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IN2P3

Institut national de **physique nucléaire**
et de **physique des particules**

SiPM readout electronics overview

Content

- **SiPM electrical modelization**
 - See talk by G. Collazuol
- **Charge / voltage / current sensitive architectures**
- **Waveform digitizers**
 - See talk by D. Breton
- **Dedicated readout chips**
 - See talks by S. Conforti and C. Nauman
- **Digital SiPM**
 - See talks by D. Schaart and M. Heller
- **Thanks to G. Colluazol, S. Ritt, E. Delagnes, C. Mazzuoca, K. Kucewicz and N. Seguin for providing me with slides**
- **And all the others I stole slides/plots from...**

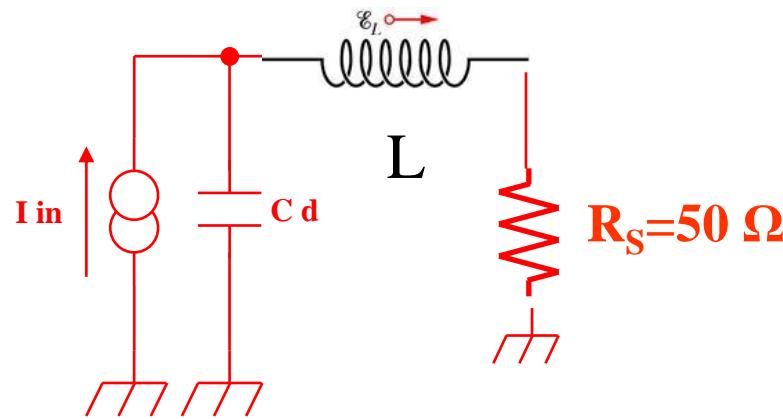
Signal & Source modelization

Vacuum Photomultipliers

G = $10^5 - 10^7$

C_d ~ 10 pF

L ~ 10 nH

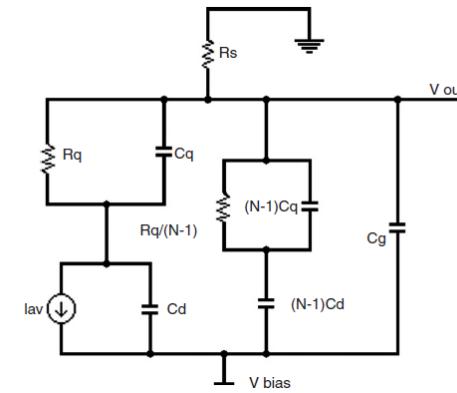
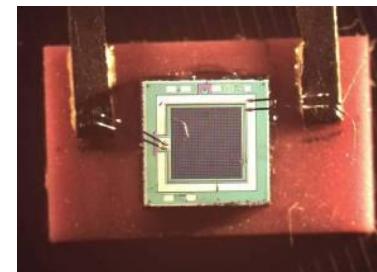


Silicon Photomultipliers

G = $10^5 - 10^7$

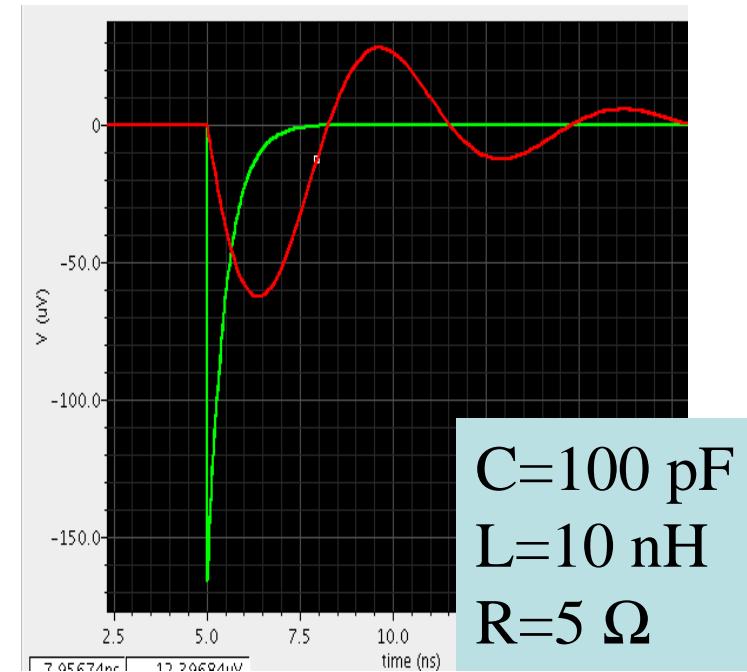
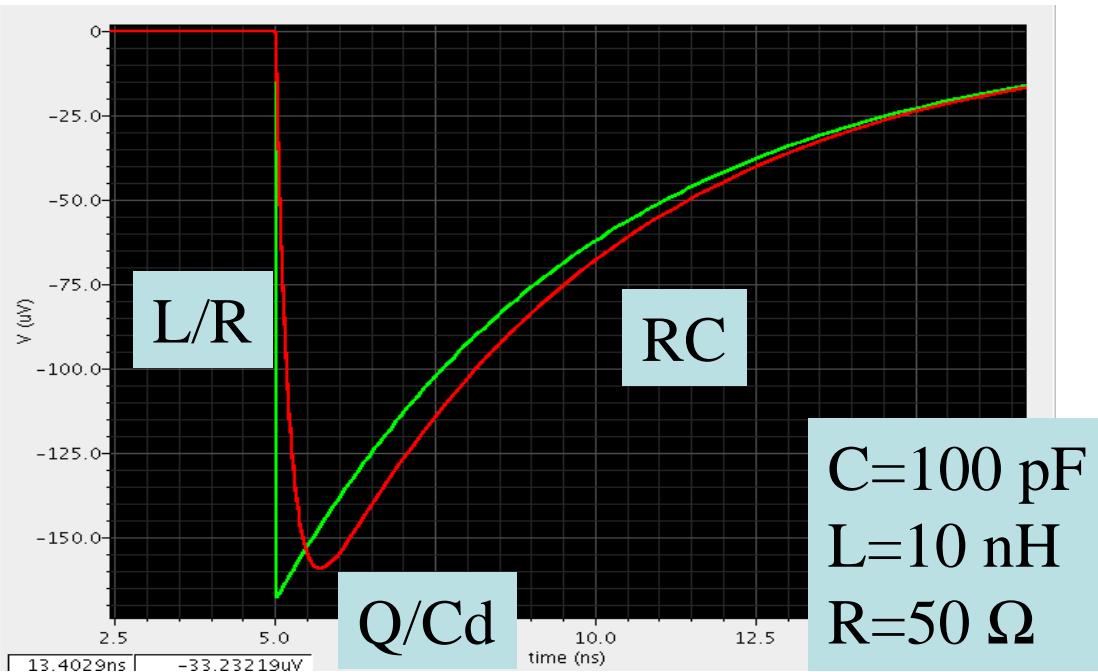
C = 10 - 400 pF

L = 1 - 10 nH



Basic pulse shapes

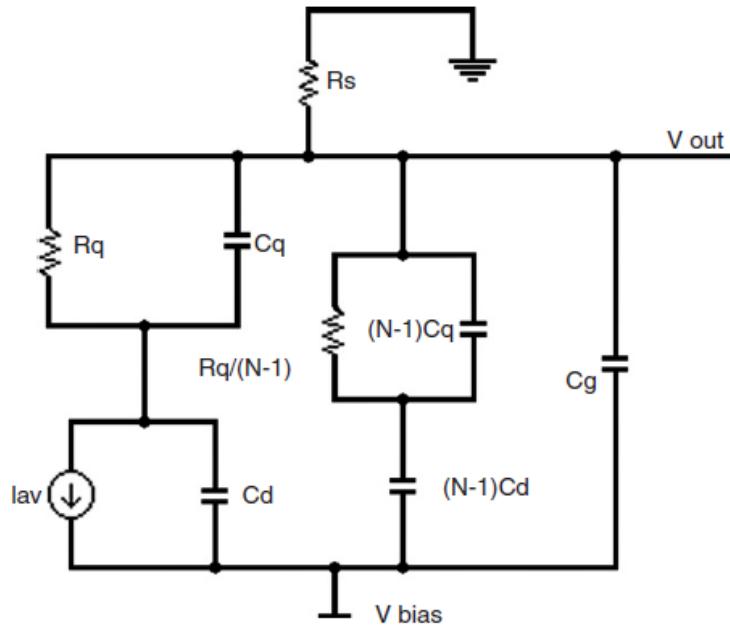
- **Short pulse : $Q=16 \text{ fC}$, $C_d=100 \text{ pF}$, $L=0-10 \text{ nH}$, $R_L=5-50 \Omega$**
- **Smaller signals with SiPM (large C_d) $\sim \text{mV/p.e.}$**
- **Sensitivity to parasitic inductance**
- **Choice of R_L : decay time, stability**
- **Convolve with current shape... (here delta impulse)**



SiPM modelization

- Modelization by Corsi et al [NIM A572 2007]

SiPM IRST,
 $N = 625$,
 $V_{\text{bias}} = 35 \text{ V}$



[F. Corsi et al. NIM A572]

| | |
|----------------------------|--------|
| $R_q (\text{k}\Omega)$ | 393.75 |
| $V_{\text{br}} (\text{V})$ | 31.2 |
| $Q (\text{fC})$ | 148.5 |
| $C_d (\text{fF})$ | 34.13 |
| $C_s (\text{fF})$ | 4.95 |
| $C_g (\text{pF})$ | 27.34 |

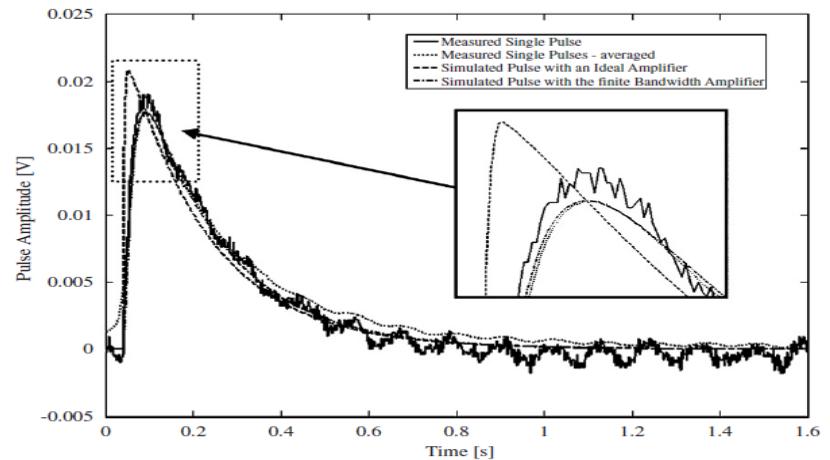


Fig. 2. Fitting of real data with the simulation results on the device model.

