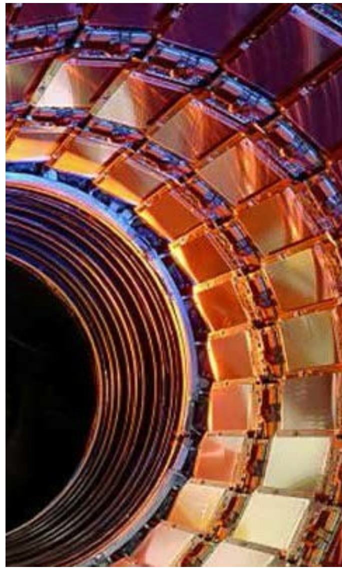

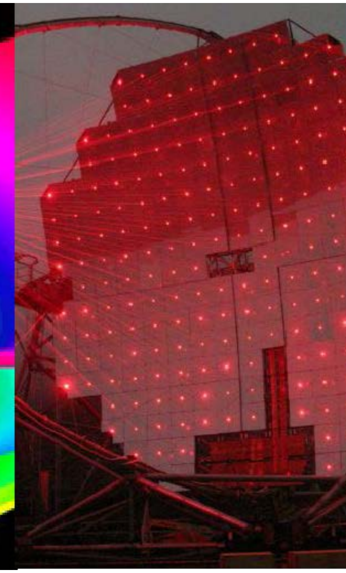
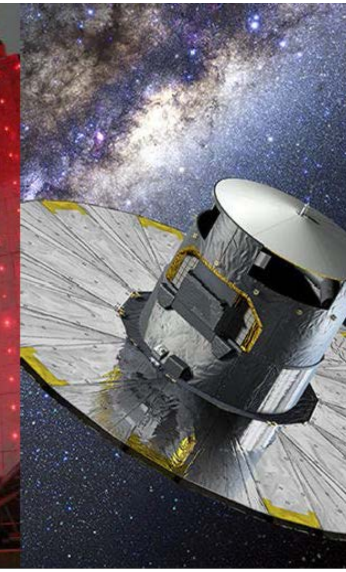

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CERN

Review of SiPM readout circuitry

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R. Ballabriga, J. M. Fernandez (CERN)

ICASiPM

14/06/2018

UNIVERSITAT DE BARCELONA

Outlook

I. **Introduction**
II. SiPM electrical parameters
III. FE circuits stage
IV. ASIC examples
V. Conclusions

I. Introduction

- Many different ASICs
  - Many possible classifications as well !
- According the input impedance
  - Current mode versus voltage mode
- According the complexity / functionality
  - Pure analogue front-end
    - Section III
  - Mixed-mode including digitization and readout
    - Section IV
- According the application
  - Many applications: PET, LIDAR, vision, life-sciences, particle physics, astrophysics, etc
  - Fast timing is a must in many of them

I. Introduction

- Disclaimers: what this talk will **not** be
  - A comprehensive review of SiPM read out chips
    - We would need hours !
  - How to measure SiPM electrical parameters
    - Some references at the end
    - Recommendation for model fine tuning and validation:
      - Compare measurements to simulations including model of the electronics!
- What we will talk about:
  - Review SiPM electrical parameters impact on signal shape and readout
  - Include effect of load ("amplifier") input impedance and interconnect
  - Review basic input stages and analog signal processing
  - Present some examples of ASICs for different applications
    - Projects in which I am involved: the ones we know better ☺

Outlook

II. SiPM electrical model

Vacuum Photomultipliers

$G = 10^5 - 10^7$

Cd ~ 10 pF

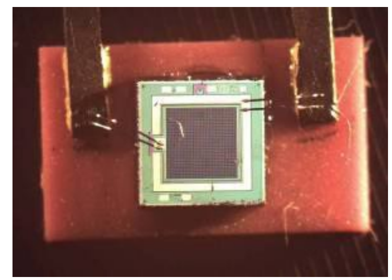
L ~ 10 nH

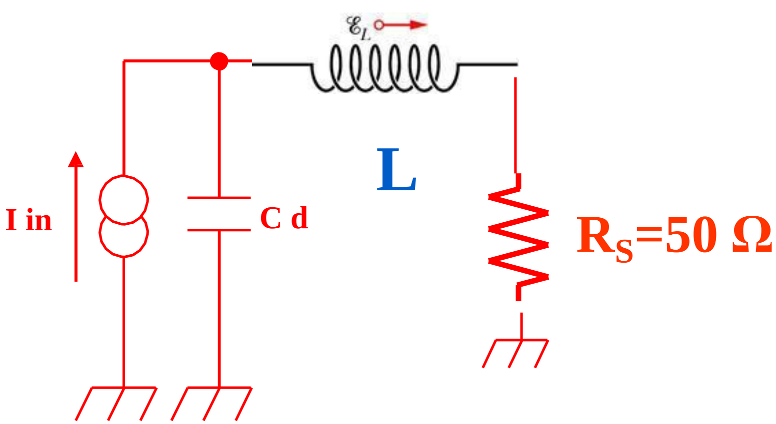
Silicon Photomultipliers

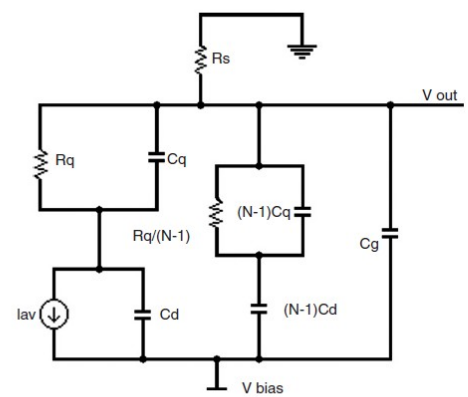
$G = 10^5 - 10^7$

C = 10 - 400 pF

L = 1 – 10 nH







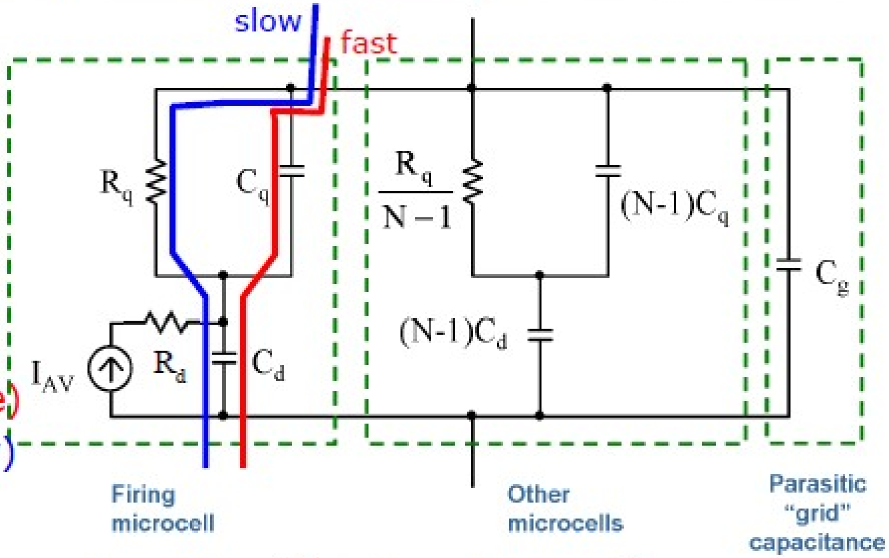
C. De LaTaille, Photodet conference, 2012

II. SiPM electrical model

Single cell model → $(R_d||C_d)+(R_q||C_q)$
SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

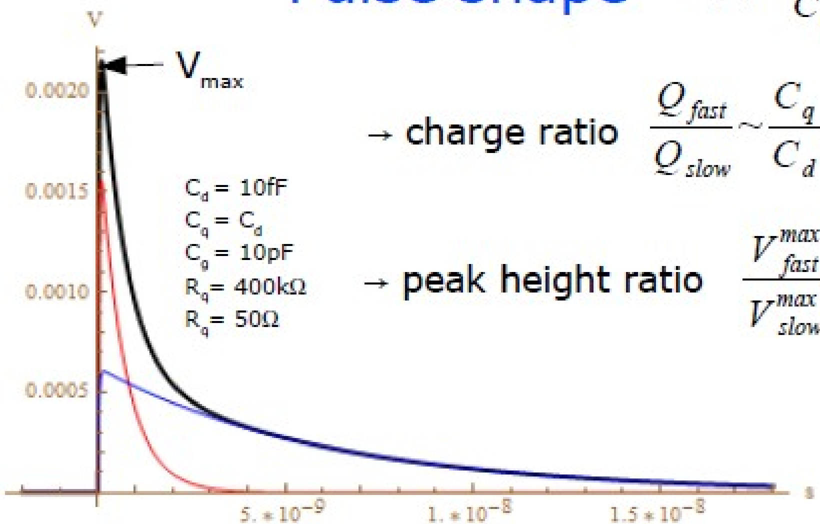
Signal = slow pulse ($\tau_{d\ (rise)}, \tau_{q\text{-}slow\ (fall)}$) +
+ fast pulse ($\tau_{d\ (rise)}, \tau_{q\text{-}fast\ (fall)}$)

- $\tau_{d\ (rise)} \sim R_d(C_q+C_d)$
- $\tau_{q\text{-}fast\ (fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{q\text{-}slow\ (fall)} = R_q\ (C_q+C_d)$ (slow; cell recovery)



Pulse shape

$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right)$$



→ charge ratio $\frac{Q_{fast}}{Q_{slow}} \sim \frac{C_q}{C_d}$

→ peak height ratio $\frac{V_{fast}^{max}}{V_{slow}^{max}} \sim \frac{C_q^2 R_q}{C_d C_{tot} R_{load}}$

increasing with Rq and $1/R_{load}$ (and Cq of course)

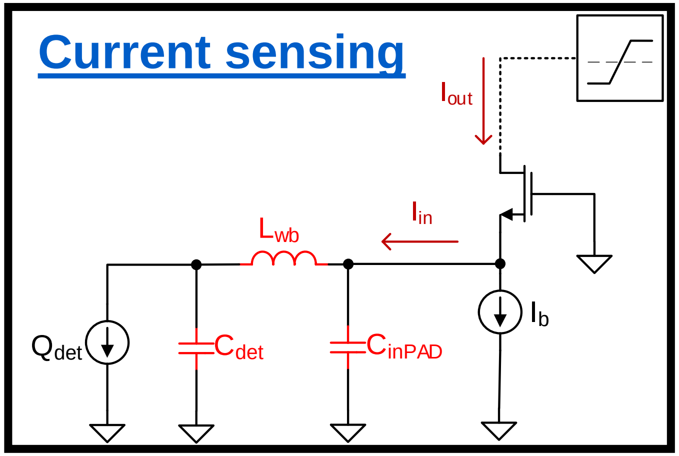
1) Peak V/I signal goes with C^{-1}

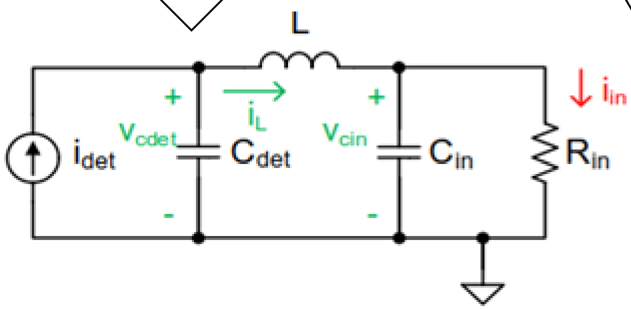
2) Peak I signal goes with R^{-1}

Increasing C_q/C_d or/and R_q/R_{load}
→ spike enhancement
→ better timing

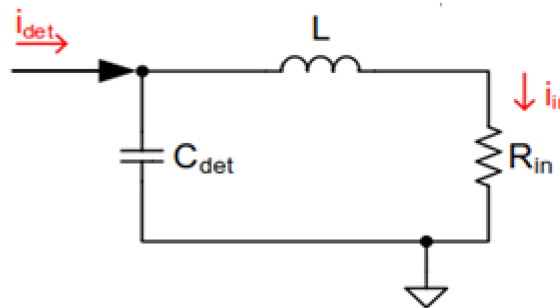
3) Fast vs slow component

II: Equivalent input network: Series and parallel resonances





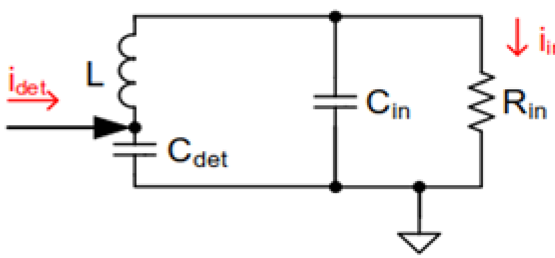
Series resonance: Cin → 0



2nd order system

- $\omega_{n,s} = \frac{1}{\sqrt{L\,C_{det}}}$
- $Q_s = \frac{\omega_{n,s}\,L}{R_{in}} = \frac{1}{R_{in}}\sqrt{\frac{L}{C_{det}}}$
- $\boldsymbol{R_{in,cr} = 2\sqrt{\frac{L}{C_{det}}}}$

Parallel resonance: Cin ≠ 0



3nd order system

- $\omega_{n,p} = \frac{1}{\sqrt{L\,(C_{det}||C_{in})}}$
- $Q_p = \frac{C_{in}^2 R_{in}}{\sqrt{(C_{det}||C_{in})^3 L}} \approx R_{in}\sqrt{\frac{C_{in}}{L}}$
- $\boldsymbol{R_{in,p} = \frac{1}{2}\frac{\sqrt{L(C_{det}||C_{in})^3}}{C_{in}^2}} \approx \frac{1}{2}\sqrt{\frac{L}{C_{in}}}$

Similar analyses in “Interfacing a SiPM to a Current-mode Front-End, F. Ciciriello et al.”, and “SiPM readout electronics overview, CNRS/IN2P3, C. de la Taille, 2012”

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II: Dynamics of the input signal

For oscillation-free input current:

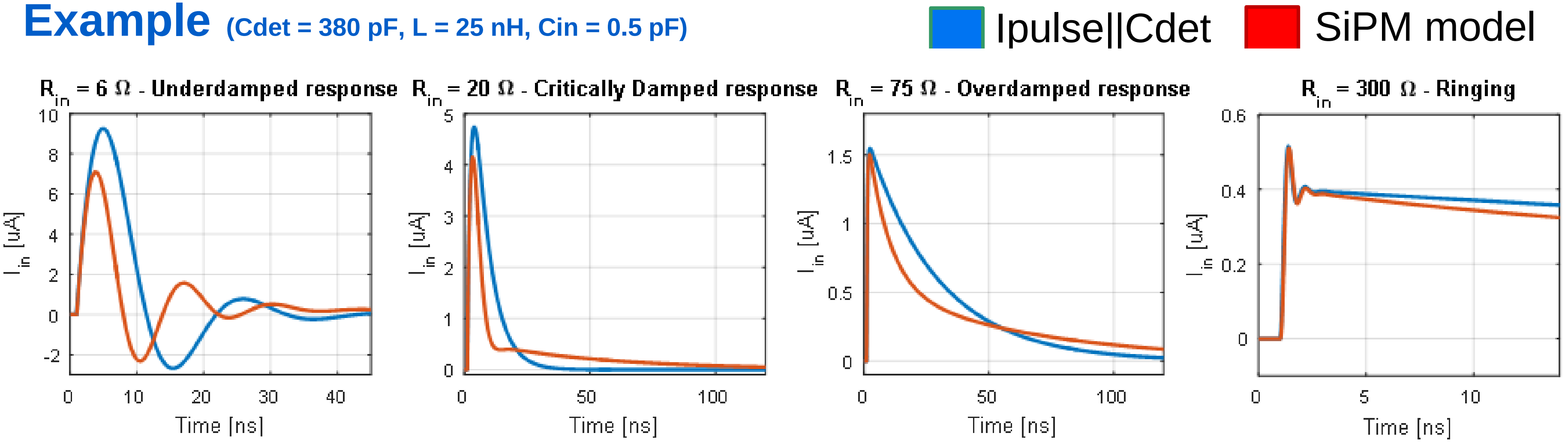
$$R_{in,cr} \leq R_{in} \leq R_{in,p} \rightarrow 2\sqrt{\frac{L}{C_{det}}} \leq R_{in} \leq \frac{1}{2}\frac{\sqrt{L(C_{det}||C_{in})^3}}{C_{in}^2} \quad \&\& \quad C_{det} \geq 18.7\, C_{in}$$

Corners: L = 5 nH (Small) / 25 nH (Large), Cdet = 10 pF (Small) / 1 nF (Large)

L / C_{det}	R_{in} range for $C_{in} = 0.1$ pF	R_{in} range for $C_{in} = 0.5$ pF	R_{in} range for $C_{in} = 1$ pF
Small / Small	$44.72\,\Omega \leq R_{in} \leq 110.15\,\Omega$	$44.72\,\Omega \leq R_{in} \leq 46.47\,\Omega$	$44.72\,\Omega \leq R_{in} \leq 30.64\,\Omega$
Small / Large	$4.47\,\Omega \leq R_{in} \leq 111.78\,\Omega$	$4.47\,\Omega \leq R_{in} \leq 49.96\,\Omega$	$4.47\,\Omega \leq R_{in} \leq 35.3\,\Omega$
Large / Small	$100\,\Omega \leq R_{in} \leq 246.29\,\Omega$	$100\,\Omega \leq R_{in} \leq 103.91\,\Omega$	$100\,\Omega \leq R_{in} \leq 68.52\,\Omega$
Large / Large	$10\,\Omega \leq R_{in} \leq 249.96\,\Omega$	$10\,\Omega \leq R_{in} \leq 111.72\,\Omega$	$10\,\Omega \leq R_{in} \leq 78.93\,\Omega$

Oscillatory response:
- **Below 5 Ω**
- **Above 250 Ω**

Example (Cdet = 380 pF, L = 25 nH, Cin = 0.5 pF)

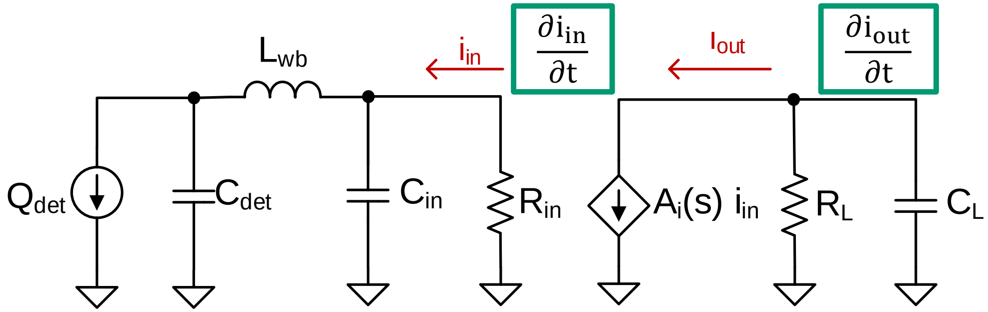


Condition for oscillation-free input current also valid for SiPM model!

II. Slew-rate degradation with bandwidth in current sensing

Convolution between the input slope and the electronics bandwidth (time domain):

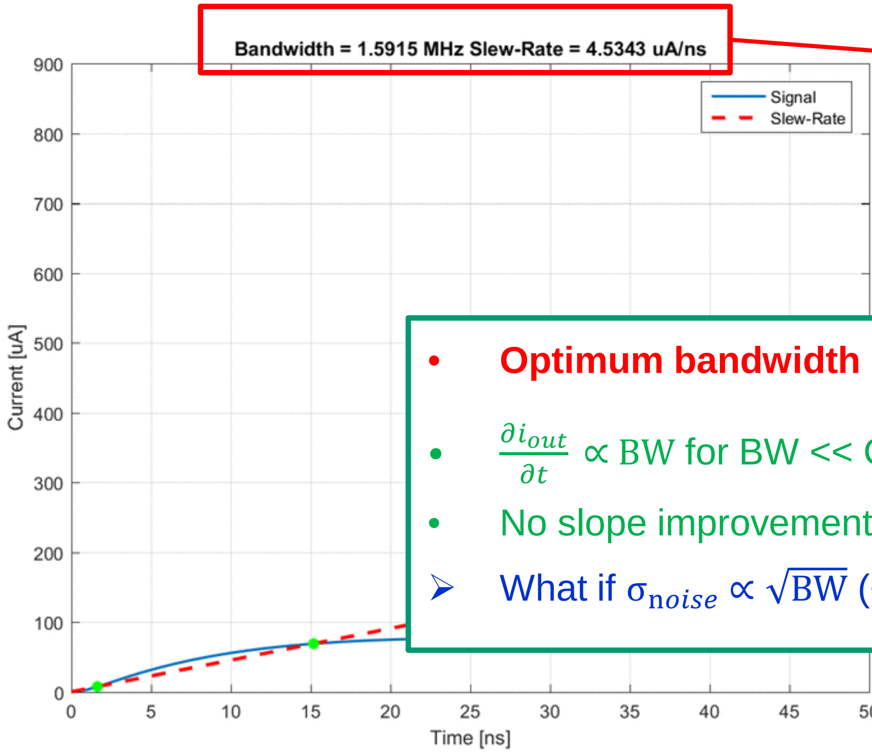
$$SR = \frac{\partial i_{out}}{\partial t} \propto \left(\frac{\partial i_{in}}{\partial t}\right) * \left(BW \cdot e^{-t \cdot BW}\right)$$

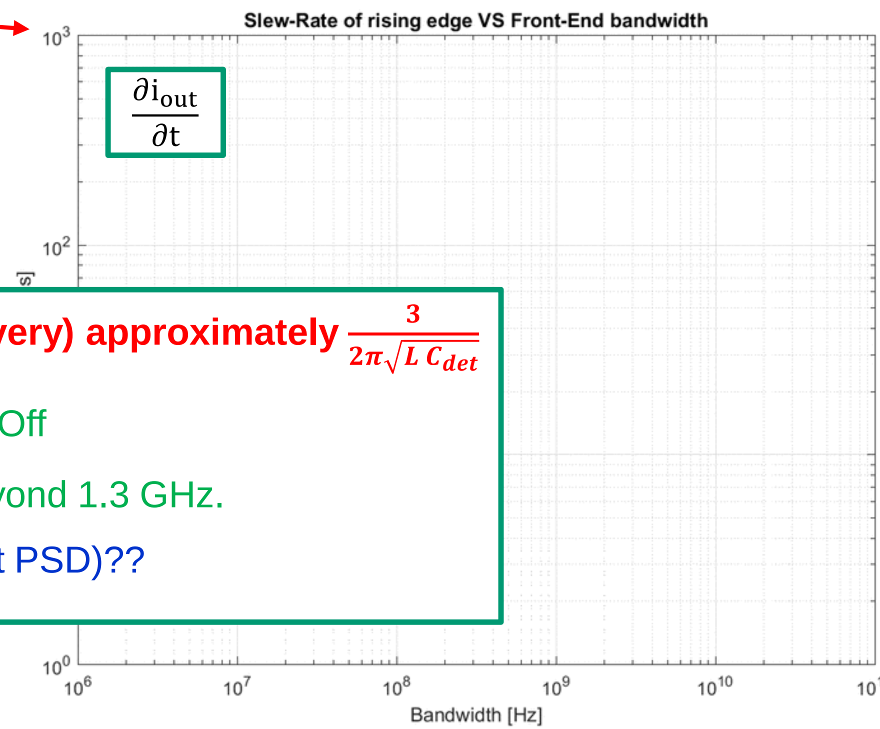


Optimum bandwidth for connecting inductances 5 nH – 25 nH and Cdet = 10 pF – 1 nF

Lwb / Cdet

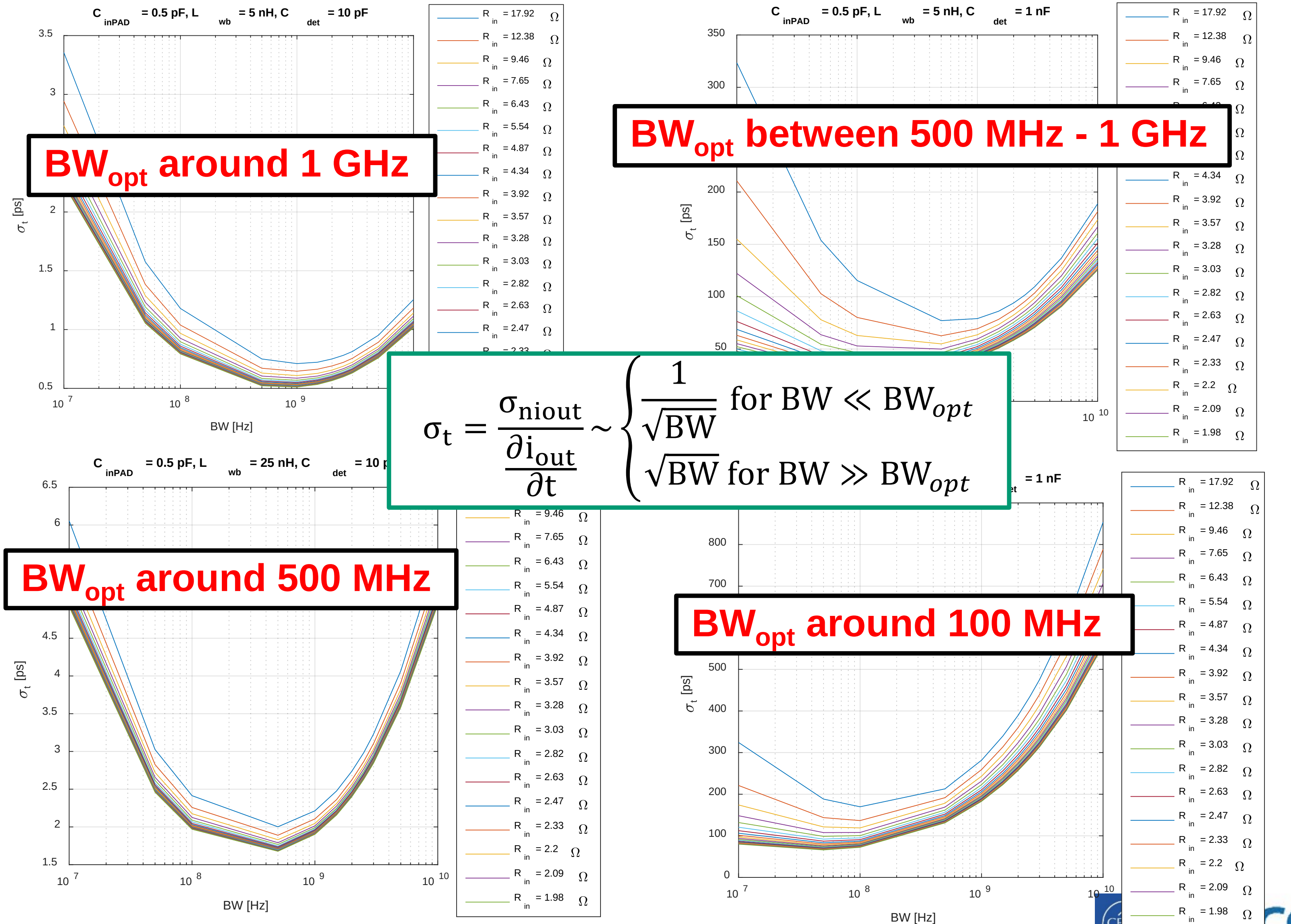
5 nH / 10 pF	5 nH / 1 nF	25 nH / 10 pF	25 nH / 1 nF
1.3 GHz	270 MHz	560 MHz	81 MHz





- **Optimum bandwidth is (very) approximately** $\frac{3}{2\pi\sqrt{L\,C_{det}}}$
- $\frac{\partial i_{out}}{\partial t} \propto$ BW for BW << Cut-Off
- No slope improvement beyond 1.3 GHz.
- ➢ What if $\sigma_{noise} \propto \sqrt{BW}$ (~flat PSD)??

II. Example of Slew-rate versus bandwidth in current sensing (assuming leading edge discrimination)



BW_{opt} around 1 GHz

BW_{opt} between 500 MHz - 1 GHz

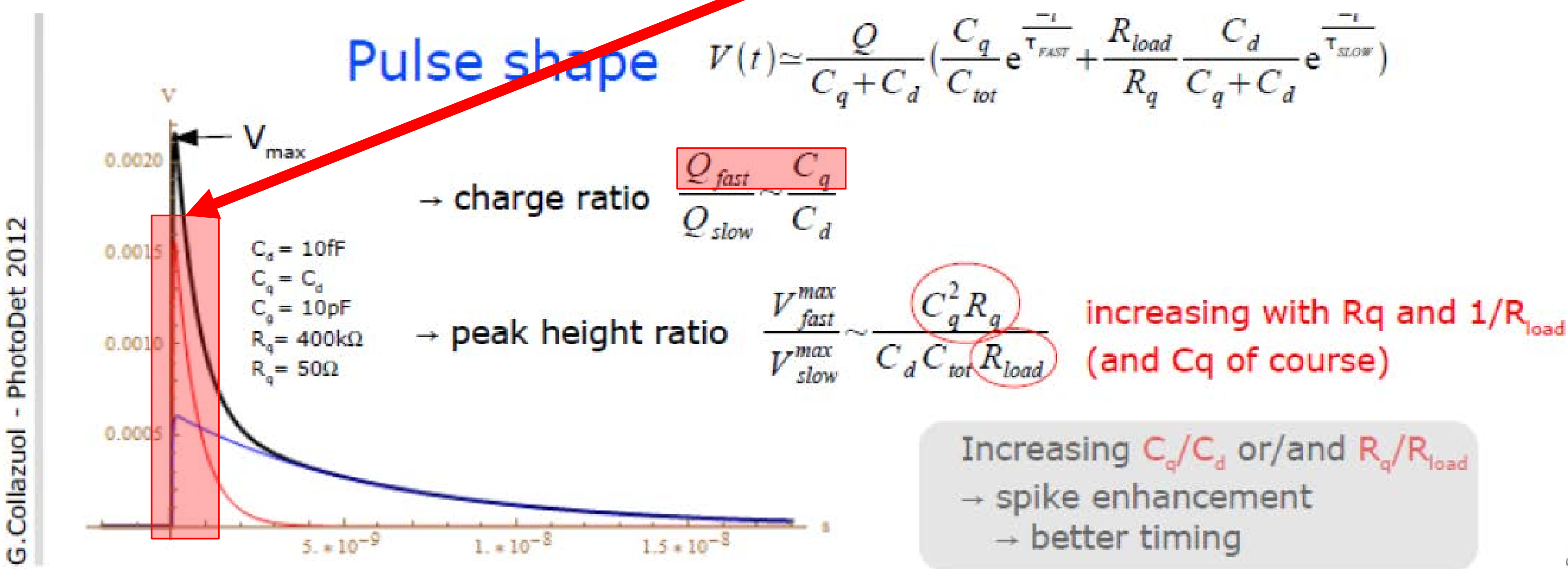
BW_{opt} around 500 MHz

BW_{opt} around 100 MHz

$$\sigma_t = \frac{\sigma_{niout}}{\frac{\partial i_{out}}{\partial t}} \sim \begin{cases} \frac{1}{\sqrt{BW}} \text{ for } BW \ll BW_{opt} \\ \sqrt{BW} \text{ for } BW \gg BW_{opt} \end{cases}$$

II. SiPM electrical model

- Front end electronics for SiPM is needed to:
  - Preamplify for SNR optimization
    - Even if "nominal" gain is in the order of 10^6 only a fraction of the charge is used for fast read-out systems
    - The "effective" gain for a fast system can be between 2 and 10 times lower than the nominal gain

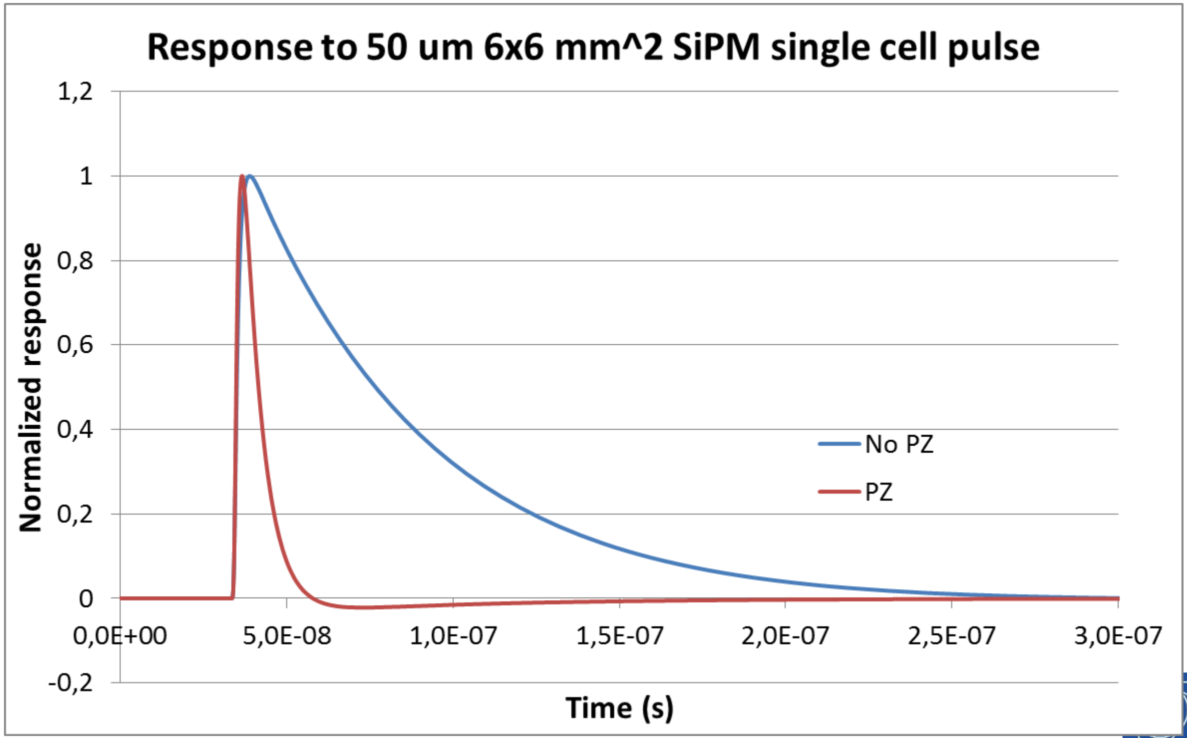


Outlook

I. Introduction
II. SiPM electrical parameters
III. FE circuits
IV. ASIC examples
V. Conclusions

III. FE circuits: Pole-Zero cancellation

- Pole-Zero (PZ) cancellation of the SiPM recovery long time constant (τ_{slow})
- The PZ shaping has an effect in the signal to noise ratio (SNR)
  - A SNR>5 is required for photopeak identification
  - Can be seen in 2 different ways:
    1) Attenuation of slow frequency components of the signal
    2) Increase of the input referred noise (ENC=Equivalent Noise Charge)

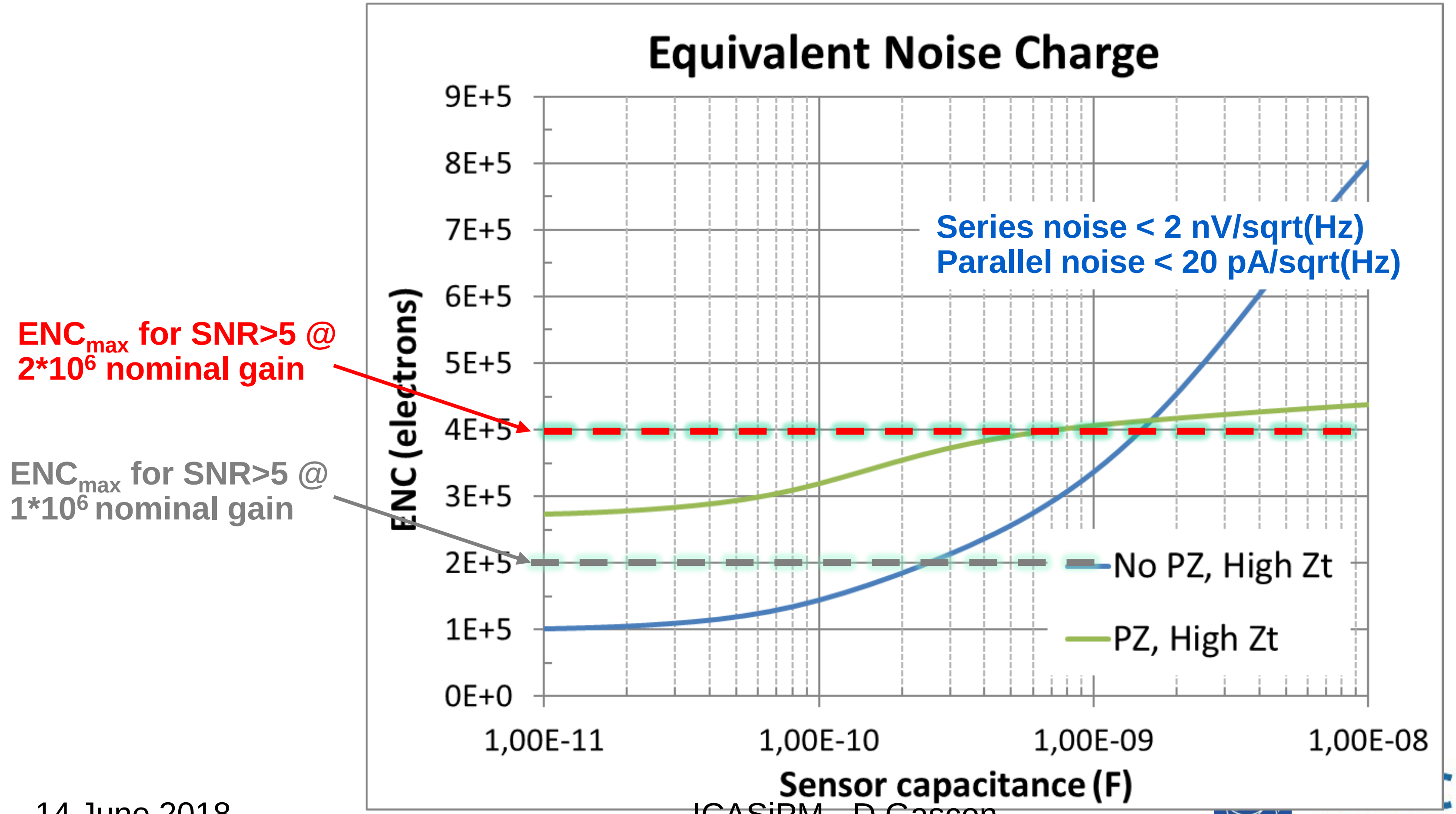


Simulation with a model obtained from 3x3 mm device

II FE circuits: effect of capacitance and shaping in noise

- Front end electronics for SiPM is needed to:
  - Low noise front end is required for large SiPMs

