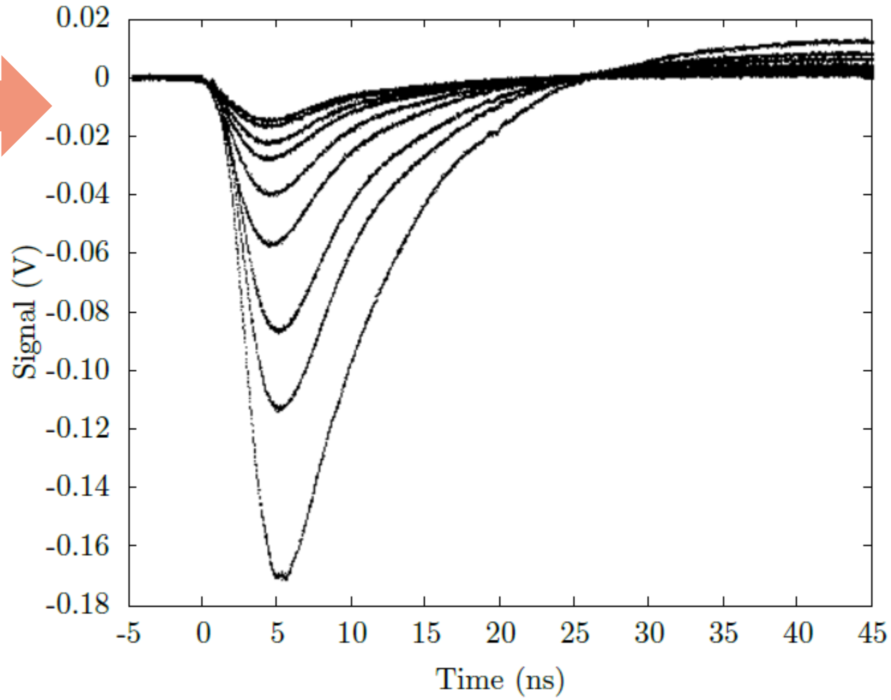
See **JINST 7 P11026** for more details

Auxiliary analog output

The analog output is buffered with a PMOS follower. It is used only for debugging, not for photon counting.

Signals at the analog output, for typical MaPMT signals at the input (330 ke$^-$ to 3.3 Me$^-$), are shown.





The AC coupling between the preamplifier and the discriminator causes an undershoot

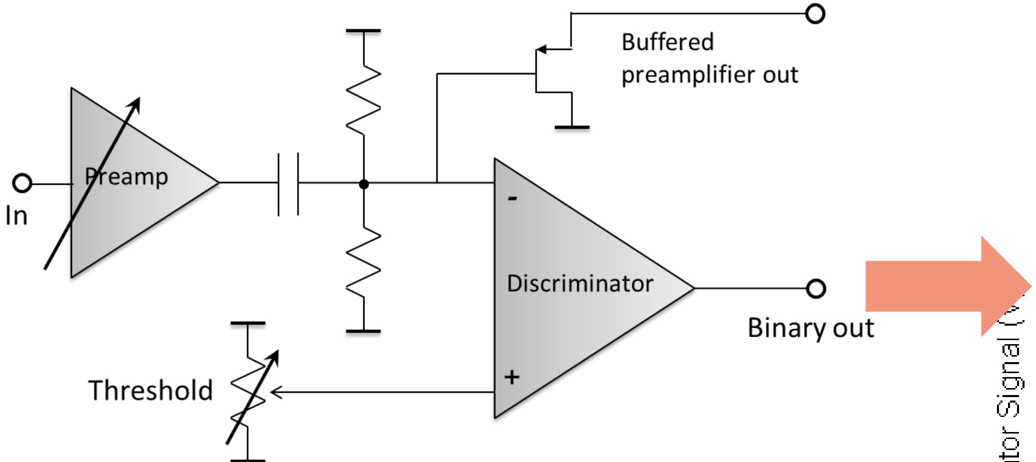
→ Threshold shift of 10% at a rate higher than about 10 MHz

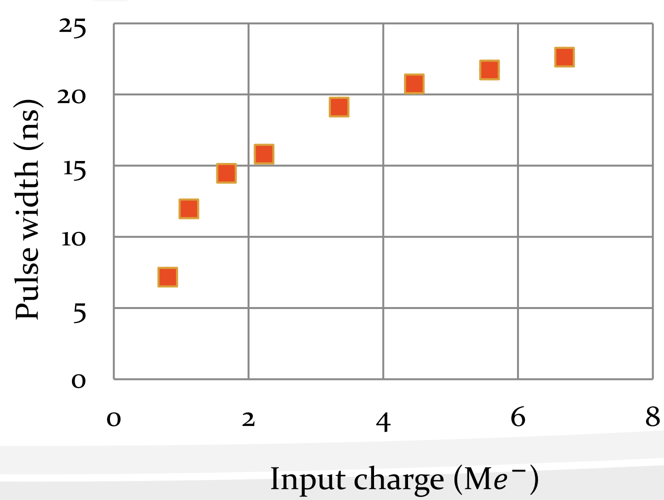
→ AC coupling removed in the new chip version

Main digital output

When the shaped signal crosses the threshold level, a binary pulse is generated on the CLARO digital output allowing the photon counting.

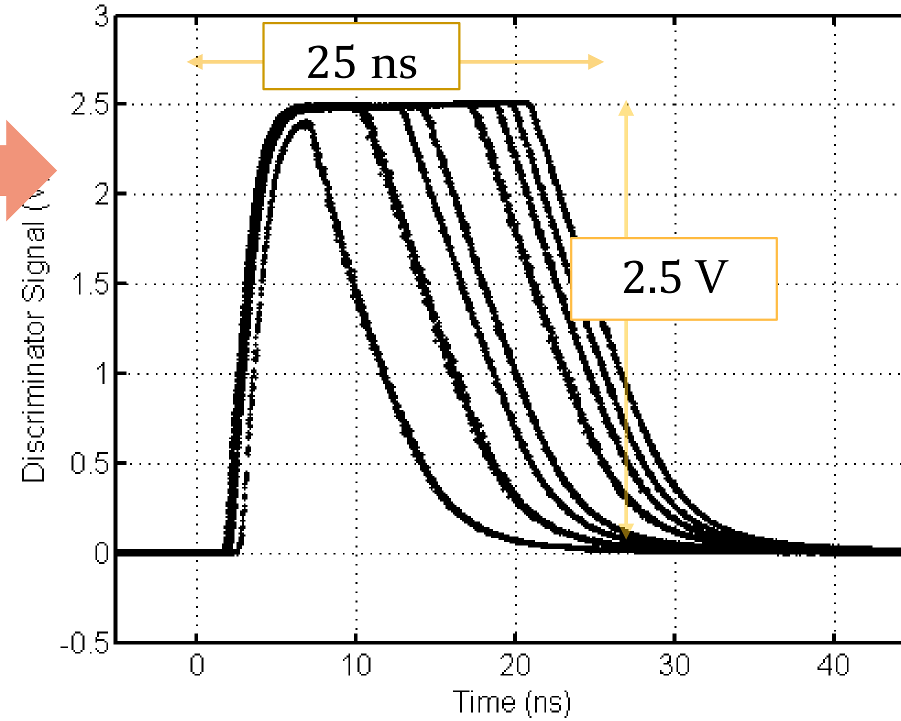
The pulse width is lower than 25 ns for signals up to 10 times over threshold.





Input charge: from 800 ke$^-$ to 5.6 Me$^-$

Threshold level: ~ 750 ke$^-$.