Electrical model of a SiPM

Collazuol
2008

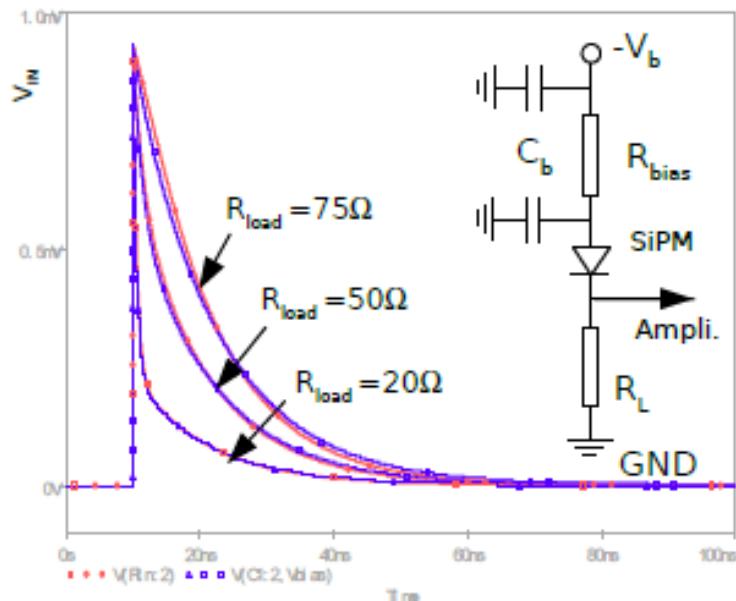
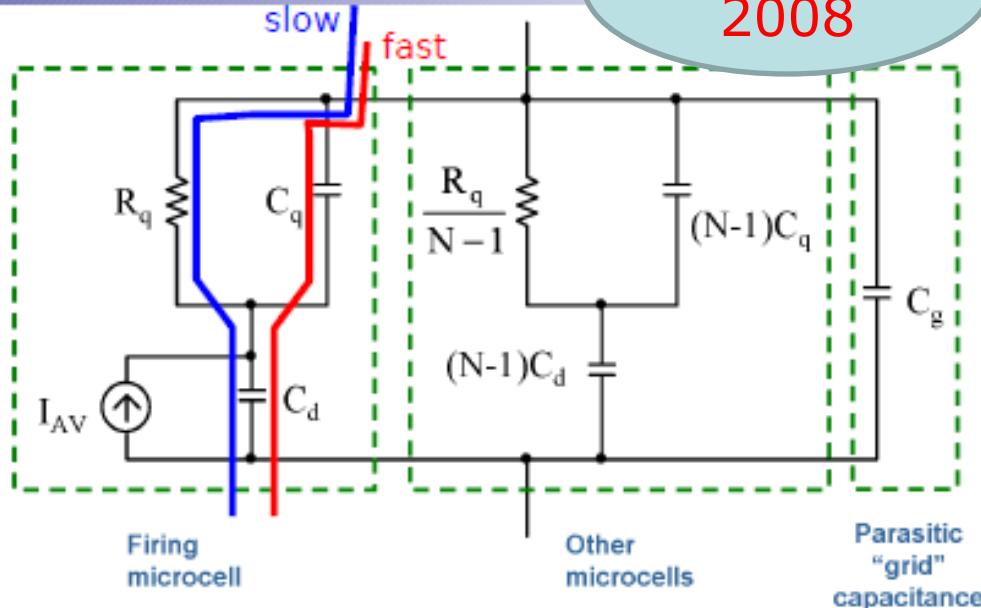
R_q : quenching resistor
(hundreds of $k\Omega$)

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 V_{bias} 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:

- $\tau_{IN} = R_s C_{tot}$ (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

SiPM equivalent circuit

Collazuol
2010

$$\text{Single cell model} \rightarrow (R_d || C_d) + (R_q || C_q)$$

$$\text{SiPM + load} \rightarrow ((Z_{\text{cell}}) || C_{\text{grid}}) + Z_{\text{load}}$$

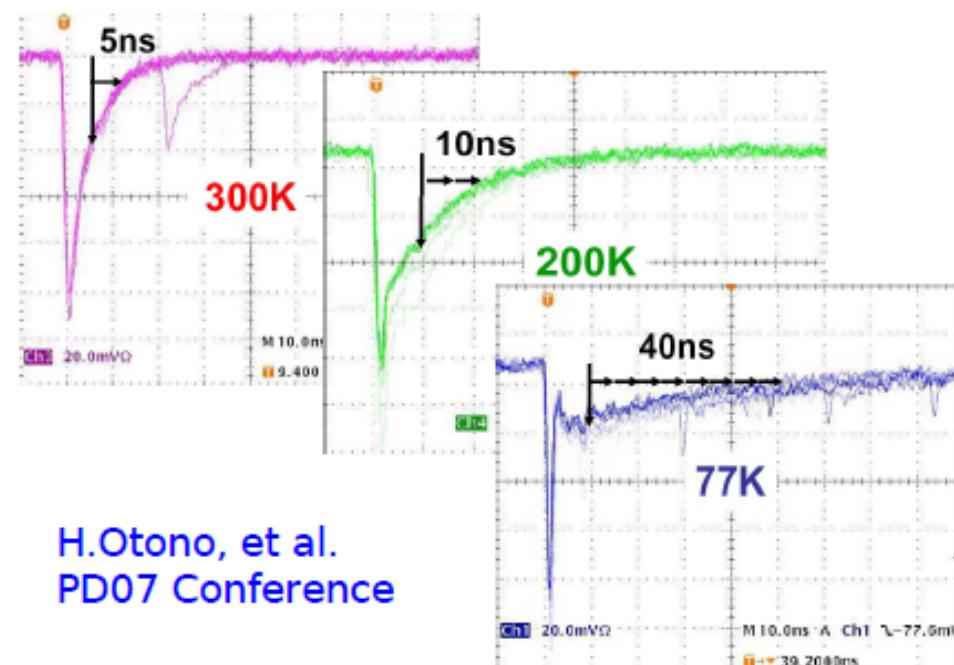
$$\text{Signal} = \text{slow pulse } (\tau_{d \text{ (rise)}}, \tau_{q-\text{slow (fall)}}) + \\ + \text{fast pulse } (\tau_{d \text{ (rise)}}, \tau_{q-\text{fast (fall)}})$$

- $\tau_{d \text{ (rise)}} \sim R_d(C_q + C_d)$

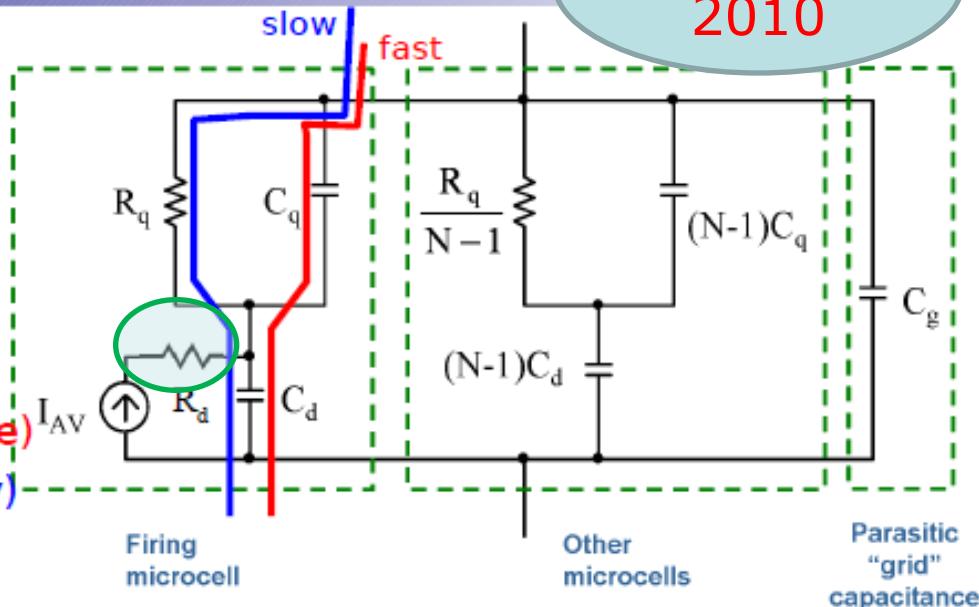
- $\tau_{q-\text{fast (fall)}} = R_{\text{load}} C_{\text{tot}}$ (fast; parasitic spike)

- $\tau_{q-\text{slow (fall)}} = R_q(C_q + C_d)$ (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

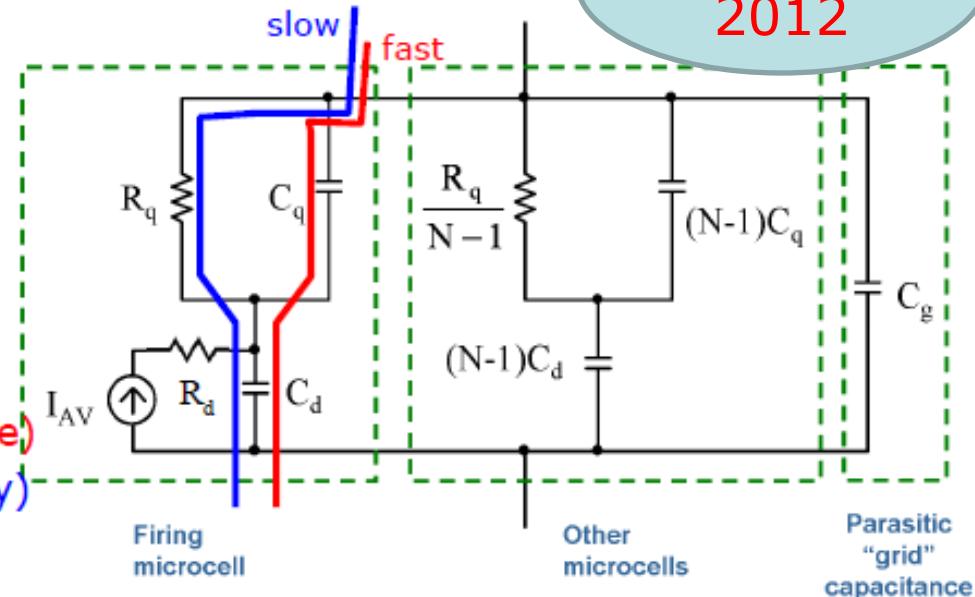
Collazuol
2012

$$\text{Single cell model} \rightarrow (R_d || C_d) + (R_q || C_q)$$

$$\text{SiPM + load} \rightarrow (|| Z_{\text{cell}}) || C_{\text{grid}} + Z_{\text{load}}$$

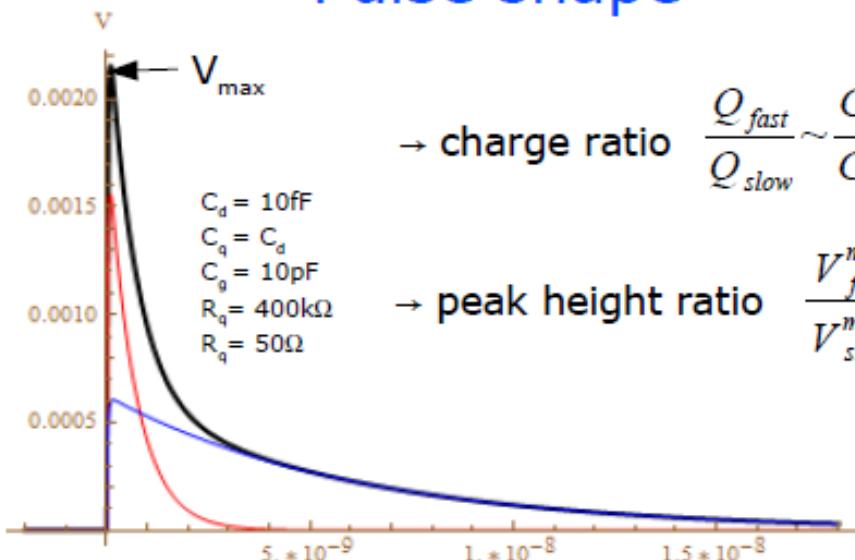
$$\text{Signal} = \text{slow pulse } (\tau_{d(\text{rise})}, \tau_{q-\text{slow fall}}) + \\ + \text{fast pulse } (\tau_{d(\text{rise})}, \tau_{q-\text{fast fall}})$$

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



Pulse shape

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



$$\rightarrow \text{charge ratio} \quad \frac{Q_{\text{fast}}}{Q_{\text{slow}}} \sim \frac{C_q}{C_d}$$

$$\rightarrow \text{peak height ratio}$$

$$\frac{V_{\text{fast}}^{\text{max}}}{V_{\text{slow}}^{\text{max}}} \sim \frac{C_q^2 R_q}{C_d C_{\text{tot}} R_{\text{load}}} \quad \text{increasing with } R_q \text{ and } 1/R_{\text{load}} \text{ (and } C_q \text{ of course)}$$