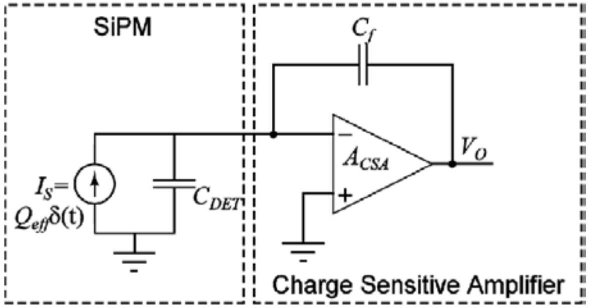
SiPM capacitances range from 10s pF to more than several nF



III. FE circuits: current versus voltage mode

- Typical photo-sensor front end circuit configurations:

Charge preamplifier



- ❑ Best noise performance
- ❑ Best with short signals
  - ➢ Long tails: pile-up!
  - ➢ Need to discharge Cf
- ❑ Best with small capacitance
  - ➢ BW=Cf/Cdet*GBW, with Cf<<Cdet typically…

Voltage preamplifier

- ❑ E.g. common-emitter/source configuration
- ❑ Large Zin // Large Zout
- ❑ Current conversion with Rin
- ❑ High power budget for high speed systems
- ❑ But can exploit RF technologies

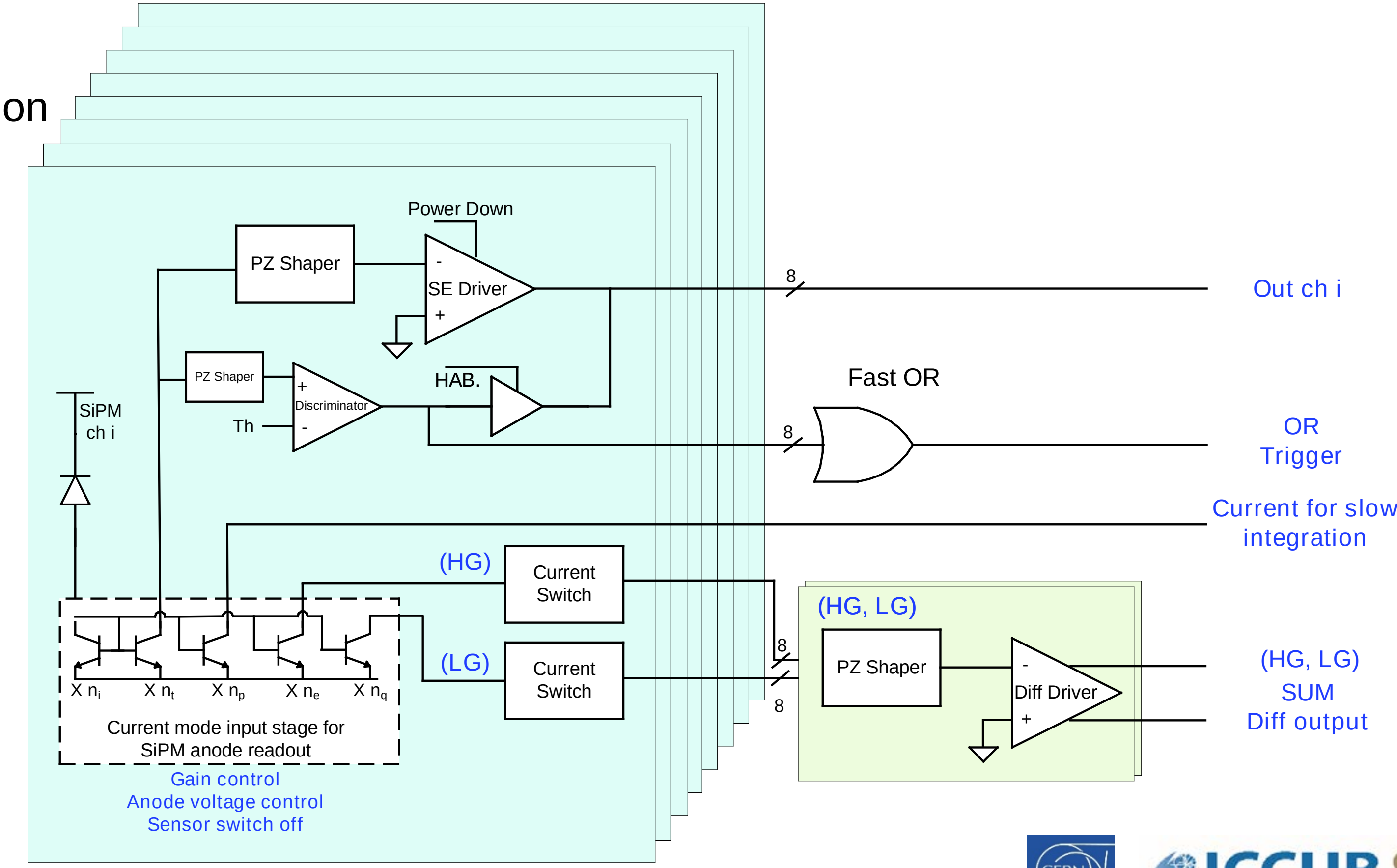
Current preamplifier

- ❑ E.g. (super) common-base/gate
- ❑ Low Zin // Large Zout
- ❑ Current conversion with Rin
- ❑ Potential stability issues
- ❑ Best for high rate applications
- ❑ Good power/BW trade-offº

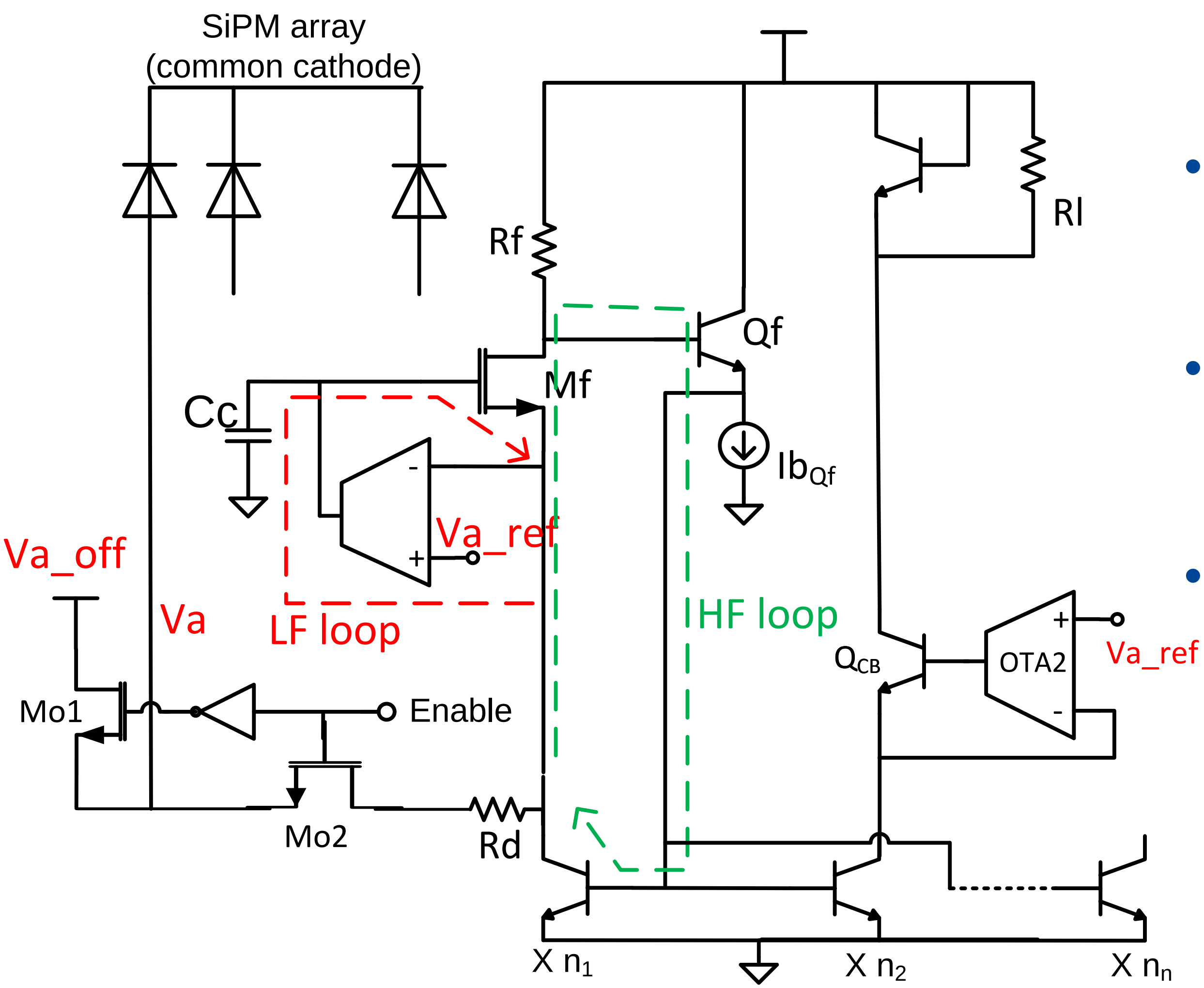
F. Ciciriello et alt., "Time performance of voltage-mode vs current-mode readouts for SiPM's," *IWASI*, 2015

III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- MUSIC: current mode, analog (binary) and designed for astroparticle (CTA) but multipurpose
  - Amplification / impedance adaptation
  - Pole zero cancellation
  - Summation
  - Discrimination



III. FE circuits: MUSIC: Multipurpose SiPM RO chip



- Possible to disable each input reducing overvoltage to Va_off.
- Double feedback loop
  - Low input impedance
  - Anode voltage control
- High bandwith

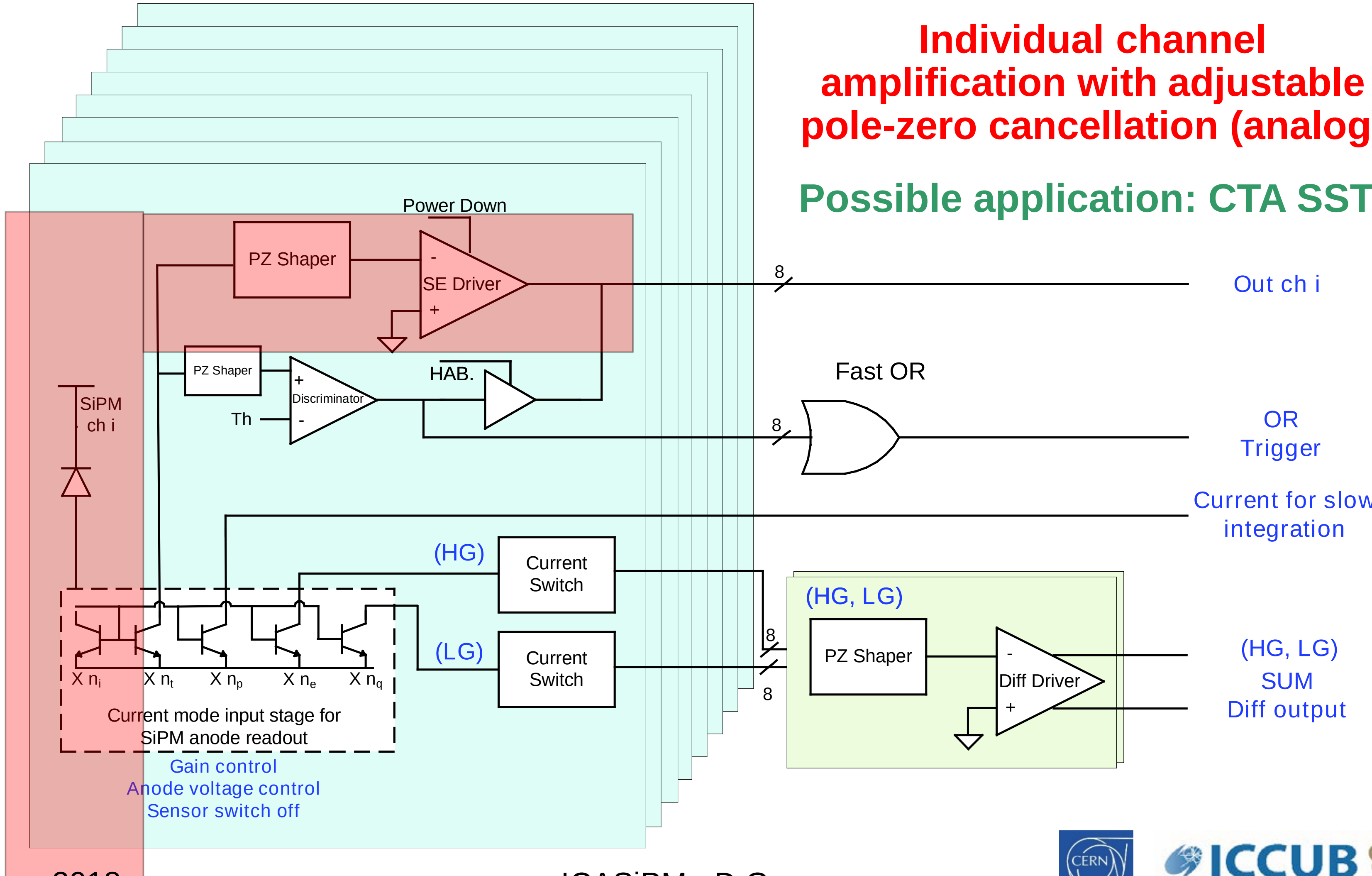
Series noise < 2 nV/sqrt(Hz)
Parallel noise < 20 pA/sqrt(Hz)

III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- MUSIC 8 ch ASIC integrates all those functionalities

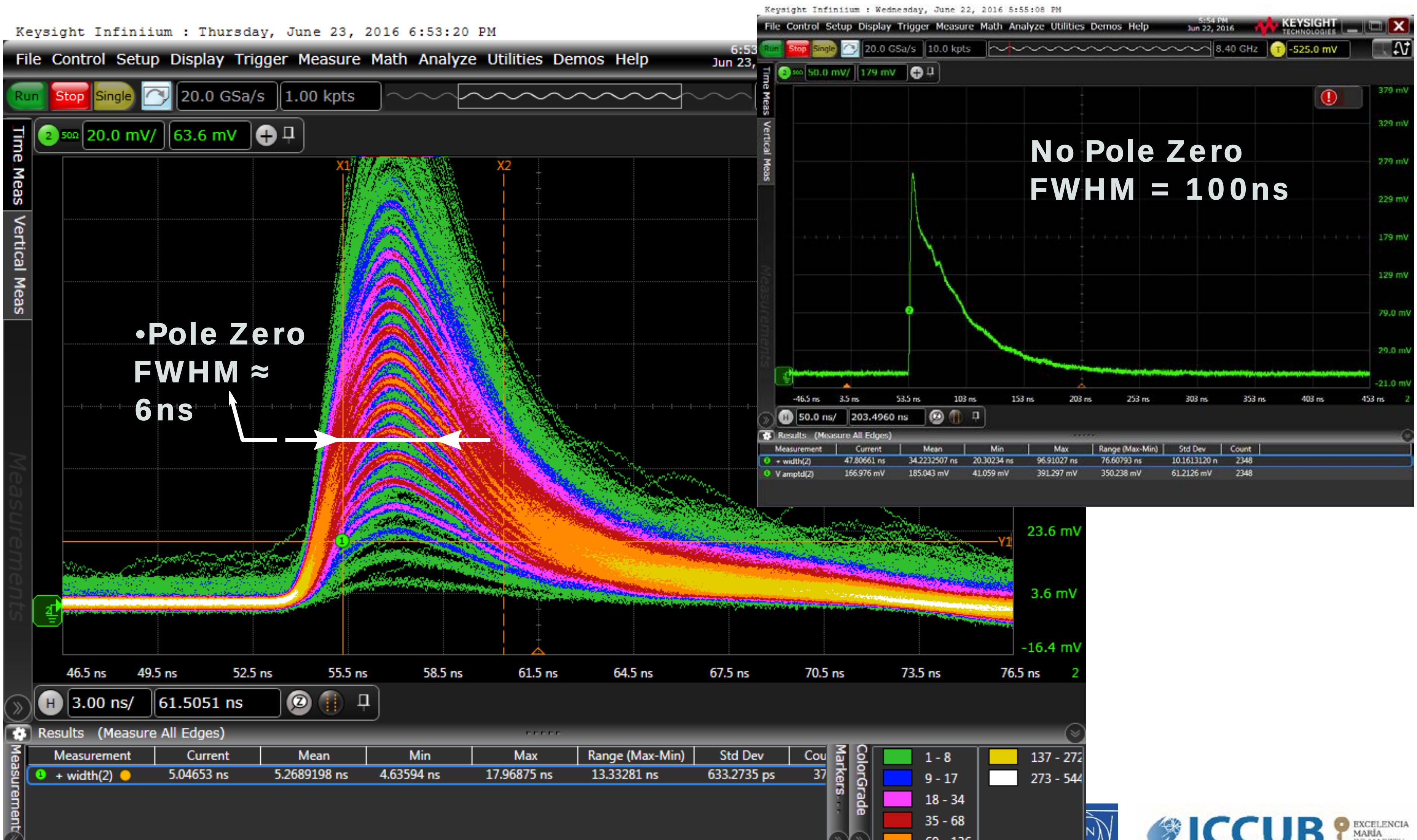
Individual channel amplification with adjustable pole-zero cancellation (analog)

Possible application: CTA SSTs



III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Output for a LCT4 MPPC (3x3 mm^2)



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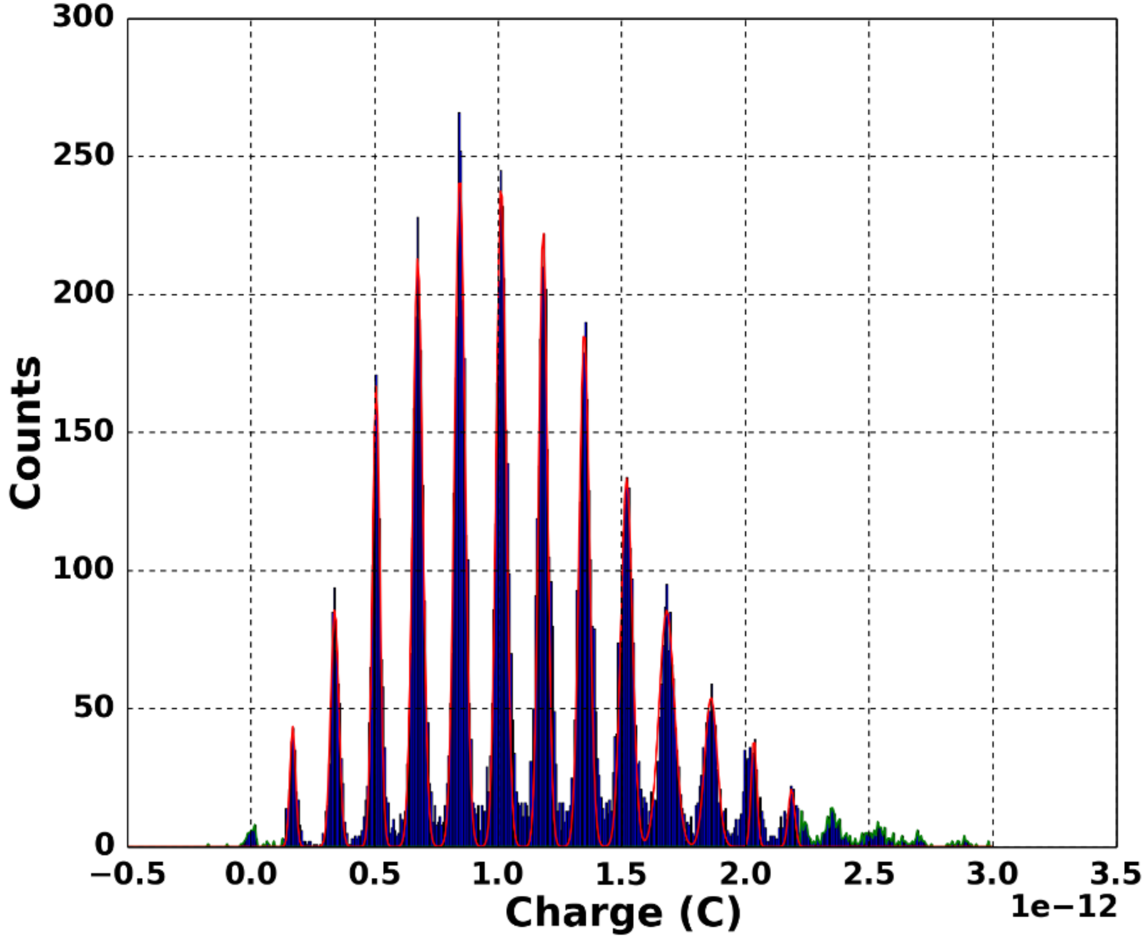
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Charge spectrum for a LCT4 MPPC (3x3 mm^2)
- Pole-zero cancellation
- Excellent resolution with FWHM of 5 ns



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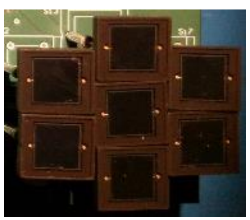
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Active summation to build large area detectors
- Why active summation?
  - Total noise for active and passive summation can be similar
    - If series noise dominates…
  - But signal (peak) is much higher !
    - Provided high summation BW

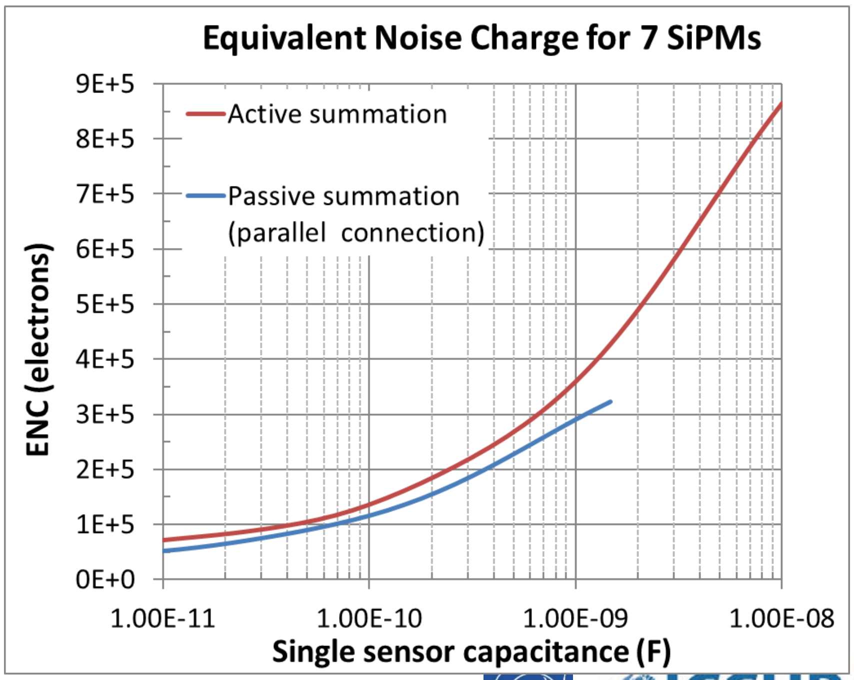
Series noise < 2 nV/sqrt(Hz)
Parallel noise < 20 pA/sqrt(Hz)

7 x SIPM
6x6 mm^2 each



≈

1 x PMT
18 mm diameter



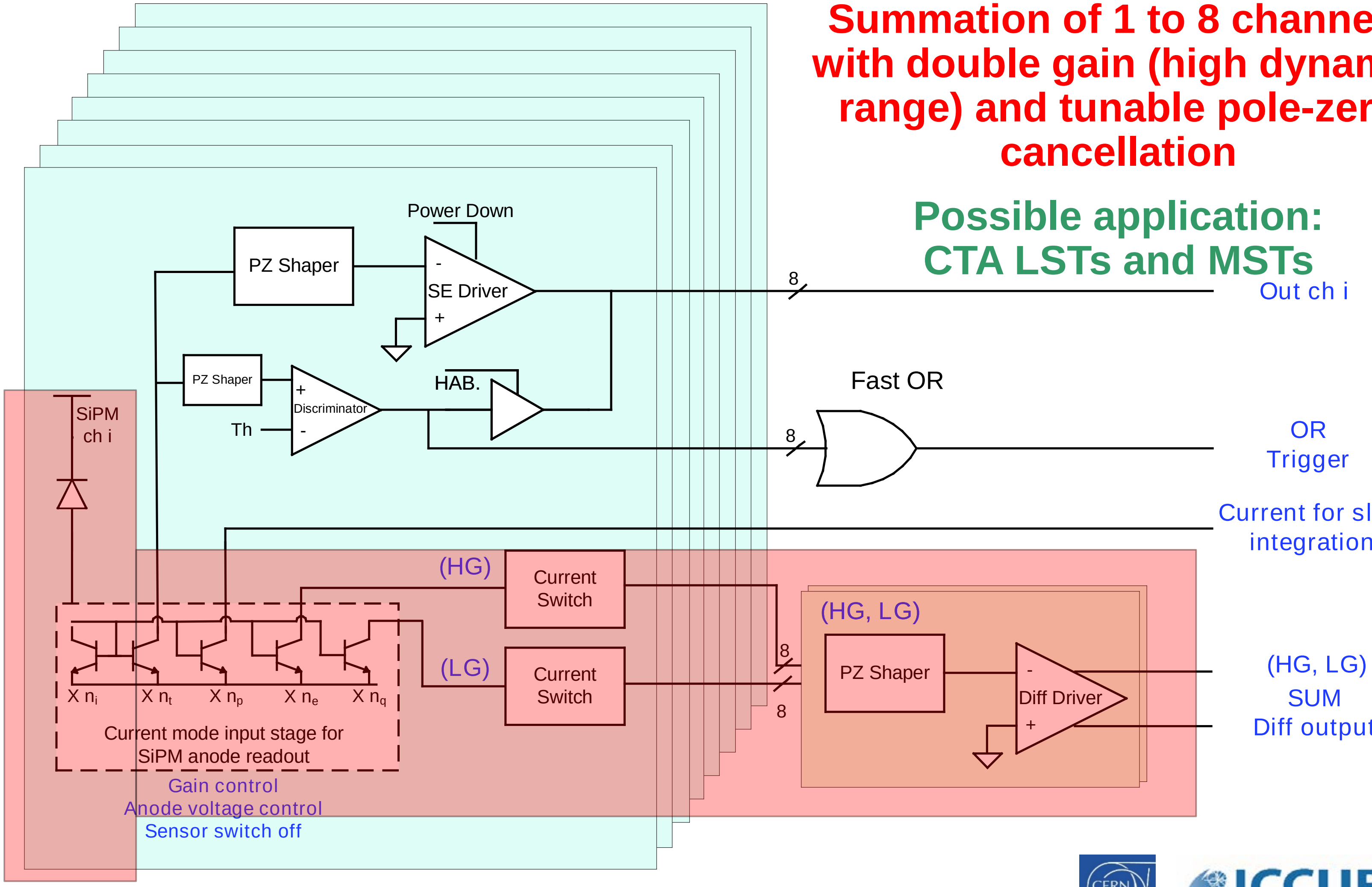
*7x7mm^2 and some custom larger SiPMs exist

III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- MUSIC 8 ch ASIC integrates all those functionalities

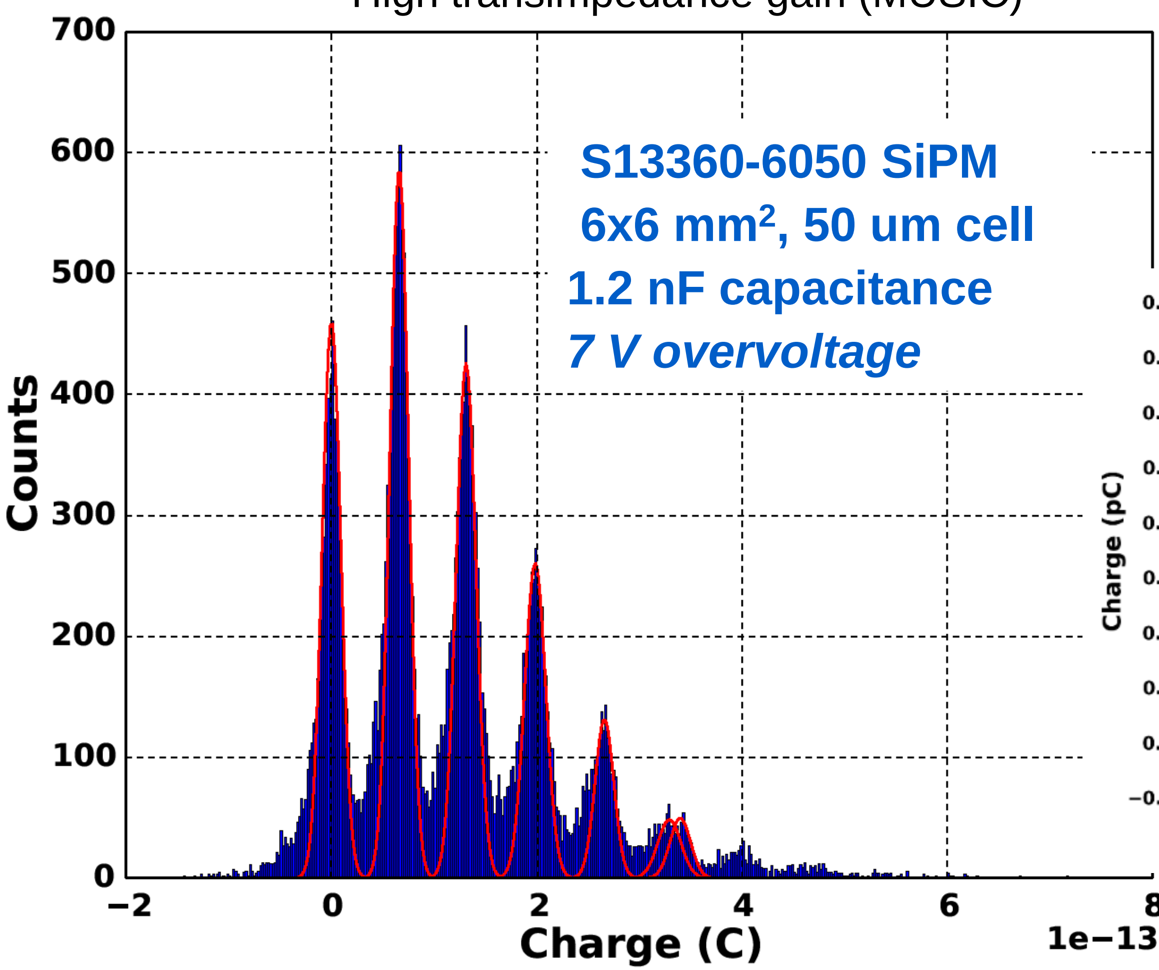
Summation of 1 to 8 channels with double gain (high dynamic range) and tunable pole-zero cancellation

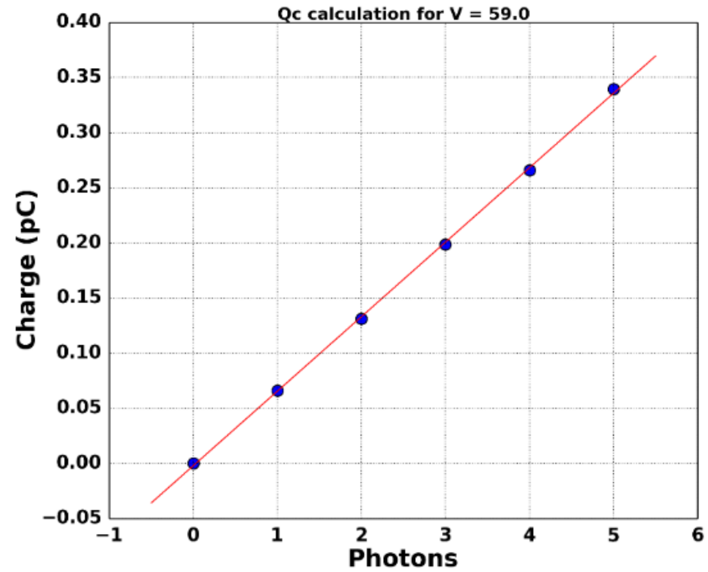
Possible application: CTA LSTs and MSTs



III. FE circuits: MUSIC: Multipurpose SiPM RO chip

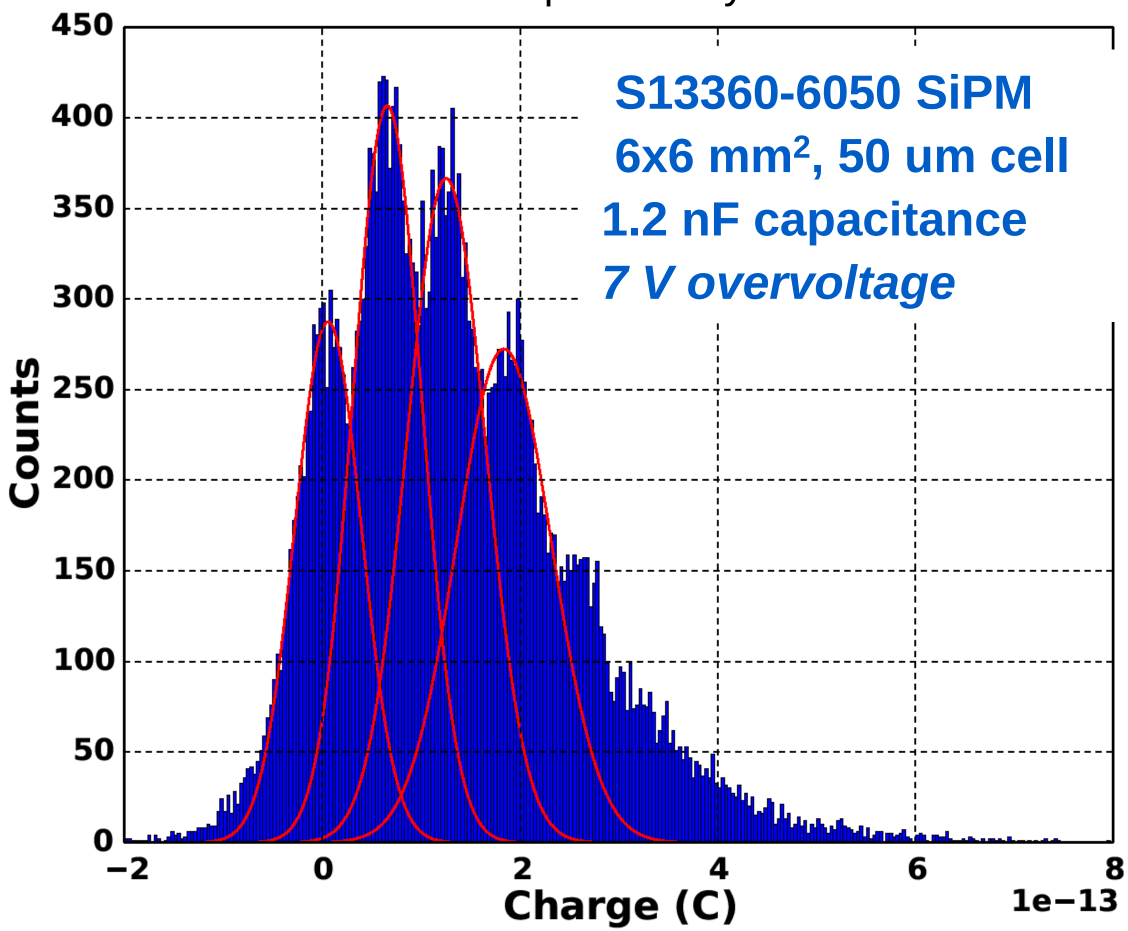
- MUSIC configuration: the adder takes only 1 channel
  - Pole-zero cancellation: trade-off between resolution and speed
  - High transimpedance gain (MUSIC)