$C_I \simeq 8$ pF

$\tau_R \simeq 2.2$ ns

$\tau_F \simeq 9.3$ ns

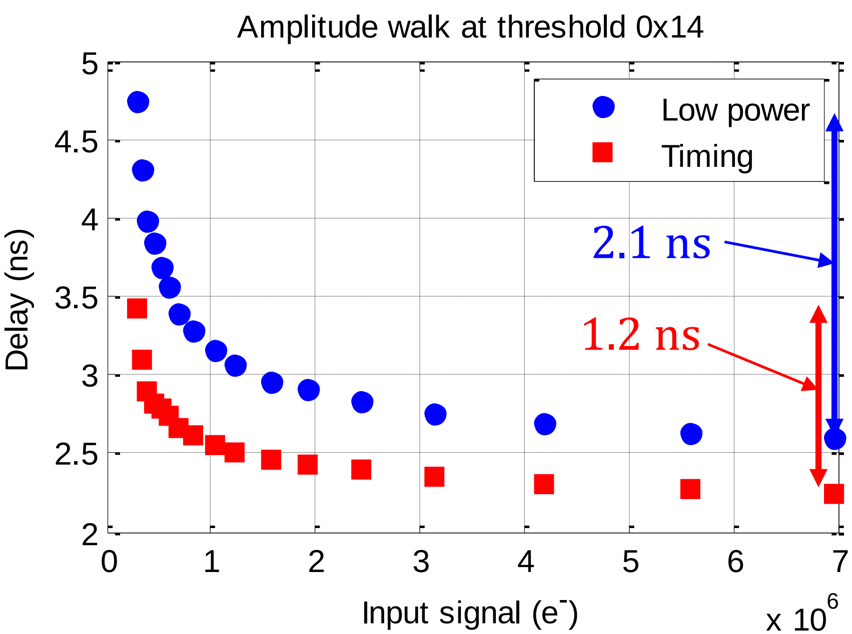
Timing performance

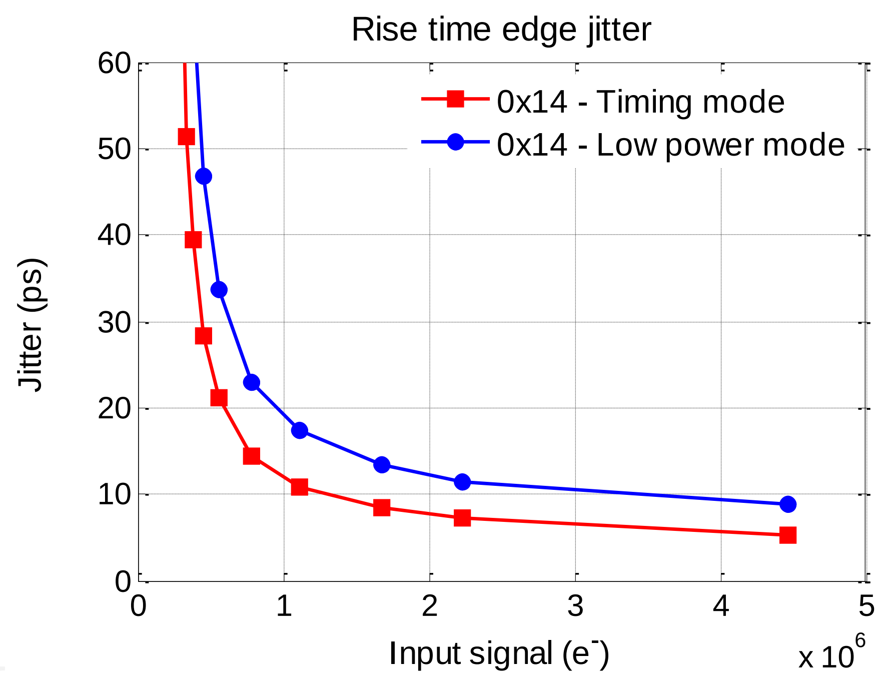
Excellent timing performance at normal «low power» mode (0.7 mW/channel) and even better in «timing mode» (1.5 mW/channel):

- Amplitude walk: 1.2 ns
- Leading edge jitter:
  - 90 ps RMS just above threshold (300 ke⁻ or 1/6 of PMT gain)
  - below 10 ps RMS for large signals (> 1 Me⁻, close to PMT gain)

Threshold set at 300 ke⁻

Ci = 3.3 pF





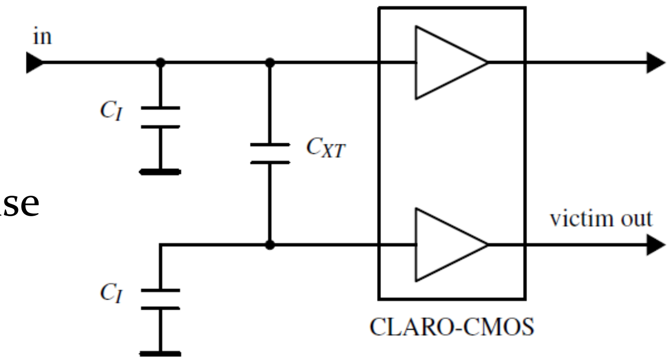
Input capacitance

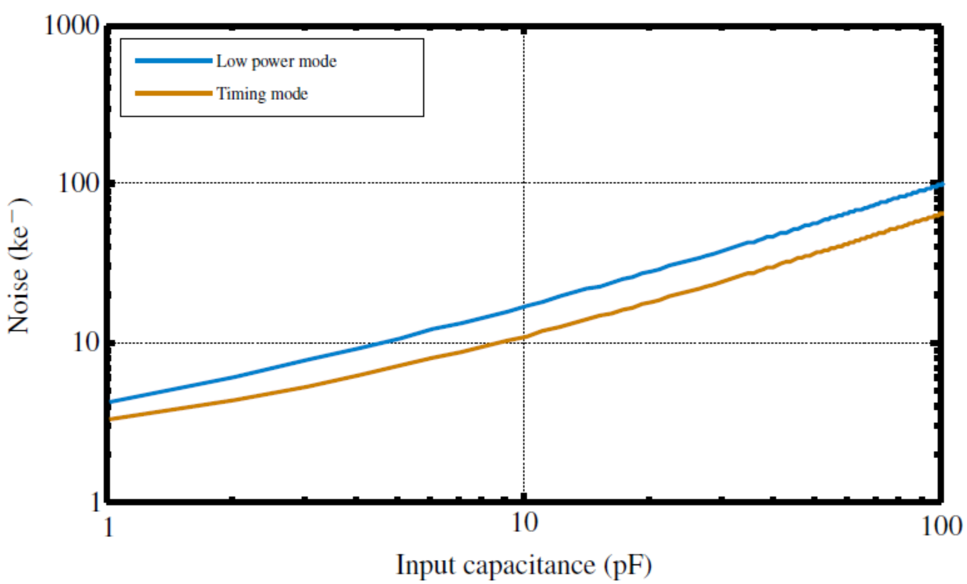
The input capacitance to ground and to neighbouring pixels should be minimized:

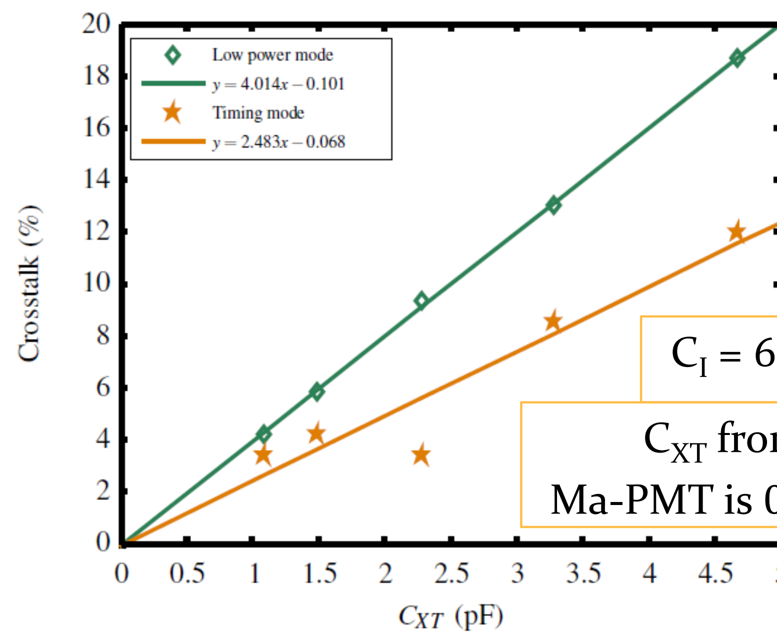
- The input capacitance to ground gives noise
- The input capacitance between pixels gives crosstalk and noise

→ The minimization of input capacitance guides the layout of the CLARO PCBs

→ It is one of the main reasons to keep low the number of channels per chip, so that the length of the traces connecting the pixels to the chip is minimized