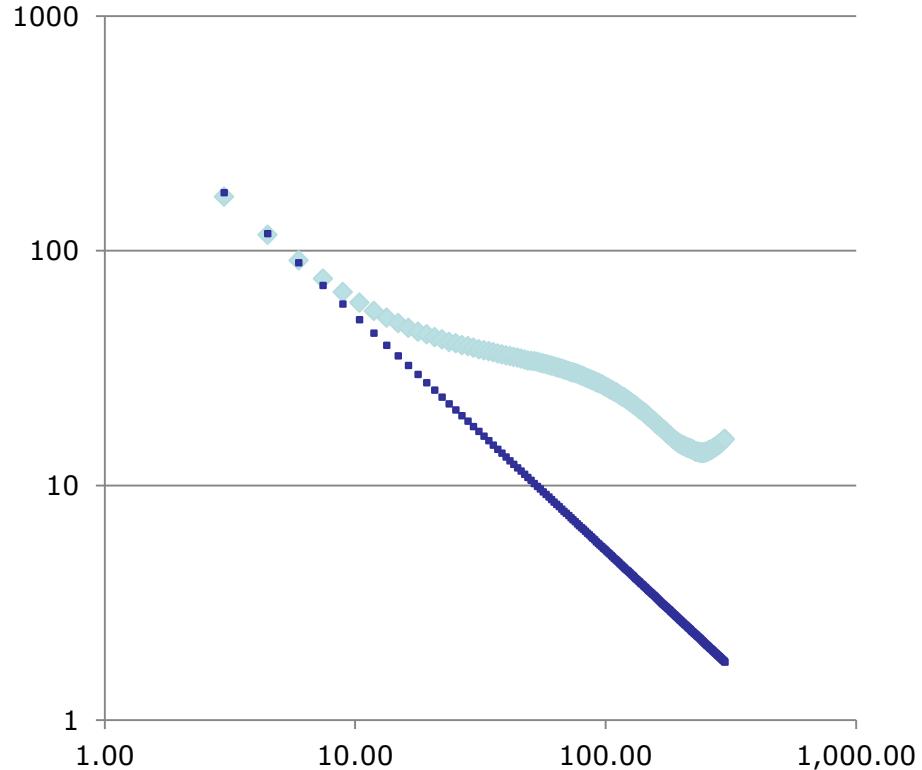
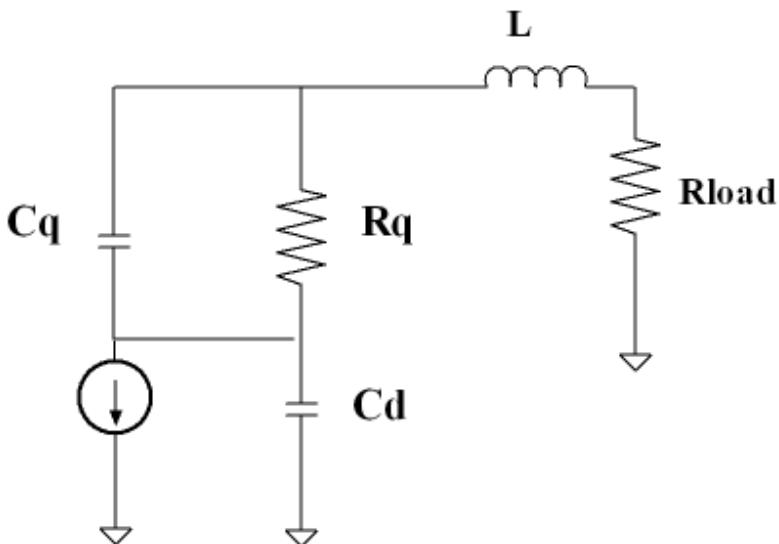
Increasing C_q/C_d or/and R_q/R_{load}
 \rightarrow spike enhancement
 \rightarrow better timing

SiPM impedance and model

- **RLC too simple, inaccurate at high frequency**

- **CdRqCqLR OK**

- May better explain HF noise behaviour



Measured impedance
 MPPC HPK 3x3 mm
 Line : $C = 320 \text{ pF}$

Charge and Current preamps

Charge preamp

Capacitive feedback **Cf**

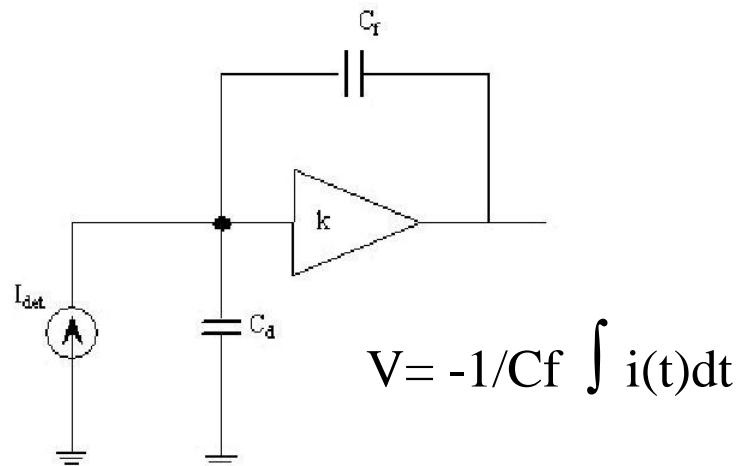
$$V_{out}/I_{in} = - 1/j\omega C_f$$

Perfect integrator : $v_{out}=Q/C_f \int$

Difficult to accomodate large
SiPM signals (200 pC)

Lowest noise configuration

Need Rf to empty Cf



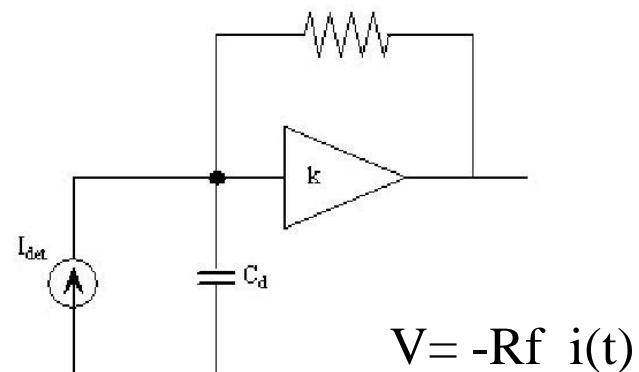
Current preamp

Resistive feedback **Rf**

$$V_{out}/I_{in} = - R_f$$

Keeps signal shape

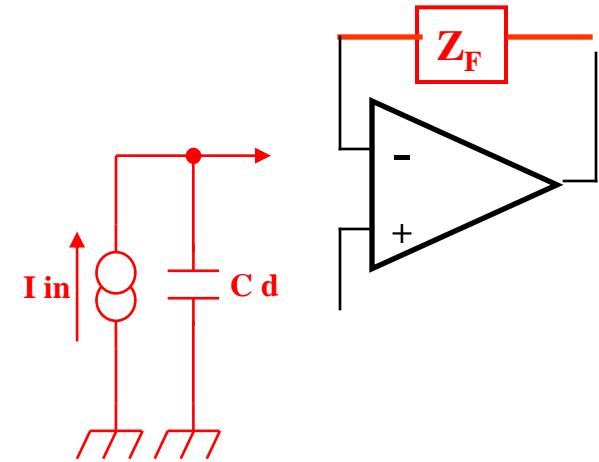
Need Cf for stability



Transimpedance configuration

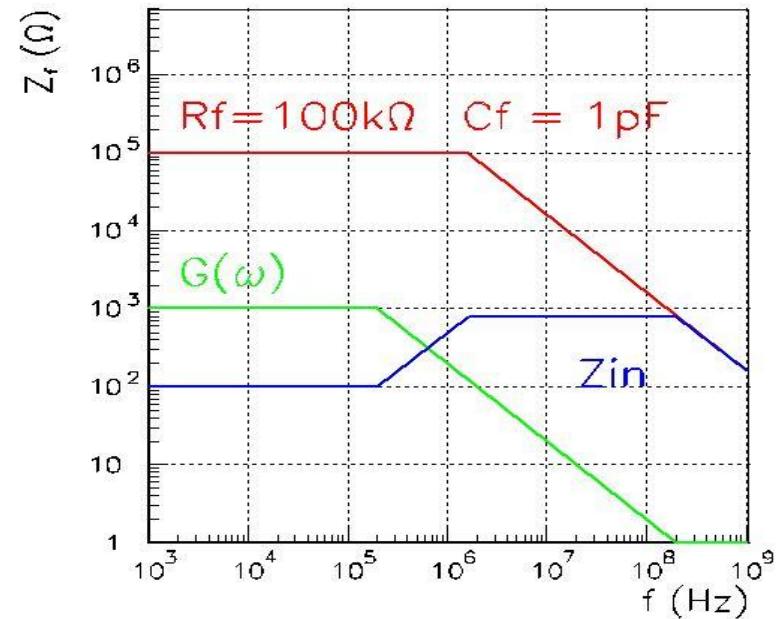
- **Transfer function**

- $V_{\text{out}}(\omega)/i_{\text{in}}(\omega) = - Z_f / (1 + Z_f / G Z_d)$
- $\sim -Z$
 - $Z_f = R_f / (1 + j\omega R_f C_f)$
- At $f \ll 1/2\pi R_f C_f$: $V_{\text{out}}(\omega)/i_{\text{in}}(\omega) = - R_f$ **current preamp**
- At $f \gg 1/2\pi R_f C_f$: $V_{\text{out}}(\omega)/i_{\text{in}}(\omega) = - 1/j\omega C_f$ **charge preamp**



- **Low Input impedance**

- $Z_{\text{in}} = Z_f / G + 1$
- $Z_{\text{in}} \rightarrow 0$ **virtual ground**
- Minimizes sensitivity to detector impedance
- Minimizes crosstalk
- **Virtual resistance** : $R_{\text{eq}} = 1/G_0 \omega_0 C_f$
- **Virtual inductance** : $L_{\text{eq}} = R_f / G_0 \omega_0$



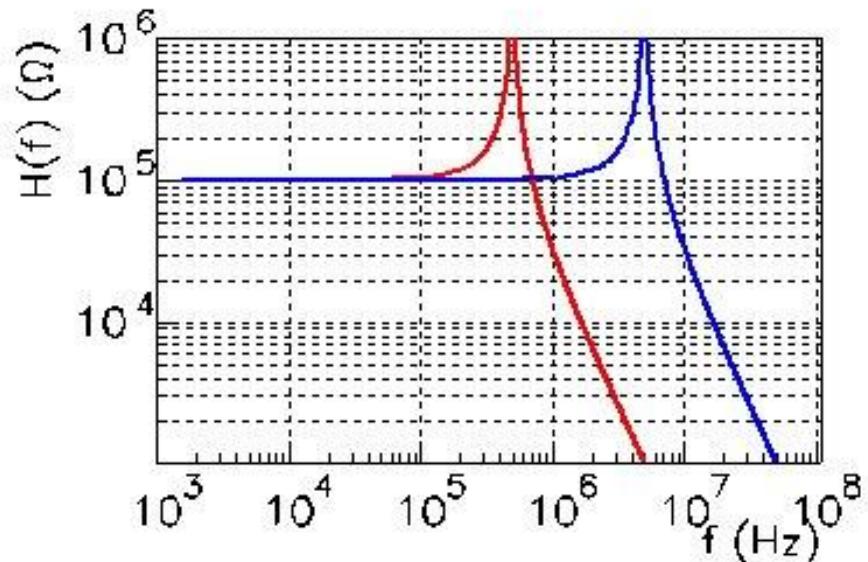
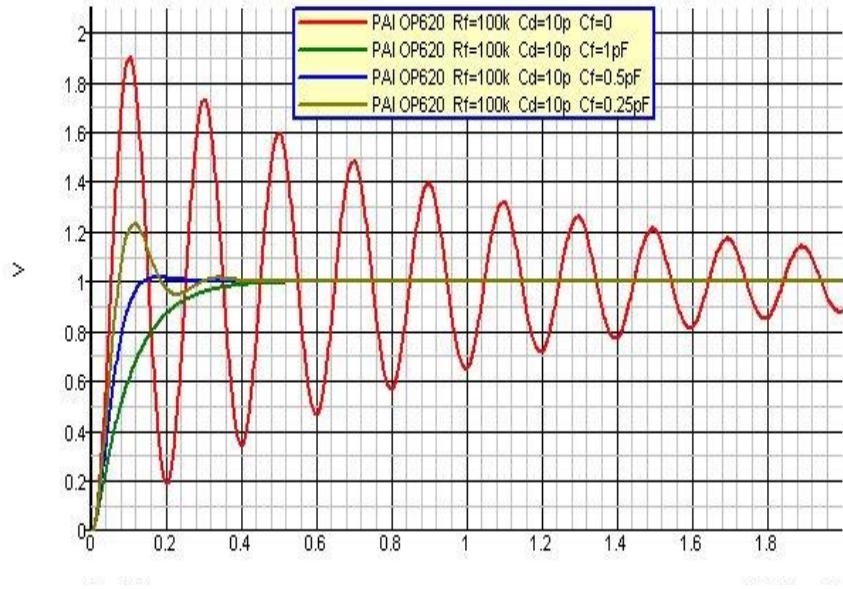
Stabilising the transimpedance amplifier

- **RLC circuit with capacitive detector**

- Resonant frequency : $f_{\text{res}} = 1/2\pi \sqrt{L_{\text{eq}} C_d}$
- Quality factor : $Q = 1/C_f \sqrt{(C_d/R_f G_0 \omega_0)}$
- $Q > 1/2 \rightarrow$ ringing
- **Damping : $Q=1/2$**
 $\Rightarrow C_f = 2 \sqrt{(C_d/R_f G_0 \omega_0)}$
- Example :
 - LM741 ($G_0 \omega_0 = 107$) : $C_f = 10\text{pF}$
 - OP620 ($G_0 \omega_0 = 109$) : $C_f = 0.3\text{pF}$