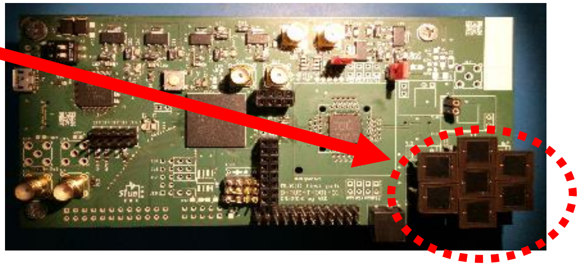


III. FE circuits: MUSIC: Multipurpose SiPM RO chip

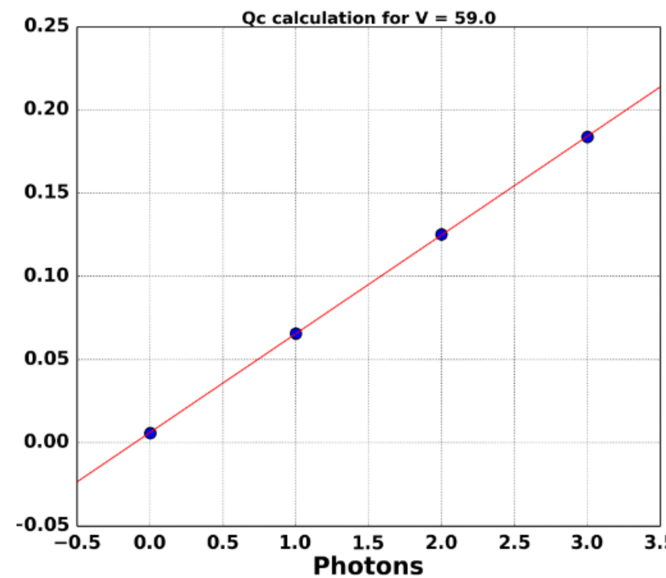
- MUSIC configuration: the adder takes 7 channels
  - Noise is much higher (sqrtr(7))
  - But pe (cell) peaks can still be identified
  - Channels have been equalized by MUSIC anode ctrl voltage



S13360-6050 SiPM
6x6 mm^2, 50 um cell
1.2 nF capacitance
7 V overvoltage



1 x PMT
18 mm diameter
≈
7 x SIPM
6x6 mm^2
each



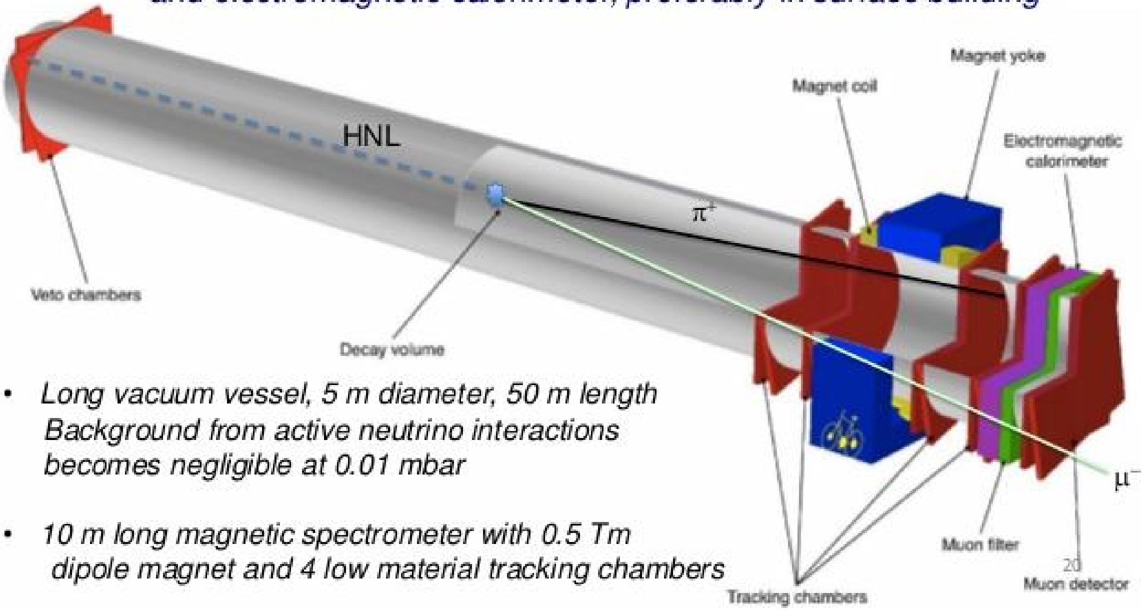
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- SHIP experiment is a new general-purpose beam dump facility at the SPS (CERN) to search for hidden particles
  - Predicted by a very large number of recently elaborated models of Hidden
  - Dark matter, neutrino oscillations, and the origin of the full baryon asymmetry

SHiP
Search for Hidden Particles

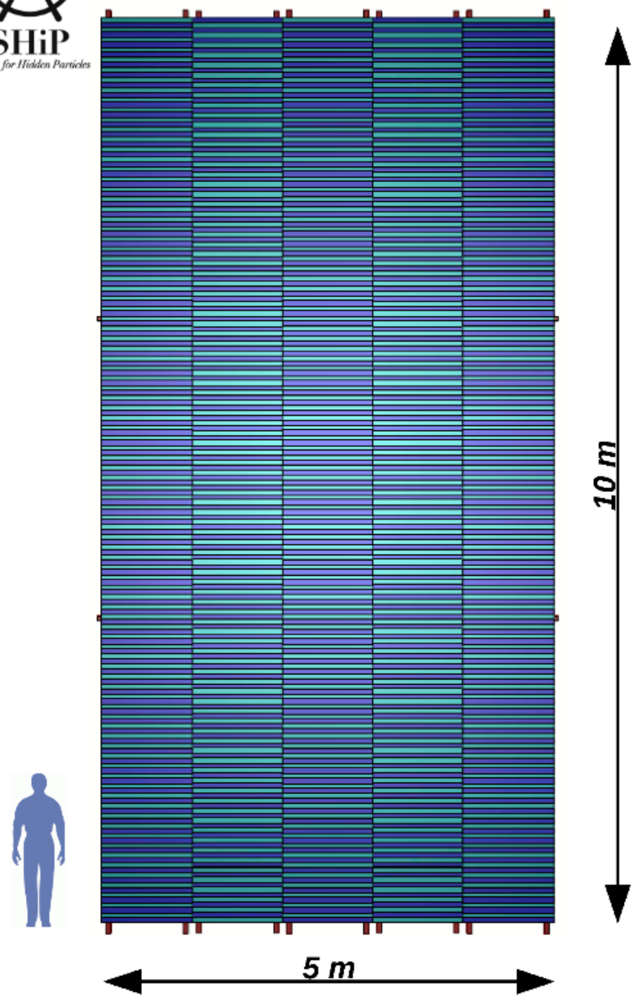
- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, μ–ρ^+ & $e^-\pi^+$*

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*

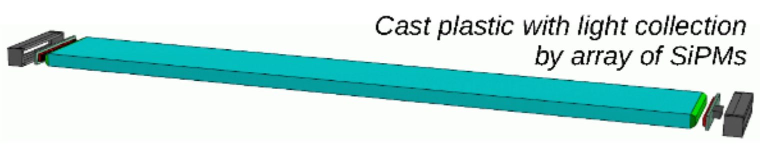


- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

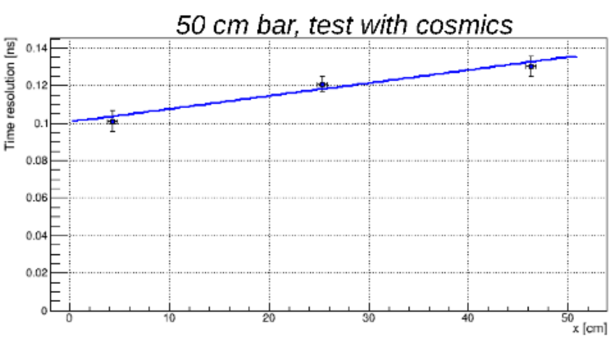
III. FE circuits: MUSIC: Multipurpose SiPM RO chip



Timing Detector in SHiP



- For the TD of size 5 m x 10 m with a bar ***100 cm x 6 cm x 1 cm***
  - 5 col x 182 row = 910 bars =>
  - 910 bars x 2 = 1820 ch =>
  - 1820 x 8 = 14560 SiPMs
- The resolution at 50 cm is ~140 ps => we can use with 1 m bar and 2-side readout to be within 100 ps.



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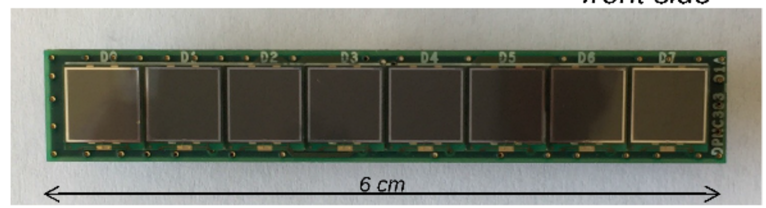
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

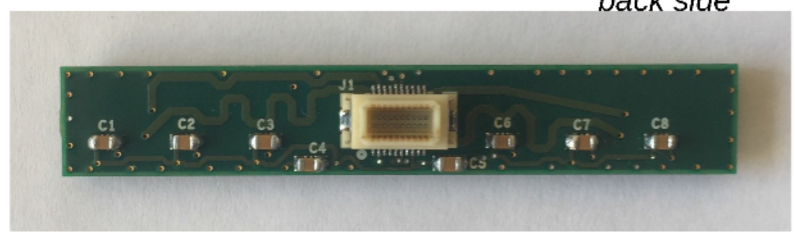
Bar and sensors for ToF/ND280

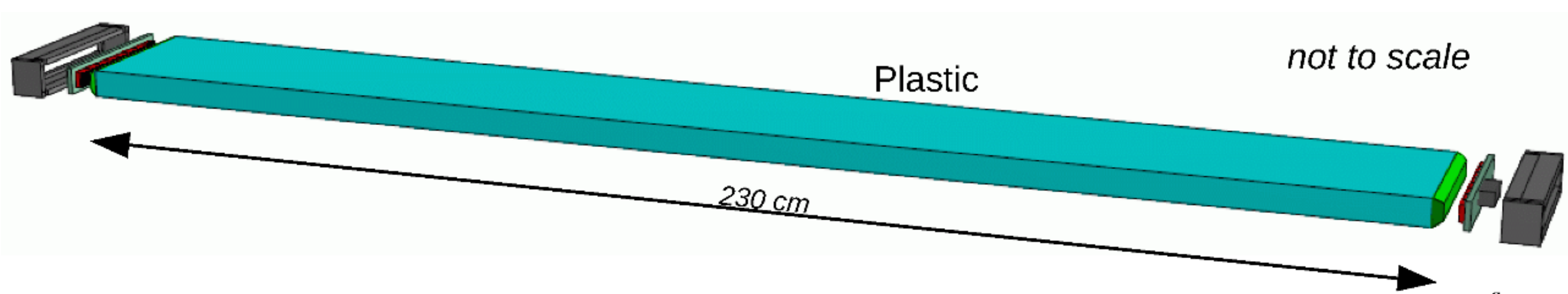
- Bar: 230 cm x 6 cm x 1 cm
- Plastic material:
  - EJ200 (BC408) or EJ208(BC412)
  - Attenuation length ~4 m
  - 1.42 kg/bar
- Readout from both ends
  - 8 sensors of 6 mm x 6 mm
  - Example: S13360-6050PE

front side



back side

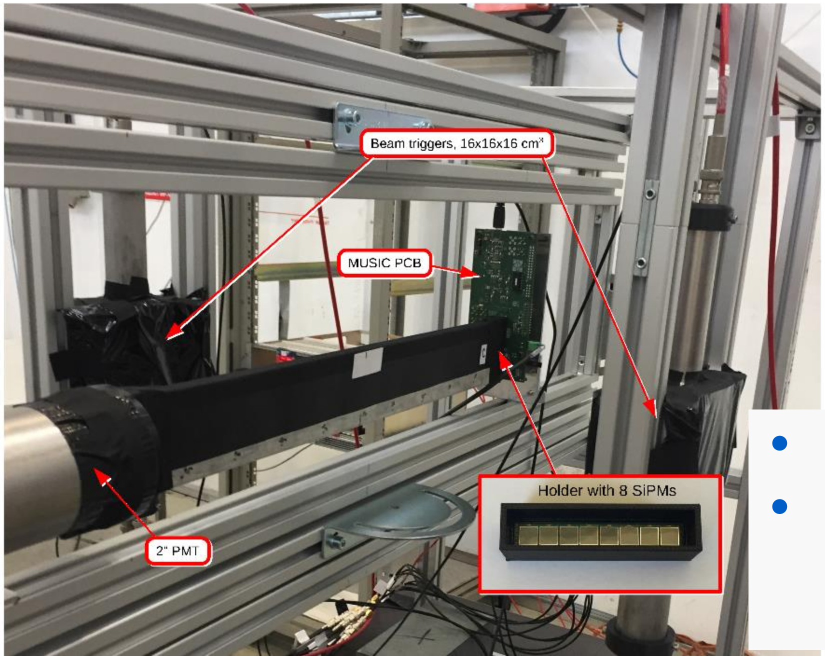


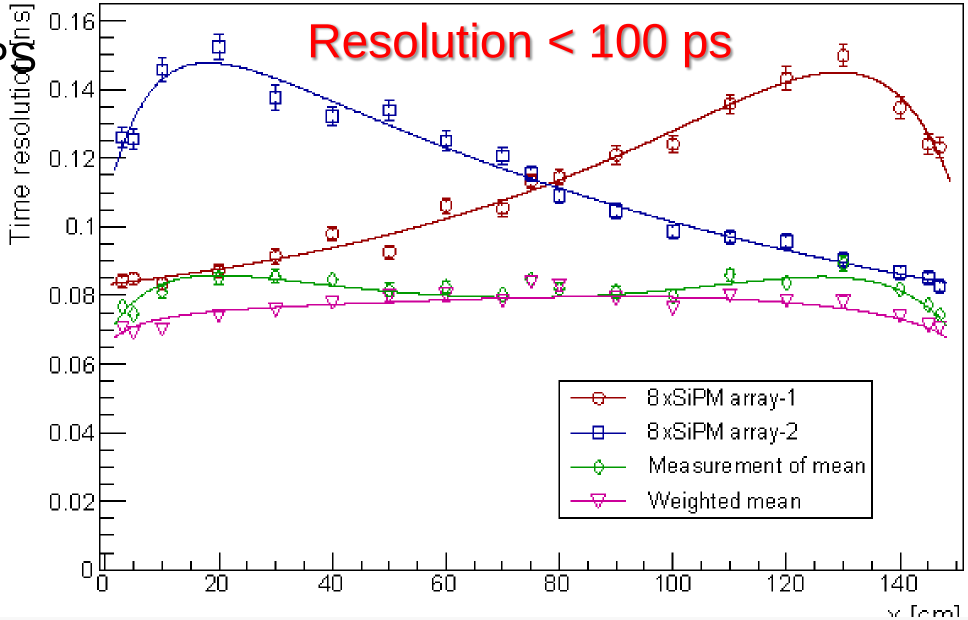


6

III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Timing sub-detector test beam with MUSIC chip
  - By Univ. Geneva & Univ. Zurich
  - MUSIC in summation mode (8 6x6 mm^2 SiPMs)
    - Bar read-out at both ends
  - 2.5 GeV/c muon beam at the CERN PS
  - Readout with Wavecatcher
    - Fast analog memory (LAL & IRFU/CEA)





- Measurements with the 150 cm x 6 cm x 1 cm bar.
- Time resolution as measured by the SiPM arrays at both ends of the bar as a function of the interaction point along the bar.

© A. Kornezev (Univ. Geneva)

Outlook

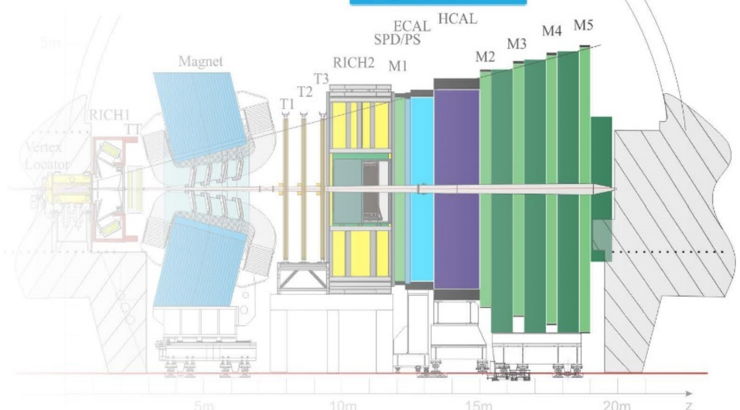
I. Introduction
II. SiPM electrical parameters
III. FE circuits
IV. ASIC examples
V. Conclusions

IV. ASICs for HEP: PACIFIC

SciFi - The New Scintillating Fibre Tracker for LHCb

Albert Comerma* on behalf of the SciFi tracker collaboration
*Physikalisches Institut, Universität Heidelberg

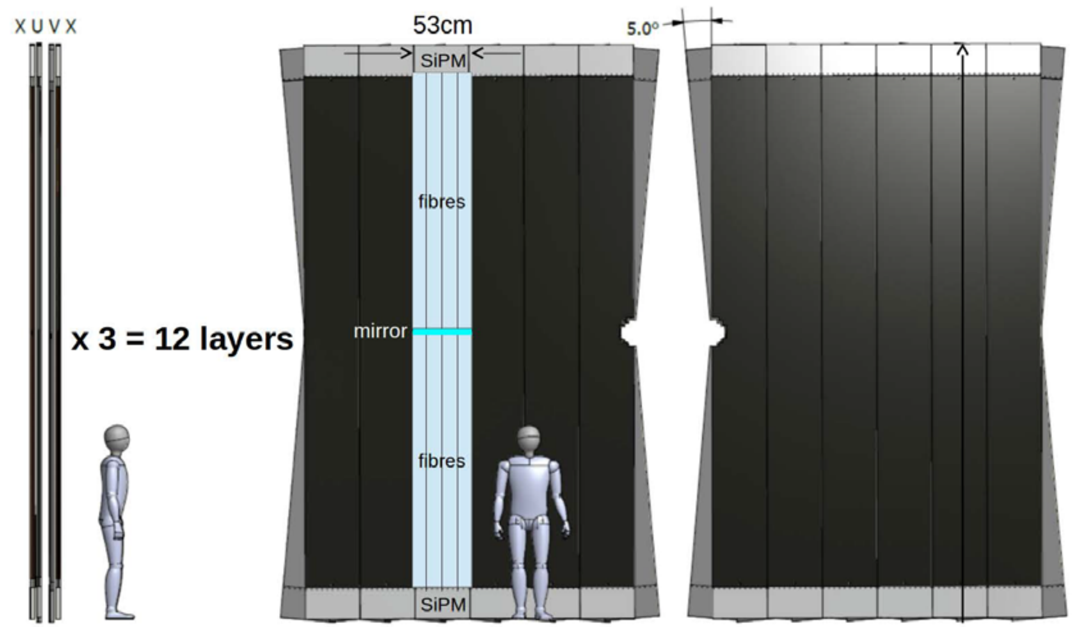
IEEE NSS-MIC, 26^{th} October 2017



IV. ASICs for HEP: PACIFIC

SciFi Overview

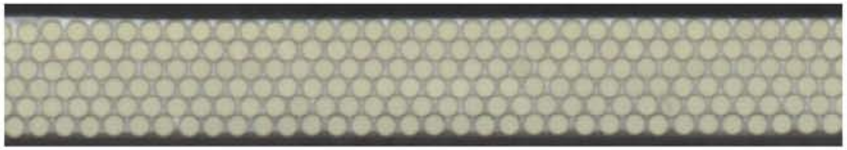
- Scintillating Fibre Tracker:
  - Light detector, $< 1\% X_0/layer$
  - Large area, total of $6 \times 5m^2$
  - XUVX planes on each station
  - Full detector is 3 stations
  - Total radiation up to 35kGy
- Requirements:
  - Hit efficiency $\approx 99\%$
  - High granularity $250\mu m$
  - Hit resolution $< 100\mu m$



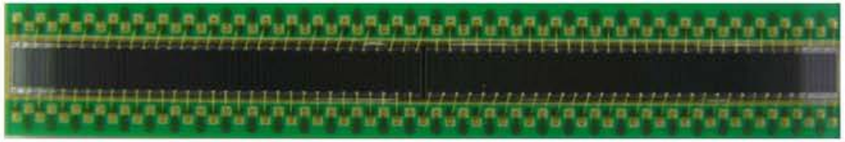
IV. ASICs for HEP: PACIFIC

SciFi Module

Total of **128 modules of** $0.5 \times 5m^2$.
Each module consists on eight fibre mats.
Each fibre mat is $240 \times 13cm^2$.
Mats constructed with 6 layers of fibres:

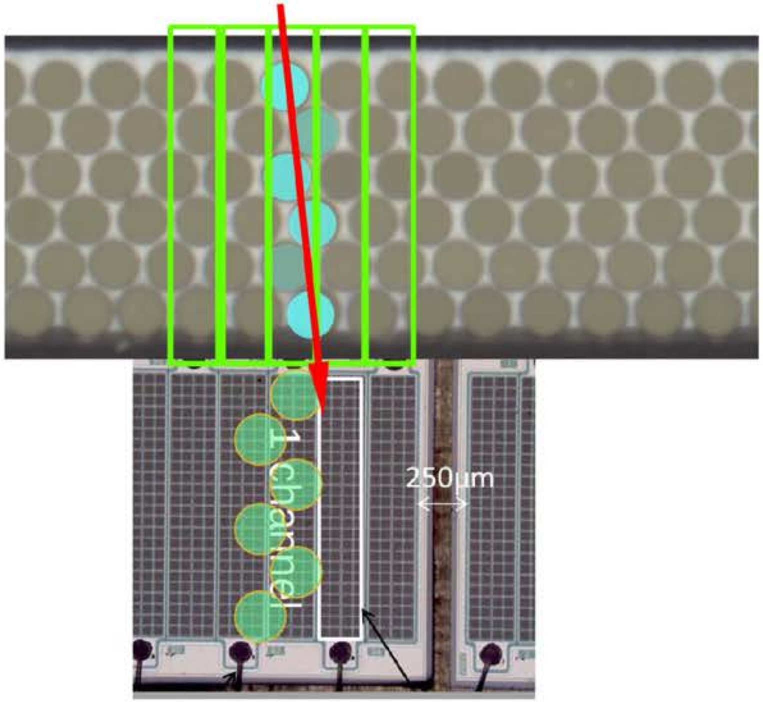


Fibres readout by SiPM array:



64 + 64 channels array (2 dies).
$60 \times 60\mu m^2$ cells, 104 pixels / channel.

Signal spread over channels, 16-20 phe.
Clustering needed:

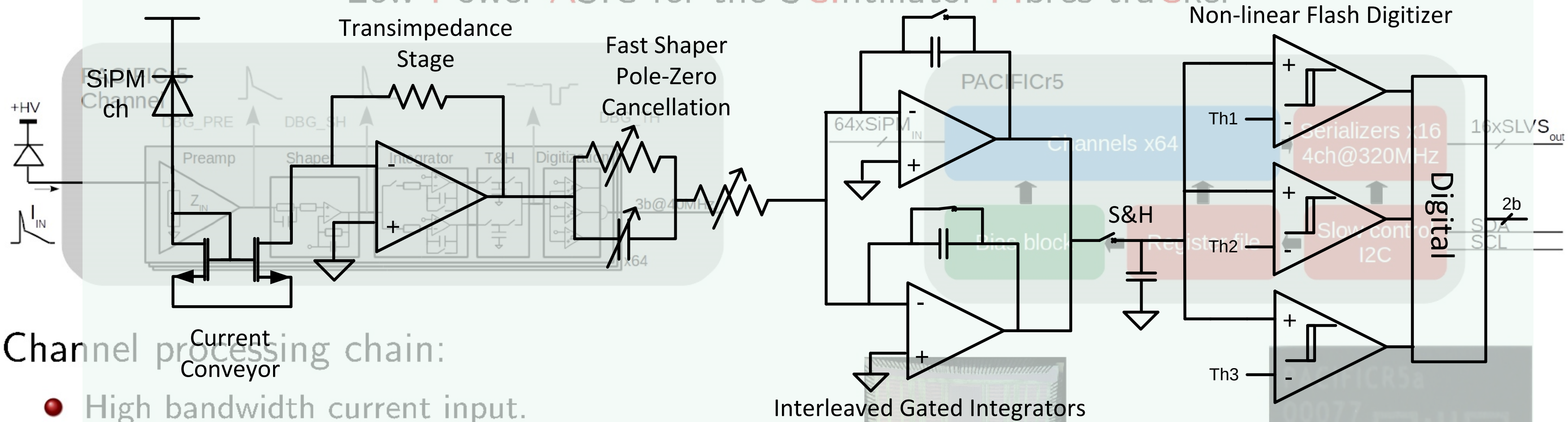


IV. ASICs for HEP: PACIFIC

PACIFIC

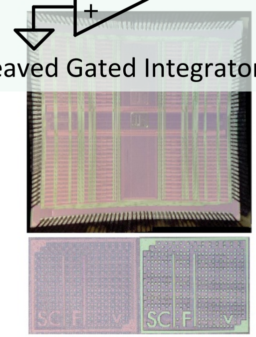
Collaboration: Heidelberg, ICCUB , LPC-Clermont, IFIC-Valencia

Low Power ASIC for the SCIntillator FIbres traCker



Channel processing chain:

- High bandwidth current input.
- Anode voltage control.
- Fast Shaper for tail adjustment.
- Double interleaved gated integrator.
- Track and hold.
- Digitization with 3 hysteresis comparators.
- Serialization and slow control (std cells).



4x3.85mm^2

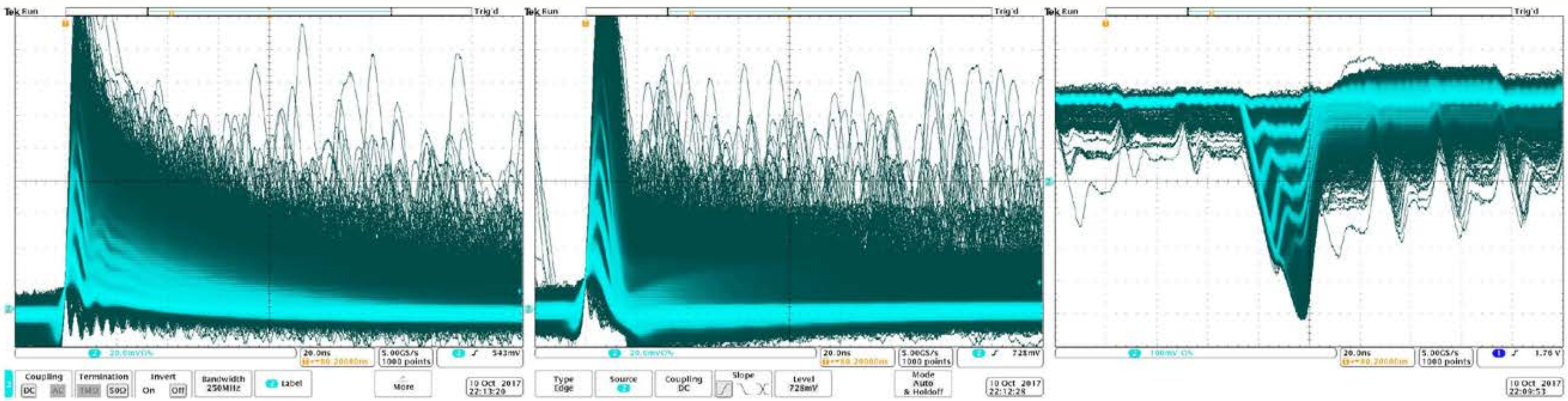
BGA package

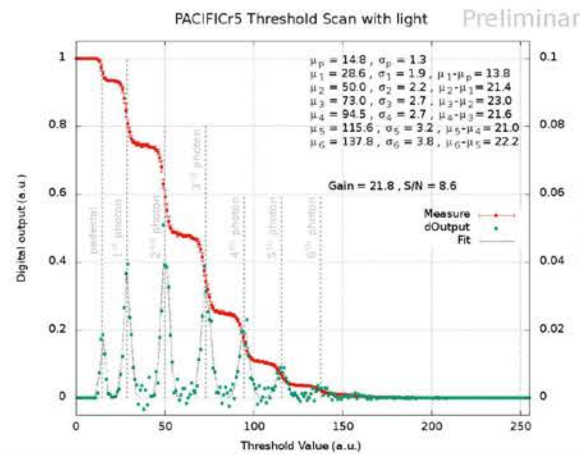
$12 \times 12mm^2$ 196pins

IV. ASICs for HEP: PACIFIC

PACIFIC

Collaboration: Heidelberg, ICCUB , LPC-Clermont, IFIC-Valencia





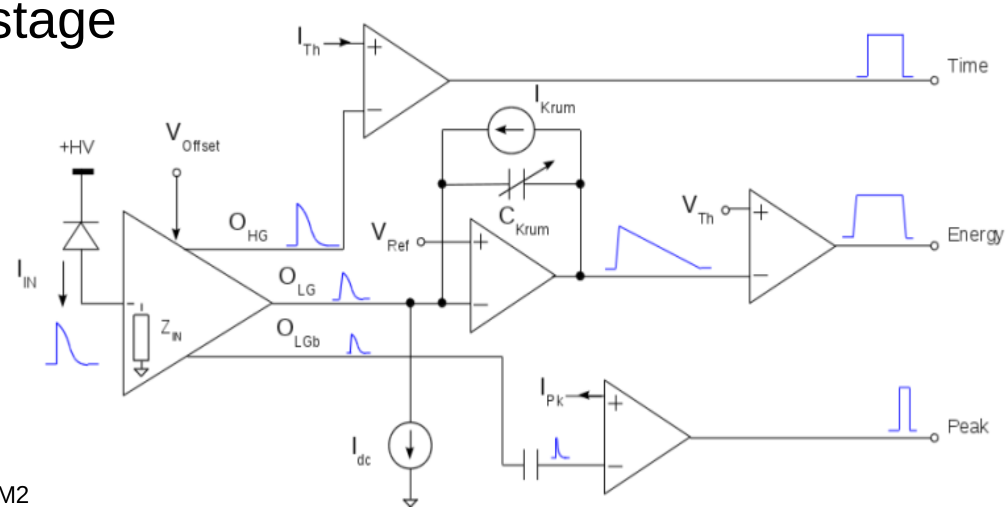
SiPM connected to PACIFIC:

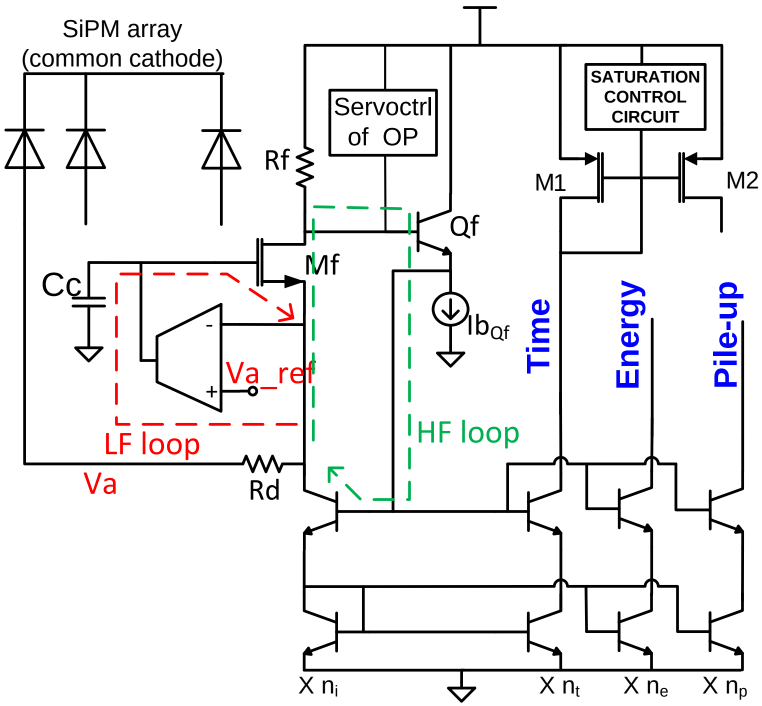
- Analog DEBUG outputs for Preamp, Shaper and TH.
- Synchronous light triggered on front of array.
- Threshold scan of one comparator to measure photons.

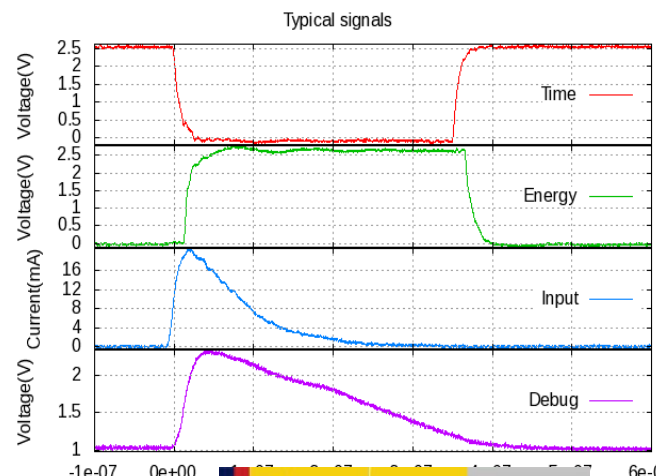
IV. ASICs for PET: FlexToT: linearized ToT RO chip

Collaboration: ICCUB and CIEMAT

- A Flexible ASIC for SiPM RO (PET, SPECT, Compton)
  - Novel current mode input stage
  - Time resolution for ToF
  - Time over Threshold RO
    - **No ADC**

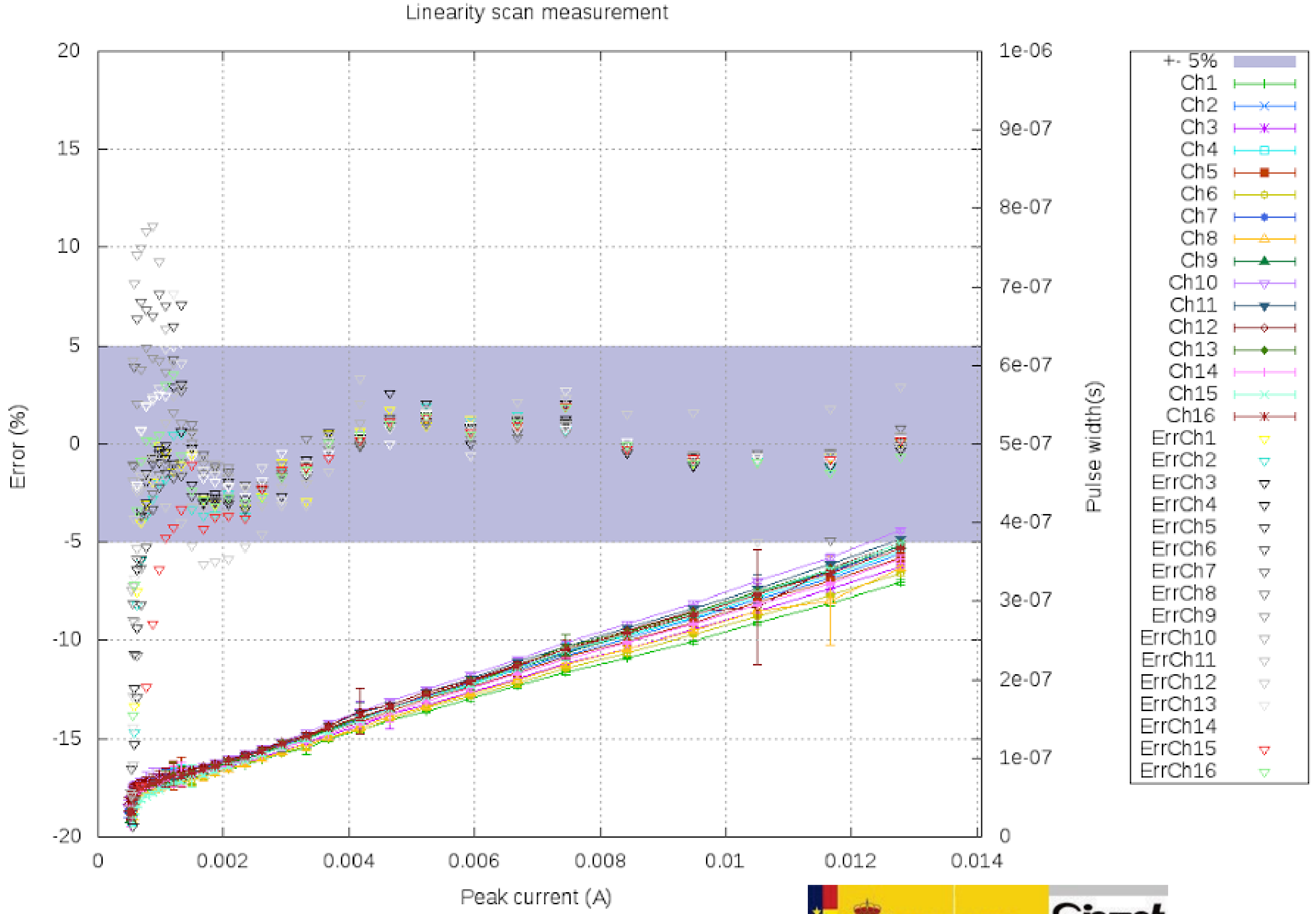






IV. ASICs for PET: FlexToT: linearized ToT RO chip

- **Good linearity and uniformity**
  - With only comparator threshold offset equalization
- **Different operating ranges can be covered**

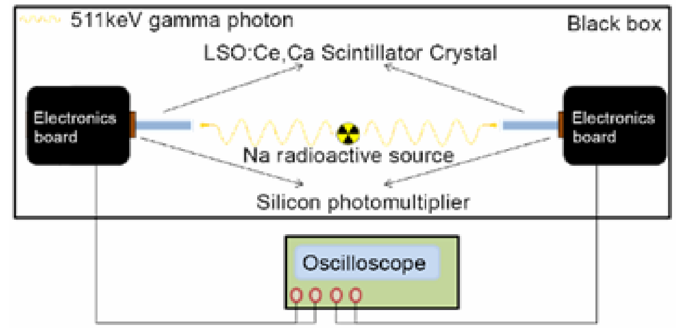


IV. ASICs for PET: FlexToT: linearized ToT RO chip

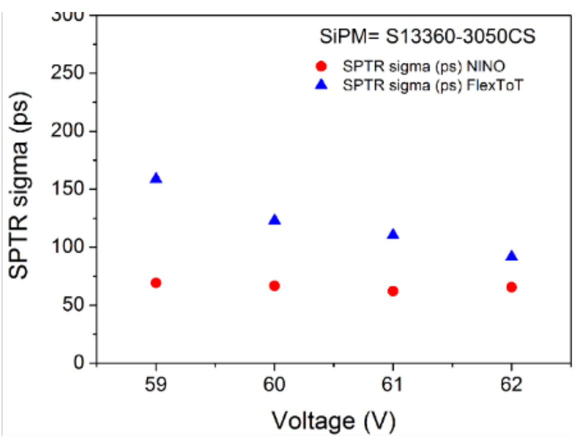
- Measured @ CERN:
  - Single Photon Time resolution (SPTR)
  - Coincidence Time Resolution (CTR)
  - Supported by FAST COST ACTION
    - Many thanks to E. Auffray and S. Gundacker
  - Similar results as for NINO but 3 times lower power consumption

Coincidence Time Resolution (CTR): 128 ps FWHM

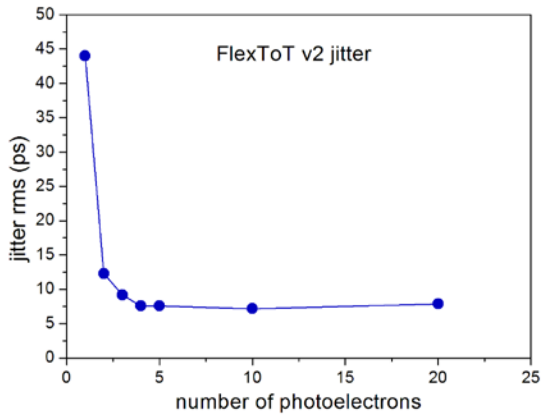
- 2x2x5 mm3 LSO:Ce,Ca crystals.
- Measurements performed in a black-box at 15 ºC.
- Coincidences corresponding to 511 KeV photopeak (±3σ).