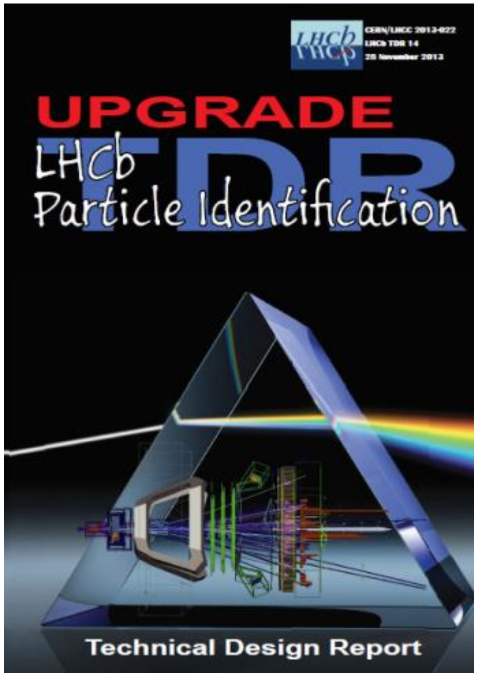




C_I = 6.5 pF

C_{XT} from the Ma-PMT is 0.5 pF

CLARO in LHCb RICH upgrade

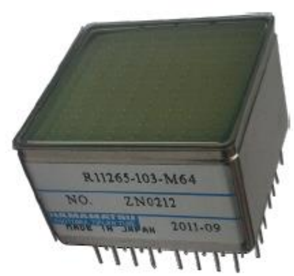


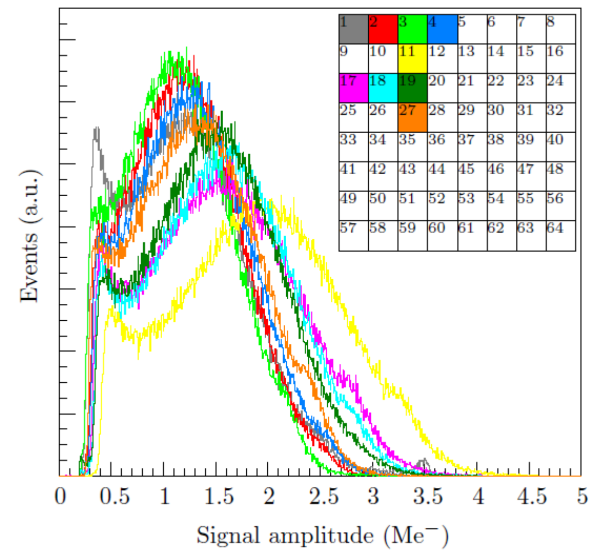
CLARO proved to be suited for the use in LHCb RICH

→ CLARO was chosen as the baseline front-end ASIC for reading the Hamamatsu R11265 MaPMT in the upgraded RICH detectors

Hamamatsu R11265 Ma-PMTs:

- Single photon peak at about 1 Me^-
- Gain spread 1: 3 between pixels



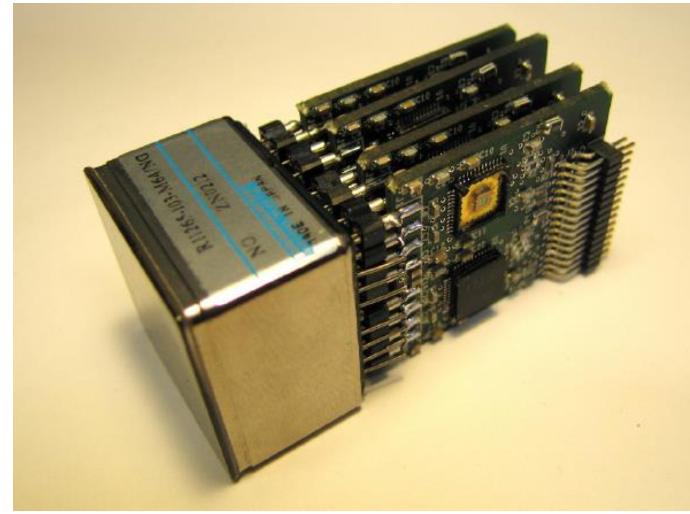


→ CLARO test with Hamamatsu R11265

→ CLARO radiation hardness tests

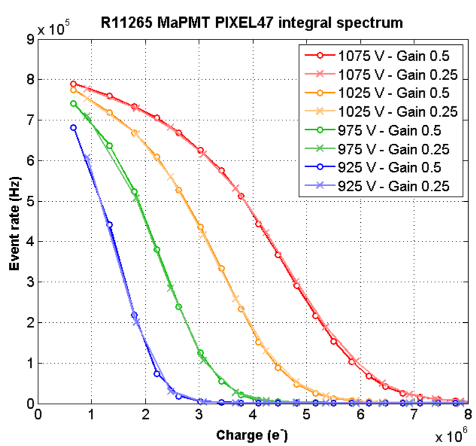
CLARO & MaPMT R11265

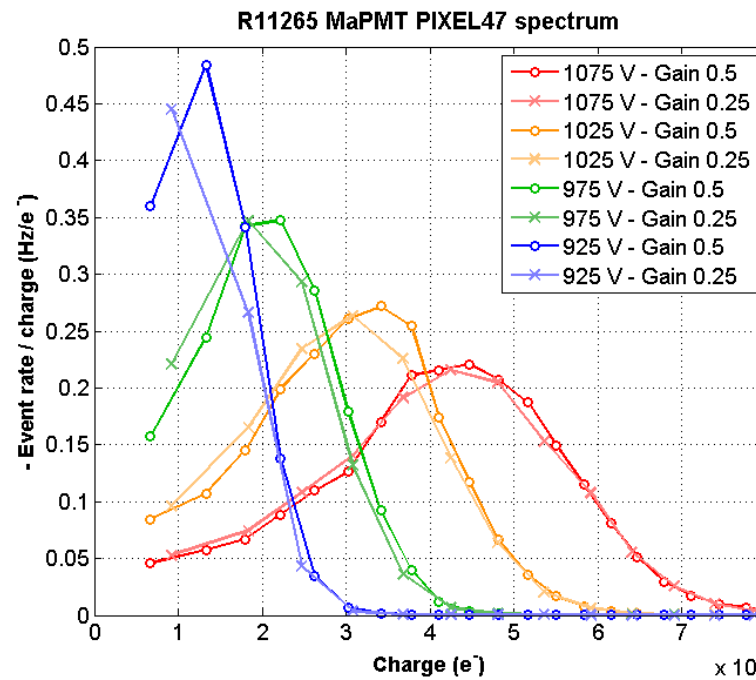
- A set of PCBs to interface the R11265 MaPMT to the CLARO were designed and tested.
- The compact design allows to minimize the parasitic capacitance at the inputs of the chip.



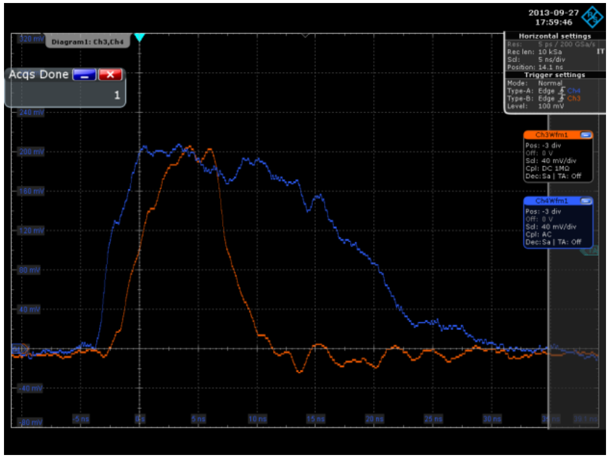
By illuminating the MaPMT with a LED and by counting the signal rates during a CLARO threshold scan, the single photon spectra of the MaPMT can be measured.

The spectra are well reconstructed: the S/N ratio is more than adequate.