- **In frequency domain**

- $H(j\omega) = -R_f / (1 + j\omega R_f C_d / G(\omega))$
 $= -R_f / (1 + j\omega R_f C_d / G_0 - \omega^2 R_f C_d / G_0 \omega_0)$



Transimpedance amplifier

- **Transimpedance :**

- $V_{out}(\omega)/i_{in}(\omega) = - Z_f / (1 + Z_f / G Z_d)$
- $Z_f = R_f / (1 + j\omega R_f C_f)$
- $G(\omega) = G_0 / (1 + j \omega / \omega_0)$
- $H \sim - R_f / (1 + j\omega R_f C_d / G_0 - \omega^2 R_f C_d / G_0 \omega_0)$

- **2nd order system, easily oscillatory**

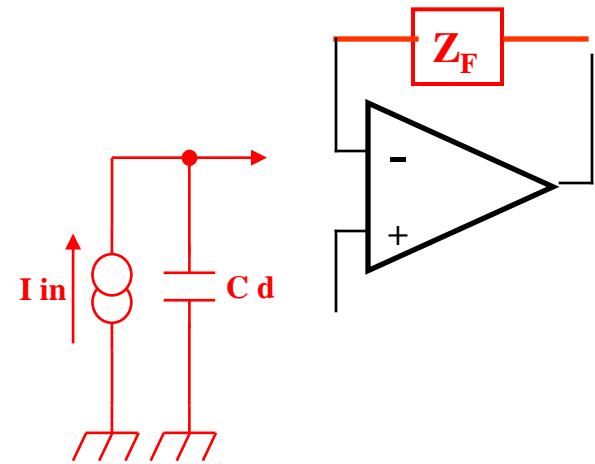
- Damped with C_f , but BW limitation at $R_f C_f$

- **Input impedance : $Z_{in} = Z_f / G$: Inductive term because $G(\omega)$**

- $R_{in} = R_f G_0$, $L_{in} = R_f / G_0 \omega_0$
- with $R_f = 500 \Omega$, $G_0 = 100$, $G_0 \omega_0 = 10 \text{ GHz}$, get $R_{in} = 5 \Omega$ and $L_{in} = 3 \text{ nH}$

- **Similar frequency response as current conveyor**

- More unstable
- Potentially lower power

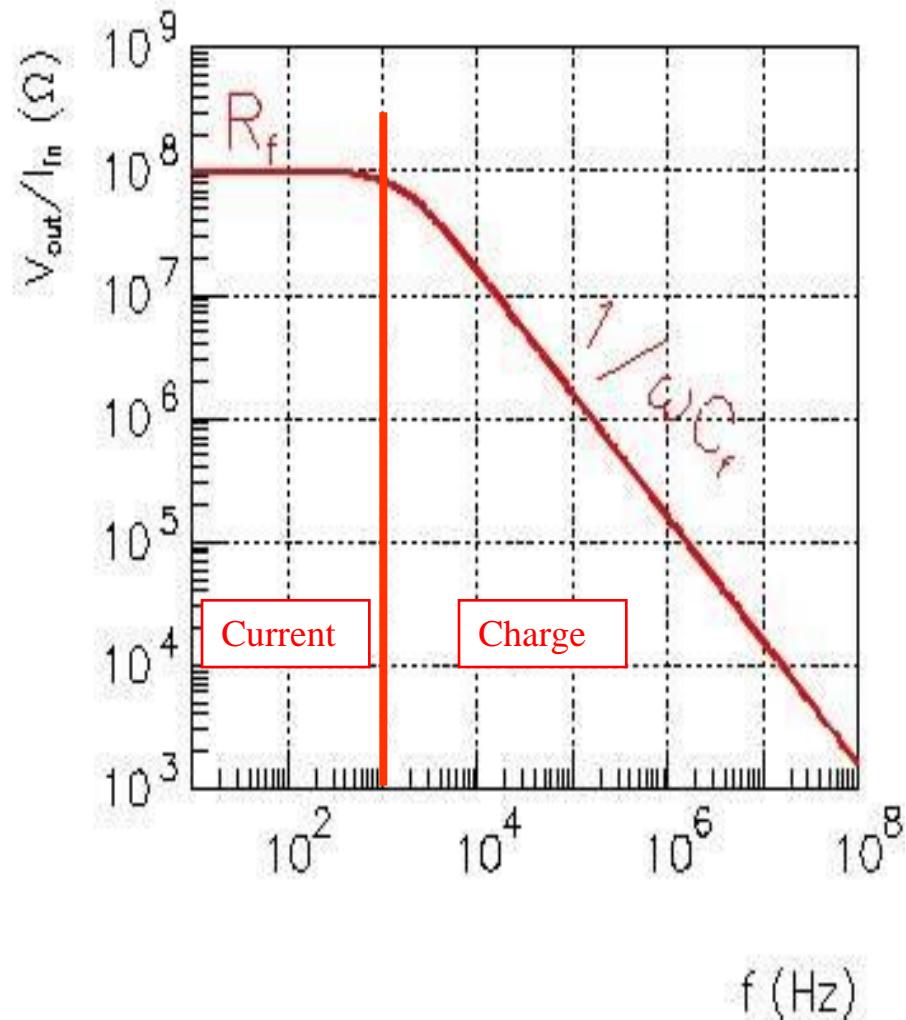


Charge vs Current preamps

- **Charge preamps**
 - Best noise performance
 - Best with short signals
 - Best with small capacitance

- **Current preamps**
 - Best for long signals
 - Best for high counting rate
 - Significant parallel noise

- **Charge preamps are not slow, they are long**
- **Current preamps are not faster they are shorter (but easily unstable)**

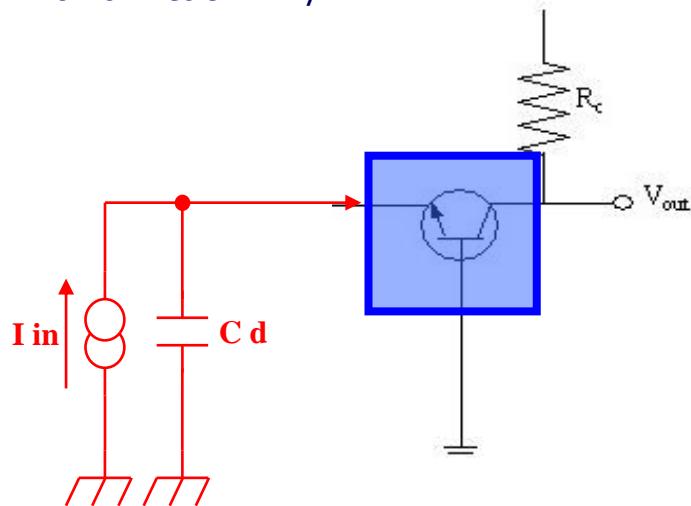


High speed configurations

- **Open loop configurations : current conveyors, RF amplifiers**
- **Usually designed at transistor level MOS or SiGe (ex PETIROC)**

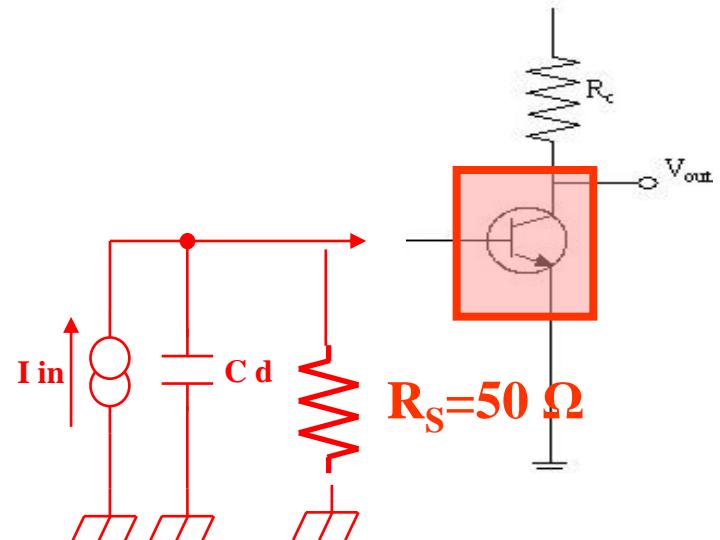
- **Current conveyors**

- Small Z_{in} : current sensitive input
- Large Z_{out} : current driven output
- Unity gain current conveyor
- E.g. : (super) common-base configuration
- Low input impedance : $R_{in}=1/gm$
- Transimpedance : R_c
- Bandwidth : $1/2\pi R_c C_u > 1 \text{ GHz}$



- **RF amplifiers**

- Large Z_{in} : voltage sensitive input
- Large Z_{out} : current driven output
- Current conversion with resistor R_s
- E.g. common-emitter configuration
- Transimpedance : $-gm R_c R_s$
- Bandwidth : $1/2\pi R_s C_t$



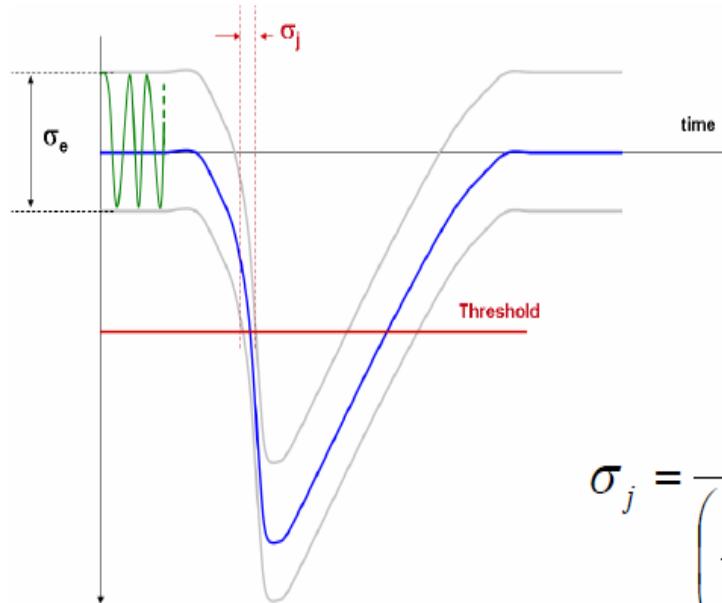
Noise and jitter

- **Electronics noise dominated by series noise en**

- Large detector capacitance
- For voltage preamp and load resistor RL,
- Output rms noise $V_n^2 = (e_n^2 + 4kT R_s) G^2 \pi/2 * BW_{-3dB}$
- Typical values : $R_s=50 \Omega$, $e_n=1 \text{ nV}/\sqrt{\text{Hz}}$ $V_n=1 \text{ mV}$ for $G=10$, $BW=1\text{GHz}$
- For current sensitive preamps, possible noise peaking due to C_d

- **Jitter**

- Part due to electronics noise :
- $\sigma_t = \sigma_v / (dV/dt)$
- Minimized by increasing BW



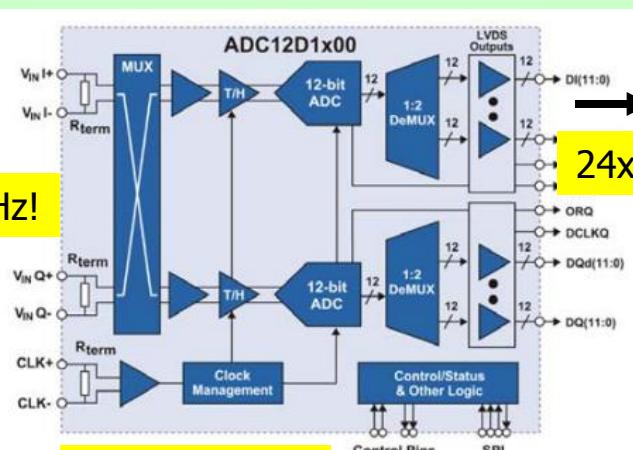
A few (personal) comments

- **Strong push for high speed front-end > GHz**
 - Essential for timing measurements
 - Several configurations to get GBW > 10 GHz
 - Optimum use of SiGe bipolar transistors
- **Voltage sensitive front-end**
 - Easiest : 50Ω termination, many commercial amplifiers (mini circuit...)
 - Beware of power dissipation
 - Easy multi-gain (time and charge)
- **Current sensitive front-end**
 - Potentially lower noise, lower input impedance
 - Largest GBW product
- **In all cases, importance of reducing stray inductance**