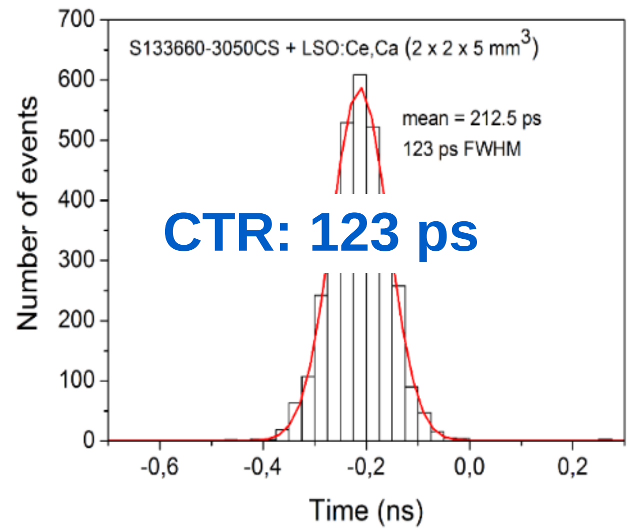
Coincidence Time Resolution (CTR) test bench setup



SPTR=90ps



Jitter floor: 7 ps rms

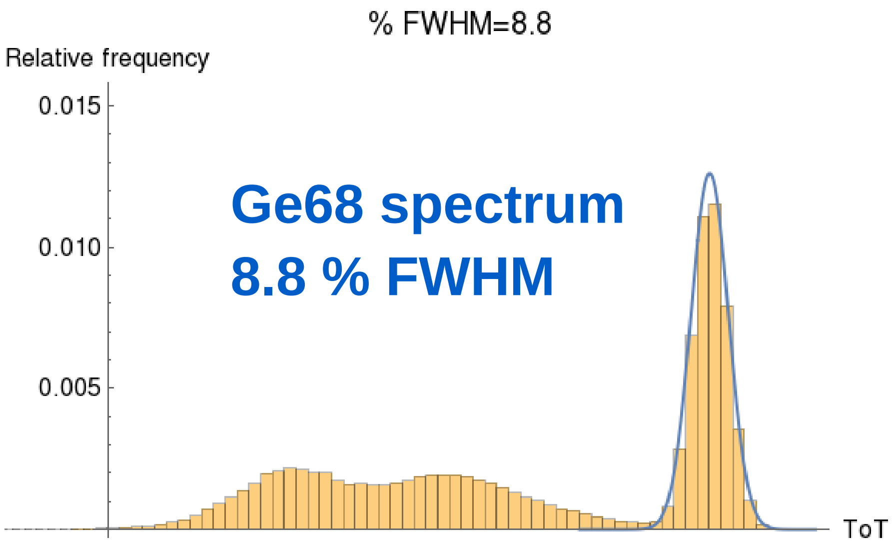


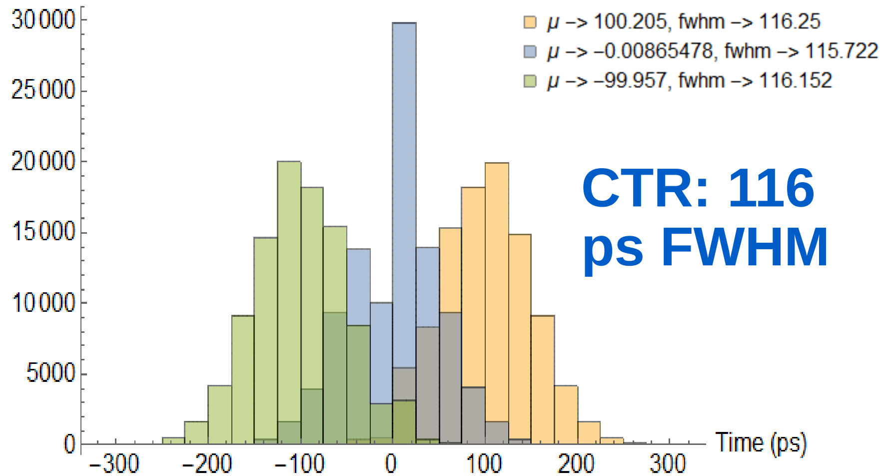
IV. ASICs for PET: FlexToT: linearized ToT RO chip

- Pisa University has develpped a FPGA based TDC readout for FlexToT
  - Based on Arria 10 FPGA
    - TDC: 38 ps resolution
  - System CTR: 116 ps FWHM !
  - Energy resolution: 8 % FWHM @ 511 KeV
  - Dead time < 5ns: event rate > 1 MHz !

P. Catra,
G. Sportelli

2 LYSO xtals 3x3x5 mm3
NUV-SiPM





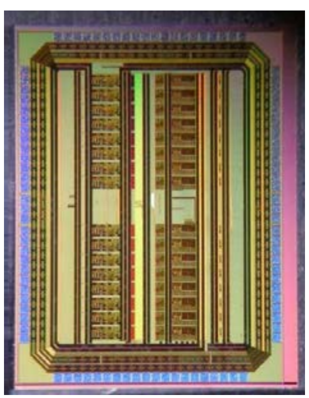
Timing distributions for different source positions

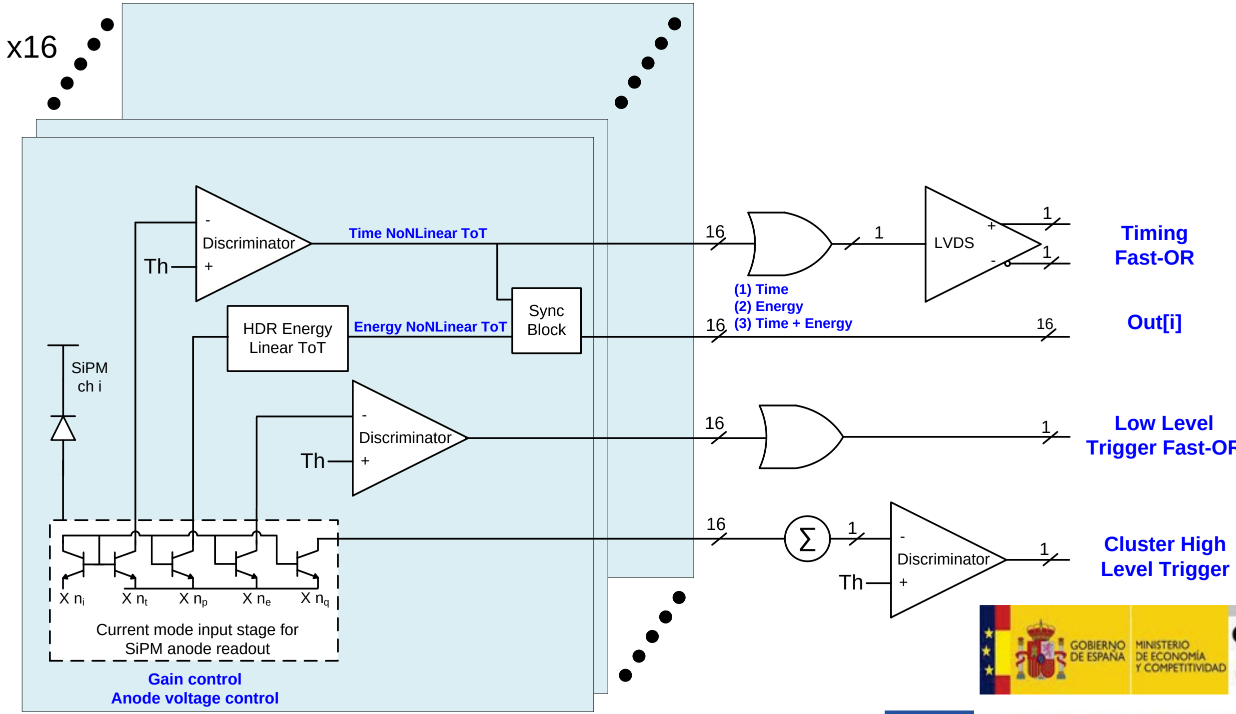
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- A new version of the FlexToT has been recently developed.
  - A linear Time over Threshold with higher resolution (>8bits)
  - Lower power consumption (about 3.5 mW/ch)
  - Different trigger levels and cluster trigger for monolithic crystals.
  - Different scintillator time constants.

HRFlexToT

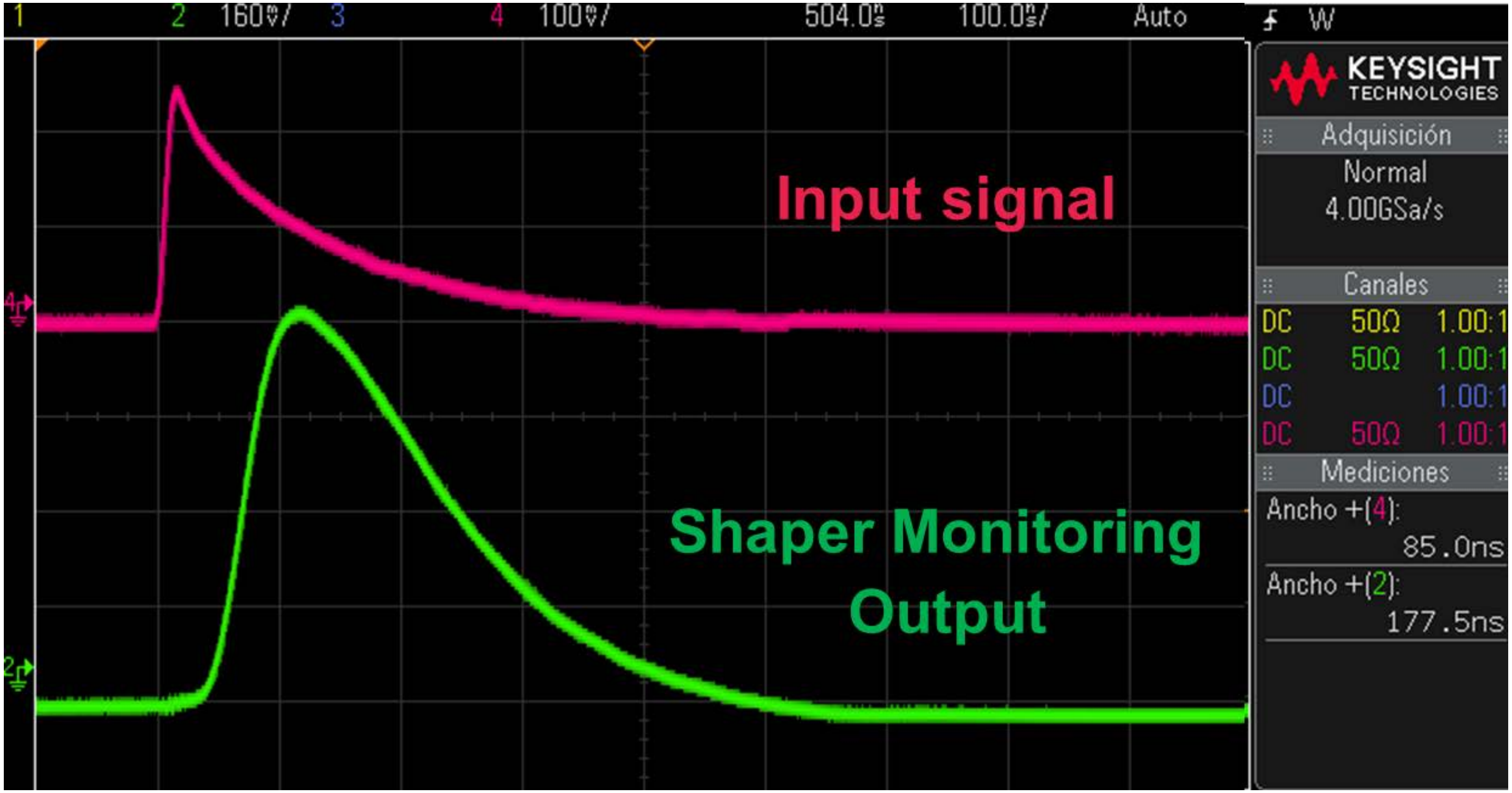
180 nm CMOS





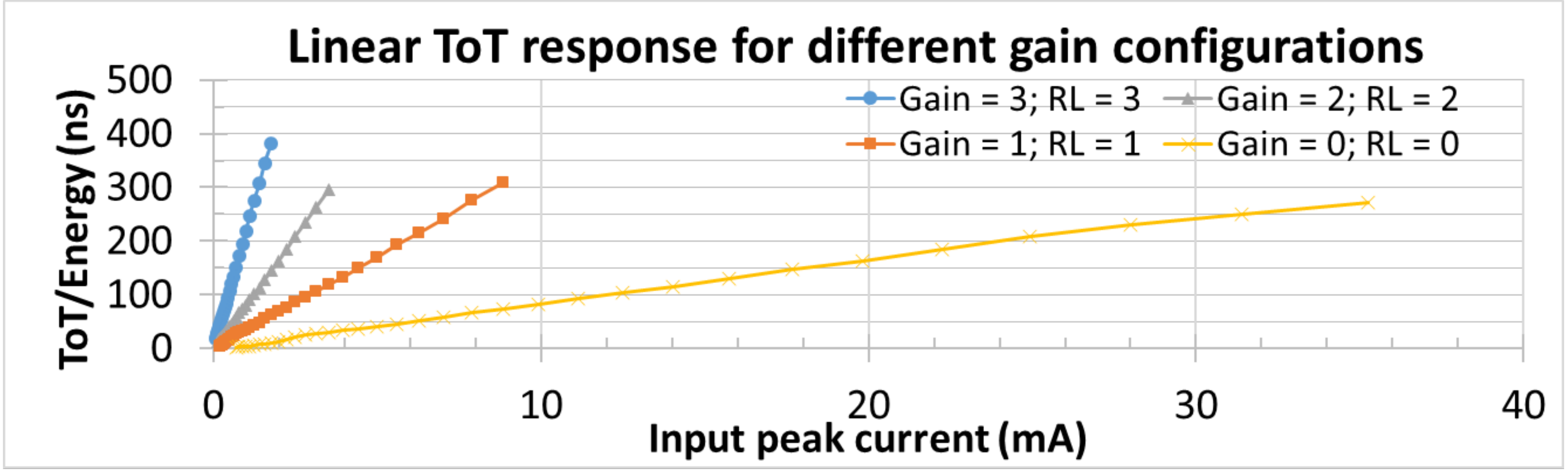
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

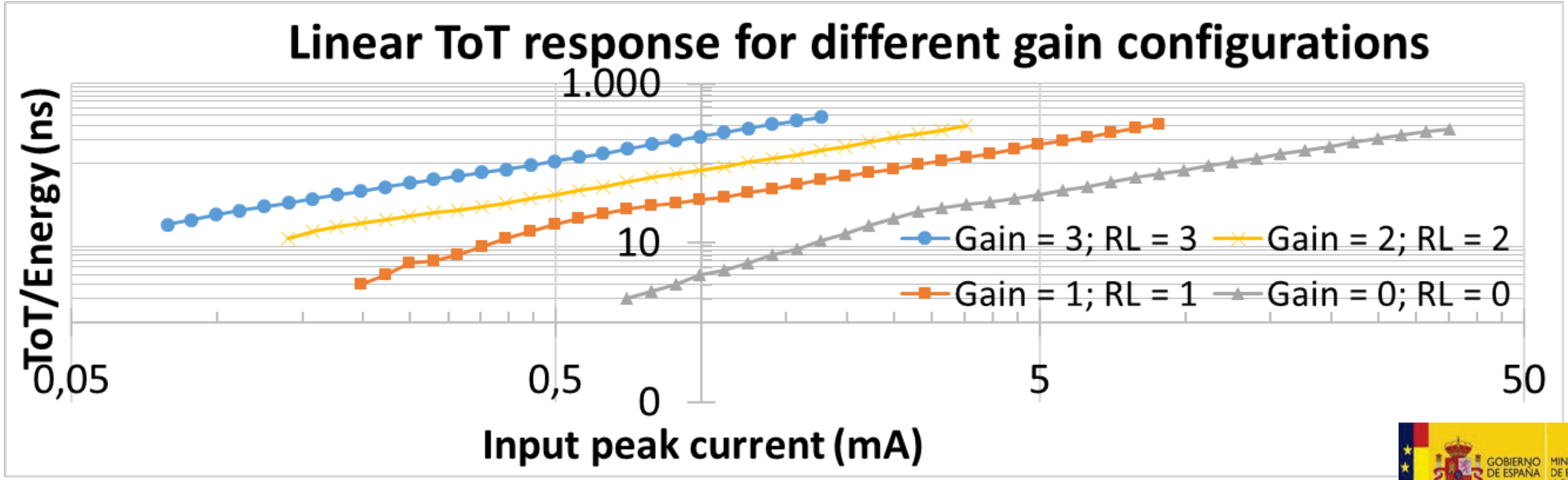
- Based on shaper and peak detector circuits



IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

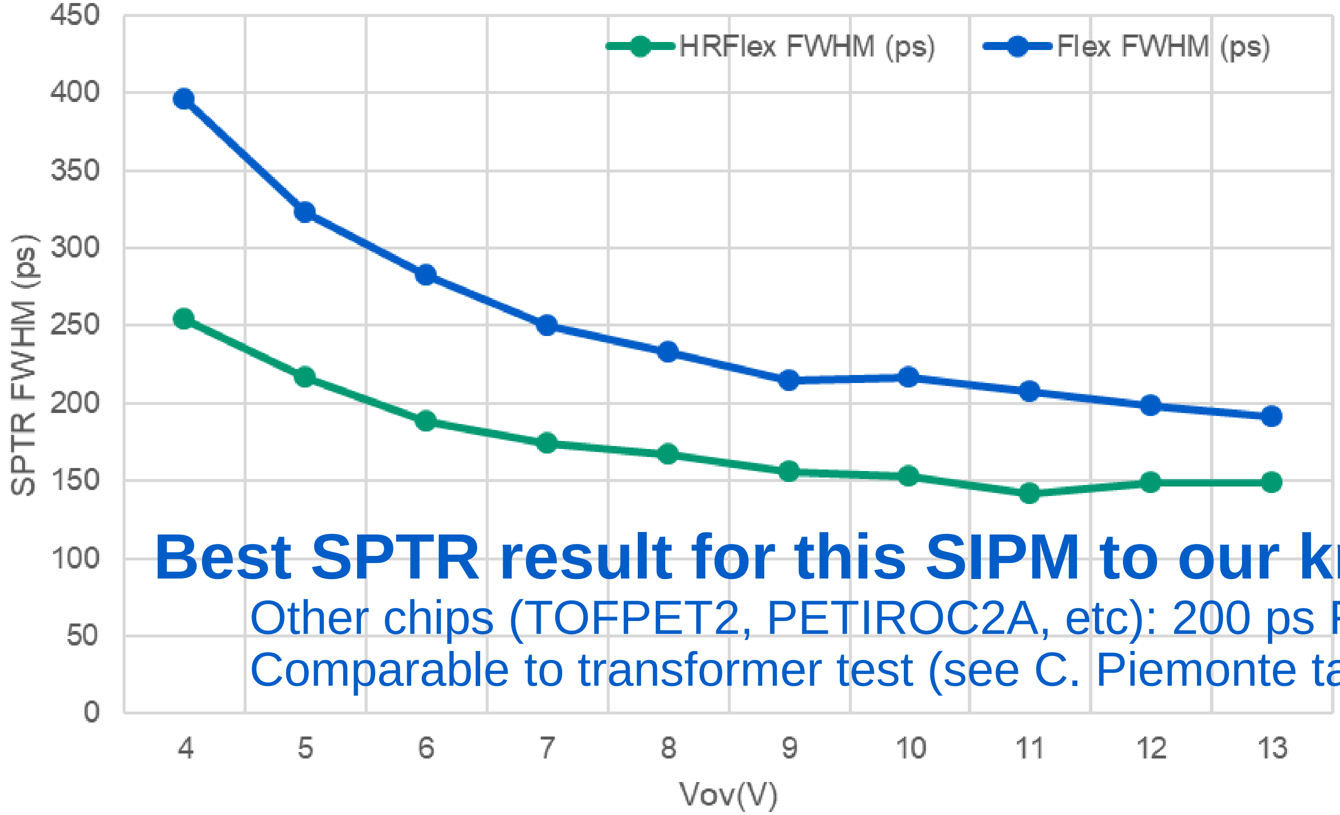
- Linearity and dynamic range





IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- Preliminary results
  - **<u>3x3 mm²</u>** HPKK device (50 um) cell, **<u>S13660</u>**.
  - ***SPTR*** of about 60 ps rms (<***<u>150 ps FWHM</u>***) with 3.5 mW/ch



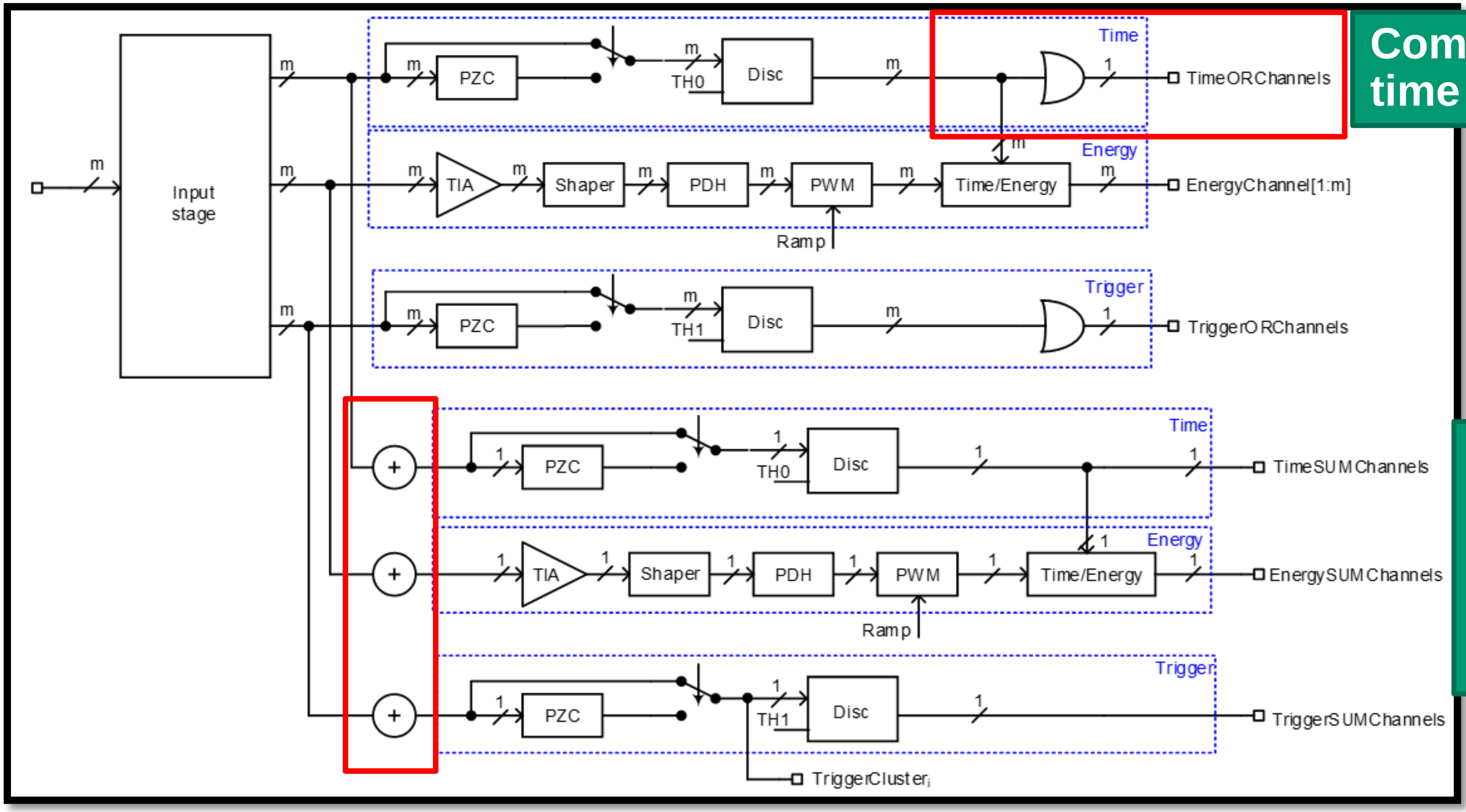
Best SPTR result for this SIPM to our knowledge:

Other chips (TOFPET2, PETIROC2A, etc): 200 ps FWHM for S13360

Comparable to transformer test (see C. Piemonte talk).

IV. ASICs for fast timing: outlook

- New ASIC ***FastIC*** in 65 nm being developed by ICCUB and CERN
  - Very low power input stage, low input impedance, summation, < 10 ps TDC…
- First step towards a Hybrid Single Photon Pixel Detector



Combined time by OR

Combined time, energy and trigger by analog summation

Outlook

I. Introduction

II. SiPM electrical parameters

III. FE circuits

IV. ASIC examples

V. Conclusions

V. Conclusions

- SiPM pulse shape depends on readout amplifier and parasitic component of ineterconnects
- In current sensing, R_{in} should be minimized for best timing (improved di/dt)
  - But any value smaller than Rin,min = 5 Ω make the parasitic input network to resonate
- In voltage sensing, R_{in} should be maximized for best timing (better dv/dt)
  - This means large tails (PZ cancellation needed) and increasing series noise
- Optimum bandwidth in the signal path, prior to discrimination $BW_{opt} \sim 3 \frac{1}{2\pi\sqrt{L\,C_{det}}}$

  → No point in designing faster circuits, since only increases noises !

  This limit can be below100 MHz for large SiPMs with high interconnect inductance.
- For an accurate design we need to consider SiPM, readout circuits and interconnects together
  - Input impedance, electronics noise and shaping determine final performance: shape, effective gain, time resolution, energy resolution, etc
  - ***In my "dream" LLL: sensor sensor and electronics are optimized together:***
    - ***3D integration and hybrid approaches: not purely analog nor purely digital***

References on SiPM modelling and FE electronics

- G. Collazoul," The SiPM Physics and Technology", Photodet 2012, https://indico.cern.ch/event/164917/contributions/1417121/attachments/198512/278663/PhotoDet12_-_collazuol_-_v3.pdf
- S. Seifert, "Simulation of silicon photomultiplier signals", IEEE Trans. Nucl. Sci., vol. 56, no. 6, pp. 3726-3733, Dec. 2009.
- F. Corsi et al., "Modelling a Silicon Photomultiplier (SiPM) as a Signal Source for Optimum Front-End Design", Nucl. Instr. and Meth. in Phys. Res., vol. A572, pp. 416-418, 2007
- F. Ciciriello, F. Corsi, F. Licciulli, C. Marzocca, G. Matarrese et al., "Accurate Modeling of SiPM Detectors Coupled to FE Electronics for Timing Performance Analysis", Nucl. Instr. and Meth. in Phys. Res., vol. A 718, pp. 331-333.
- F. Ciciriello, F. Corsi, F. Licciulli, C. Marzocca and G. Matarrese, "Design of Current Mode Front-End Amplifiers with Optimal Timing Performance for High-gain Photodetectors," in European Conference on Circuit Theory and Design, 2015.
- C. de la Taill, "SiPM readout electronics overview", Photodet 2012, https://indico.cern.ch/event/164917/contributions/1417117/attachments/198508/278657/1-cdlt_Photodet2012.pdf

http://icc.ub.edu/congress/TechnoWeek2018

Third Barcelona Techno Week

Course on semiconductor detectors

Institute of Cosmos Sciences, Barcelona
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CERN ICCUB Institute of Cosmos Sciences EXCELENCIA MARÍA DE MAEZTU

Thanks a lot for your attention !!!

Questions ?

dgascon@fqa.ub.edu

II: Input stage optimization

- In current sensing, R_{in} should be minimized for best timing (improved di/dt), **but any value smaller than $R_{in,min}$ = 5 Ω make the parasitic input network to resonate.**
  - Low R_{in} trade-offs with power consumption; it can be reduced by means of feedback schemes, at the cost of compromising stability.
  - In practice, R_{in} in the range 15 Ω – 20 Ω are desirable in order to be compatible with detectors showing Cdet = 10 pF (PMTs/MCPs) – 1 nF (Large SiPMs).
- In voltage sensing, R_{in} should be maximized for best timing (improved dv/dt). **Signal dynamics are favourable since underdamped response is not possible under such a case.**
  - The parallel resonance can boost the slew-rate even more, but one should rely on parasitics…
  - Large R_{in} results in degraded count-rate capabilities. PZ cancellation becomes compulsory.
- Optimum bandwidth in the signal path, prior to discrimination $BW_{opt} \sim 3 \frac{1}{2\pi\sqrt{L\,C_{det}}}$
  - The minimum LC_{det} product (5 nH short connection / 10 pF in PMT) already results in 1 GHz optimum bandwidth.

→ No point in designing current sensing circuits faster than 1 GHz, since only noise would be integrated, worsening σ_t!

I. Introduction: current IACTs cameras

- Even some CTA telescopes will still be based on PMTs

incoming photon

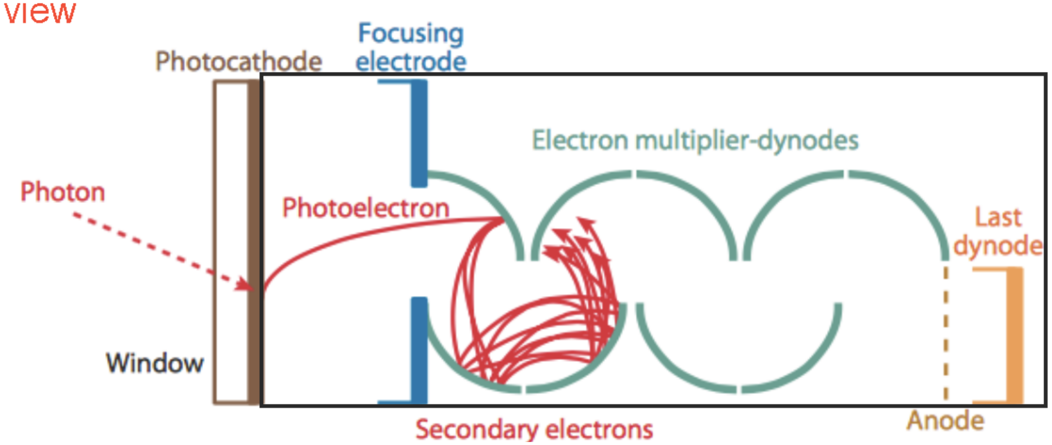
photoelectric effect PE
(generation of the primary electron)

electron multiplication chain
- production of secondary electrons
=> **measurable electric signal**

photomultiplier tube (**PMT**) - THE photodetector!