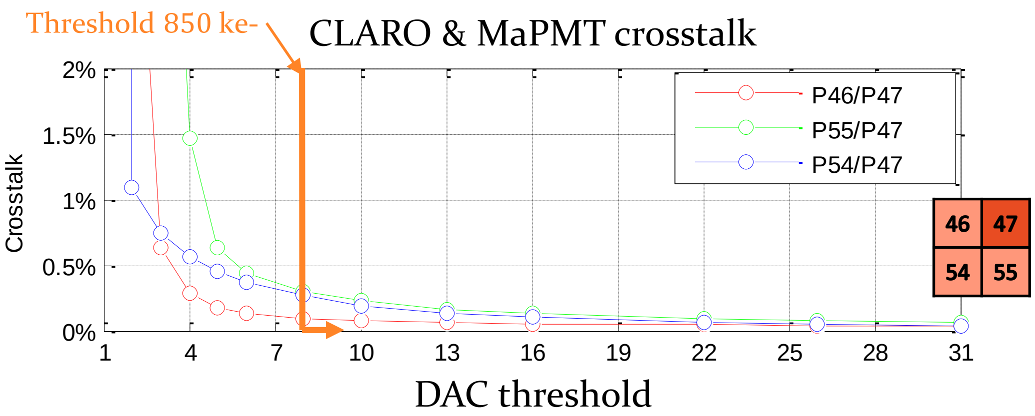
Crosstalk with MaPMT R11265



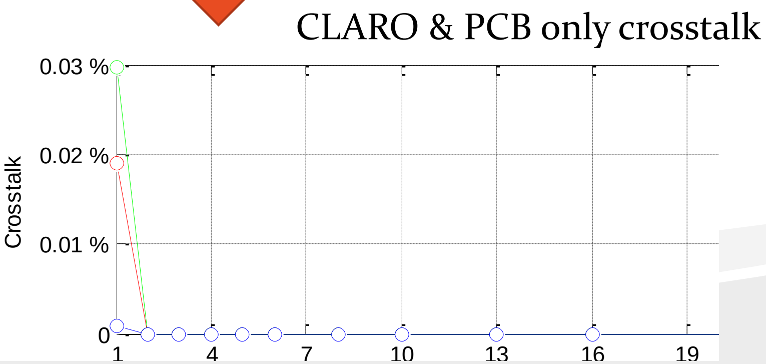
By triggering in coincidence two neighbour pixels (thanks to a beautiful R&S RTO 1044 oscilloscope) it is possible to evaluate the crosstalk rate.

Crosstalk is **below 0.3%** at the binary output

with a threshold of 850 ke⁻ (the most meaningful with the PMT biased to 1100 V, gain 4.2 Me⁻)



If only one pixel of the PMT is connected, crosstalk is almost zero
→ All the contribution comes from the PMT inter-pixel capacitance



LHCb RICH radiation environment

Accordingly to the simulations[a], the worst-case radiation levels expected in the RICH detectors for 1 year running in the current geometrical configurations are[b]:

	Neutrons $1\ MeV\ n_{eq}\ [cm^{-2}]$	Hadrons $E_H > 20\ MeV\ [cm^{-2}]$	Total ionizing dose $[krad]$
RICH-1	$\mathbf{6.1 \cdot 10^{11}}$	$2.3 \cdot 10^{11}$	39.6
RICH-2	$3.1 \cdot 10^{11}$	$1 \cdot 10^{11}$	15.9

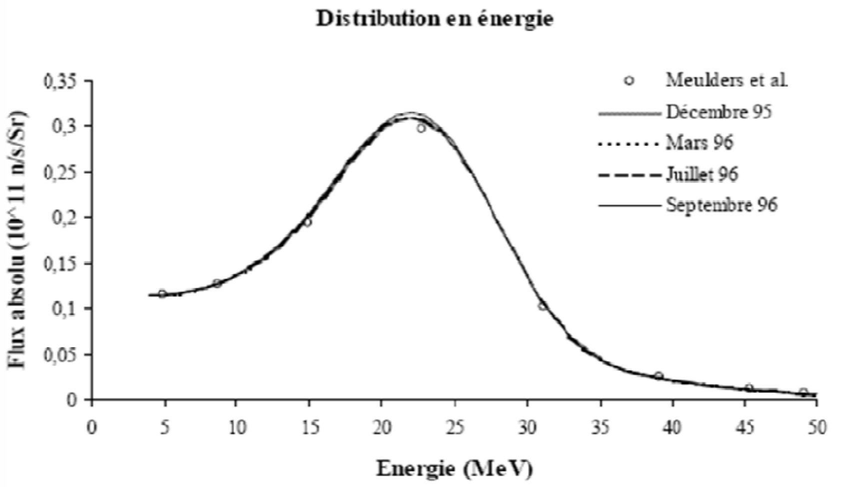
NOTES

- Final geometry and materials have not been implemented.
- 10-30% of statistical errors.
- No safety factor included

a) Presented by M. Karacson on February 14th, 2013 at the LHCb Upgrade Electronics Meeting (http://indico.cern.ch/event/225746/contribution/2/material/slides/0.pdf).
b) Assumptions: 1 year running ($10^7\ s$), LHC luminosity: $L = 2 \cdot 10^{33}\ s^{-1}cm^{-1}$, cross section $\sigma = 84\ mbarn$

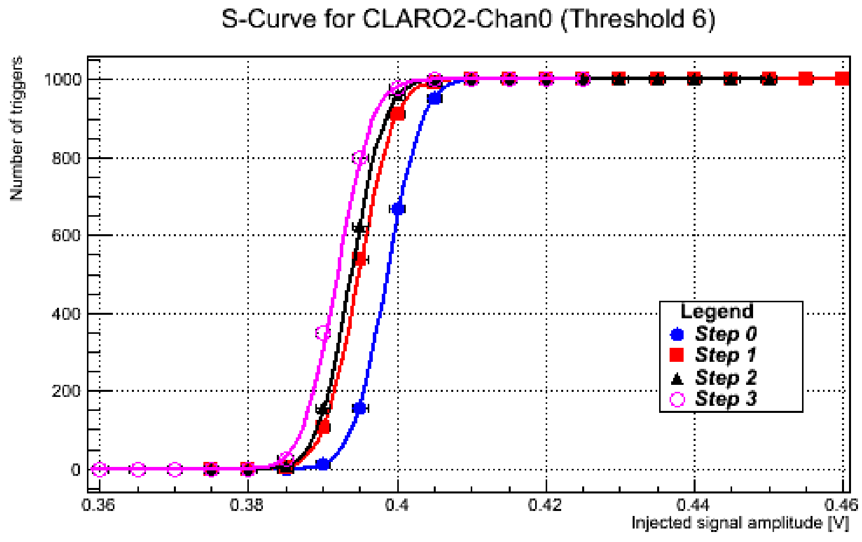
Neutron irradiation

The neutron irradiation was performed in Louvain-la-Neuve (Belgium) in May 2013.



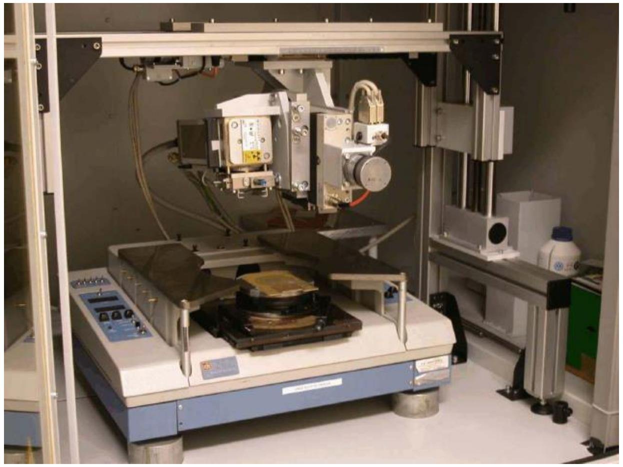
4 samples were powered and irradiated up to a fluence of 10^{14} 1-MeV n_{eq} cm^{-2} (about 160 years in LHCb) in three steps.