Waveform digitizers [S. Ritt]

FADCs

- 8 bits – 3 GS/s – 1.9 W → 24 Gbits/s
- 10 bits – 3 GS/s – 3.6 W → 30 Gbits/s
- 12 bits – 3.6 GS/s – 3.9 W → 43.2 Gbits/s
- 14 bits – 0.4 GS/s – 2.5 W → 5.6 Gbits/s

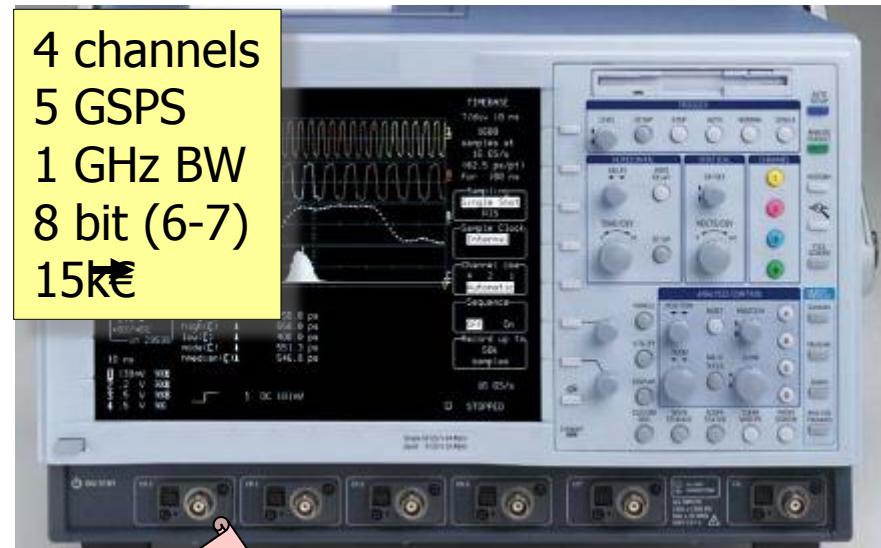


1/10 k€/ch

PX1500-4:
2 Channel
3 GS/s
8 bits

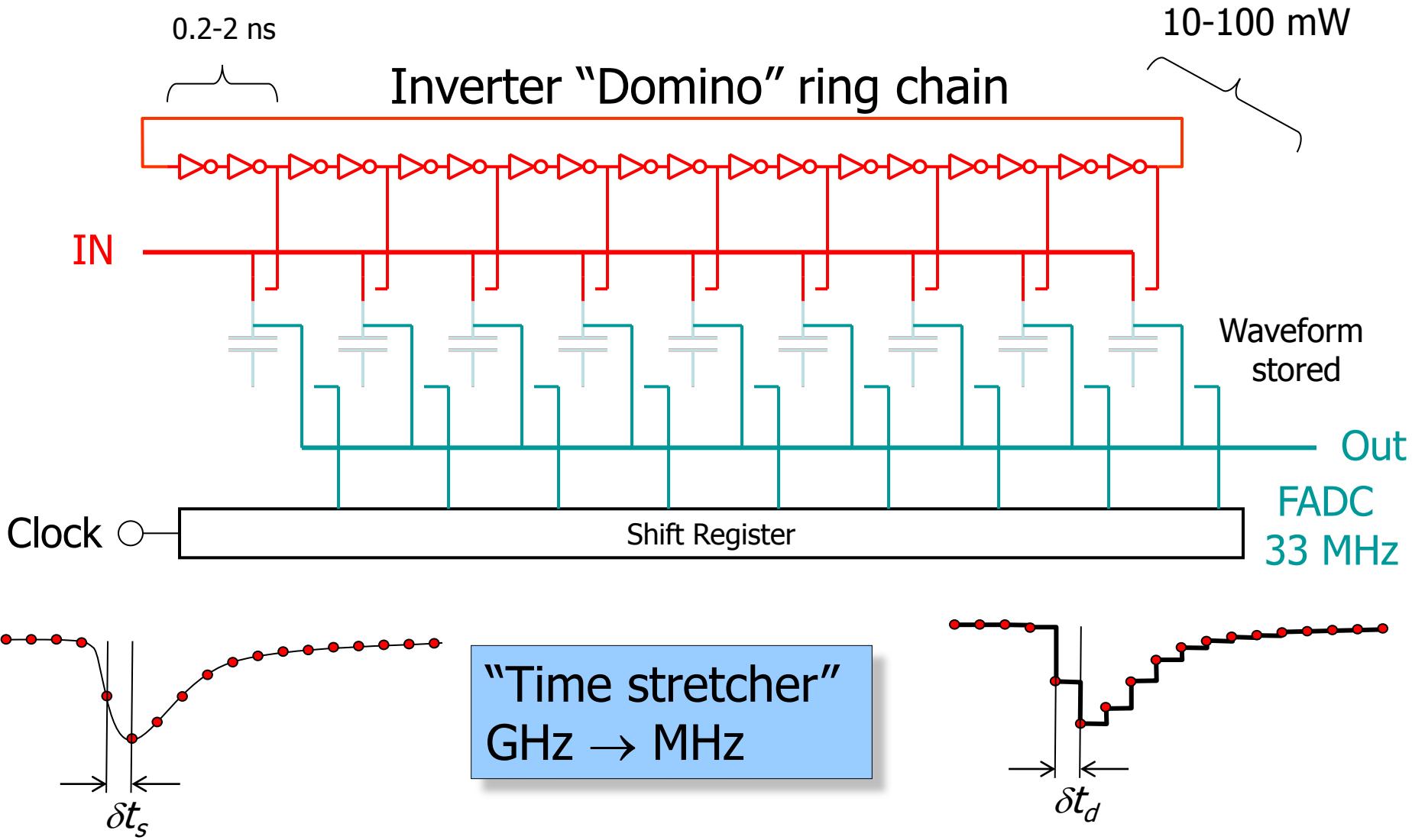


4 channels
5 GS/s
1 GHz BW
8 bit (6-7)
15k€

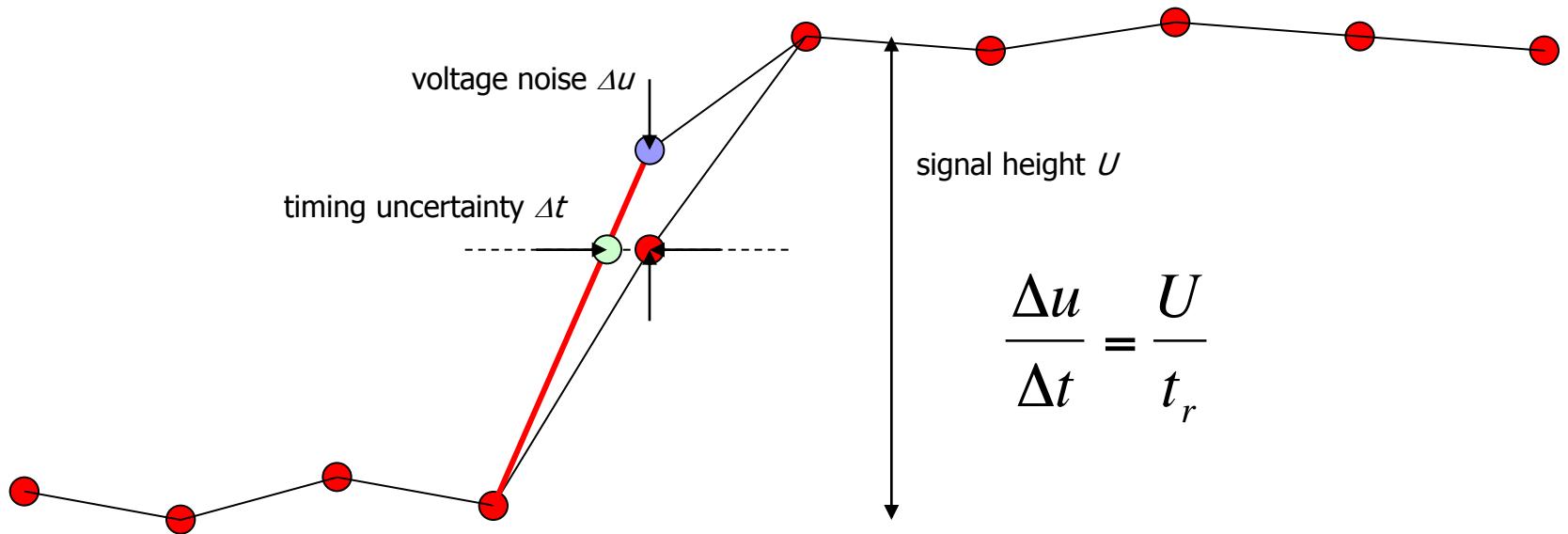


See talk by D. Breton





How is timing resolution affected?



$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

$$\Delta t = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3f_s \cdot f_{3dB}}}$$

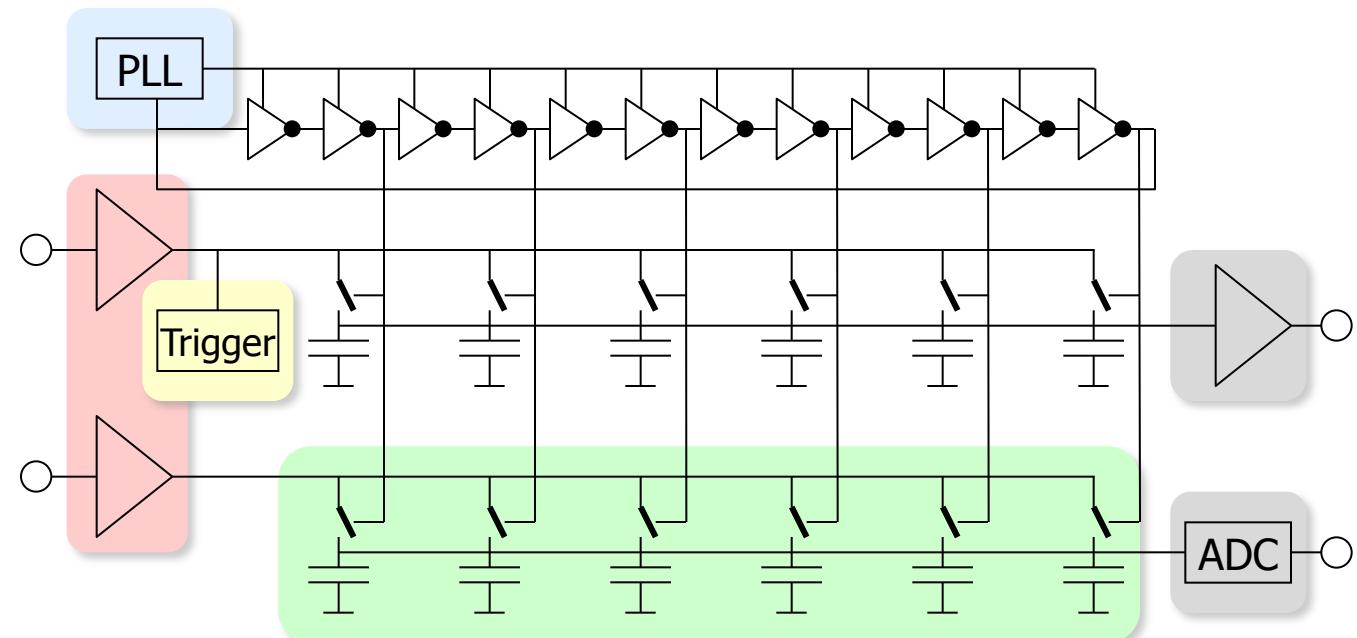
Assumes zero
aperture jitter
↓

today:
optimized SNR:
next generation:

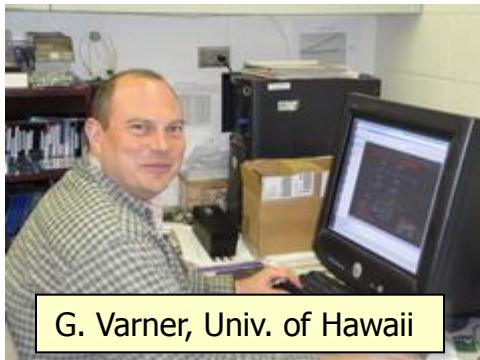
| | U | Δu | f_s | f_{3db} | Δt |
|------------------|--------|------------|---------|-----------|------------|
| today: | 100 mV | 1 mV | 2 GSPS | 300 MHz | ~10 ps |
| optimized SNR: | 1 V | 1 mV | 2 GSPS | 300 MHz | 1 ps |
| next generation: | 1V | 1 mV | 10 GSPS | 3 GHz | 0.1 ps |