NO Si-based!

schematic view

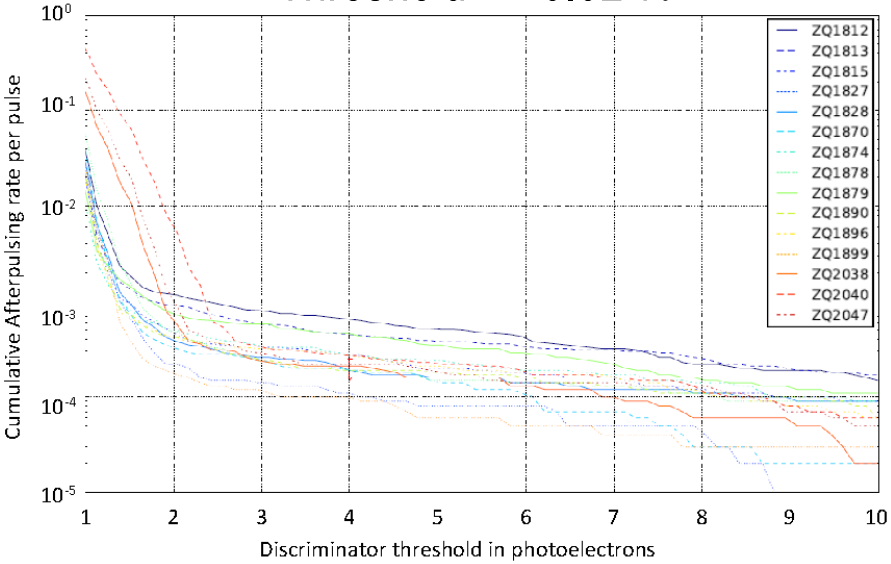


C. Casella, "Application of photosensors", ICCUB- Technoweek, 2016.

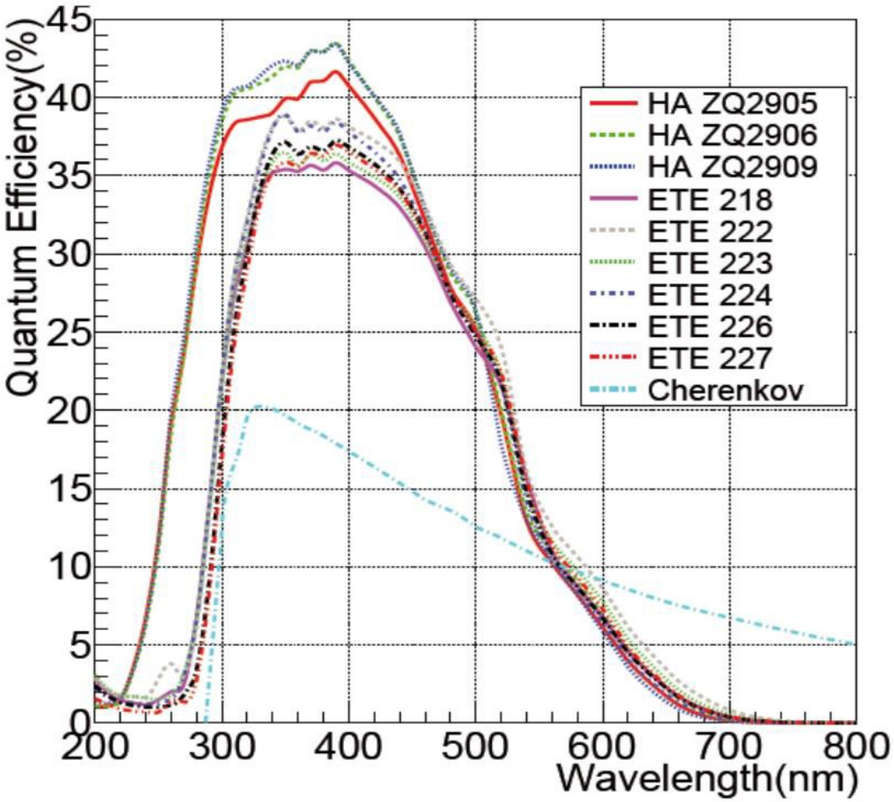
I. Introduction: current IACTs cameras

- Even some CTA telescopes will still be based on PMTs
- Amazing progress in last 10 years
  - PMTs developped for CTA

Afterpulsing at 4 ph.e.
Threshold << 0.02 %



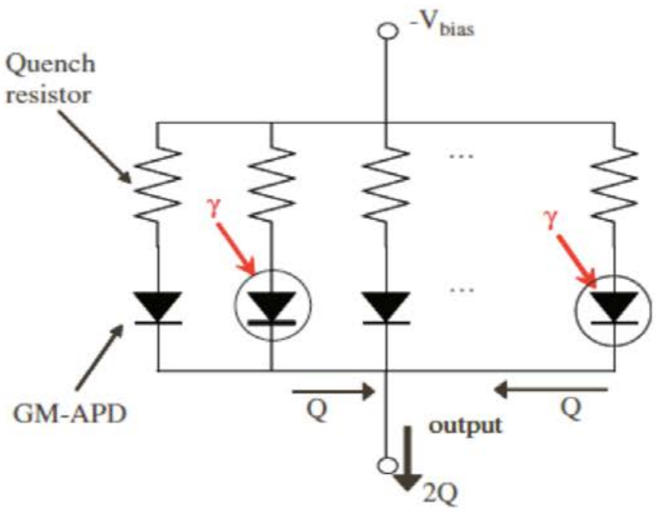
Peak PDE > 35 %

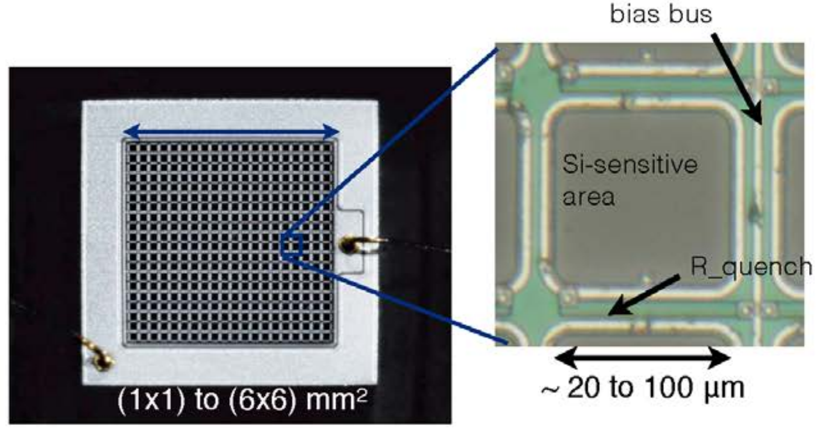


22.04.2015 APPEC TF,
Razmik Mirzoyan:
Recent Progress on PMT and SiPM, where we are going to

I. Introduction: SiPM based IACTs cameras

- SiPM principle





nr cells ~ 100 to 15000 / mm²

SiPM : array of micro-cells ***APD-like operated in G-mode*** connected to a **common bias** through **independent quenching resistors**, all integrated within a sensor chip.
The output is the **analogue sum of all cells**

individual cell (i.e. one diode, *APD-like*)
- Vbias > Vbreakdown
- Gain ~ 10^6 - 10^7
- Geiger regime (fully saturated)
- **No analogue info at the single cell level !**

- when hit by 1(2,3...n) photon(s)
  => full discharge
  => Qcell = Ccell (Vbias - Vbreakdown)
  overvoltage

C. Casella, "Application of photosensors", ICCUB- Technoweek, 2016.

I. Introduction: SiPM based IACTs cameras

- What is crosstalk in a SiPM?

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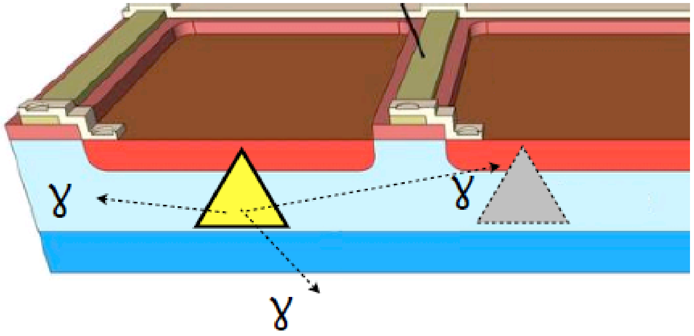
Correlated Noise

Optical Cross Talk

During the avalanche a large nr of photons are produced { **O(1photon/10^5 charge carriers)** }
=> Reach neighbours pixels and start a second avalanche

correlated noise
contribution **added** to the primary signal
stochastic process => contributes to ENF

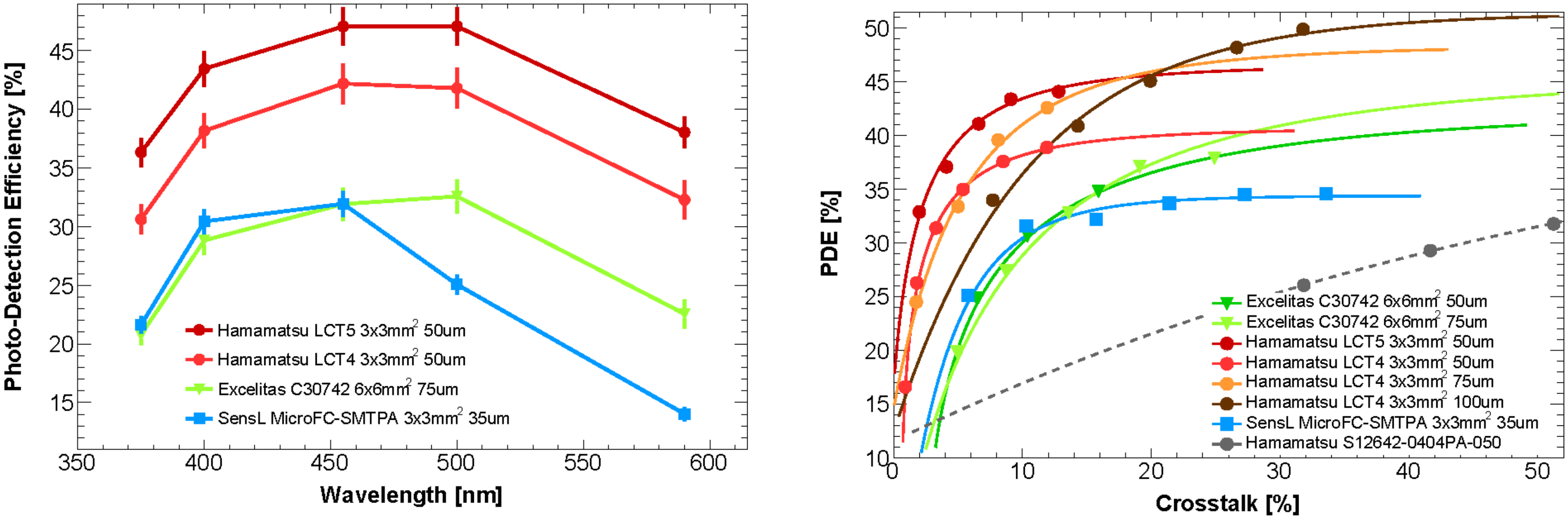
- **larger Vov => larger gain => higher P_XT**
- **smaller pixel size => higher P_XT**
- **XT ~ 30 - 40 % (w/o trenches)**
- **significant impact of trenches = optical separation**



C. Casella, "Application of photosensors", ICCUB- Technoweek, 2016.

I. Introduction: SiPM requirements for IACTs

- High PDE > 40 %
  - A higher PDE results in a higher reconstruction rate of Cherenkov photons and decreases the energy threshold
- Low crosstalk
  - Crosstalk degrades the single photon charge resolution
- Trade-off between PDE and crosstalk

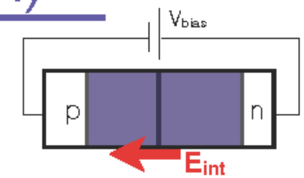


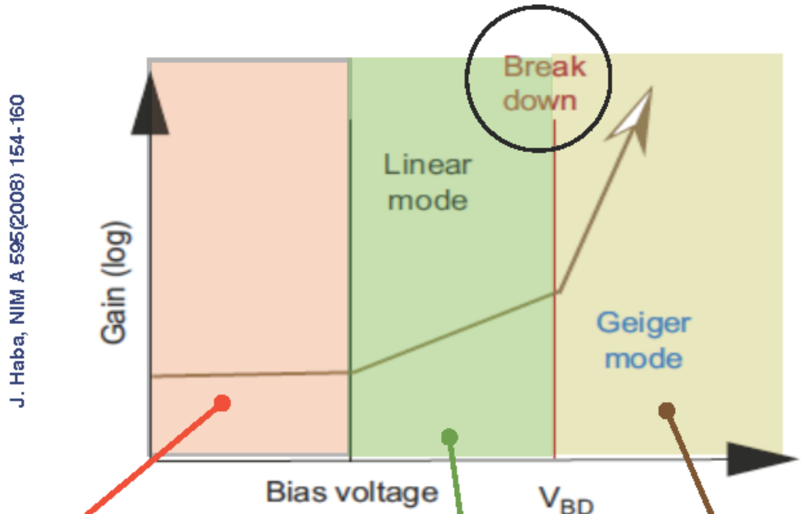
J. Biteau et alt. "Performance of Silicon Photomultipliers for the Dual-Mirror Medium-Sized Telescopes of the Cherenkov Telescope Array", ICRC2015

I. Introduction: SiPM based IACTs cameras

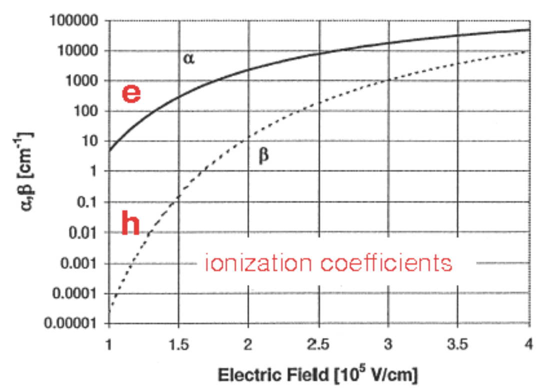
Solid state photodetectors (i.e. p-n junction)

Reversed bias pn junction - Different regimes





Vbias :
- enlarge depletion region
- increase electric field
- secondary ionization



PIN Diode
- no bias
- no gain

AVALANCHE PHOTODIODE (APD)
- voltage
- secondary ionization from electrons
- avalanche
- linear regime

GEIGER MODE AVALANCHE (G-APD)
- V > V_breakdown
- secondary ionization from electrons and holes
- "broken" junction , avalanche
- Geiger regime, not linear anymore

SILICON PHOTOMULTIPLIER (SiPM) :
array of micro-cells operated in G-APD

C. Casella, "Application of photosensors", ICCUB- Technoweek, 2016.

I. Introduction: SiPM based IACTs cameras

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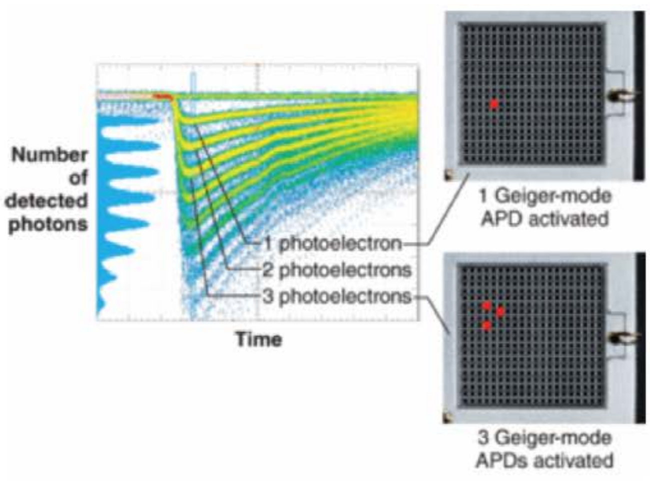
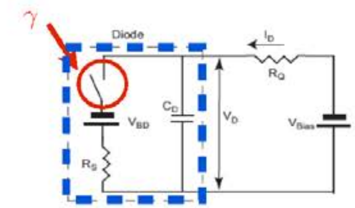
SiPM properties : Photon Counting

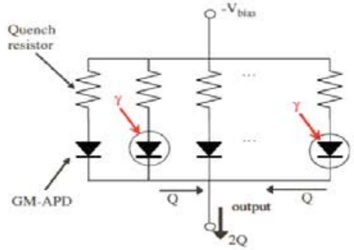


The output signal is 'quantized' and proportional to the Nr of fired cells

$$Q_{1cell} = C_{cell}\, \mathbf{V_{ov}}$$

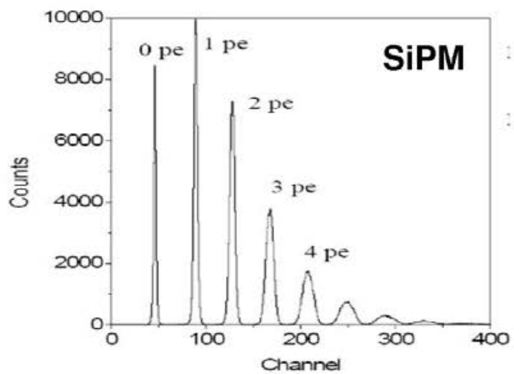
$$\mathbf{Q_{total} = N\ Q_{1cell}}$$

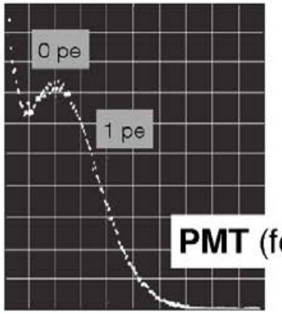




Excellent single photon counting capability

D. Renker, 2009 JINST 4 P04004



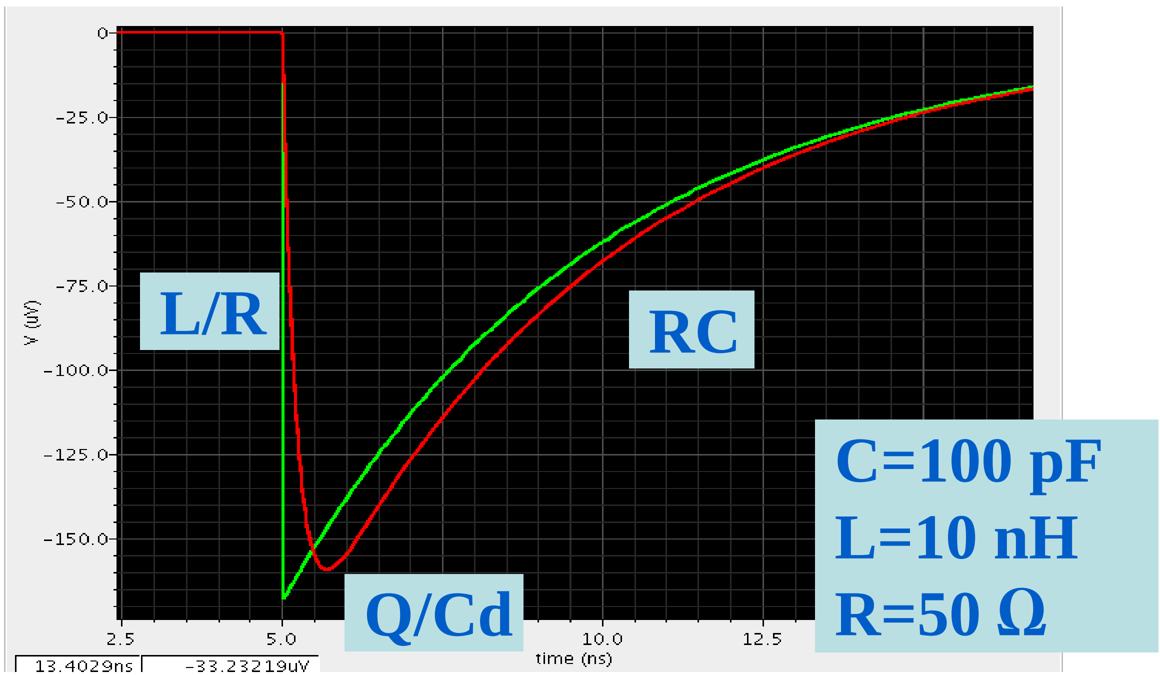


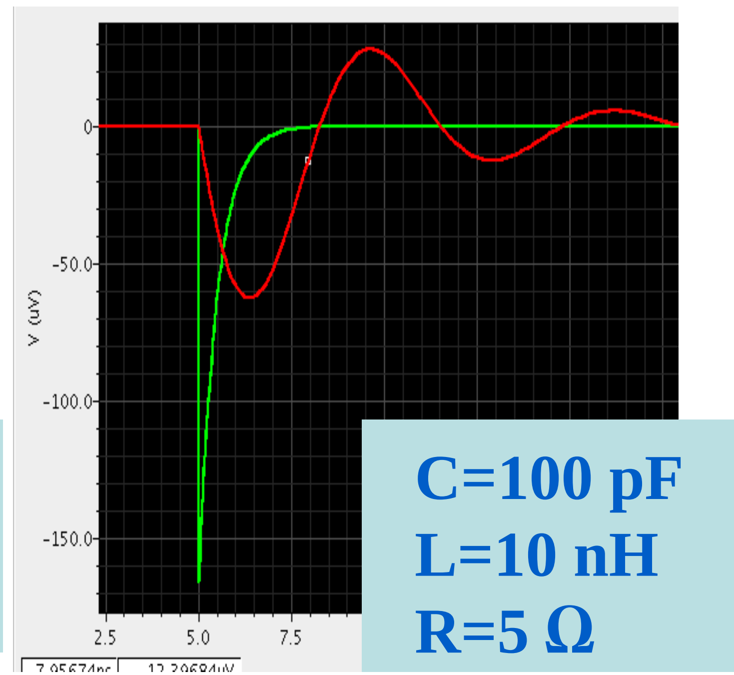
PMT (for comparison)

C. Casella, "Application of photosensors", ICCUB- Technoweek, 2016.

Basic pulse shapes

- **Short pulse : Q=16 fC, Cd=100 pF, L=0-10 nH, RL=5-50 Ω**
- **Smaller signals with SiPM (large Cd) ~ mV/p.e.**
- **Sensitivity to parasitic inductance**
- **Choice of RL : decay time, stability**
- **Convolve with current shape… (here delta impulse)**

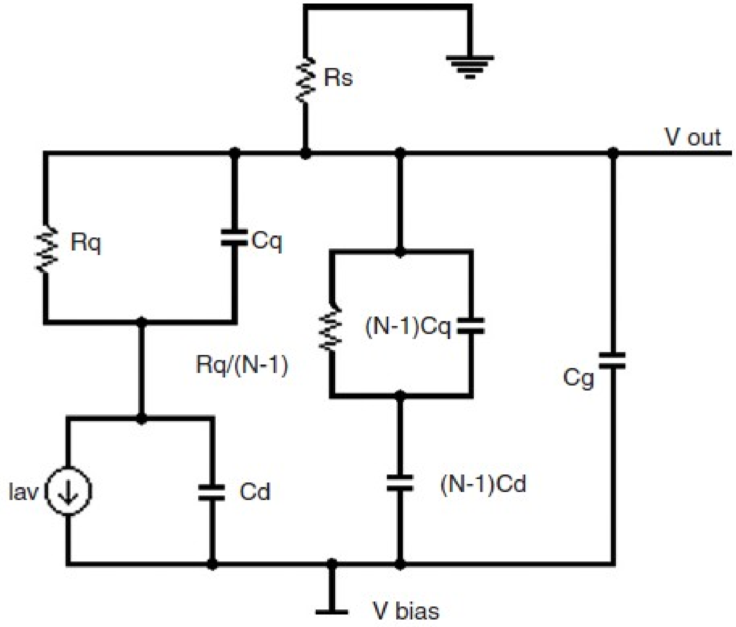




C. De LaTaille, Photodet conference, 2012

SiPM modelization

- **Modelization by Corsi et al [NIM A572 2007]**



[F. Corsi et al. NIM A572]

	SiPM IRST, $N = 625$, $V_{bias} = 35\,V$
R_q (kΩ)	393.75
V_{br} (V)	31.2
Q (fC)	148.5
C_d (fF)	34.13
C_s (fF)	4.95
C_g (pF)	27.34

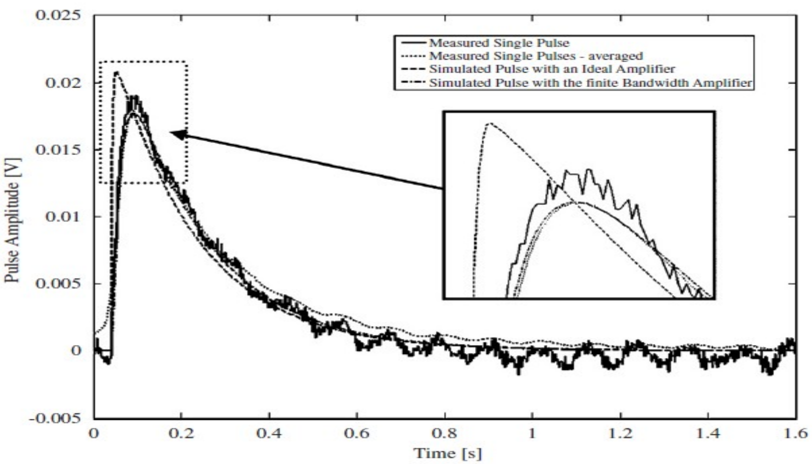


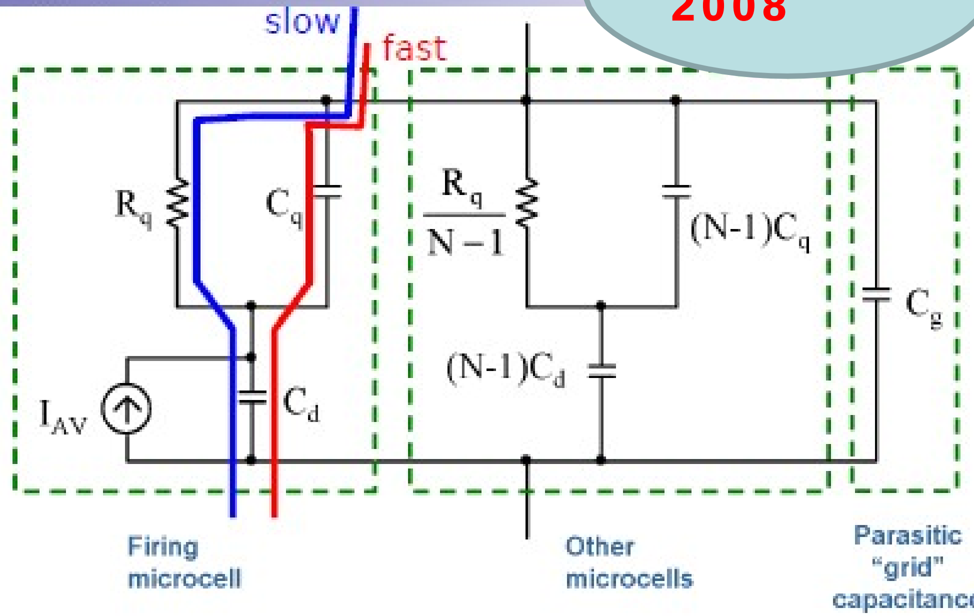
Fig. 2. Fitting of real data with the simulation results on the device model.

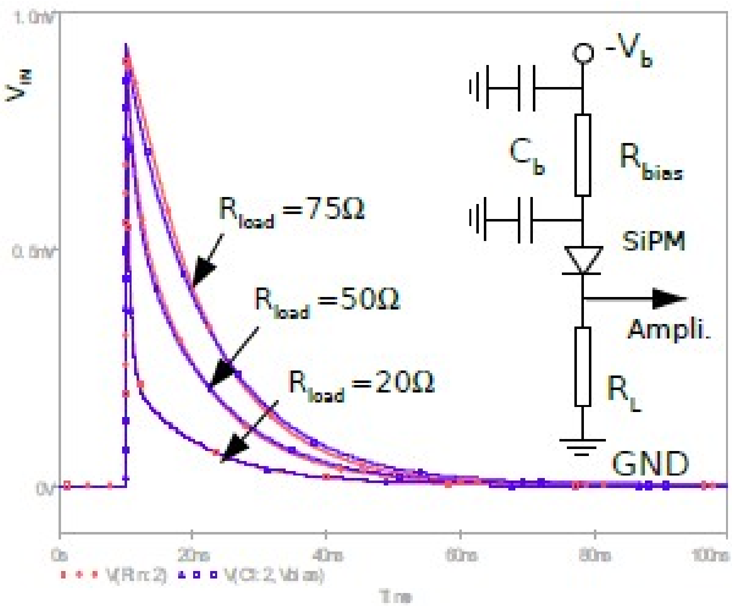
CERN ICCUB Institute of Cosmos Sciences EXCELENCIA MARÍA DE MAEZTU

Electrical model of a SiPM

Collazuol 2008

R_q: quenching resistor
(hundreds of kΩ)
C_d: junction capacitance
(few tens of fF)
C_q: parasitic capacitance in parallel to R_q (few tens of fF, $C_q < C_d$)
I_{AV}: SiPM ~ ideal current source
current source modeling the total charge delivered by a cell during the avalanche $Q=\Delta V(C_d+C_q)$
C_g: parasitic capacitance due to the routing of Vbias to the cells (metal grid, few tens of pF)





1) the peak of V_{IN} is independent of R_s

A constant fraction Q_{IN} of the charge Q delivered during the avalanche is instantly collected on $C_{tot}=C_g+C_{eq}$.

2) The circuit has two time constants:

- $\tau_{IN} = R_L C_{tot}$ (fast)
- $\tau_r = R_q (C_d+C_q)$ (slow)

Decreasing R_s, the time constant τ_{IN} decreases, the current on R_s increases and the collection of Q is faster

F. Corsi, C. Mazzocca et al.

SiPM equivalent circuit

Collazuol 2010

Single cell model → $(R_d||C_d)+(R_q||C_q)$

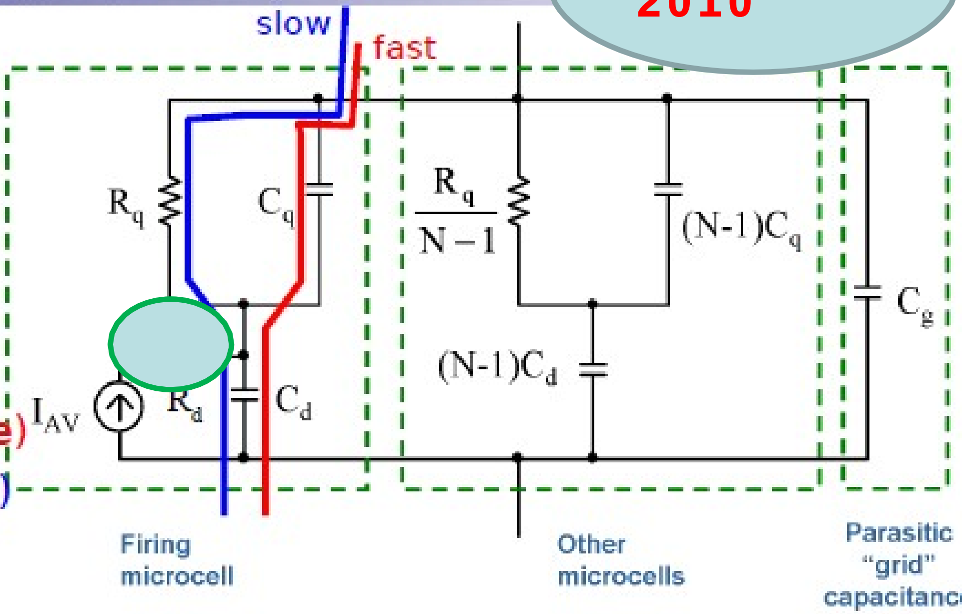
SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

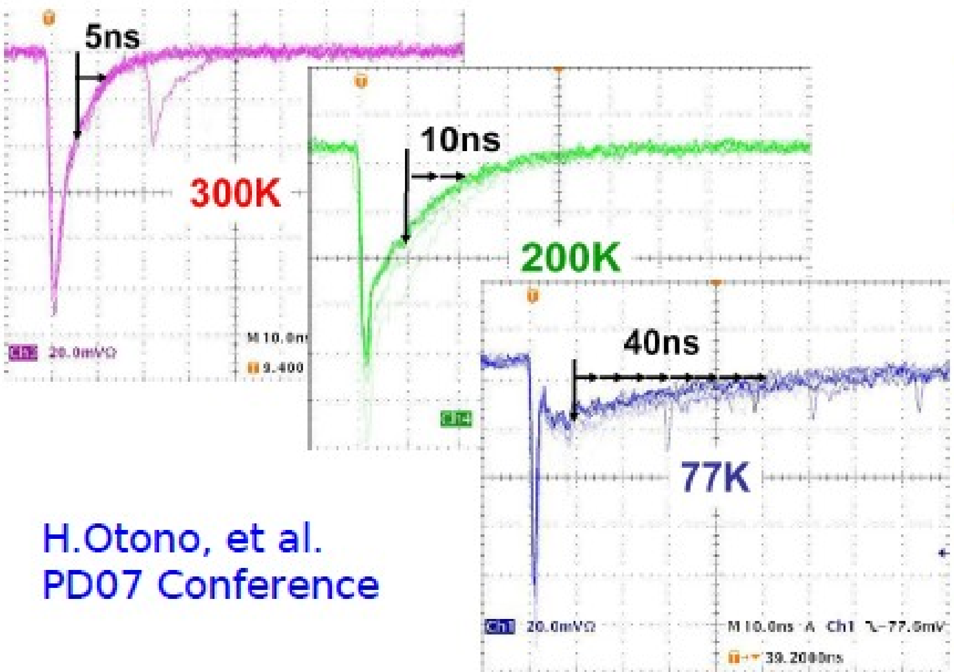
Signal = slow pulse ($\tau_{d\ (rise)}, \tau_{q\text{-}slow\ (fall)}$) +

+ fast pulse ($\tau_{d\ (rise)}, \tau_{q\text{-}fast\ (fall)}$)

- $\tau_{d\ (rise)} \sim R_d(C_q+C_d)$
- $\tau_{q\text{-}fast\ (fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{q\text{-}slow\ (fall)} = R_q\ (C_q+C_d)$ (slow; cell recovery)

F. Corsi, et al. NIMA 572(2007)





H.Otono, et al.
PD07 Conference

Pulse shape:

The two current components show different behavior with Temperature

→ fast component is independent of T because stray C_q couple with external R_{load} (no dependence on T) while R_q is strongly dependent on T

(we used low light level, BW filters against noise and AC coupling → difficult to disentangle the two components)

Optimizing signal shape for timing

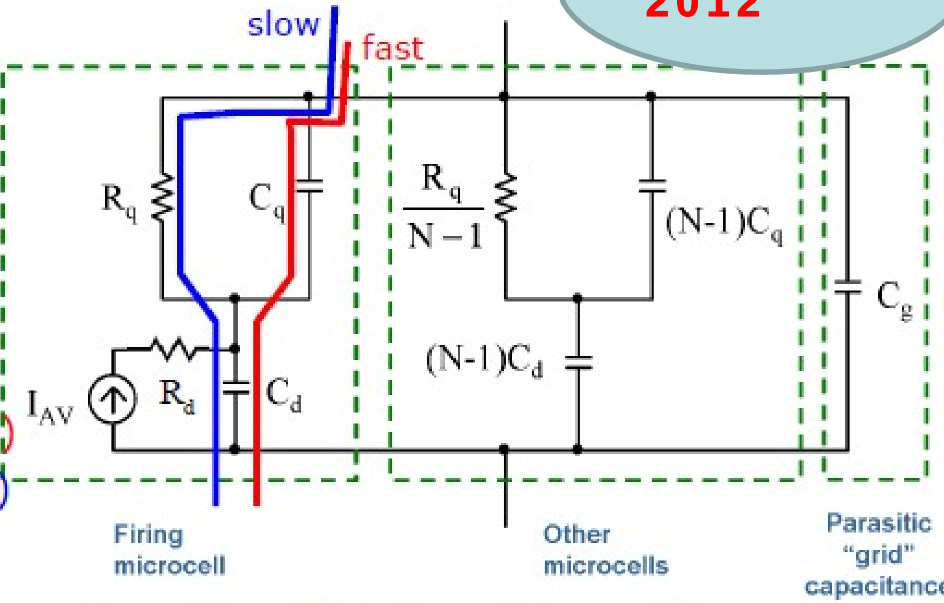
Collazuol 2012

Single cell model → $(R_d||C_d)+(R_q||C_q)$

SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

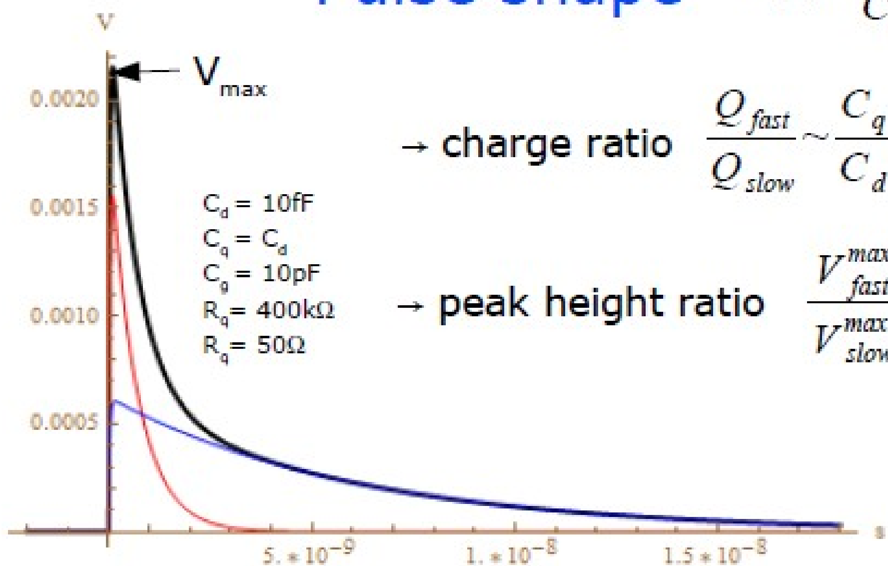
Signal = slow pulse ($\tau_{d\,(rise)},\tau_{q\text{-}slow\,(fall)}$) +
+ fast pulse ($\tau_{d\,(rise)},\tau_{q\text{-}fast\,(fall)}$)

- $\tau_{d\,(rise)} \sim R_d(C_q+C_d)$
- $\tau_{q\text{-}fast\,(fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{q\text{-}slow\,(fall)} = R_q\,(C_q+C_d)$ (slow; cell recovery)



Pulse shape

$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right)$$



→ charge ratio $\frac{Q_{fast}}{Q_{slow}} \sim \frac{C_q}{C_d}$

→ peak height ratio $\frac{V^{max}_{fast}}{V^{max}_{slow}} \sim \frac{C_q^2 R_q}{C_d C_{tot} R_{load}}$

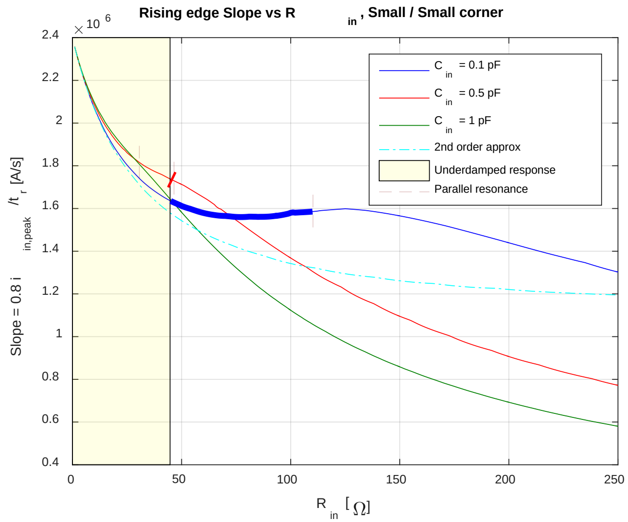
increasing with Rq and $1/R_{load}$
(and Cq of course)

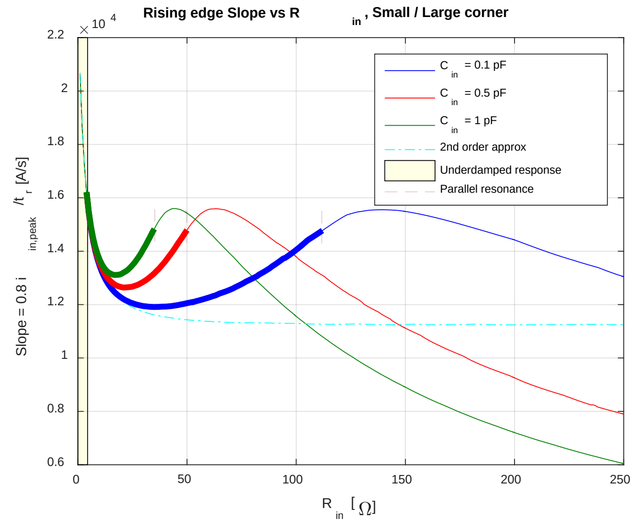
Increasing C_q/C_d or/and R_q/R_{load}
→ spike enhancement
→ better timing

G.Collazuol - PhotoDet 2012

II. Slew-rate in current and voltage sensing

Current sensing



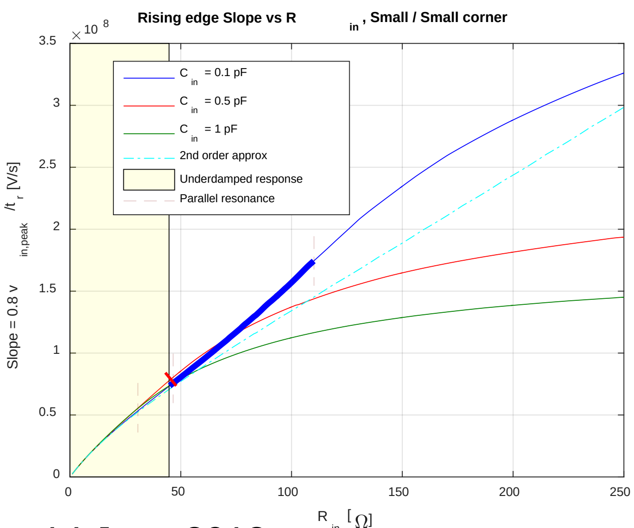


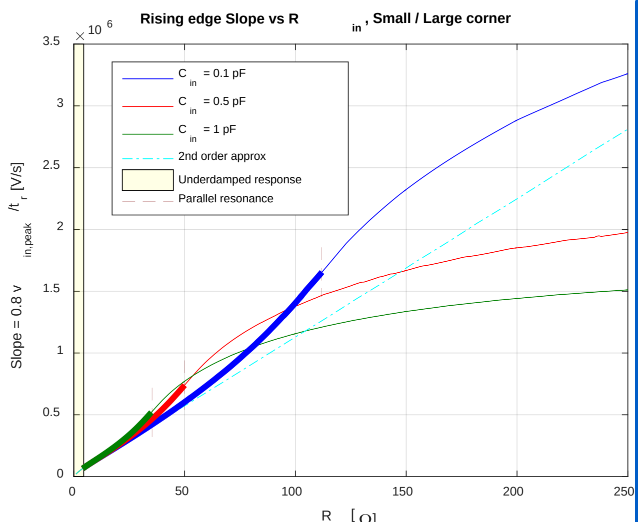
SR improves with <u>small</u> R_{in}:

$$\frac{\partial i_{in}}{\partial t} \propto \frac{Q_{det}}{L \cdot C_{det}}$$

- Specially true when entering in underdamped region.
- Underdamping can be problematic (multiple crossing in discrimination).
- Independent of R_{in} deep in overdamping regime. Parallel resonance enhances the SR.