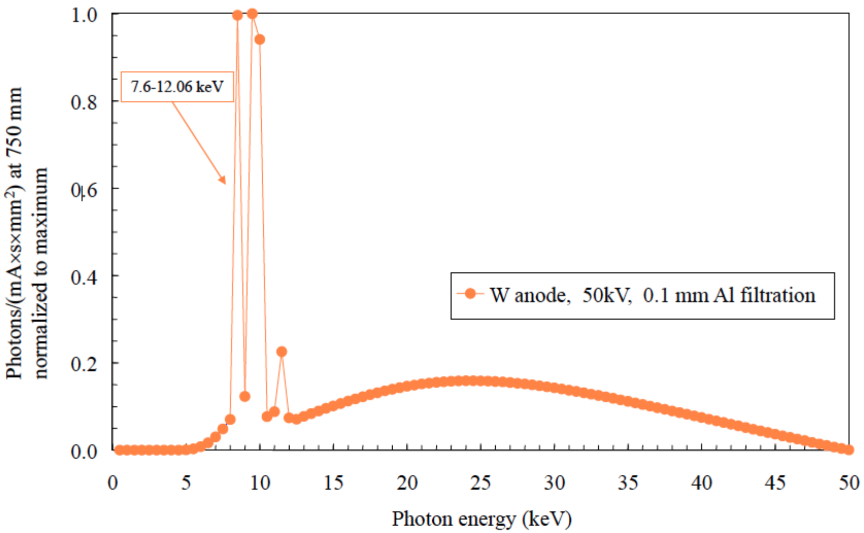
- No SEU / SEL observed
- No variation in supply current
- No significant variation in thresholds and noise



X-ray irradiation

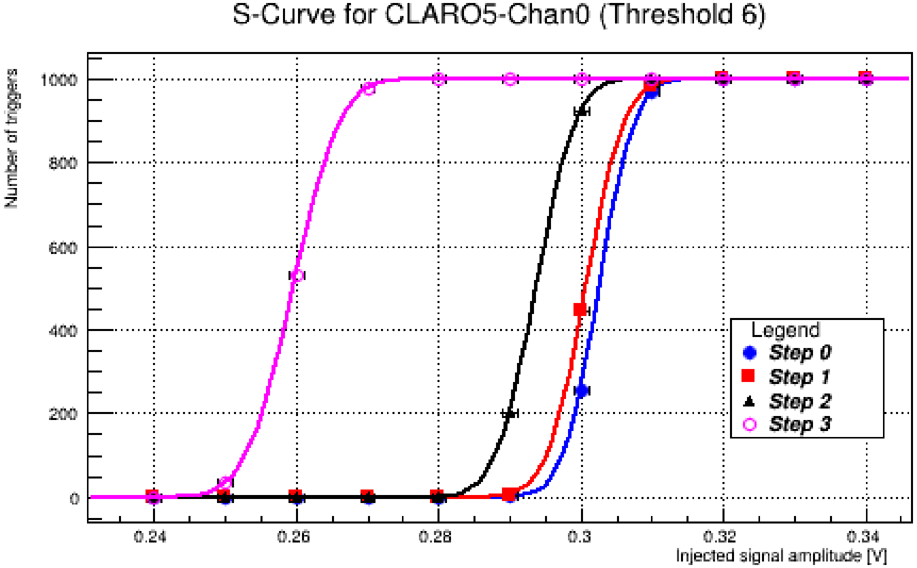
The X-ray irradiation was performed in Legnaro (Italy) in September 2013.





2 samples (with the package lid removed) were powered and irradiated up to 4 Mrad (about 110 years in LHCb) in three steps.

- No SEU / SEL observed
- 10-15% decrease in supply current
- 10-15% variation in channel threshold



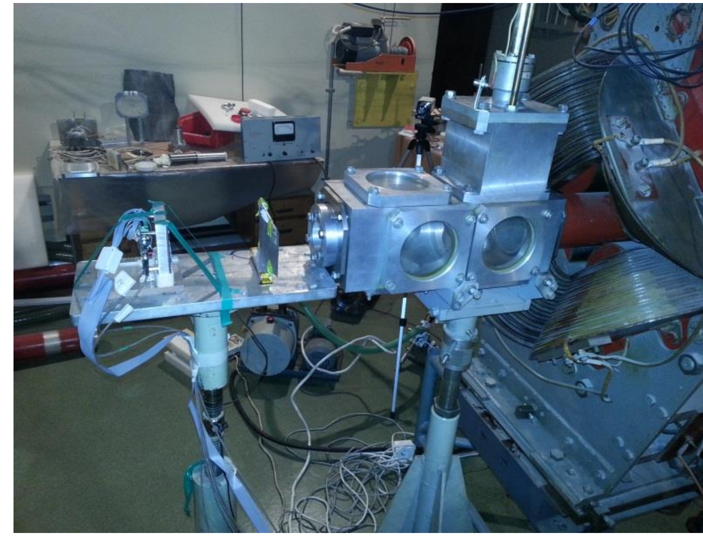
Proton irradiation

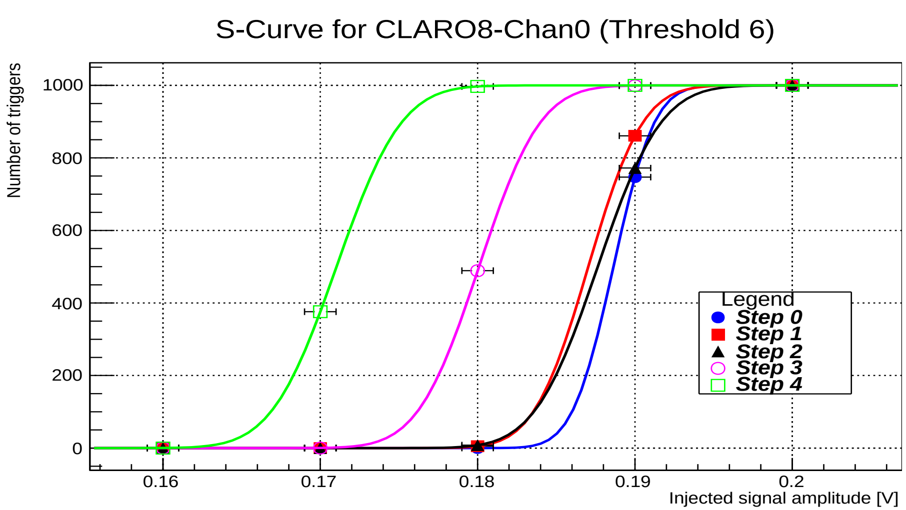
The proton irradiation was performed in Krakow (Poland) in February 2014.

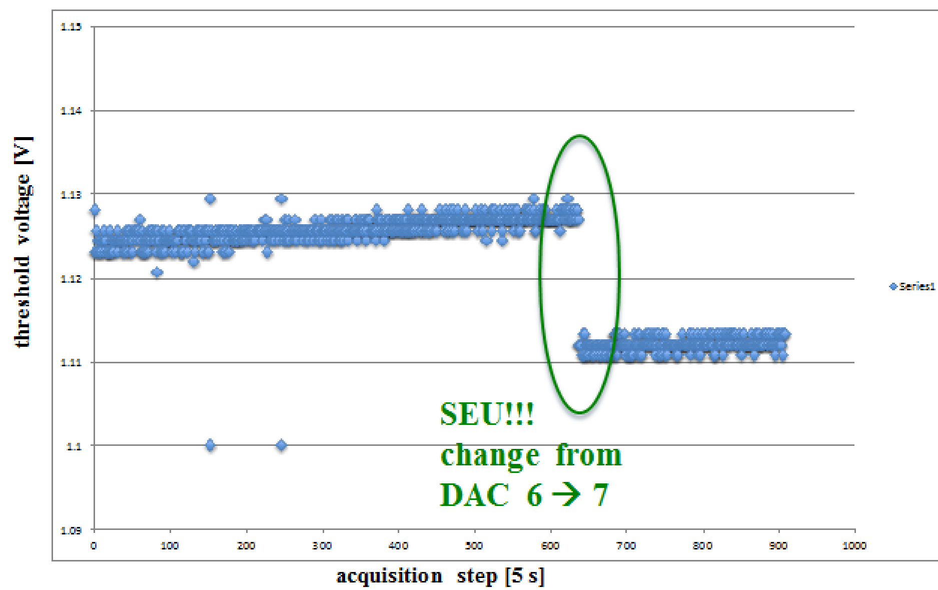
Beam energy: 60 MeV.

3 samples (with the lid removed) were powered and irradiated up to 7.6 Mrad (about 190 years in LHCb) in three steps.