Design Options

- CMOS process (typically $0.35 \dots 0.13 \mu\text{m}$) → sampling speed
- Number of channels, sampling depth, differential input
- PLL for frequency stabilization
- Input buffer or passive input
- Analog output or (Wilkinson) ADC
- Internal trigger
- Exact design of sampling cell



Switched Capacitor Arrays for Particle Physics

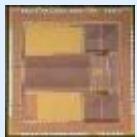


G. Varner, Univ. of Hawaii

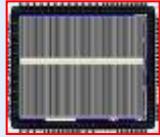


H. Frisch et al., Univ. Chicago

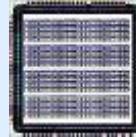
STRAW3



LABRADOR3



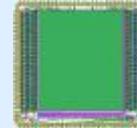
TARGET



- 0.25 μm TSMC
- Many chips for different projects (Belle, Anita, IceCube ...)

www.phys.hawaii.edu/~idlabs/

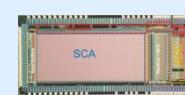
AFTER



SAM



NECTAR0



- 0.35 μm AMS
- T2K TPC, Antares, Hess2, CTA

matacq.free.fr

PSEC1 - PSEC4

Poster 232

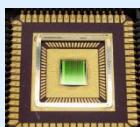
- 0.13 μm IBM
- Large Area Picosecond Photo-Detectors Project (LAPPD)

psec.uchicago.edu

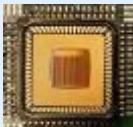
DRS1



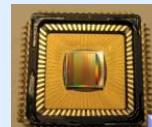
DRS2



DRS3



DRS4



2002

2004

2007

2008

- 0.25 μm UMC

- Universal chip for many applications
- MEG experiment, MAGIC, Veritas, TOF-PET

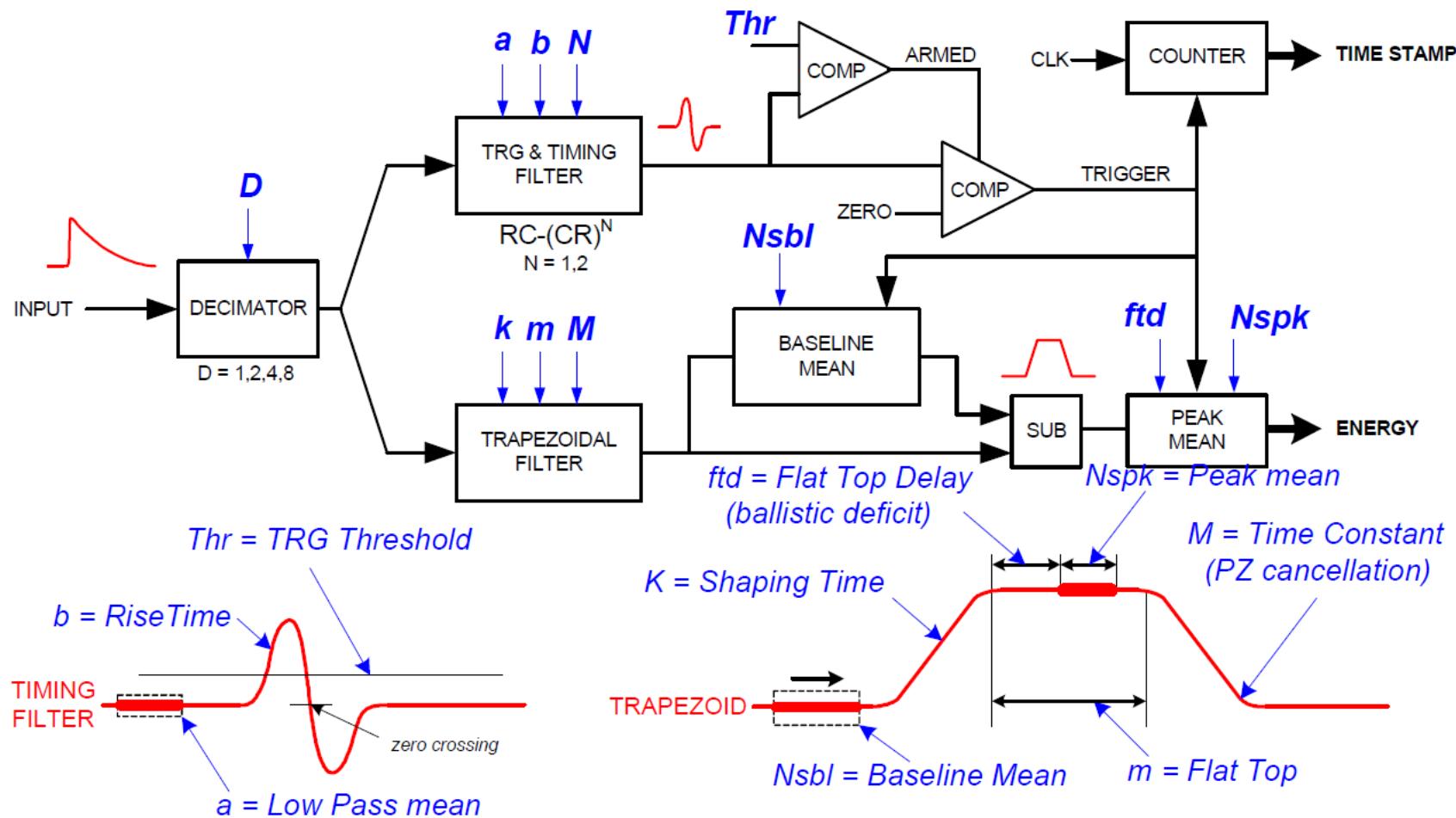
Poster 15, 106



Stefan Ritt
R. Dinapoli
PSI, Switzerland

drs.web.psi.ch

Digital Pulse Processing (DPP)



C. Tintori (CAEN)
V. Jordanov *et al.*, NIM **A353**, 261 (1994)

Things you can buy

- DRS4 chip (PSI)
- 32+2 channels
- 12 bit 5 GSPS
- > 500 MHz analog BW
- 1024 sample points/chn.
- 110 μ s dead time



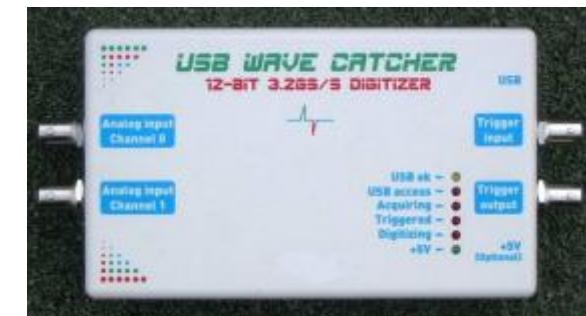
- MATACQ chip (CEA/IN2P3)
- 4 channels
- 14 bit 2 GSPS
- 300 MHz analog BW
- 2520 sample points/chn.
- 650 μ s dead time



- DRS4 Evaluation Board
- 4 channels
- 12 bit 5 GSPS
- 750 MHz analog BW
- 1024 sample points/chn.
- 500 events/sec over USB 2.0



- SAM Chip (CEA/IN2PD)
- 2 channels
- 12 bit 3.2 GSPS
- 300 MHz analog BW
- 256 sample points/chn.
- On-board spectroscopy



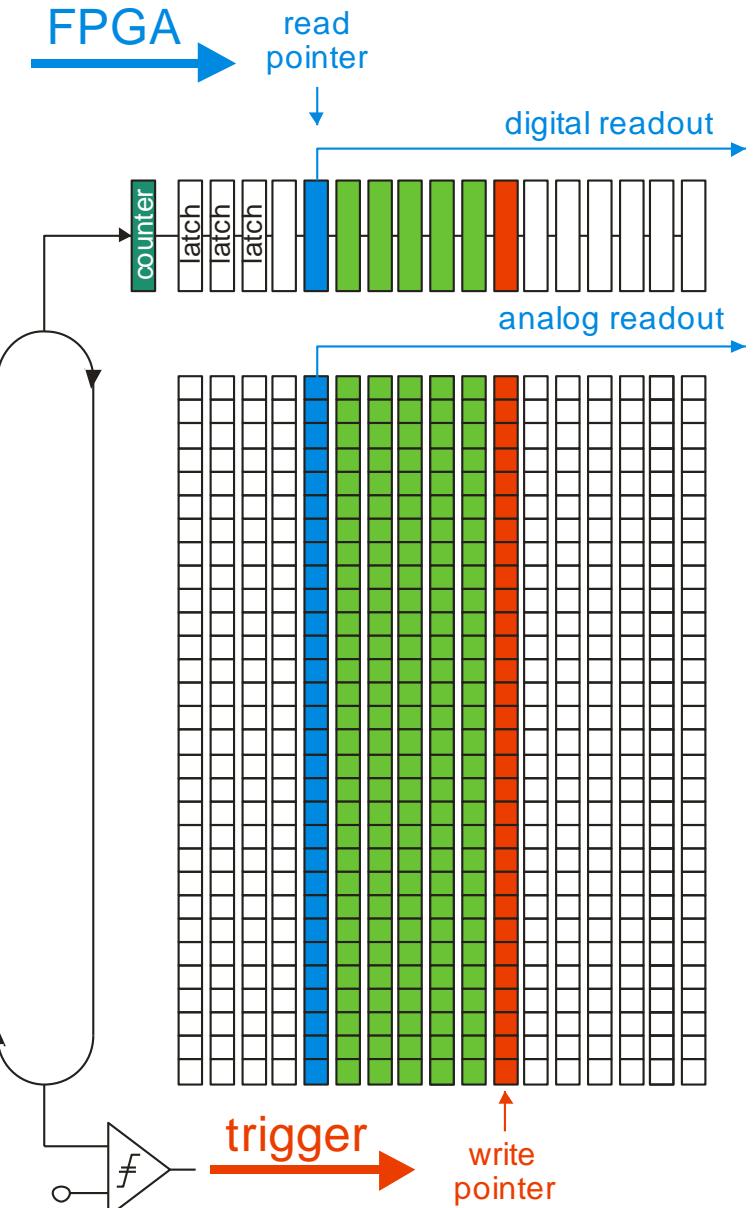
Plans

DRS5 (PSI)

- Self-trigger writing of 128 short 32-bin segments (4096 bins total)
- Storage of 128 events
 - Accommodate long trigger latencies
 - Quasi dead time-free up to a few MHz,
 - Possibility to skip segments
→ second level trigger
- Attractive replacement for CFG+TDC
- First version planned for 2013

CEA/Saclay

- Dual gain channels
- Dynamic power management (Read/Write parts)
- Region-of-interest readout



Comments

- **Trends**

- Reduce dead time
- increase analog bandwidth
- Increase depth, give more latency
- Include high speed low noise preamps (NECTAR...)