Voltage sensing





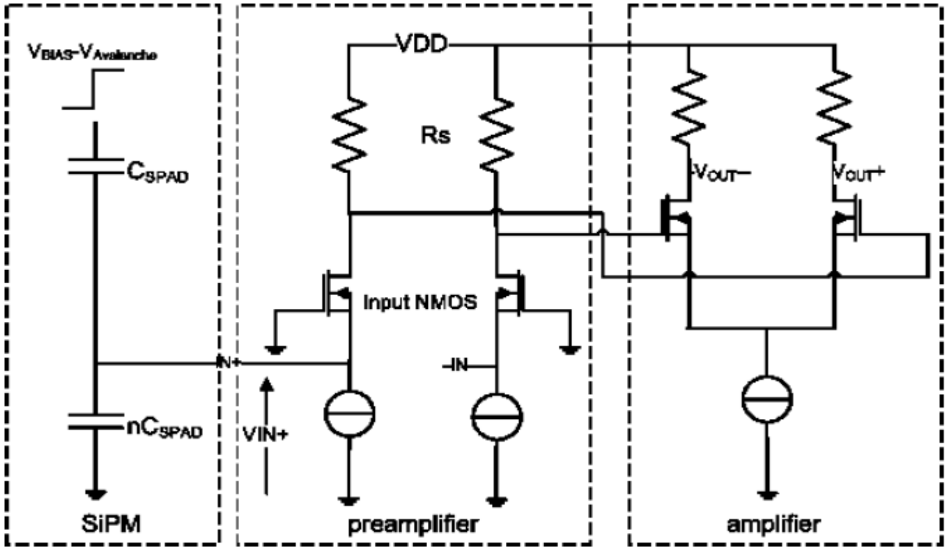
SR improves with <u>large</u> R_{in}:

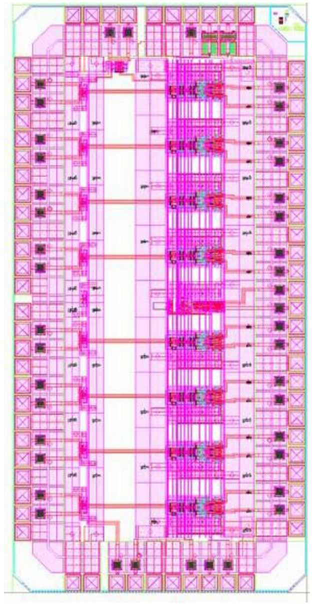
$$\frac{\partial v_{in}}{\partial t} = R_{in} \cdot \frac{\partial i_{in}}{\partial t} \propto \frac{Q_{det} \cdot R_{in}}{L \cdot C_{det}}$$

- Almost linear relationship between SR and R_{in}.
- Parallel resonance can be exploited for peak enhancement.
- Problem: reduced count-rate for large R_{in}.

III. FE circuits: NINO

- NINO: current mode, binary and quite generic
- Chip designed by CERN group for ALICE TOF RPCs but quite used for SiPM read-out
  - 8 channels amplifier and discriminator
  - Common grid current conveyor, high speed differential discriminator
  - High speed time measurement (10 ps),
  - Pd = 25 mW/ch, Manufactured in IBM 0.25 um

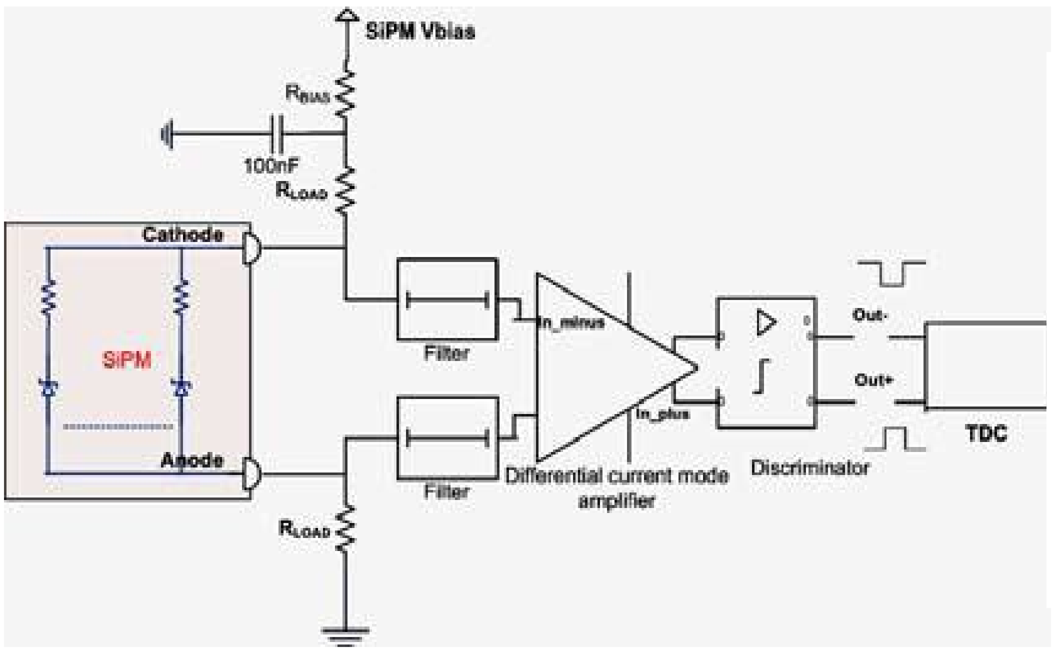


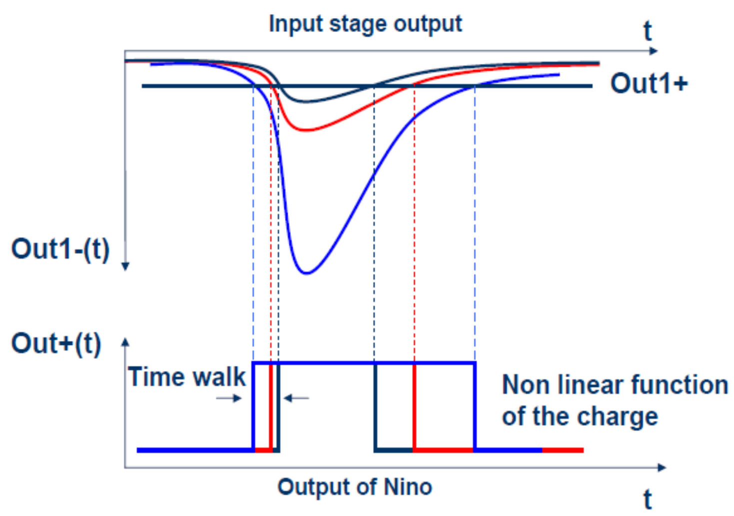


F. Anghinolfi, P. Jarron et al. NINO, NIM A, 2004, Vol. 533 page 183-187

III. FE circuits: NINO

- NINO: current mode, binary and quite generic
- Binary: usually connected to TDC for Time-Over-Threshold (ToT) energy
  - Simple discriminator: ToT is not linear
- Differential connection to the SiPM

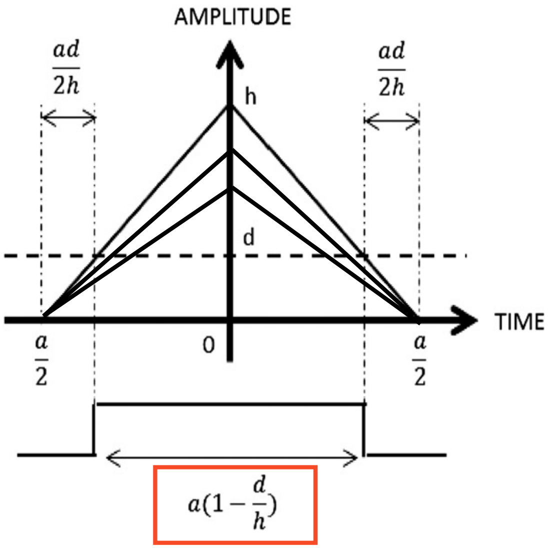


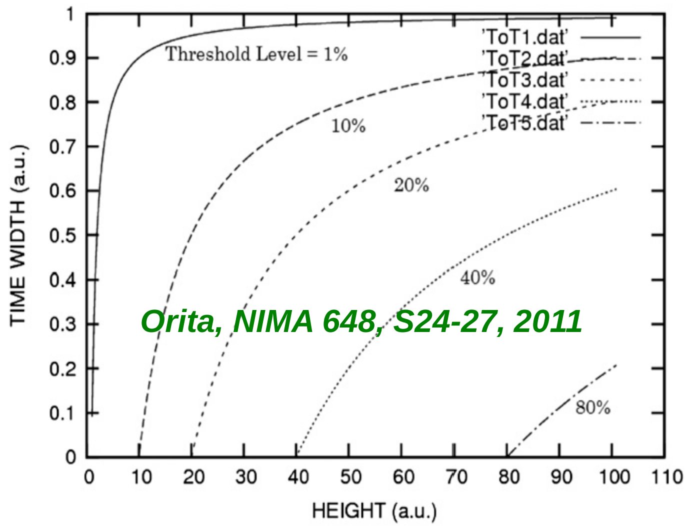


F. Anghinolfi, P. Jarron et al. NINO, NIM A, 2004, Vol. 533 page 183-187

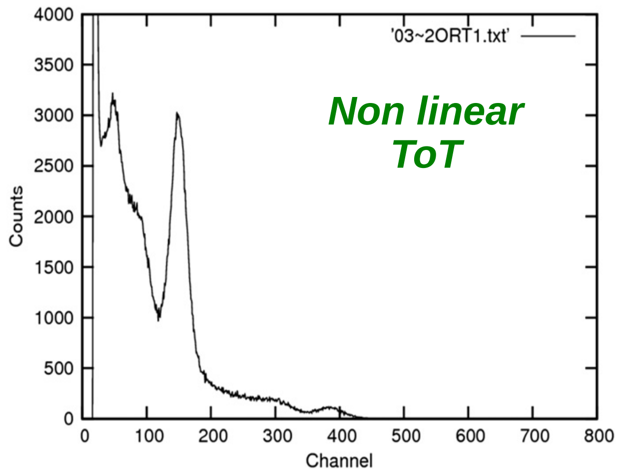
III. FE circuits: NINO

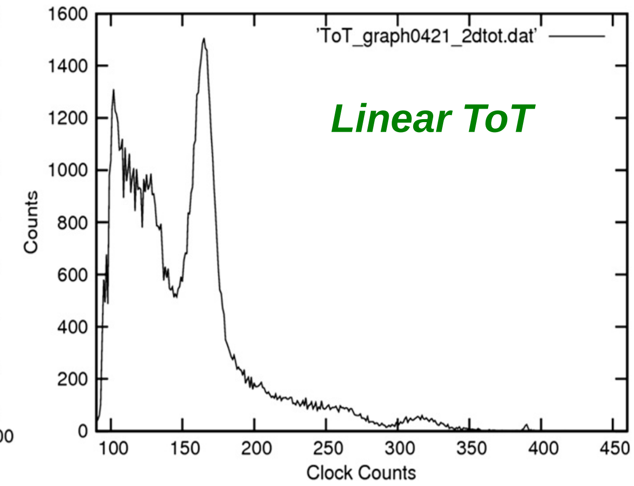
- Classical ToT is non-linear





- It has an impact on energy resolution
  - Calibration is possible
  - But not perfect…



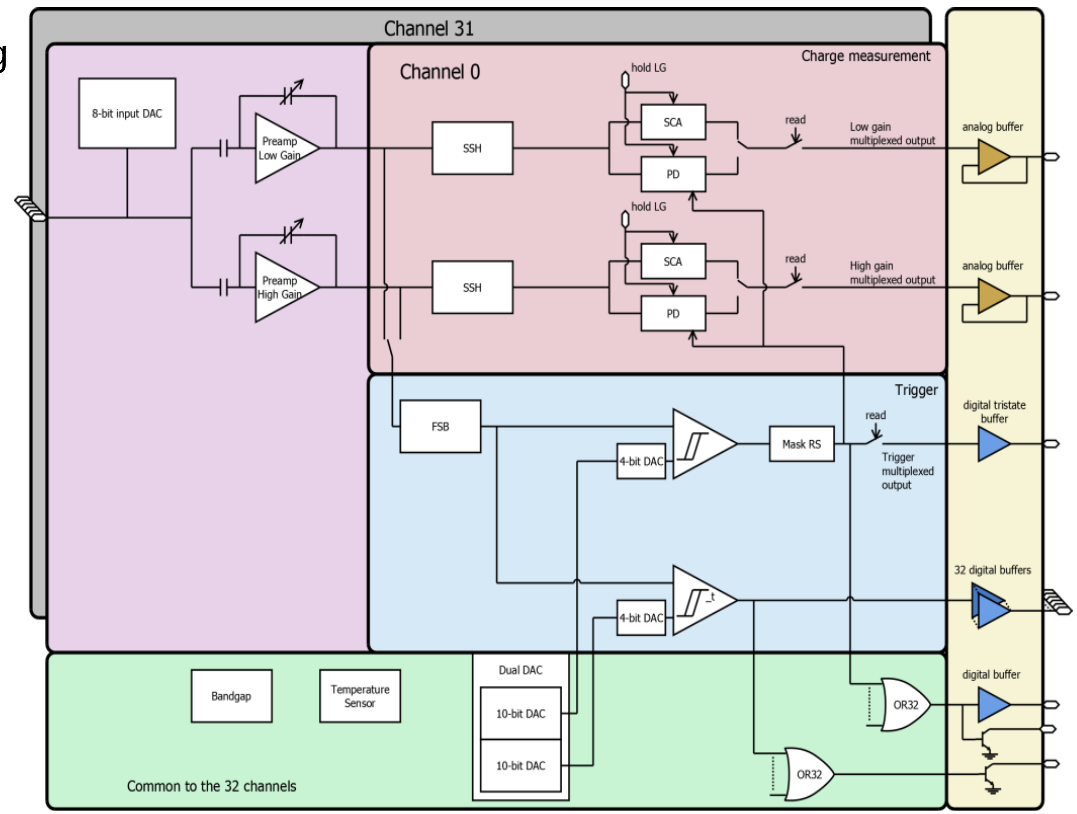


Orita, NIMA 648, S24-27, 2011

III. FE circuits: CITIROC

- CITIROC: voltage mode, analogue and for CTA SSTs ASTRI camera
- Part of Omega/Weeroc family: CITIROC, PETIROC, PETIROC2, TRIROC, etc

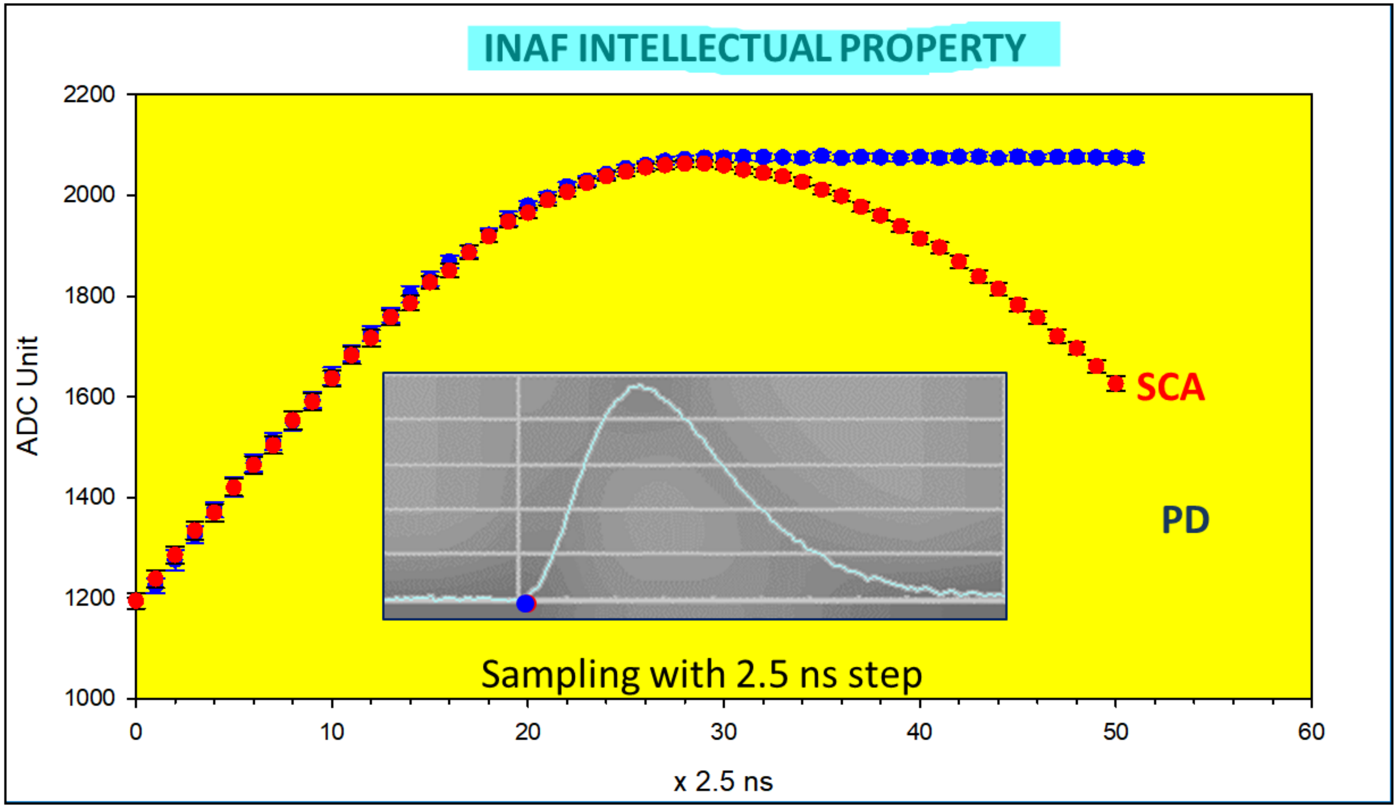
- General ASIC
  - 32 channel, charge and trigger outting
  - 6.26mW/Ch. Power pulsed
- Front-end
  - Trigger
    - Fast shaper connected to either low or high gain preamp
    - Two discriminator : one for timing, one for event validation on energy
  - Energy measurement
    - 2 voltage preamplifier (10x gain difference) followed by shaper
    - Analogue memory : track and hold or peak detector
    - Analogue multiplexer
    - ***Peaking time between 12.5 and 100 ns***
      - ***Valid only for SSTs***



https://www.weeroc.com/fr/products/citiroc-1a

III. FE circuits: CITIROC

SAMPLING & HOLD Vs. PEAK DETECTION

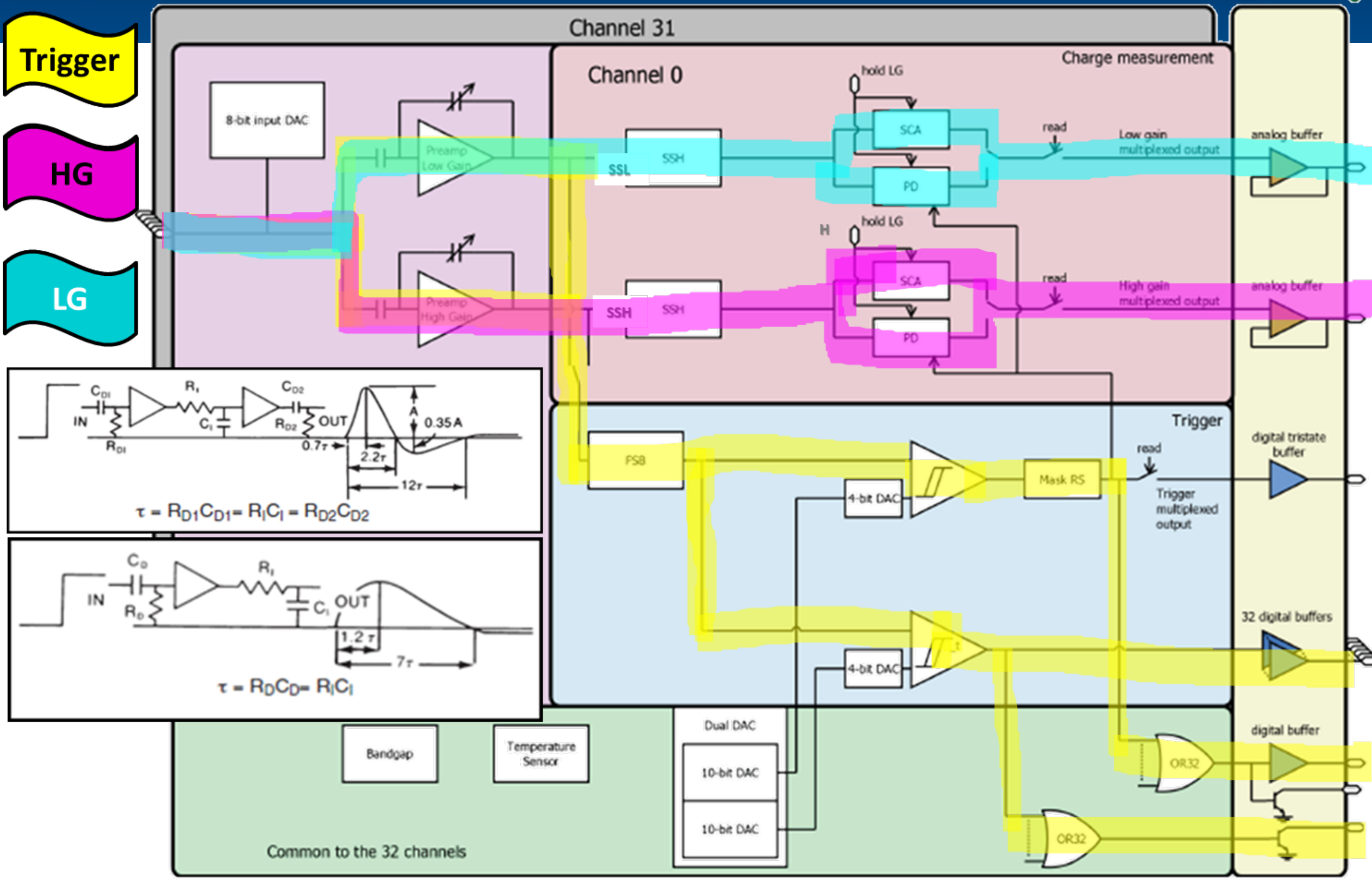


Same pulse measured in SCA and PD mode as a function of delayed HOLD

https://www.weeroc.com/fr/products/citiroc-1a

Osvaldo Catalano– 3rd SiPM Advanced Workshop- Palermo 26-28 May 2015

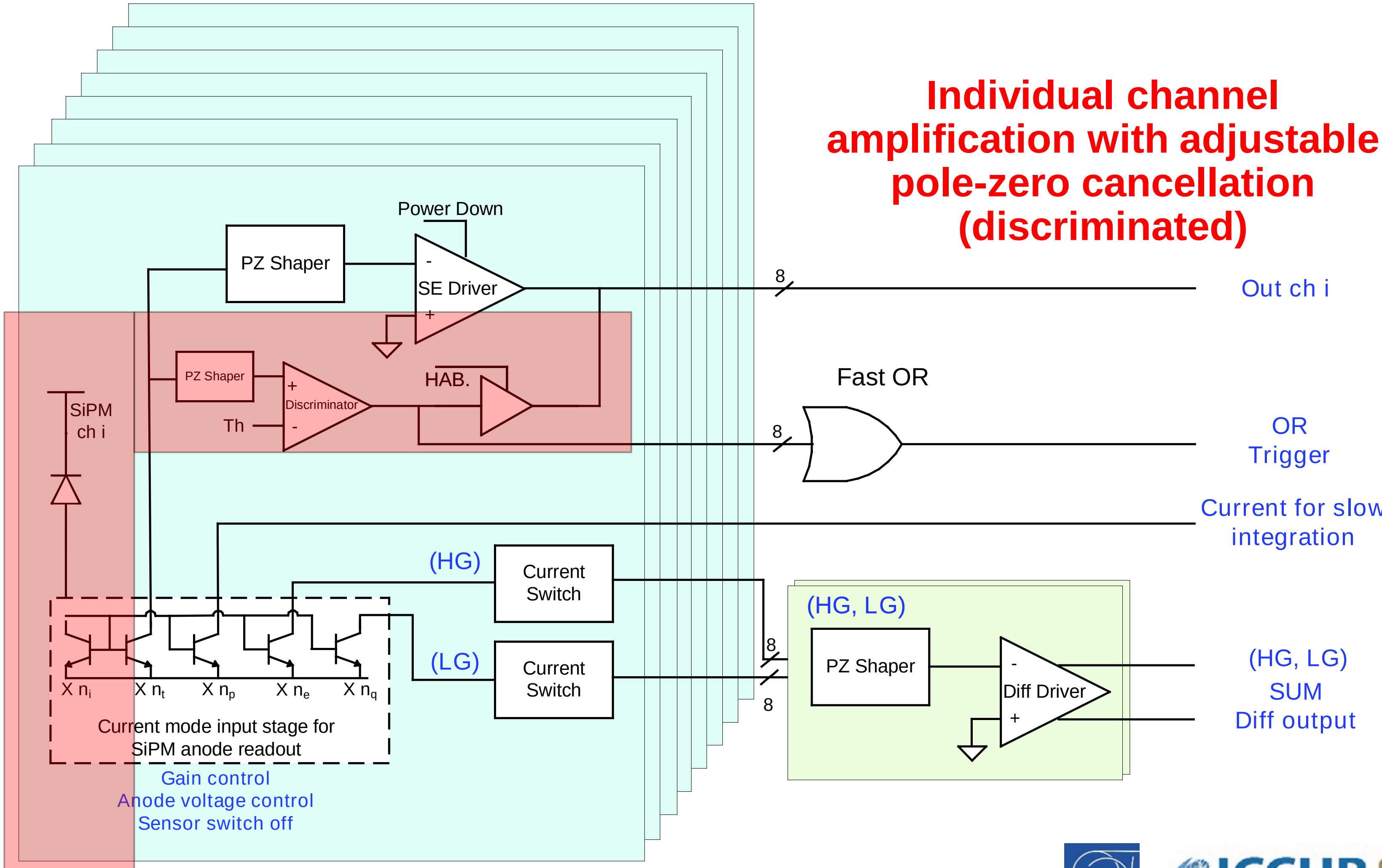
CITIROC SCHEMATIC DIAGRAM



Osvaldo Catalano– 3rd SiPM Advanced Workshop- Palermo 26-28 May 2015

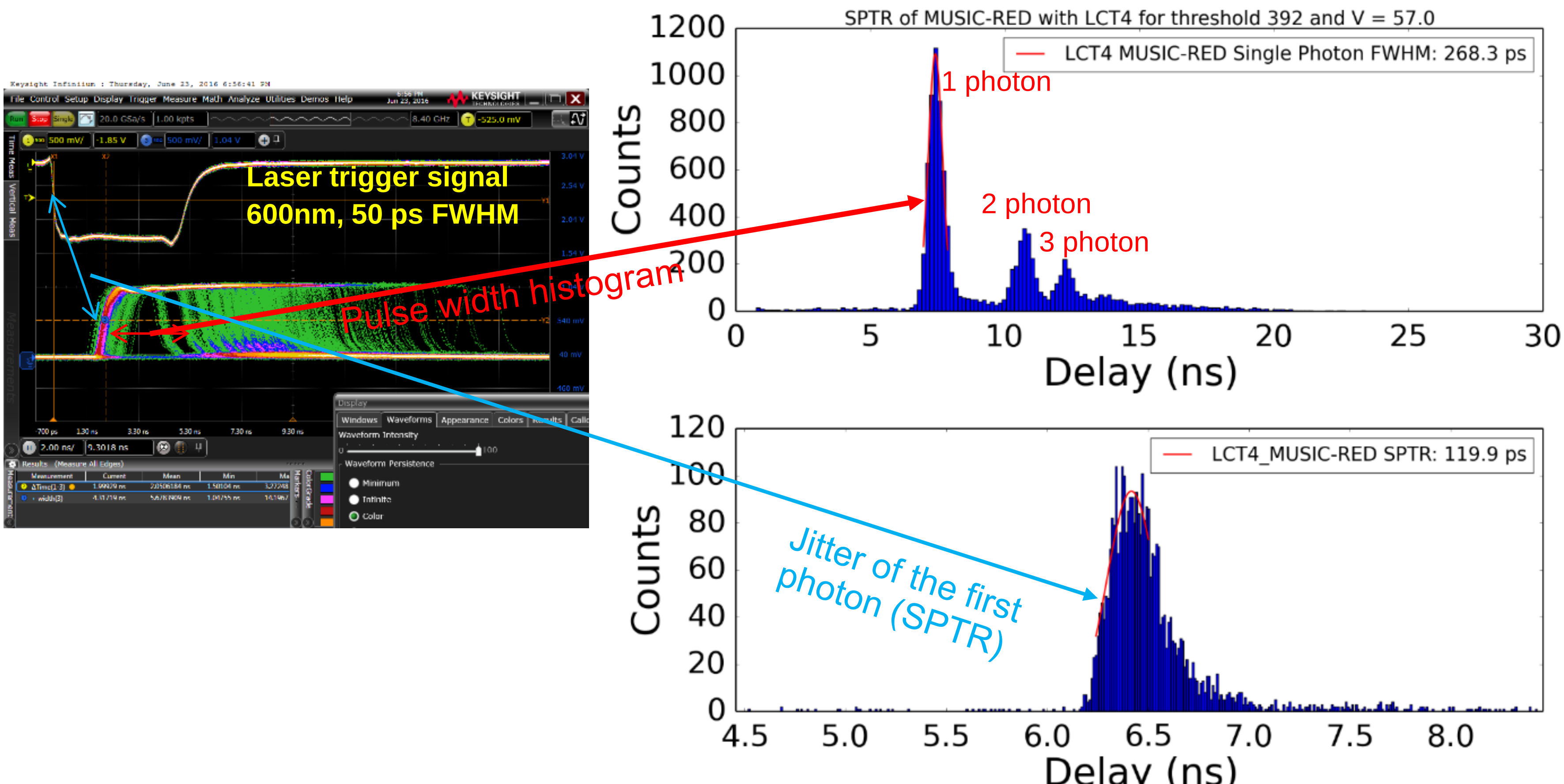
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- MUSIC 8 ch ASIC integrates all those functionalities



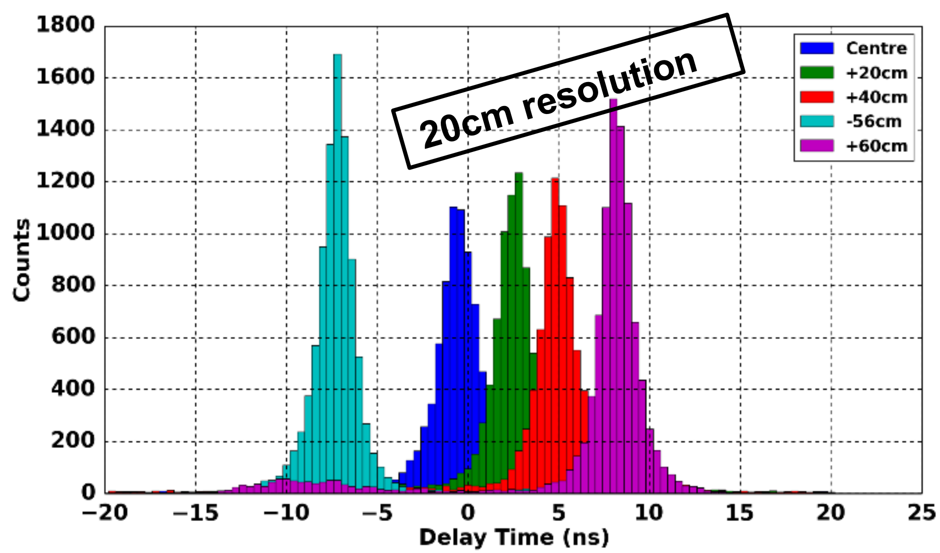
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Output for a LCT4 HPKK MPPC (3x3 mm^2)
  - Picosecond laser
  - Pole-zero cancellation
  - Single Photon Time Resolution about 100 ps (@ 5V OV)



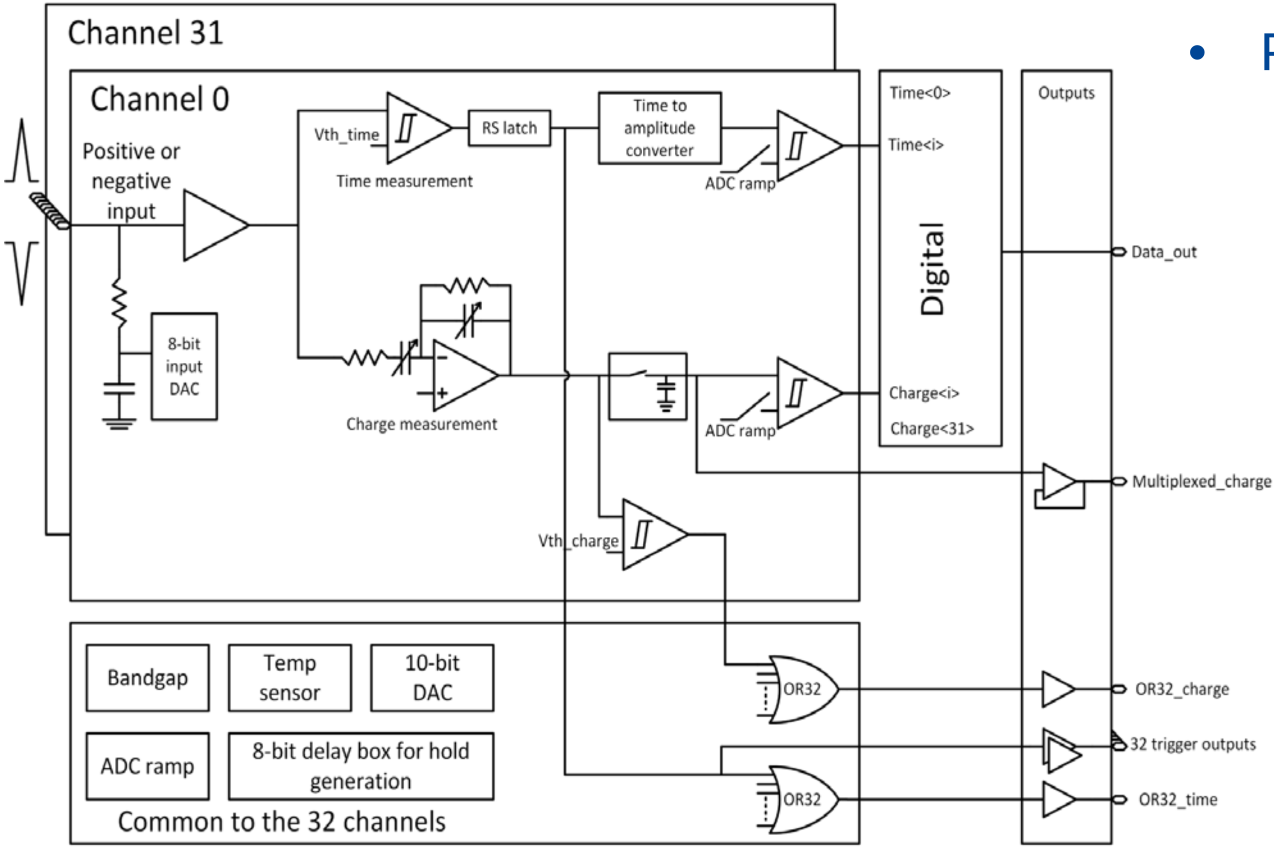
III. FE circuits: MUSIC: Multipurpose SiPM RO chip