- 1 SEU observed
- No SEL observed
- 10-15% decrease in supply current
- 10-15% variation in channel threshold





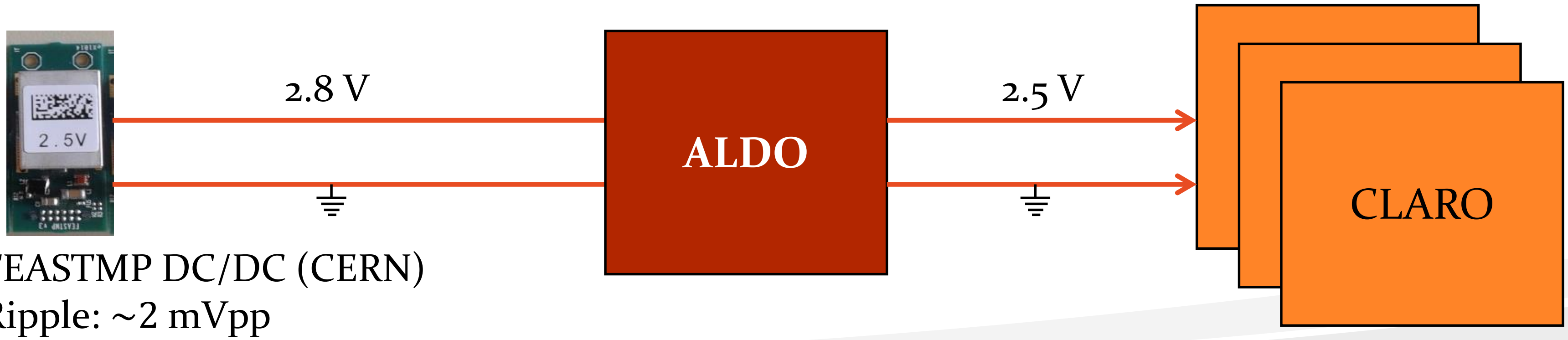


CLARO power supply – ALDO

- During LHCb RICH upgrade operation CLARO will be powered by CERN FEASTMP DC/DC
- FEASTMP noise from datasheet is very good (max 2 mVpp ripple)
- While waiting for some FEASTMP samples for more comprehensive test with CLARO..

..we designed ALDO:

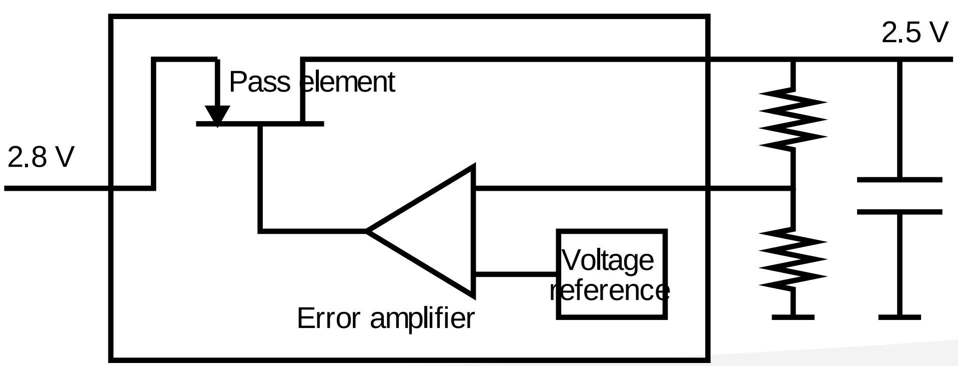
- **An Adjustable Low Drop-Out (ALDO) linear regulator with 0.5 A max output current, tailored for the CLARO**
- It was submitted to the foundry in July, tested in Q4 2014
- Would allow to filter and stabilize the power supply for the CLARO, for even lower noise
- After the testing phase, we can consider using it in the RICH upgrade, if needed



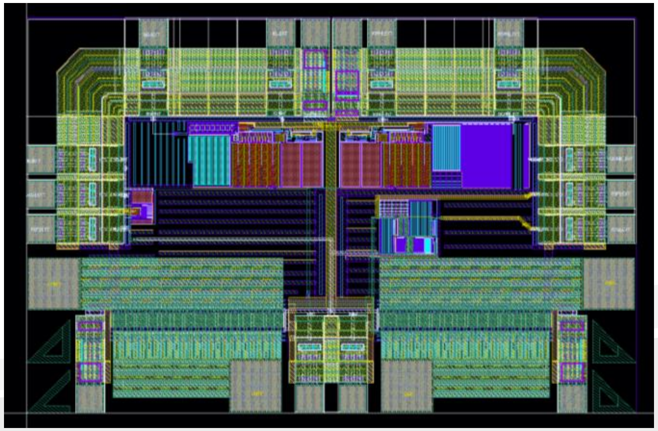
FEASTMP DC/DC (CERN)
Ripple: ~2 mVpp
Switching freq: ~2 MHz

ALDO characteristics

- Standard externally compensated LDO layout (best: ~100 µF, ESR <0.3 ohm)
- Adjustable output voltage
- Radiation hardened by design (all-MOS bandgap + careful layout in the output PMOS)
- Same tech as CLARO which proved to have good radiation tolerance
- It is designed to power 8 CLARO8 (a full 64 pixel R11265 MaPMT)
- PSRR: 45 dB @ 2 MHz (FEASTMP DC/DC switching freq) when 8 CLAROs are counting at 8 MHz (real-life mean rate in RICH hottest areas)
- Output noise: $<5\ nV/\sqrt{Hz}$ @ f > 100 kHz



Die area 2.1 x 1.4 mm²



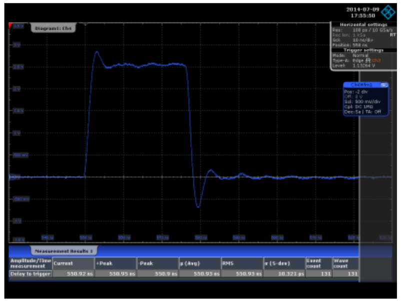
Conclusions, status and plans

CLARO-CMOS: built & deeply characterized

- The 4-channel CLARO-CMOS, even if designed in the quite old 0.35 μm AMS CMOS technology, demonstrated the capability to count single photons from MaPMTs at a 40 MHz rate with a very low power consumption (< 1 mW / channel)
- It fulfills the performance demands for the upgrade of LHCb RICH

CLARO8: built & promising first tests

- 8-channel version with many improvements. Designed in the first half of 2014
- Amplifier DC-coupled to the discriminator, pseudo-differential structure
- Finer and tunable threshold steps
- Configuration register protected against SEU by triple modular redundancy and equipped with a SEU counter



CLARO4v1: (backup solution) built but lower priority due to CLARO8 promising tests

- Many small improvements over the first 4 channel prototype (many inherited from the CLARO8)
- Same AC coupling configuration as in CLARO-CMOS (tweaked to reduce overshoot)