- **Comments**

- Unbeatable for pulse shape analysis or discrimination
- Ultra low timing measurements (ps)
- More power hungry than dedicated front-end (many CdV/dt...), needs careful study for large systems ($>>$ kch)

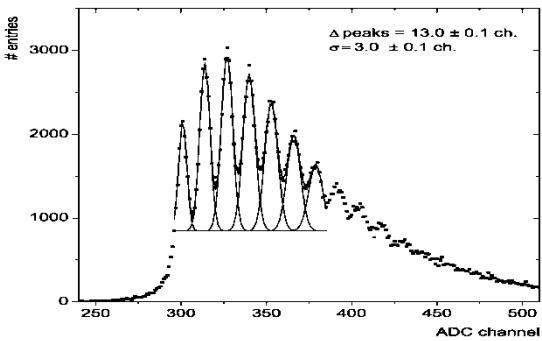
SiPM readout chips

© W. Kucevisz (Krakow)

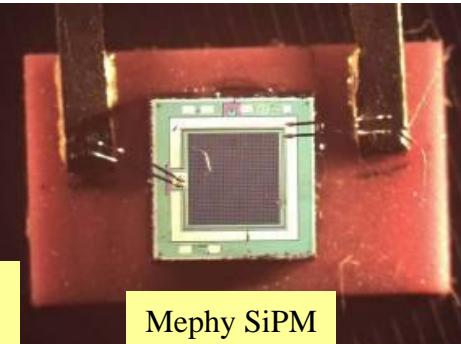
| Chip name | group | year | Technology | channels | Application |
|-----------------|------------|------|-----------------|----------|-------------|
| FLC_SiPM | OMEGA | 2004 | BiCMOS 0.8μm | 18 | ILC HCAL |
| NINO | CERN | 2004 | CMOS 0.25μm | 8 | ALICE TOF |
| MAROC2 | OMEGA | 2006 | SiGe 0.35μm | 64 | ATLAS lumi |
| SPIROC | OMEGA | 2007 | SiGe 0.35μm | 36 | ILC HCAL |
| PETA | Heidelberg | 2008 | CMOS 0.18μm | 40 | PET |
| RAPSODI | Krakow | 2008 | CMOS 0.35μm | 2 | Snooper |
| BASIC | Bari | 2009 | CMOS 0.35μm | 32 | PET |
| SPIDER | Ideas | 2009 | CMOS 0.35μm | 64 | Spider rich |

Precursor : CALICE AHCAL (2004)

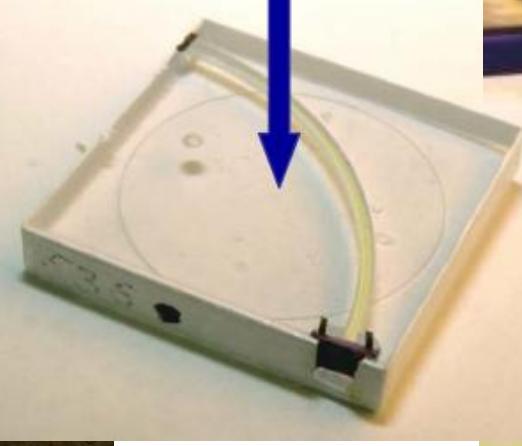
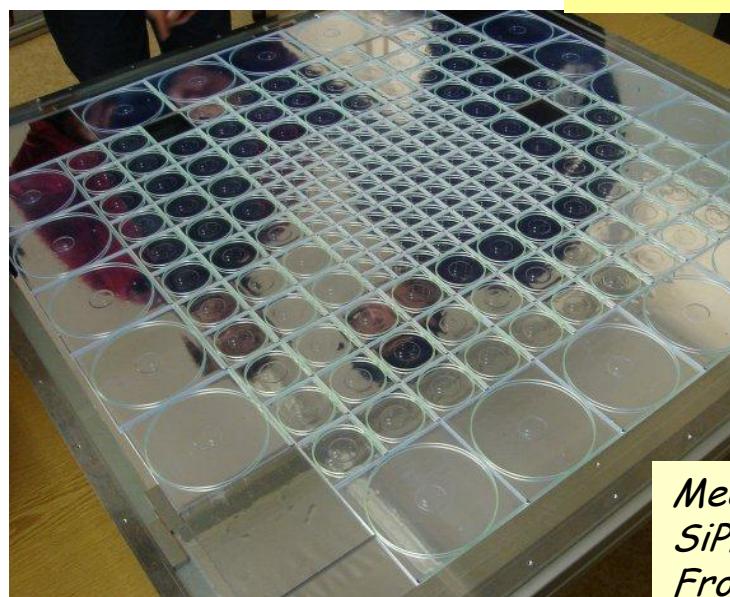
- Hadronic calorimeter prototype for the ILC : 1 cubic metre, 38 layers, 2cm steel plates
- 8000 tiles with SiPMs fabricated by MePHY group



FLC_SiPM
ASIC



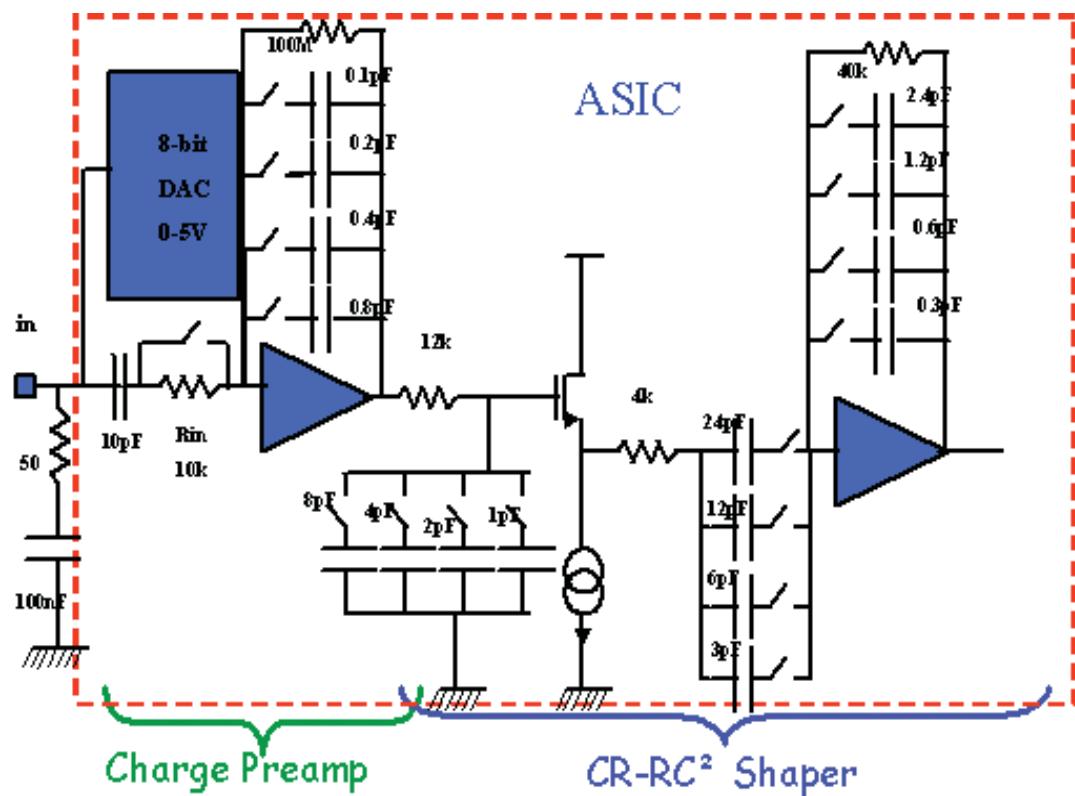
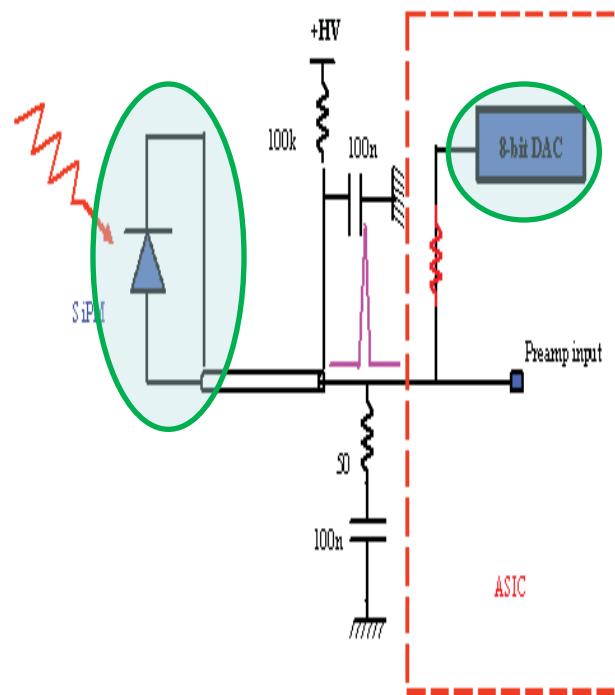
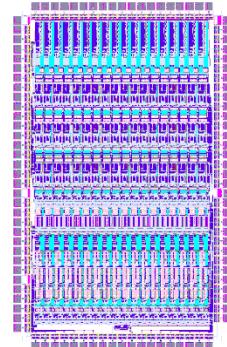
Mephy SiPM



*Mechanics and front end boards: DESY
SiPM : Mephy Pulsar Moscow
Front end ASICs: LAL*



- Voltage variable gain amplifier + variable CRRC² shaper
- Input 5V 8bit-DAC for bias point adjustment
- 18 channels, Analogue readout, 12 mW/ch
- 1000 chips produced in AMS BiCMOS 0.8 μm



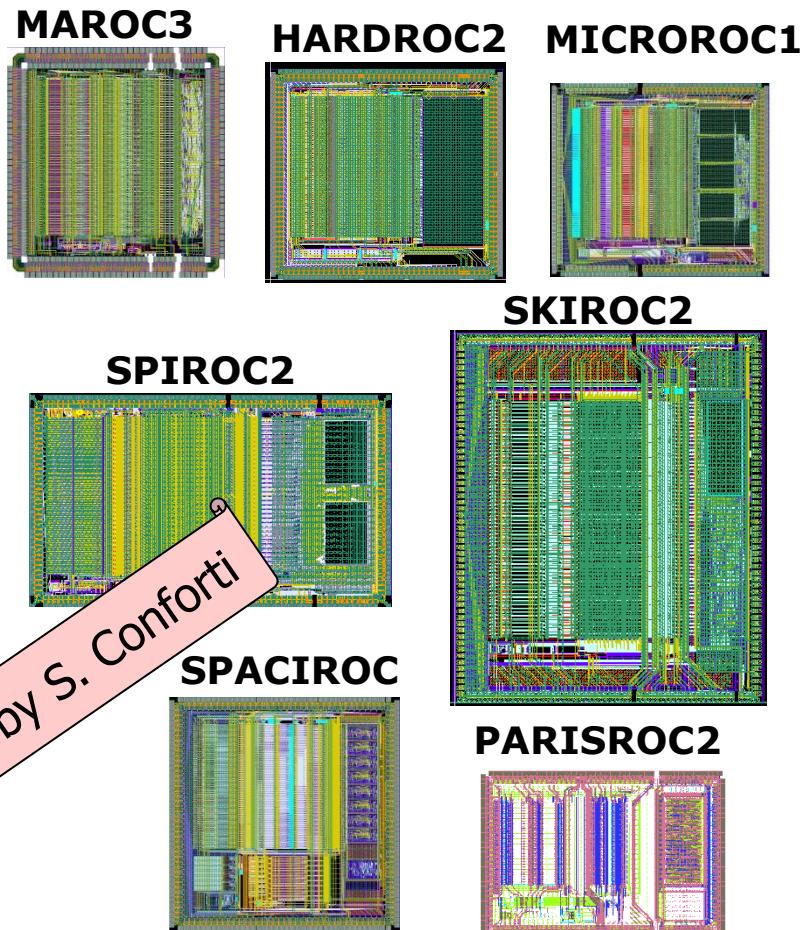
Successors : OMEGA/Orsay « ROC chips »

Omega

- Move to Silicon Germanium 0.35 µm BiCMOS technology in 2004
- Readout for MaPMT and SiPM for ILC calorimeters and other applications
- Very high level of integration : System on Chip (SoC) <http://omega.in2p3.fr>

| Chip | detector | ch | DR (C) |
|----------|----------|----|----------|
| MAROC | PMT | 64 | 2f-50p |
| SPIROC | SiPM | 36 | 10f-200p |
| SKIROC | Si | 64 | 0.3f-10p |
| HARDROC | RPC | 64 | 2f-10p |
| PARISROC | PM | 16 | 5f-50p |
| SPACIROC | PMT | 64 | 5f-15p |
| MICROROC | µMegas | 64 | 0.2f-e |