- Studying the possibility to develop a beam loss monitoring system based on scintillating fibers
  - Collaboration with Alba synchrotron General idea:
  - Fiber along the beam pipe or in selected regions
  - Losses are detected by a rate increase
  - With timing information, additional postion information
    - Preliminary results: 20 cm resolution for a 2 m fiber of 1 mm diameter



Thanks to C. Joram (CERN) for providing SciFibers

IV. ASICs for PET: PETIROC



- PETIROC2:
  - Voltage mode,
  - Configurable: analogue, binary or digital
    - S&H + Wilkinson ADC
  - For medical imaging (PET)
  - Versatile: analog or digital
  - But shaping time > 10 ns
  - Max ev. rate is 40 KHz in digital mode
  - Power:

https://www.weeroc.com/fr/products/petiroc-2a

Detector Read-Out	SiPM, SiPM array
Number of Channels	32
Signal Polarity	Positive or Negative
Sensitivity	Trigger on first photo-electron
Timing Resolution	~ 35 ps FWHM in analogue mode (2pe injected) - ~ 100 ps FWHM with internal TDC
Dynamic Range	3000 photo-electrons (10^6 SIPM gain), Integral Non Linearity: 1% up to 2500 ph-e
Packaging & Dimension	TQFP208 – TFBGA353

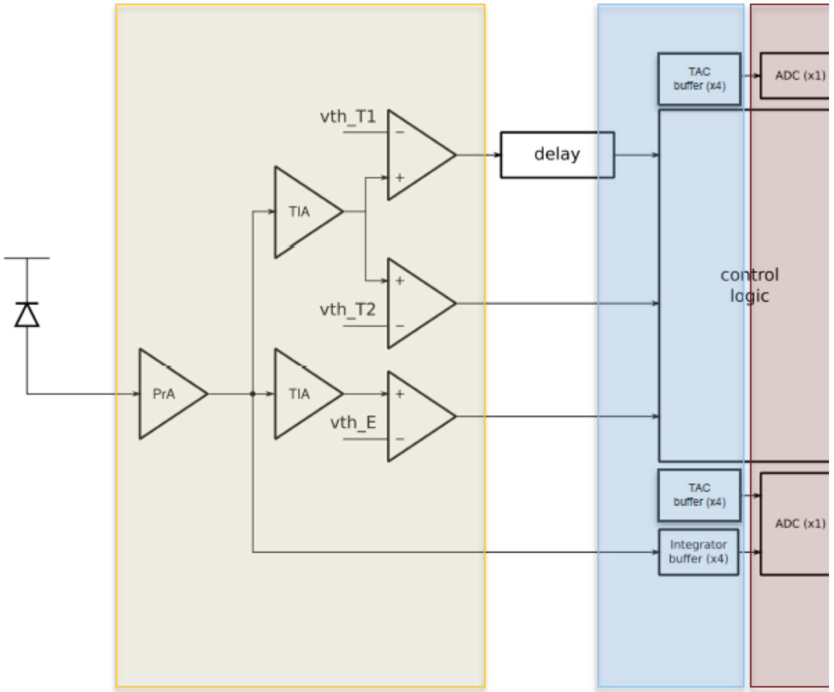
IV. ASICs for PET: TOFPET

- Pre-amplifier: low input impedance current conveyor
- Two post-amplifiers (TIA) for time and energy measurements
- Three leading edge discriminators;
  - Very low threshold (1-5 p.e.) for optimum PET time resolution
  - multi-level event rejection

- Time to Amplitude Converter (TAC)
- Charge Integrator (CI)
  - configurable integration windows
  - linear amplitude measurement
  - TAC and Charge Integrator are quad-buffered
    - No dead-time due to Poisson fluctuations

- Two 10-bit ADCs per channel
  - Time and amplitude measurements
  - Optionally: Time-over-Threshold

- TOFPET2: current mode, digital (linear ToT) and for medical imaging (PET)
  - Power: 8 mW/ch
  - Max rate 200 KHz/ch

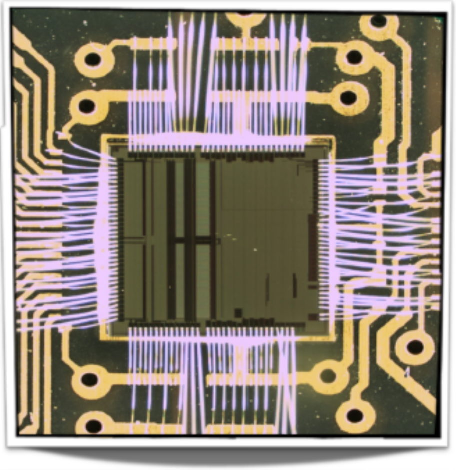


J. Varela, "New results with TOFPET2", FAST, Ljubljana, Jan 2018

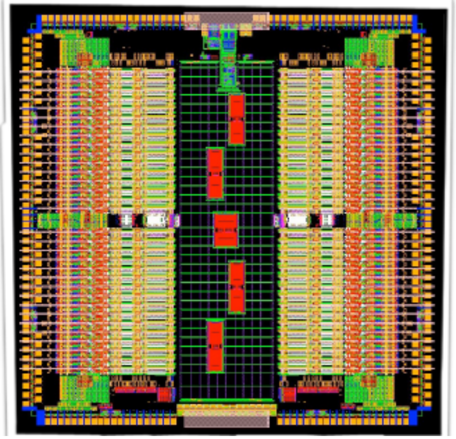
IV. ASICs for PET: STiC

- STiC: current mode, digital (linear ToT) and for medical imaging (PET)

STiC 2.1
[on test PCB]



STiC 3.0
[Chip layout]



Features:

STiC 2.1: 16 channels
STiC 3.0: 64 channels

Differential and single-ended readout …

Integrated TDC [ZITI, Fischer et al.] and digital data processing …

Timing and ToT-based linearized energy measurement …
[SPTR:180 ps; MPPC S10362-11-100]

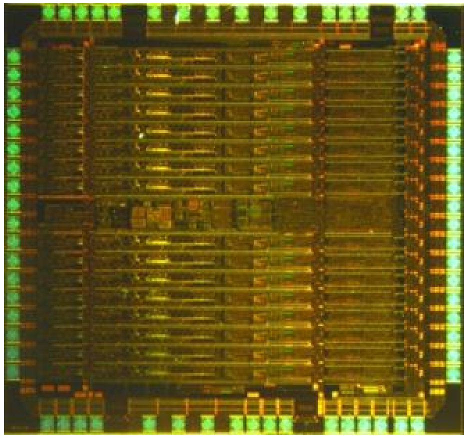
SiPM bias tuning …
[Tuning range: ~ 500 mV]

Serial interface for data transmission and configuration …

STiC — a mixed mode silicon photomultiplier readout ASIC for time-of-flight applications
T. Harion et alt., 2014 JINST 9 C02003

IV. ASICs for PET: FlexToT: linearized ToT RO chip

- Joint project with CIEMAT to develop a time-over-threshold ASIC for SiPM based PET
  - ICCUB: expertise on electronics and microelectronics design for detector FE
  - CIEMAT: expertise on PET and medical imaging instrumentation

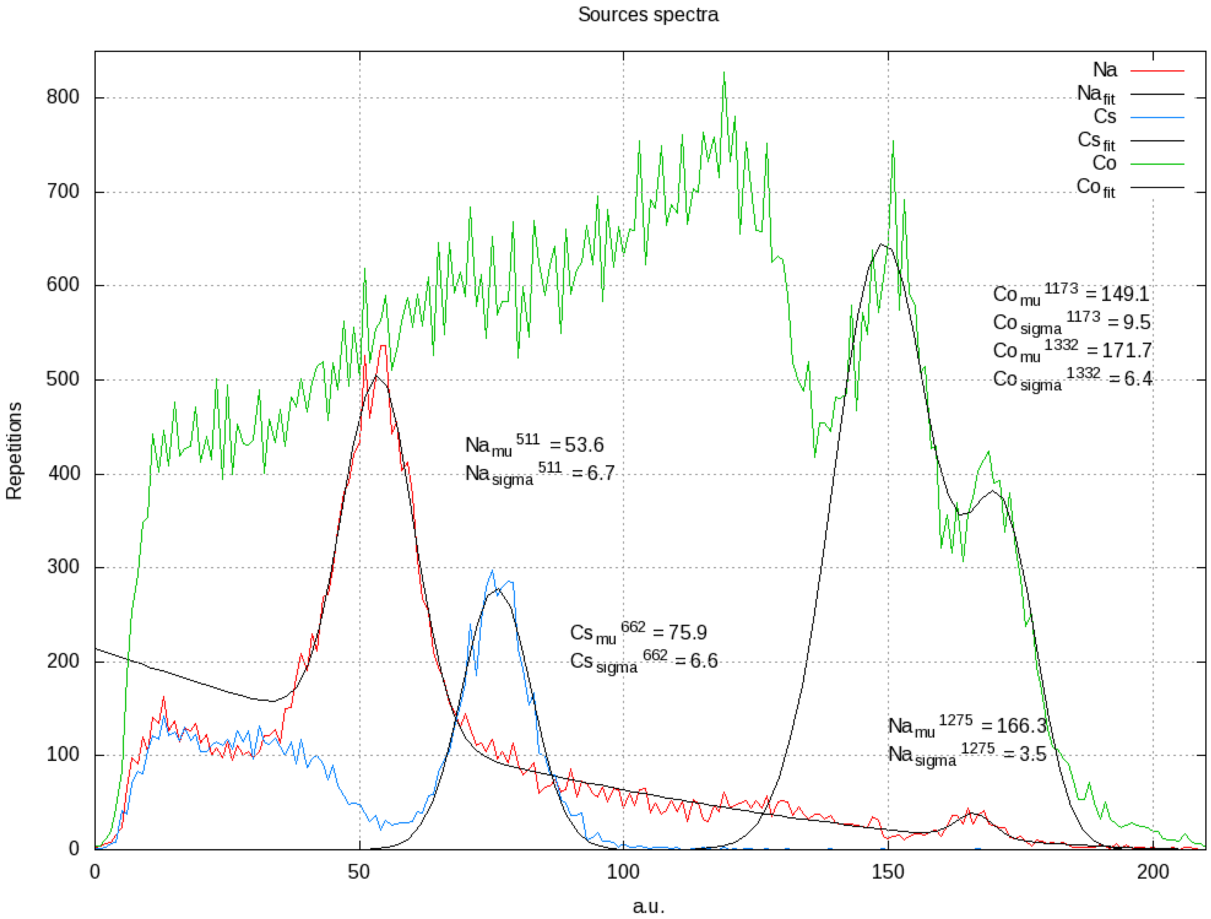


FlexToT

16 channel
SiGe BiCMOS 0.35um
Aaustriamicrosystem
10 mm^2
3.3 V (10 mW/ch)
QFN 64

IV. ASICs for PET: FlexToT: linearized ToT RO chip

- **Spectroscopy with linear ToT**

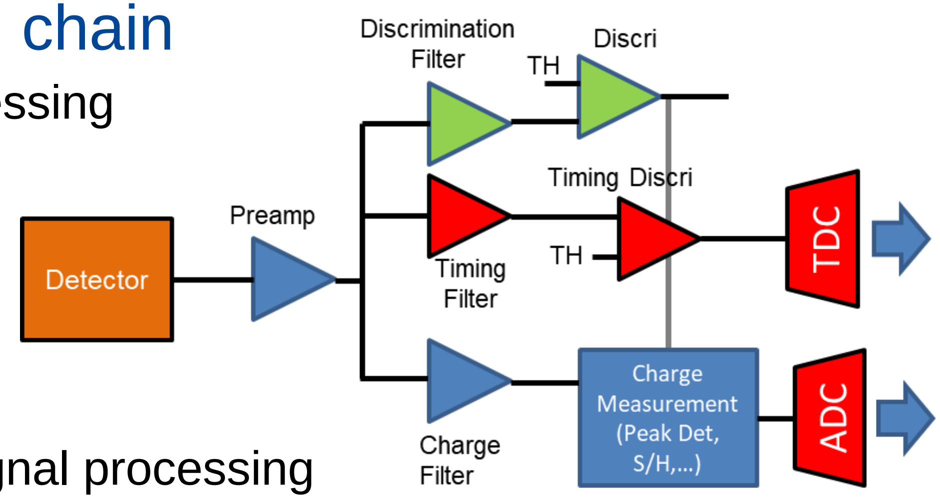


Outlook

III. Digitization: basic options

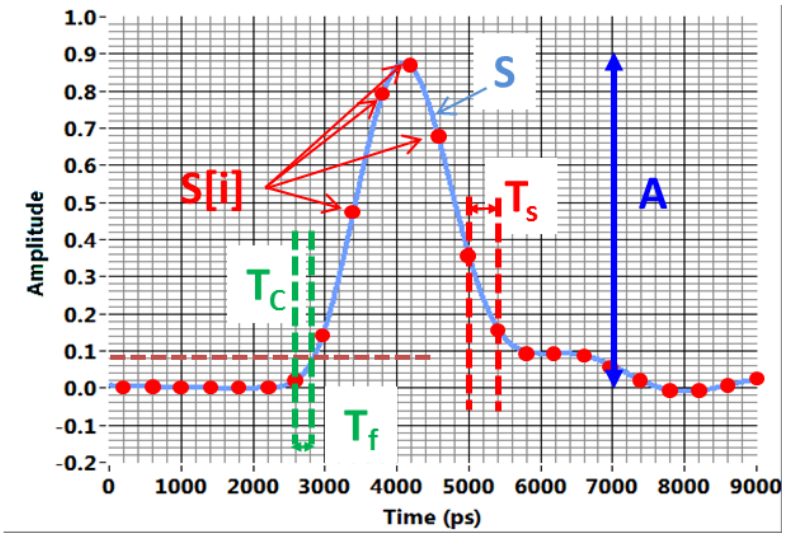
1) "Classical" signal processing chain

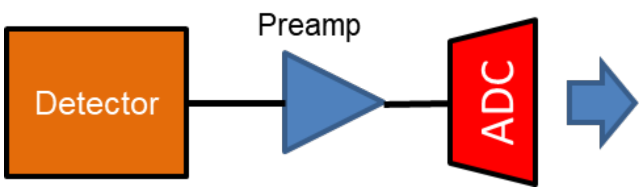
- Requires complex analogue processing
- Not so flexible
- Optimal in power for specific app.



2) Digital signal processing

- Waveform sampling and digital signal processing
- Ideally one should sample at fs > 2 x signal BW (x5)

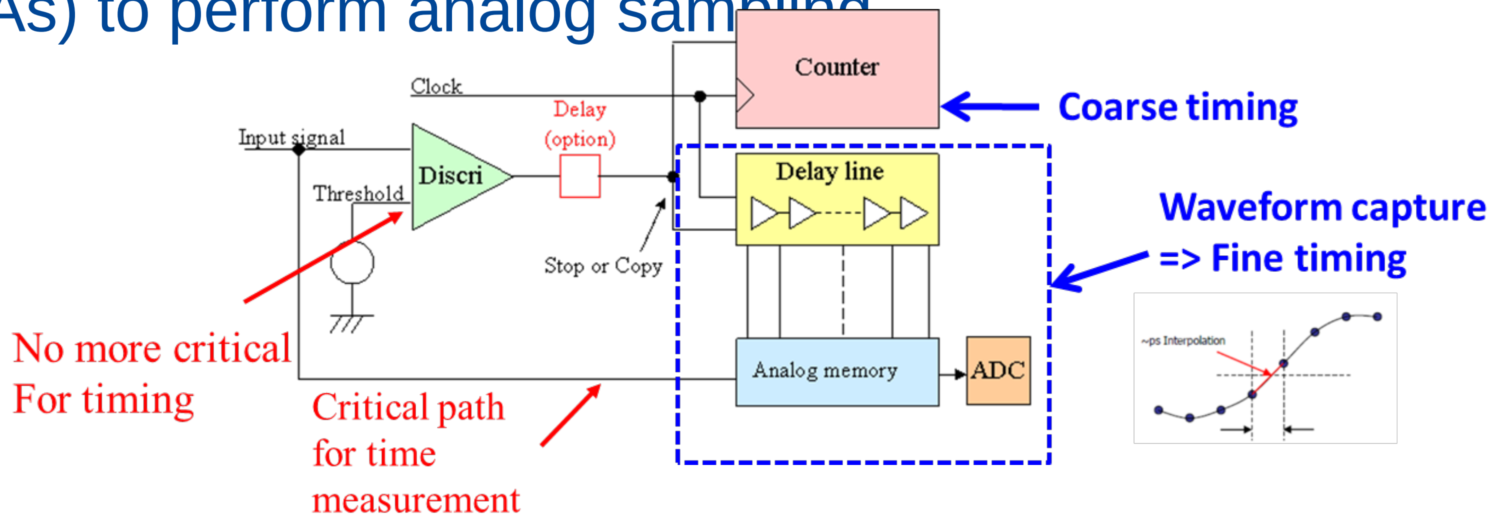




E. Delagnes, "Precise Pulse Timing based on Ultra-Fast Waveform Digitizers", IEEE NSS 2011

III. Digitization: waveform sampling

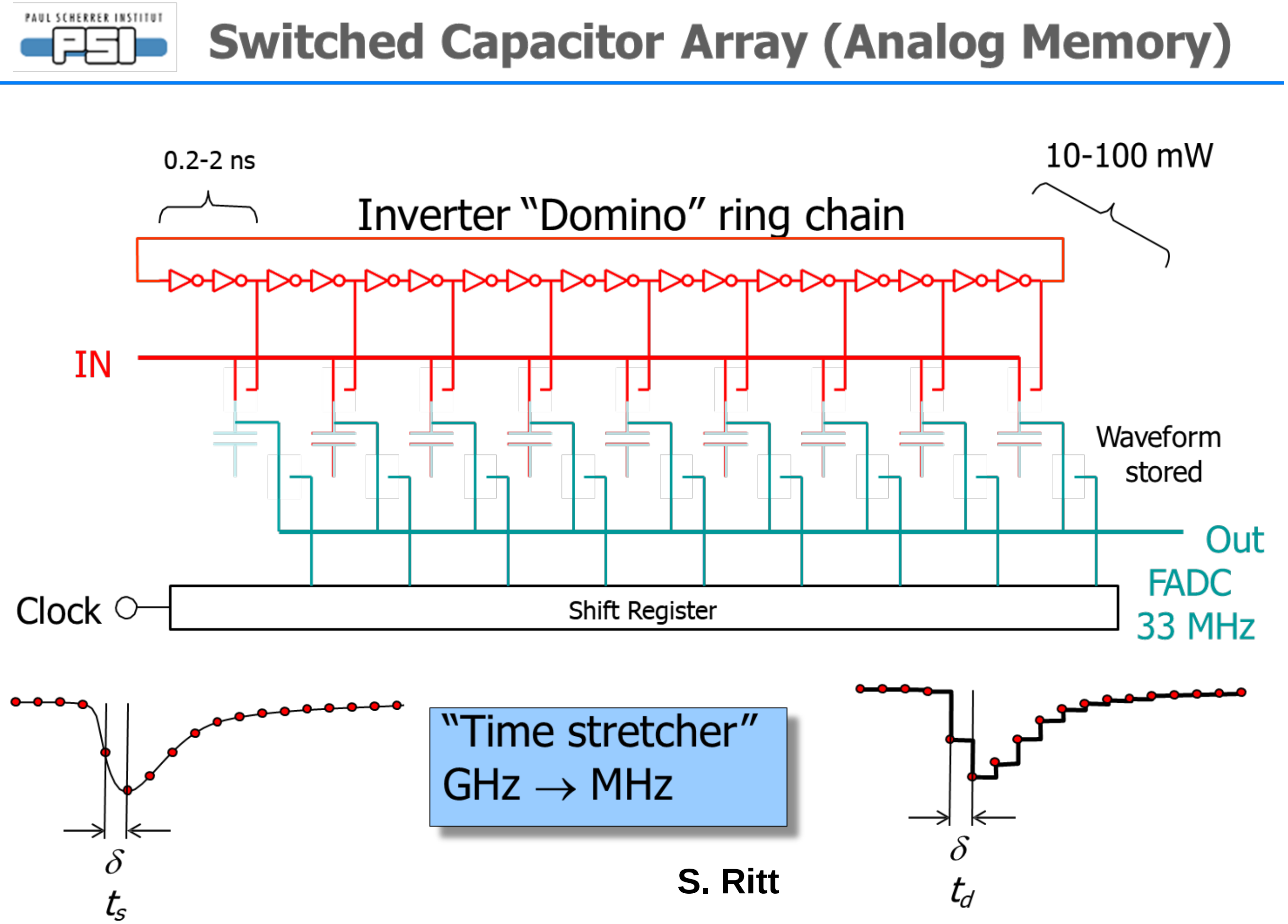
- Very demanding sampling specs for IACTs
  - Dynamic range of about 12 bits (with several gains)
  - Analog BW> 300 MHz requires 1-2 GS/s
    - Power consumption and ADC cost !
    - Alternative: FlashCAM digitizes at much lower speed and tries to extract signal parameters by signal processing
      - But NSB will be there anyway, so energy threshold will be degraded…
- Many projects have been using Switch Capacitor Arrays (SCAs) to perform analog sampling



E. Delagnes, "Precise Pulse Timing based on Ultra-Fast Waveform Digitizers", IEEE NSS 2011

III. Digitization: waveform sampling

- SCAs sample the signal which is digitized at a lower speed



S. Ritt

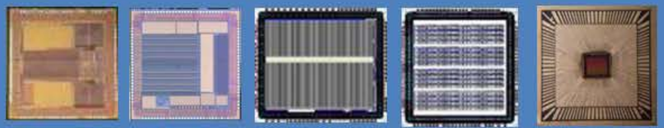
III. Digitization: waveform sampling

G. Varner Univ. Hawaii

TARGET

CTA SCT and SST

Many chips for different projects
Buffered and unbuffered
Very deep arrays
ADC on chip.
Philosophy => pushing the limit of the SCA technology



H. Frisch et al., Univ. Chicago

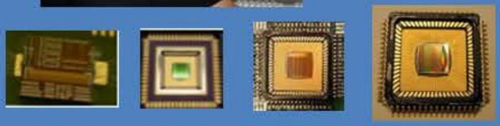
Goal: reach a 1ps precision !
Pioneering R&D work
130nm IBM
18 GSPS, 256 samples, 6ch
ADC on chip

Initiator of a networking activity on SCAs and ps-timing

From an Orignal slide of S. Ritt

S. Ritt, R. Dinapoli PSI

Universal chip for many applications
8 + 1 channels 1024 cells
5GSPS, 950 MHz BW
Low power consumption
Short readout time
Several possible modes of operation



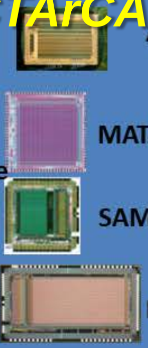
DRS4

CTA LST

D. Breton IN2P3/LAL
E. Delagnes CEA/Saclay

NECTAr

CTA MST-NECTArCAM



More than 120.000 SCAs operating worldwide
Buffered (f_{-3dB} 400-500MHz) 3.2GSPS
High dynamic range
Robust (minimum calibration or ext. control)
Conservative technologies
Moderate depth 256-1024 cells/ 2ch
On-chip ADC in the last chip

E. Delagnes, "Precise Pulse Timing based on Ultra-Fast Waveform Digitizers", IEEE NSS 2011

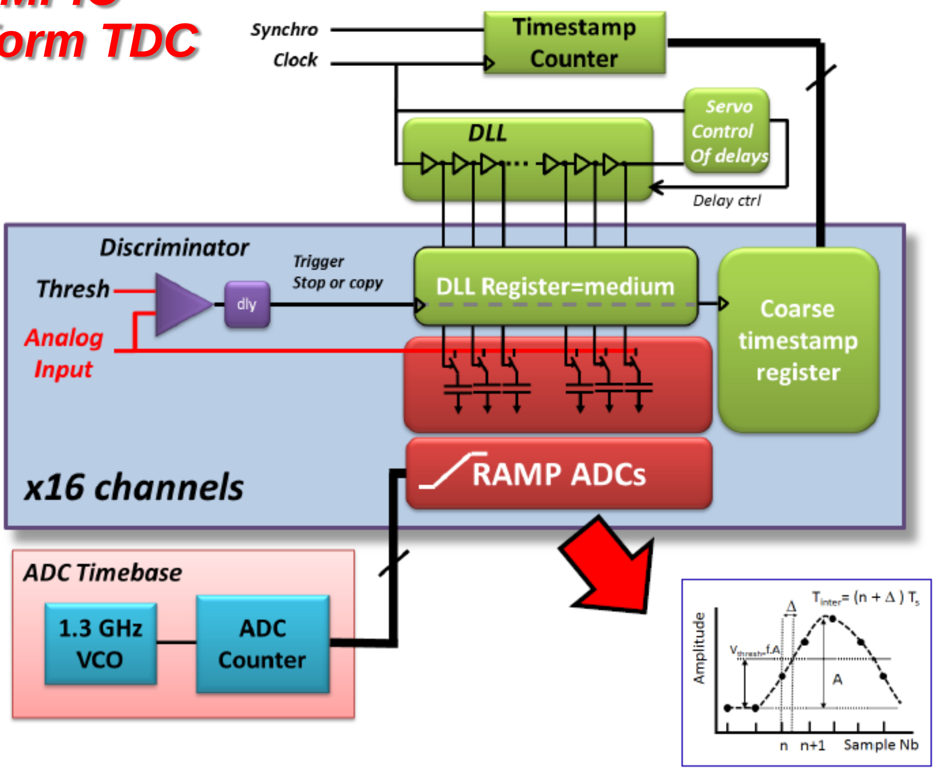
CERN

ICCUB Institute of Cosmos Sciences

EXCELENCIA MARÍA DE MAEZTU

III. Digitization: waveform sampling

SAMPIC Waveform TDC



Global time = counter (~10ns) + DLL (~100ps) + waveform(~ps)

Waveform is available for extraction of other parameters (Q, A)

- **One** Common **12-bit Gray Counter** (FClk up to 160MHz) for **Coarse Timestamping**.
- **One** Common **servo-controlled DLL**: (from 1.6 to 10.2 GHz) used **for medium precision timing & analog sampling**

- **16 independent WTDC channels each with :**
  - ✓1 discriminator for self triggering
  - ✓Registers to store the timestamps
  - ✓64-cell deep SCA analog memory
  - ✓One 11-bit ADC/ cell

  (Total : 64 x 16 = 1024 on-chip ADCs)

- **One** common 1.3 GHz oscillator + counter used as timebase for all the **Wilkinson A to D converters**.

- **Read-Out interface**
- **SPI Link** for Slow Control configuration

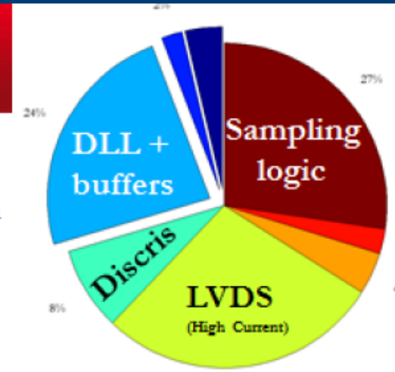
D. Breton, 4th FAST WG3/4/5 Meeting, Ljubljana, January7/8 2018

III. Digitization: waveform sampling

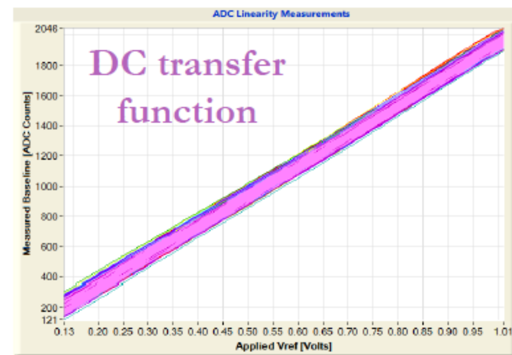
SAMPIC Waveform TDC

SAMPIC_V1 PERFORMANCES

- Power consumption: **10mW/channel** → Power distribution
- 3dB bandwidth > **1 GHz**
- Discriminator noise **~ 2 mV rms**
- Counting rate **> 2Mevts/s** (full chip, full waveform), **up to > 10 Mevts/s** with Region Of Interest (ROI)

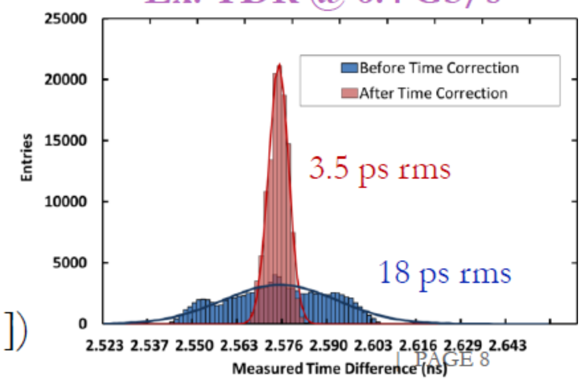


- Wilkinson ADC works with internal **1.3 GHz** clock
  - Dynamic range of **1V**
  - Gain dispersion between cells ~ **1%** rms →
  - Non linearity **< 1.4 %** peak to peak
  - After correction of each cell (linear fit): noise = **0.95 mV rms**



- Time Difference Resolution (TDR):
  - Raw non-gaussian sampling time distribution due to DLL non-uniformities (TINL)
  - Easily calibrated & corrected (with our sinewave crossing segments method [D. Breton&al, TWEPP 2009, p149])

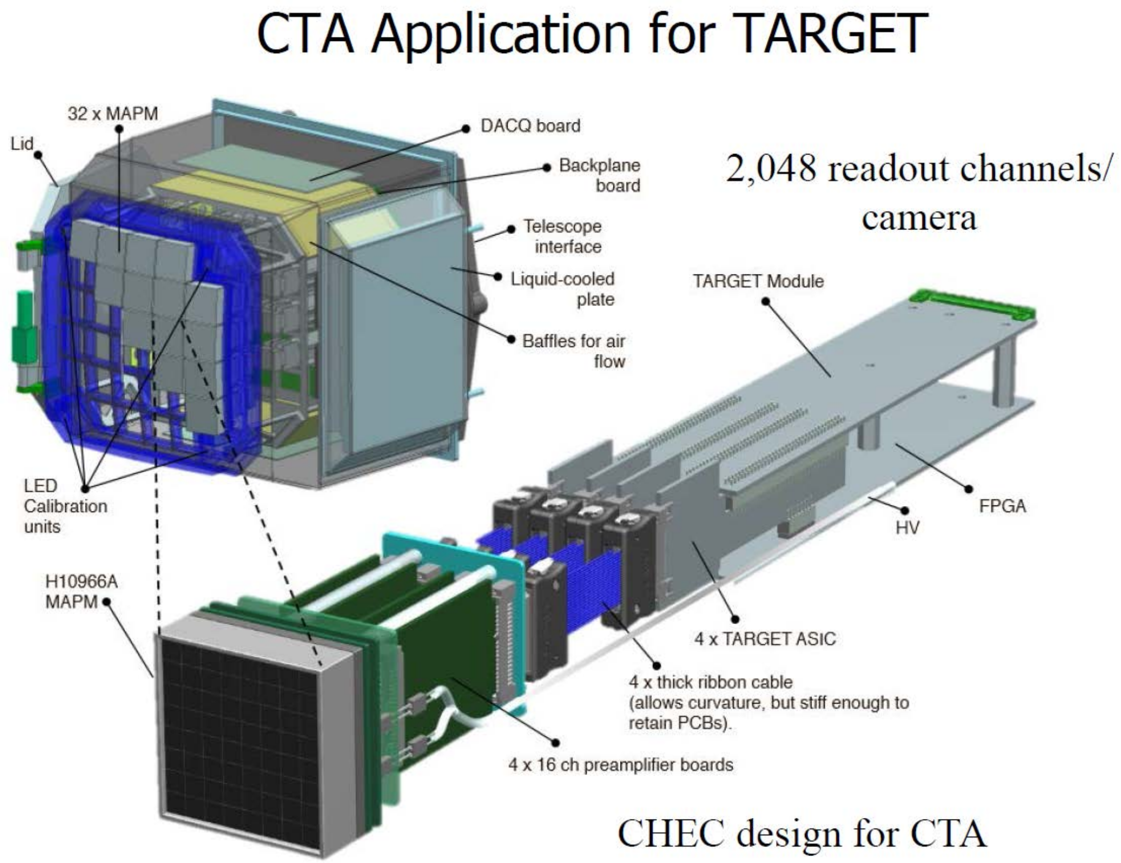
Ex: TDR @ 6.4 GS/s



D. Breton, 4th FAST WG3/4/5 Meeting, Ljubljana, January7/8 2018

III. Digitization: waveform sampling

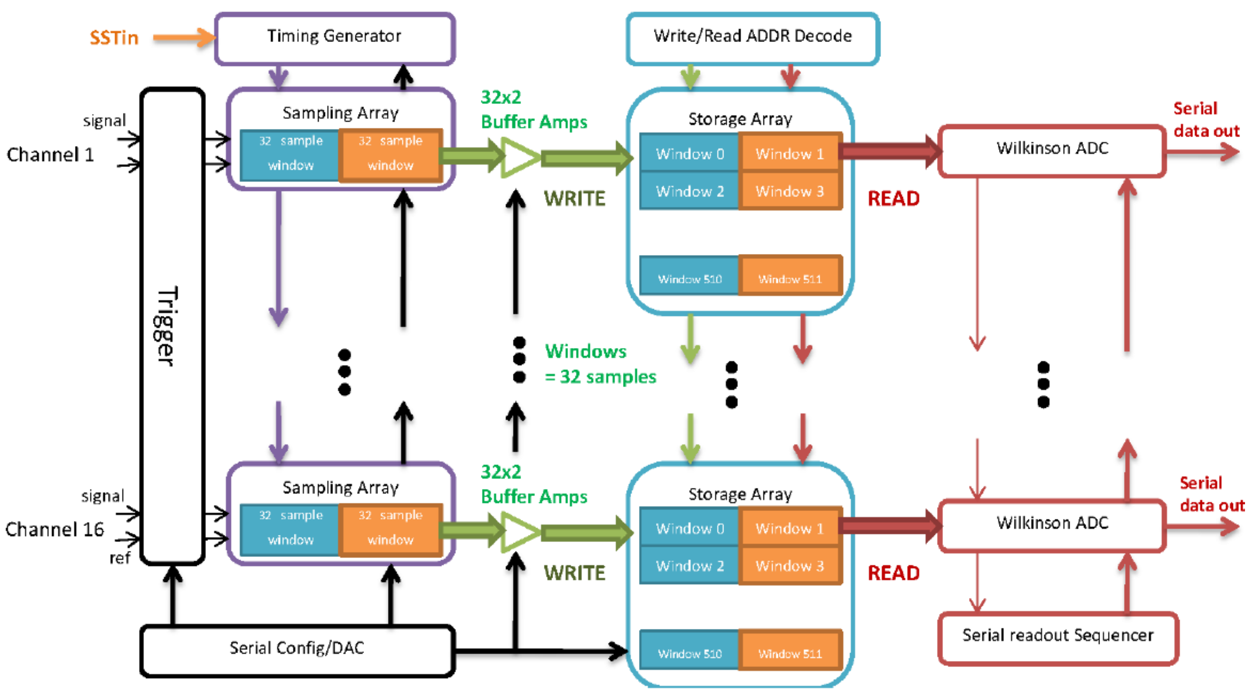
- CHEC camera is an interesting example of compact readout