ALDO: submitted to AMS foundry in Q3, will be tested in Q4

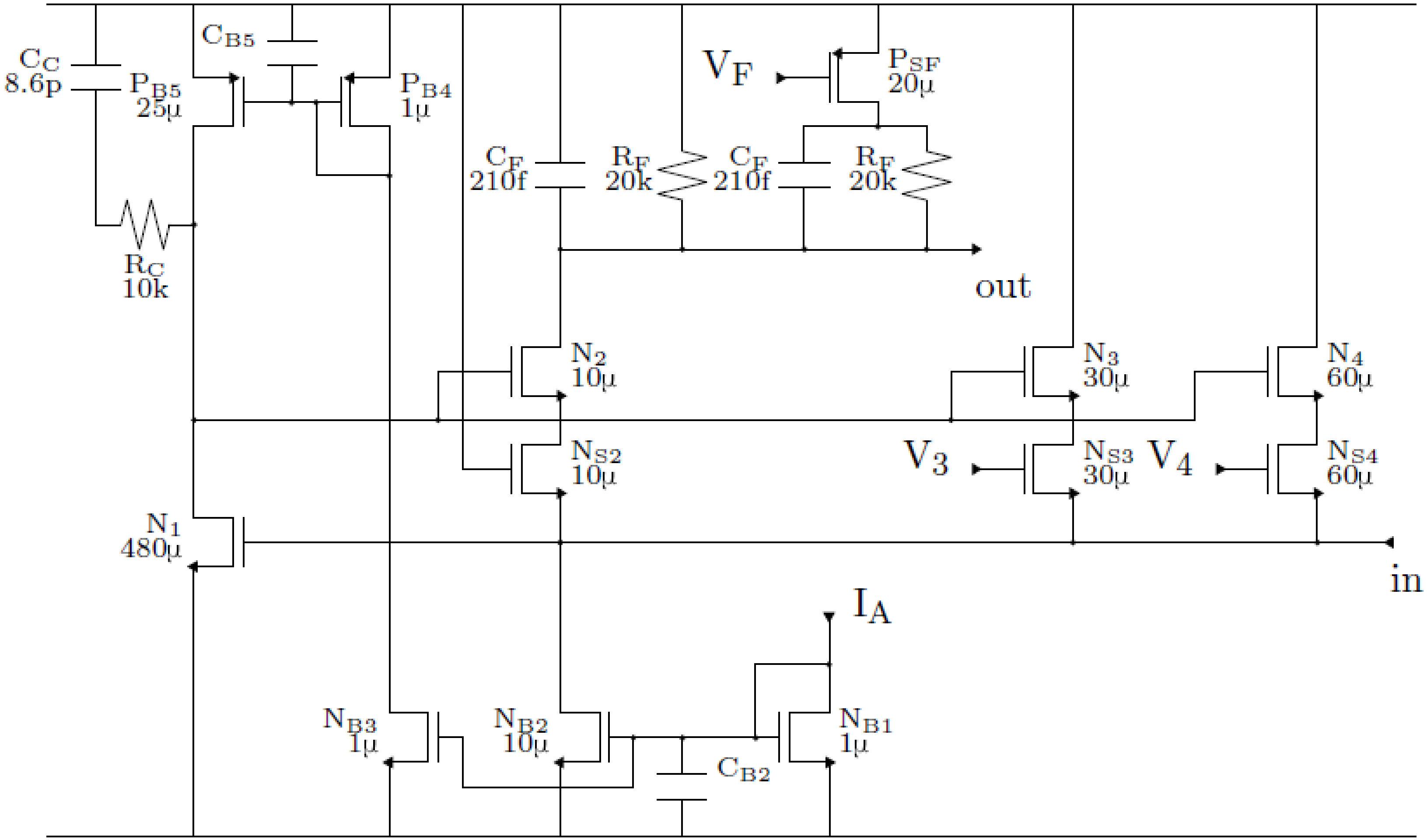
- High-PSRR and rad-hard LDO linear regulator


TWEPP 2014
Thank you
Merci
Grazie

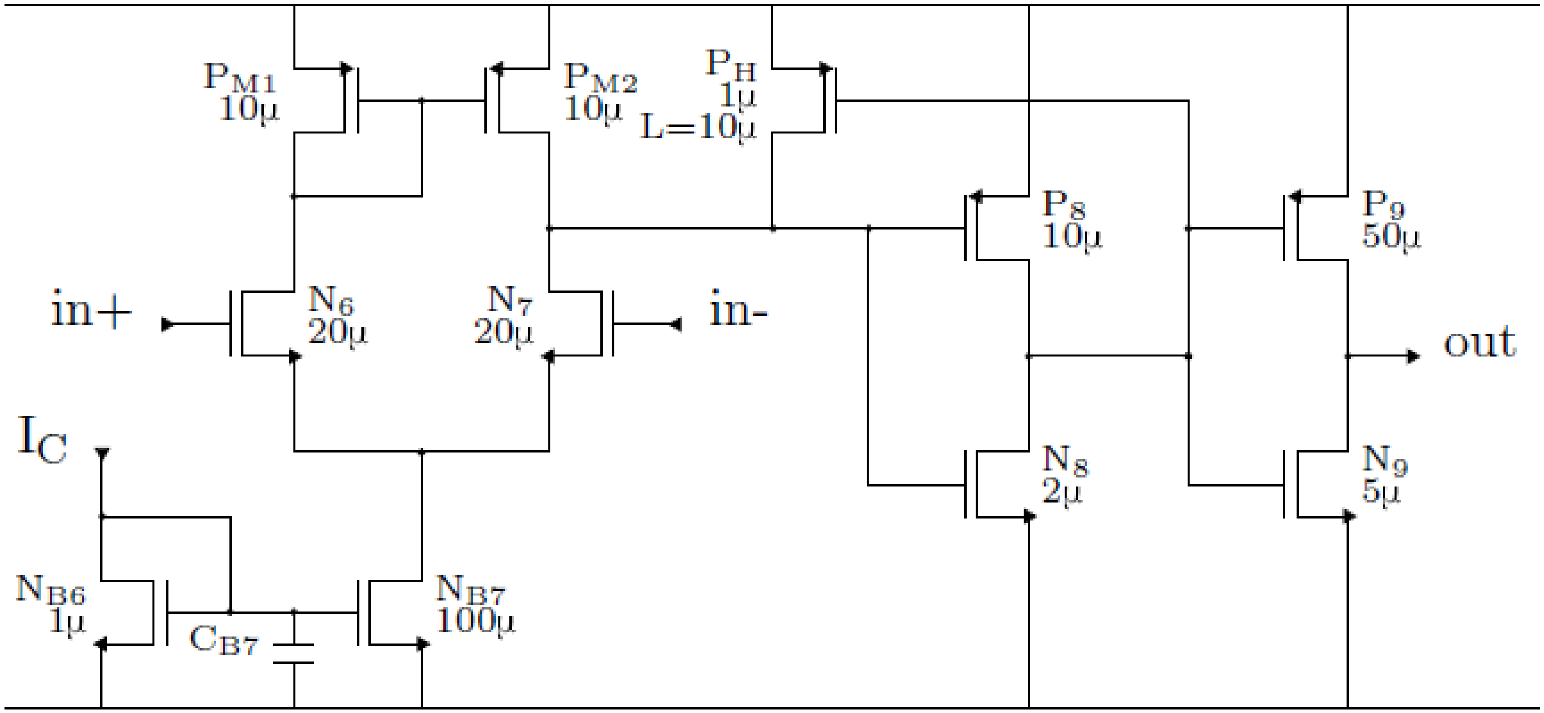
Backup

CLARO-CMOS – Preamplifier

$$V_O = \frac{Q}{C_F} \frac{\tau_F}{\tau_F - \tau_R} \left(e^{-\frac{t}{\tau_F}} - e^{-\frac{t}{\tau_R}} \right)$$



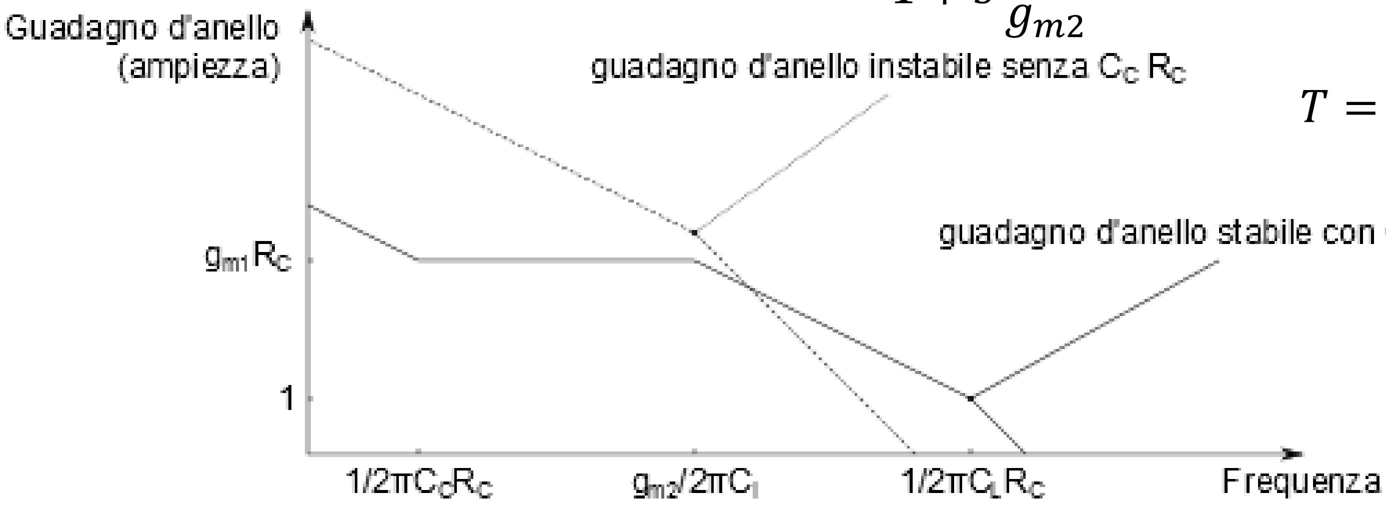
CLARO-CMOS – Comparator



Preamplifier loop gain

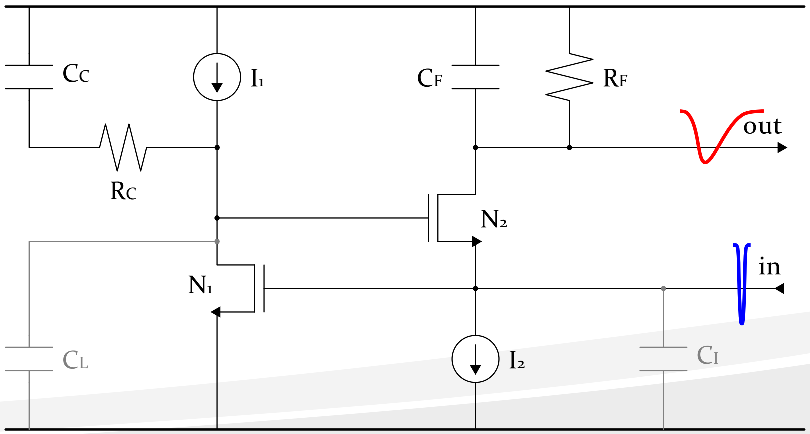
$$T = -\frac{g_{m1}}{sC_L}\frac{1}{1+s\frac{C_I}{g_{m2}}}$$

$$T = -\frac{g_{m1}R_C}{1+s\frac{C_I}{g_{m2}}}$$



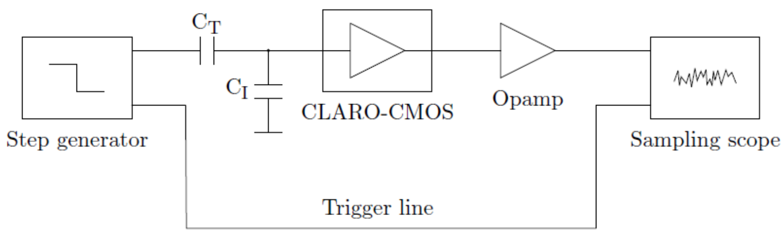
$$\frac{1}{\beta} = \frac{1}{C_F}\frac{R_F C_F}{1+sR_F C_F}$$

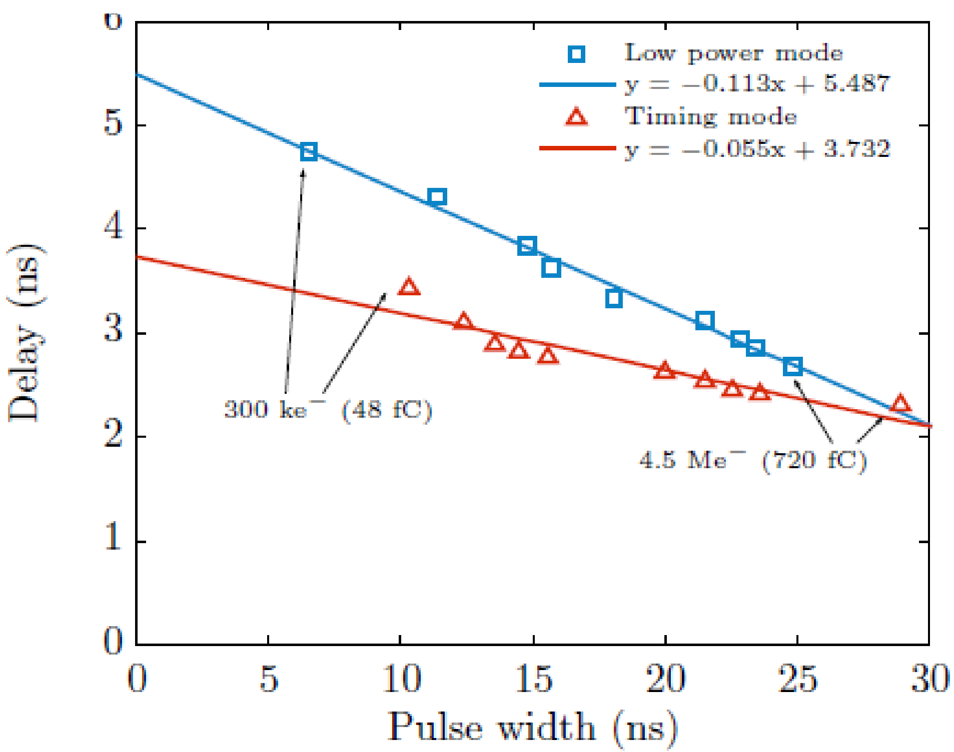
$$A_f = \frac{1}{\beta}\frac{-T}{1-T} = \frac{1}{C_F}\frac{R_F C_F}{1+sR_F C_F}\frac{1}{1+s\frac{C_I}{g_{m2}g_{m1}R_C}}$$

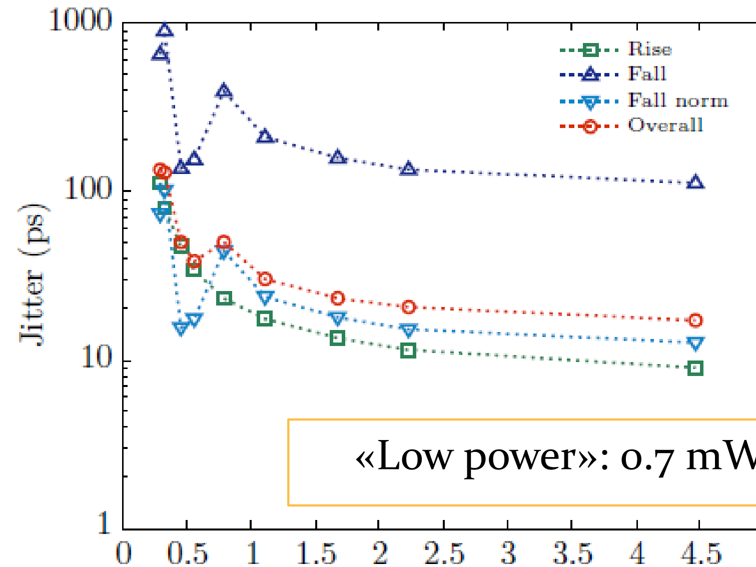


More on timing performance

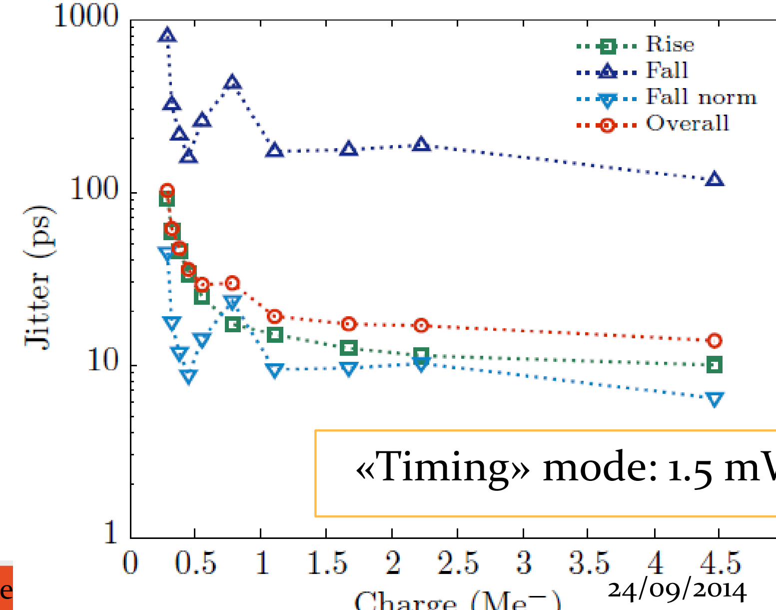
Test performed with a Agilent 81130A pattern generator and a Agilent DCA-X 86100D sampling oscilloscope







«Low power»: 0.7 mW/ch



«Timing» mode: 1.5 mW/ch

Tests with SiPMs

Test performed with 1x1 mm^2 and 3x3 mm^2 devices.

Signals are slower because of the large input capacitance with respect to the design specification.

Nevertheless, signals corresponding to different numbers of photons can still be resolved.