Gary S. Varner, 2nd Adv SiPM Workshop, Geneva, 2014

III. Digitization: waveform sampling

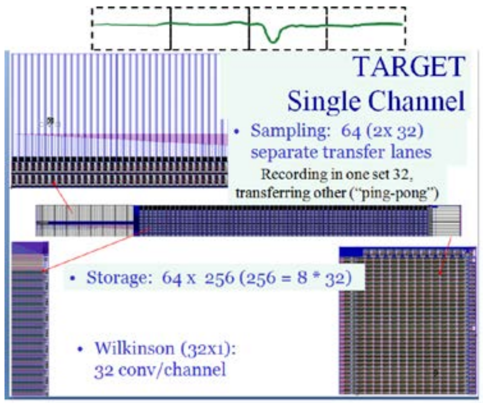
- Several iterations to have a functional chip: TARGET7



Gary S. Varner, 2nd Adv SiPM Workshop, Geneva, 2014

TARGET7 Specification Summary

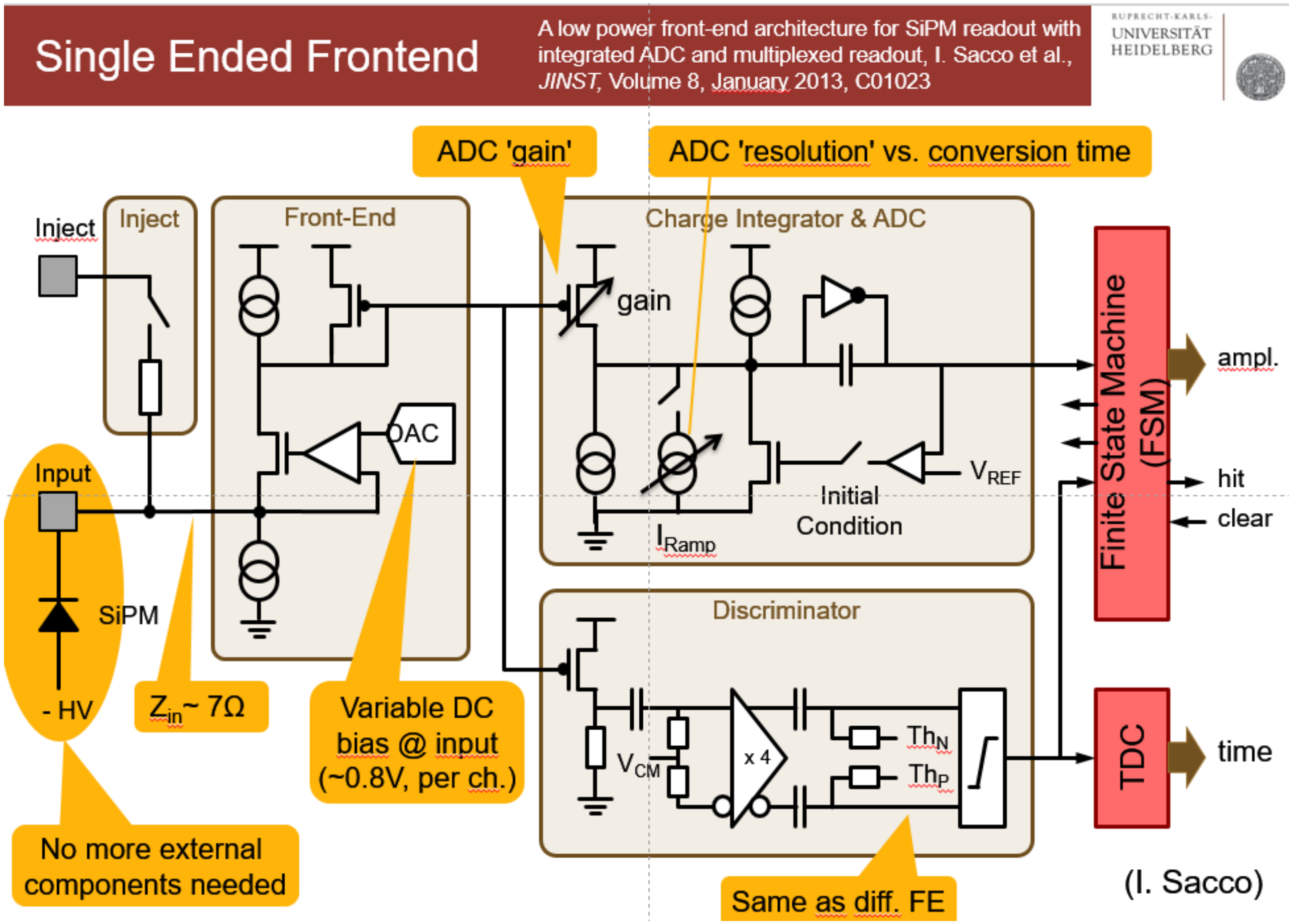
16384	samples/chan (16-32us trig latency)
16	channels/TARGET ASIC
Σ4 –> 4	Trigger channels (indep. Thr/Width)
~9-10	bits resolution (12-bits logging)
32	samples convert window (~32-64ns)
0.5-1	GSa/s
1	word (RAM) chan, sample readout
<10	us to convert 512 samples (at once)
>100	kHz sustained readout (multibuffer)



Outlook

IV. ASICs for PET: PETA

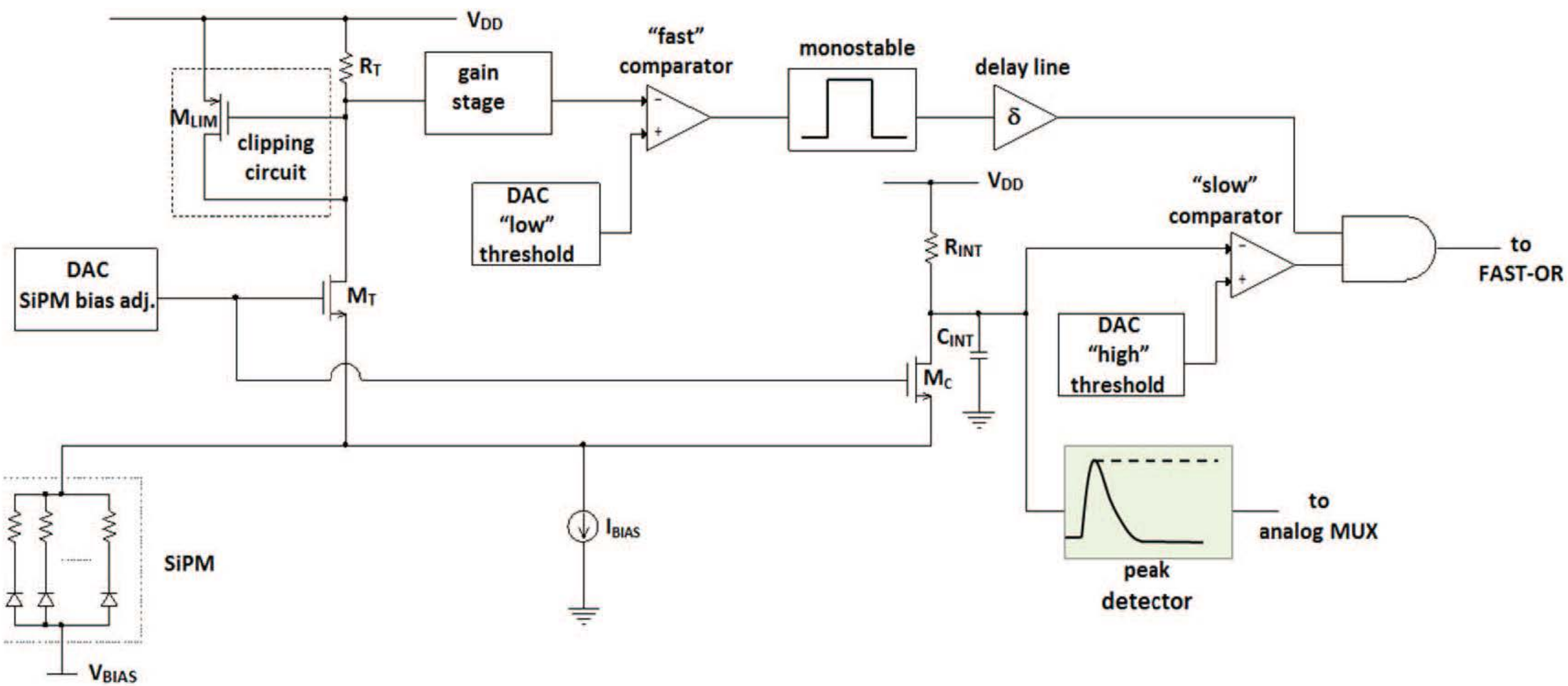
- PETA: current mode, charge (ADC) and time (TDC), for PET
  - Choice between Differential FE (both polarities, MRT immune) and Single Ended FE (low Zin, DC bias adjustment, no external coupling parts)
  - Readout rates >200 kHz per channel (in all channels)
  - Power consumption ~30mW / channel



P. Fischer, Heidelberg University, The PETA Chip Family FAST Workshop, FBK 2016

IV. ASICs for PET: BASIC64

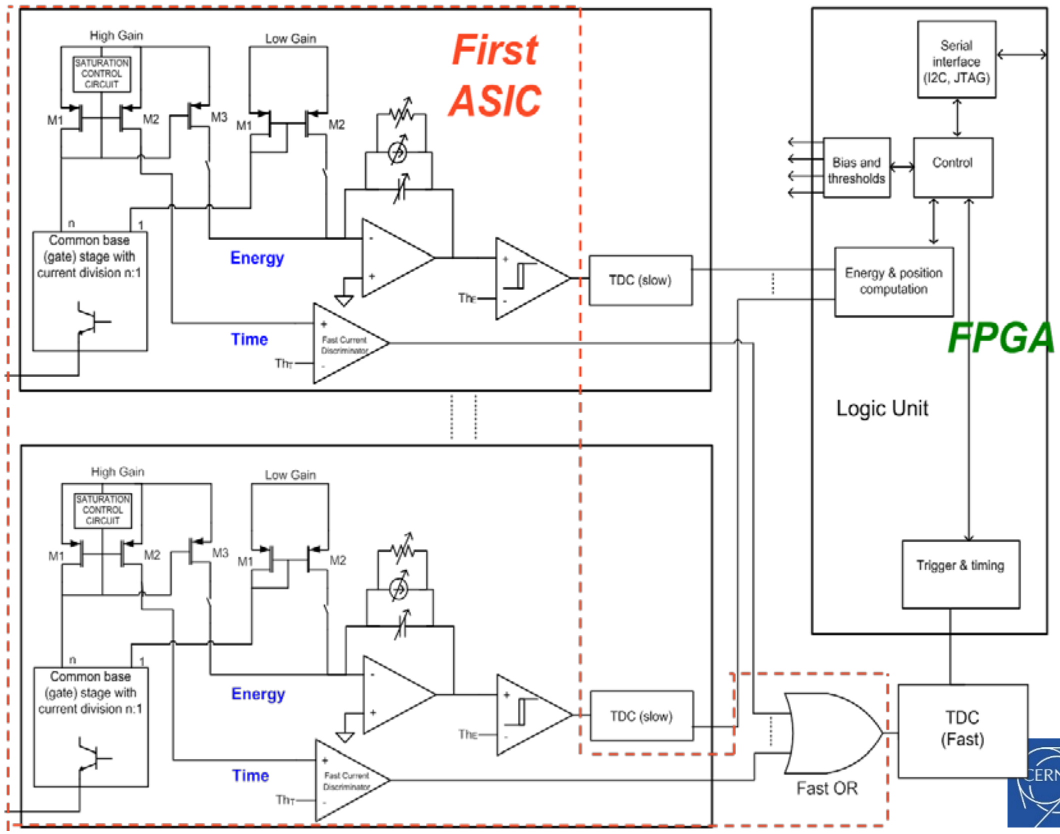
- BASIC64: current mode, digital (peak detector + ADC) and for PET
  - Power: 10 mW/ch
  - Max rate: 75 KHz/ch
  - No TDC for timing



C. Marzocca et alt., "BASIC64: A new mixed-signal front-end ASIC for SiPM detectors," NSS 2016

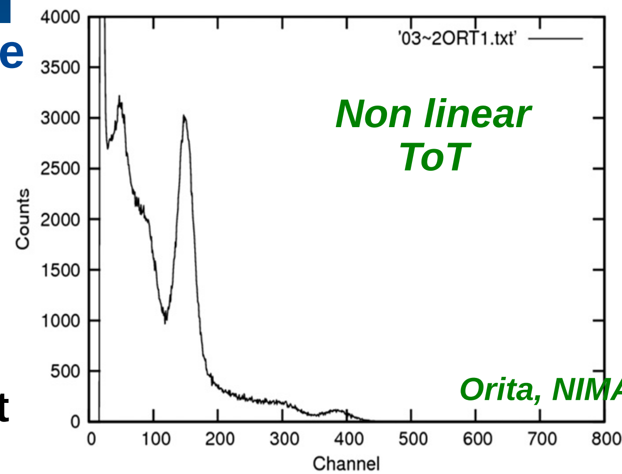
IV. ASICs for PET: FlexToT: linearized ToT RO chip

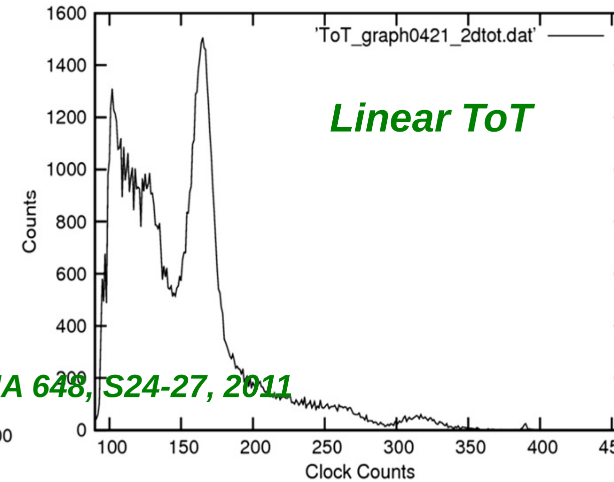
- Why FlexToT is flexible?
  - Different scintillator time constants
  - Trading-off resolution versus rate
  - Accurate analog processing directly connected to FPGA
    - TDCs and signal processing are in FPGA: reconfigurable !



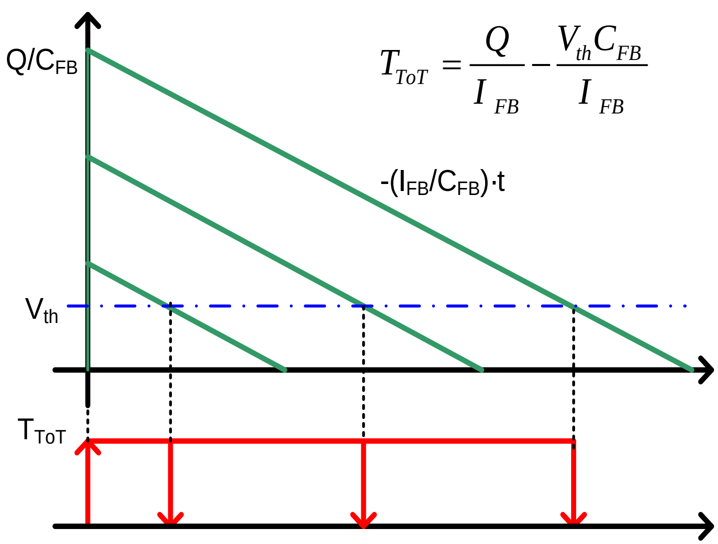
IV. ASICs for PET: FlexToT: linearized ToT RO chip

- **No linear ToT may degrade resolution**
- **Linear ToT is possible**
  - **Used in Medipix, Timepix, Dosepix ASICs family**
  - **Also proposed for PET**
  - **Tuneable feedback current (IFB)**
    - **Rate vs resolution**

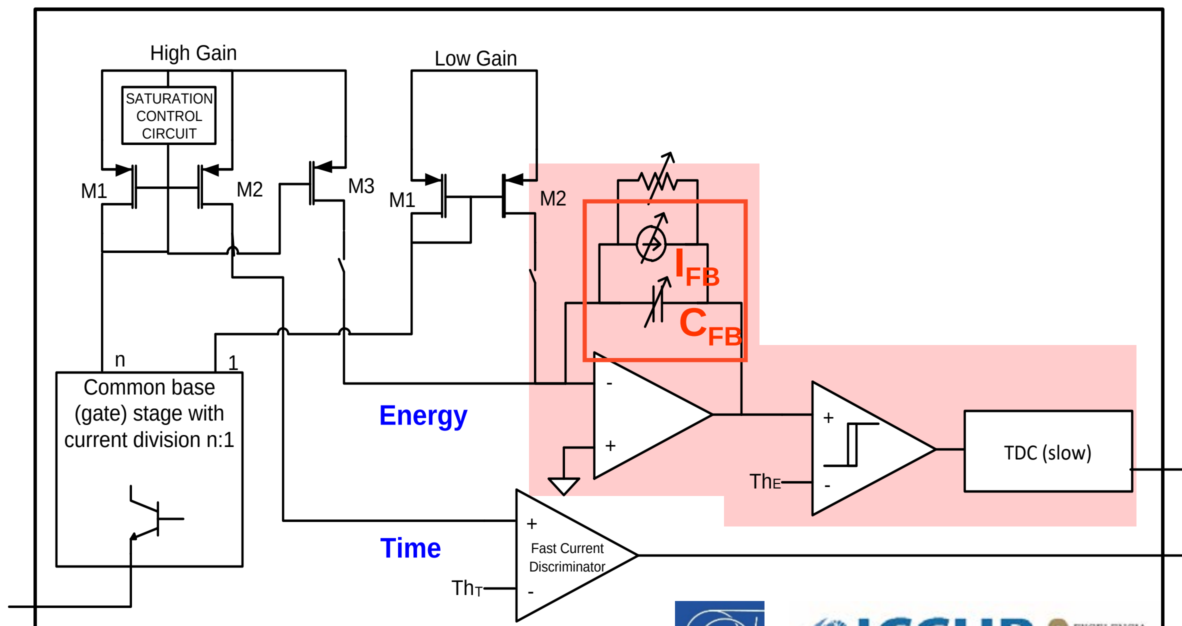




Orita, NIMA 648, S24-27, 2011

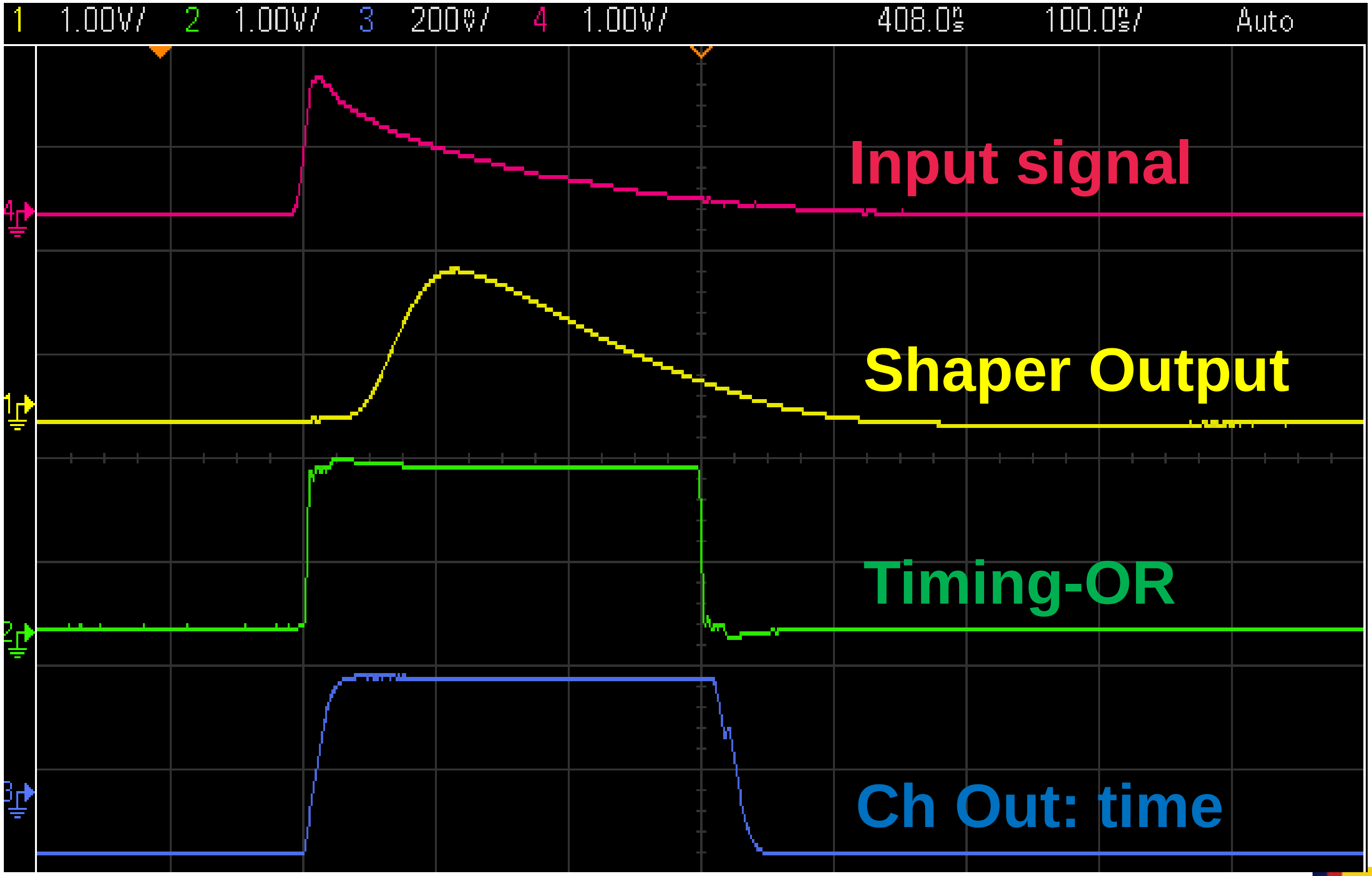


$$T_{ToT} = \frac{Q}{I_{FB}} - \frac{V_{th} C_{FB}}{I_{FB}}$$



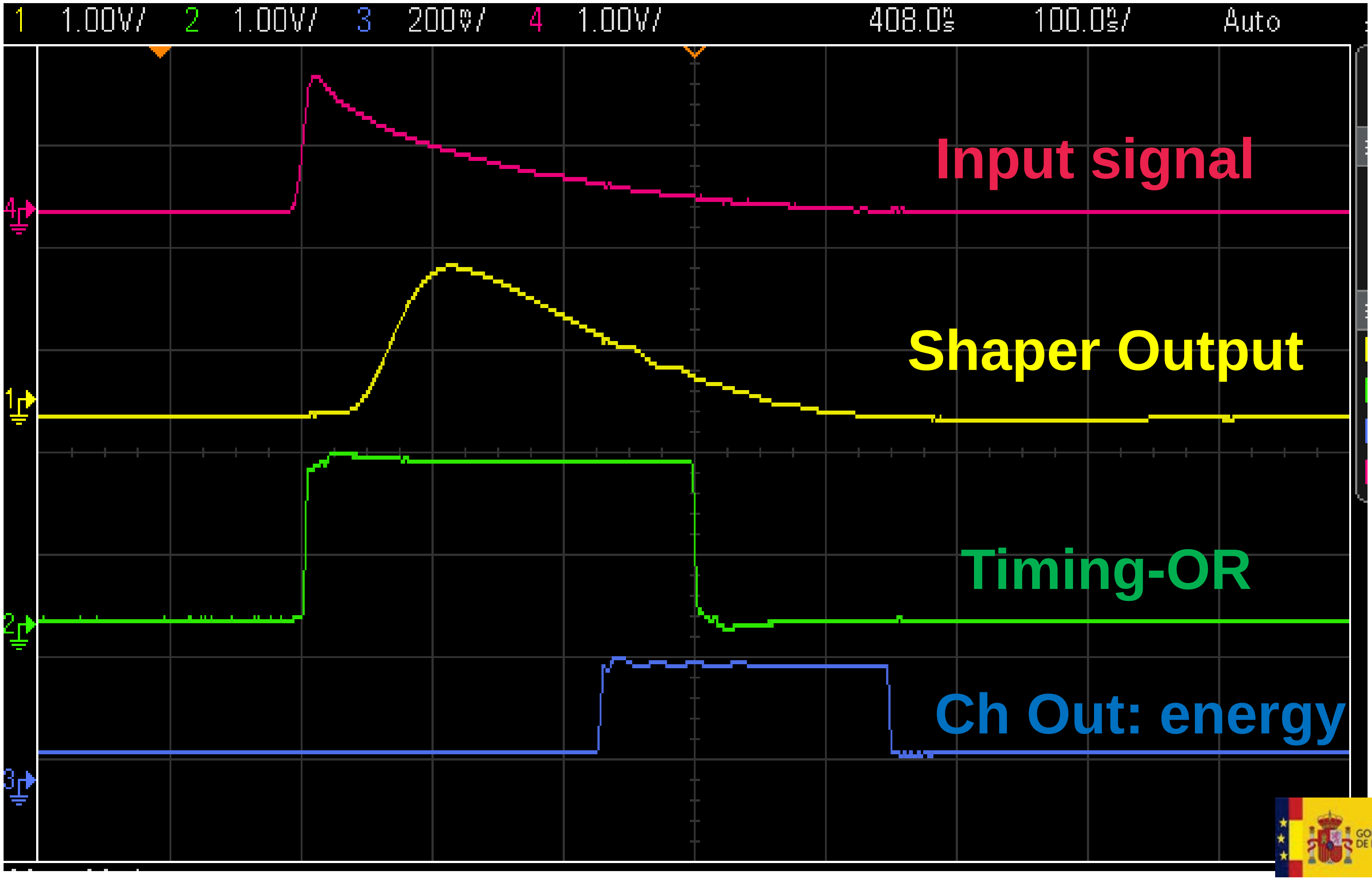
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- Preliminary results



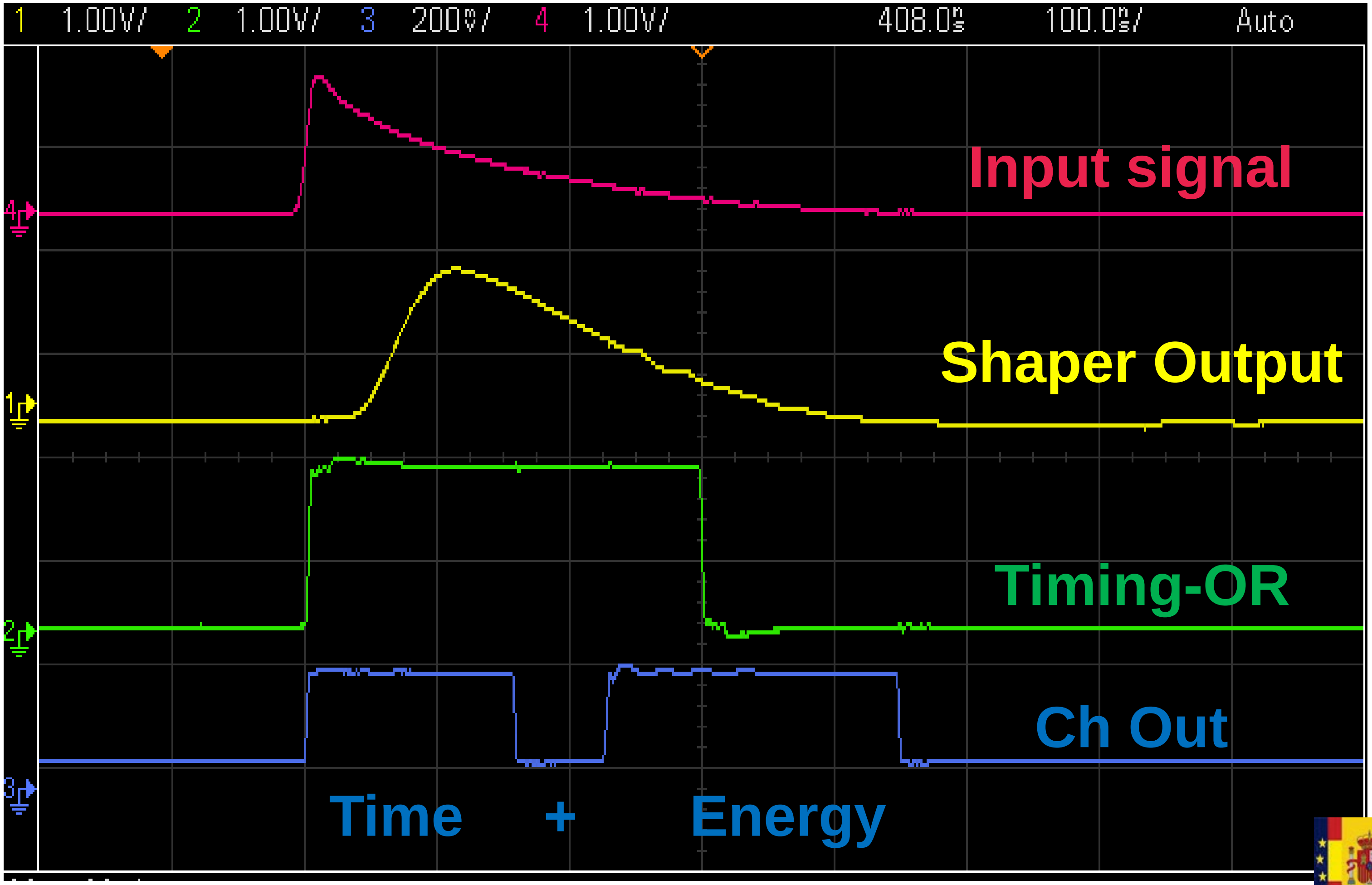
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- Preliminary results



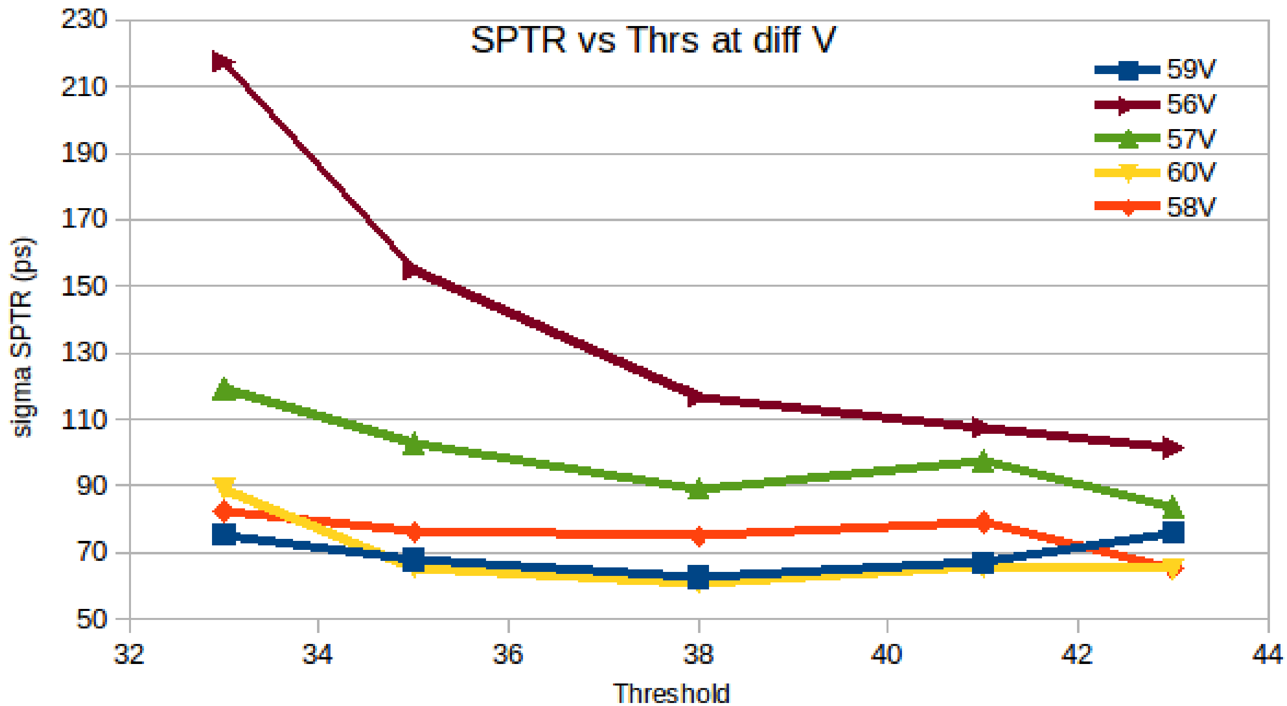
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- Preliminary results



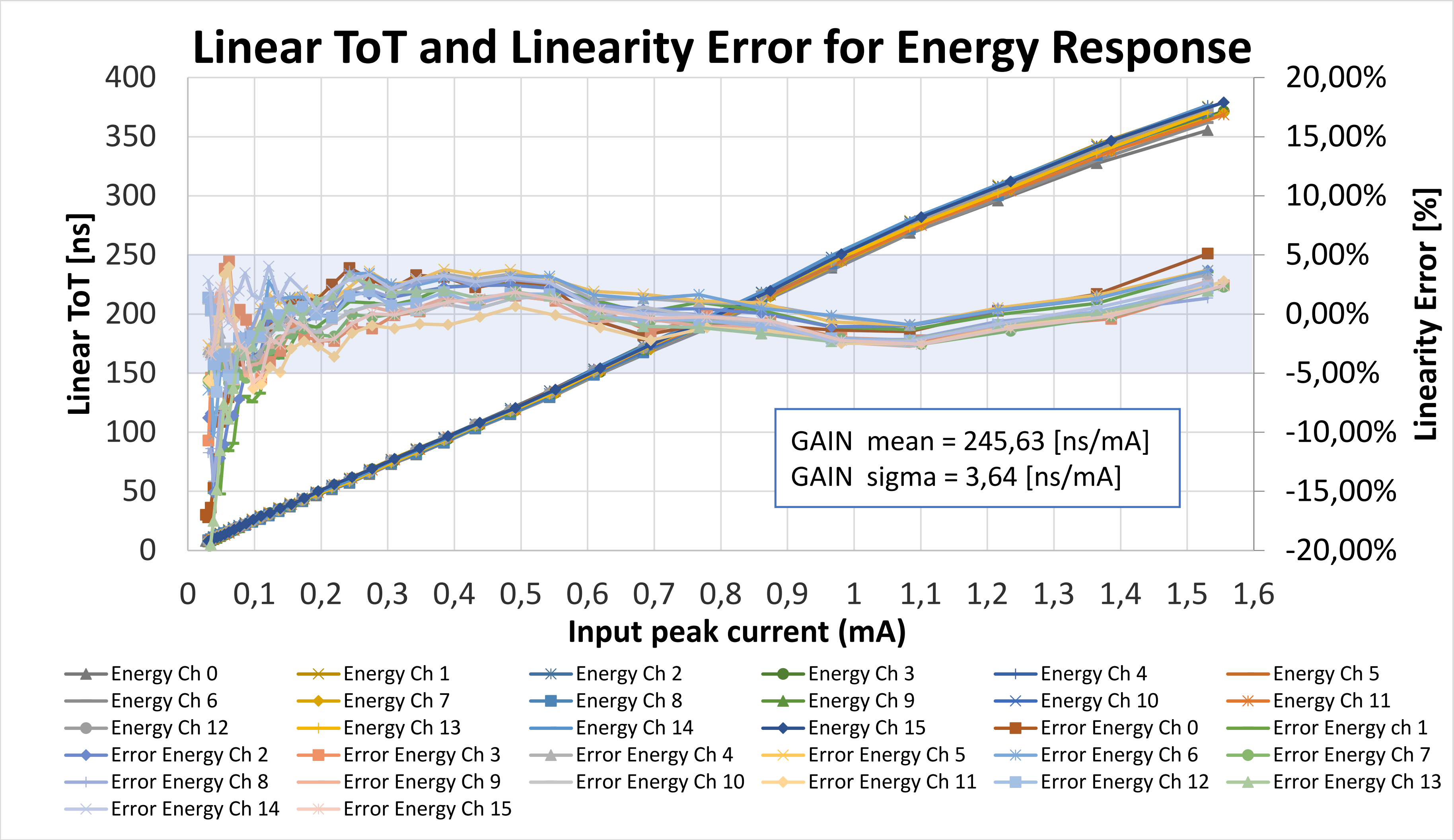
IV. ASICs for PET: HRFlexToT: linearized ToT RO chip

- Preliminary result
  - **3x3 mm²** HPKK device (75 um) cell, 4 year old.
    - Soon test with more recent devices
  - ***SPTR*** of about 65 ps rms (***150 ps FWHM***)



Inverted logic: low code means high threshold

IV. HRFlexToT: Linearity analysis: Channel Uniformity Peak Detector mode and Max Gain (G=3, RL=3)



- Maximum current limited by injection system with amplifiers.

IV. ASICs for fast timing: outlook

- In order to improve CTR we need to progress in
  - Crystals: prompt light emission
  - Sensors: SPTR
    - In the the limit, the single SPAD SPTR: 20 ps FWHM ?
- A cost/power effective mixed-mode approach:
  - Use small SiPMs
    - Better SPTR
  - Low power input stage
    - Demonstrated with HRFlexToT chip
  - Fast analog summation
    - Demonstrated with MUSIC chip
  - Multi threshold comparators
    - Provides estimation of the time of arrival of several photons
  - High performance TDCs and synchronization
    - < 10 ps timing resolution demonstrated in 130 nm technology