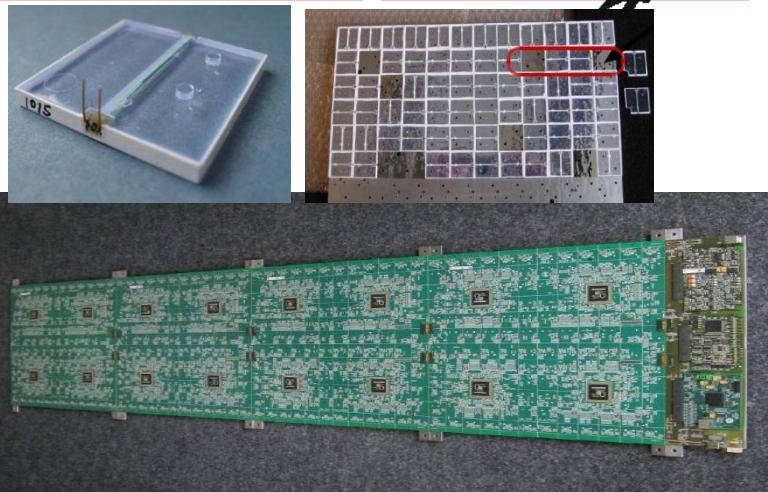
See talk by S. Conforti



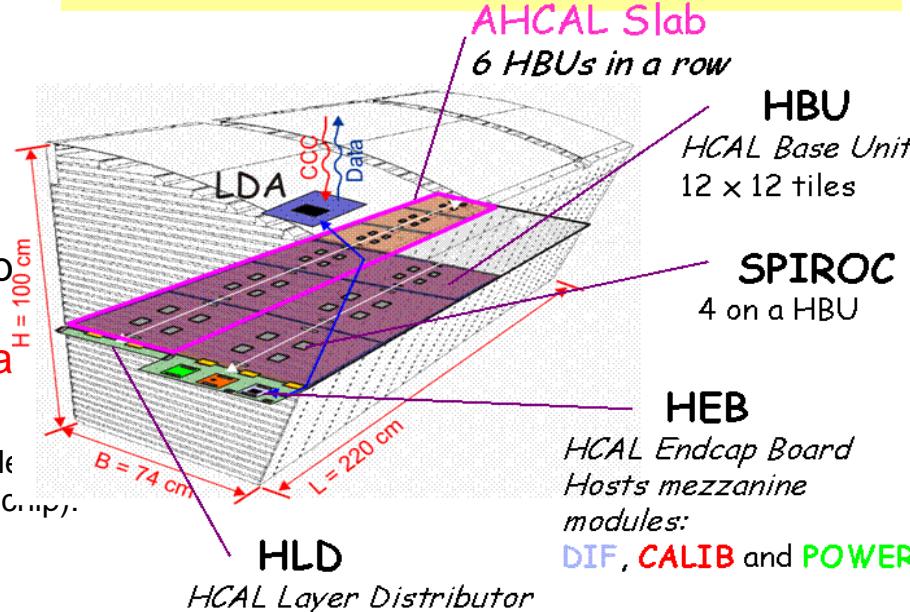
SPIROC for SiPM

Omega

- SPIROC : Silicon Photomultiplier Integrated Readout Chip to read out the analog hadronic calorimeter for CALICE (ILC)
- **Ultra low-power 36-Channel ASIC**
- **Internal input 8-bit DAC** (0-5V) for individual SiPM gain adjustment
- **Energy measurement : 14 bits, 1 pe to 2000 pe**
 - pe/noise ratio : ~11
- **Auto-trigger on MIP or on single photo-electron**
 - Auto-Trigger on 1/3 pe (50fC)
- **Time measurement :**
 - 12-bit Bunch Crossing ID (coarse time)
 - 12-bit step~1 ns TDC->TAC (fine time)
 - Analog memory for time and charge measurement : depth = 16
 - **Low consumption** : ~25 μ W per channel (in pulsing mode)
 - **4kbytes internal memory and daisy chain rea**



$(0.36m)^2$ Tiles + SiPM + SPIROC (144ch)

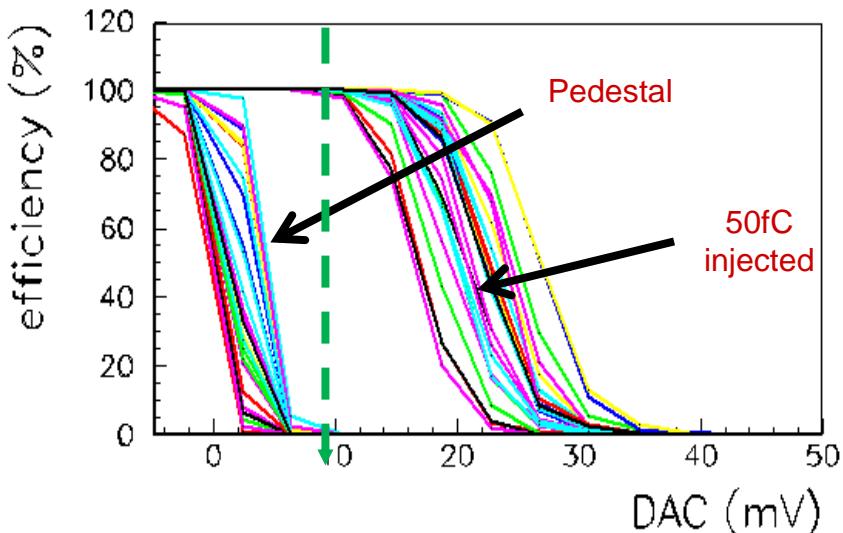


M. Bouchel, S. Callier, F. Dulucq, J. Fleury, J.-J. Jaeger, C. de La Taille, Martin-Chassard, and L. Raux, "SPIROC (SiPM integrated read-out chip), Dedicated very front-end electronics for an ILC prototype hadronic calorimeter with SiPM read-out," J. Instrum. 6(01), C01098 (2011).

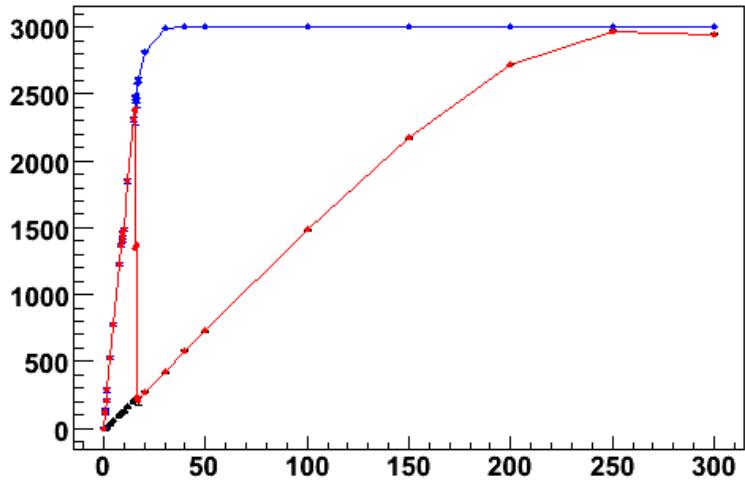
SPIROC: trigger efficiency measurements

Omega

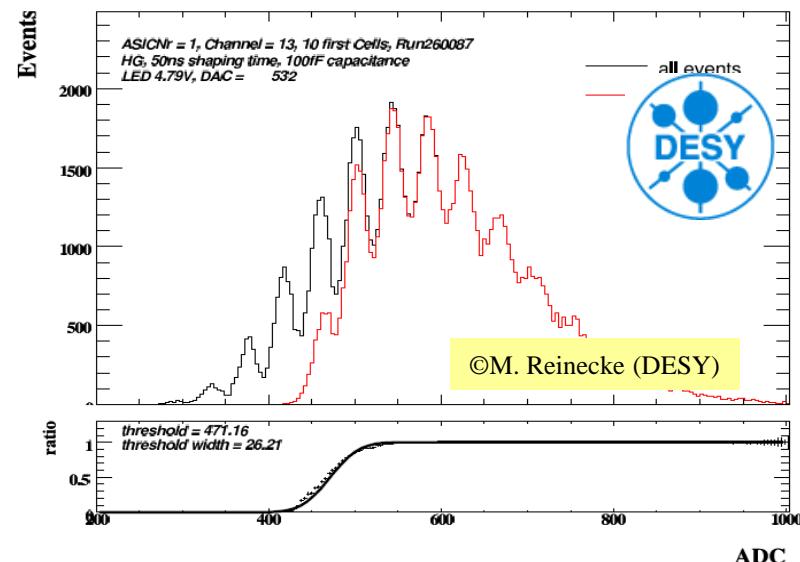
36-channel S-curves: trigger efficiency versus threshold (1 LSB = 2 mV)



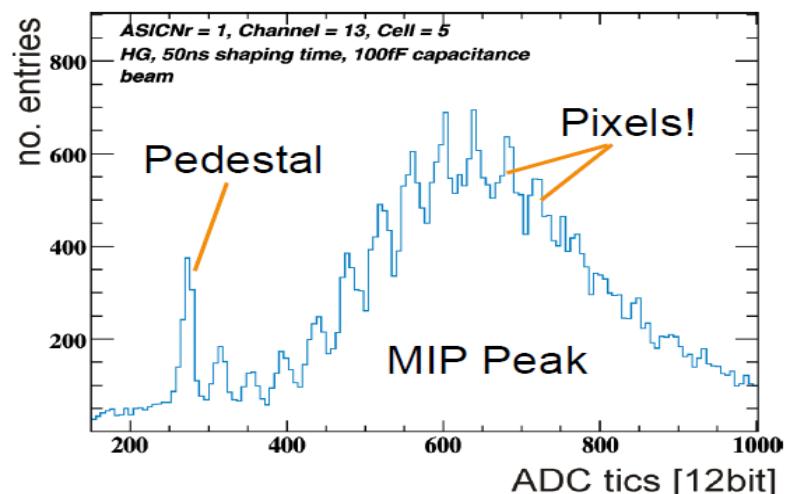
linearity using the auto gain mode
and internal ADC



SiPM SPECTRUM with Autotrigger



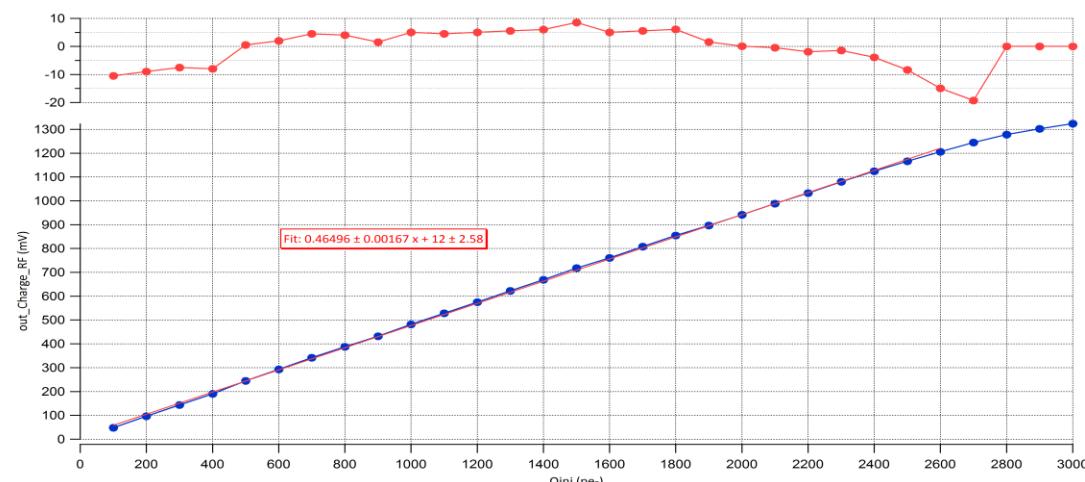
MIP response in DESY
6 GeV electron testbeam



New R&D developments: PETIROC

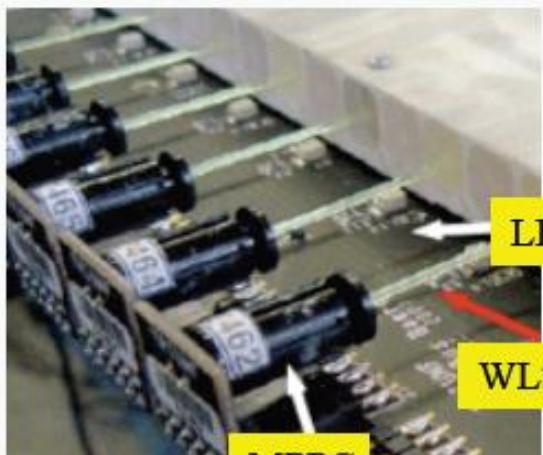
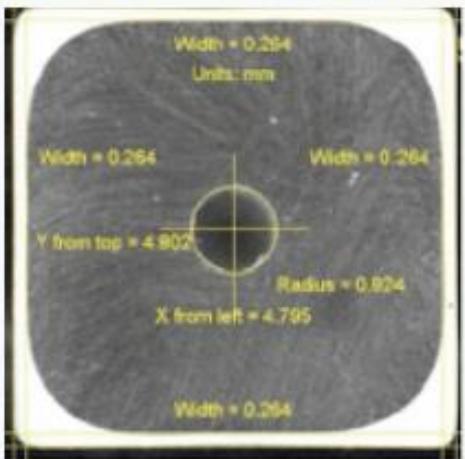
Omega

- SiPM readout in 0.35 μ m SiGe, for high timing and TOF PET MRI
- 12 channels with 3 different architectures (end of 2011)
- High bandwidth preamp (GBW> 10 GHz) and ultra fast discriminator
- Ptot<3 mW/ch, tr<0.5 ns, measured jitter ~10 ps
- internal TDC (step=25 ps)
- Dual time and charge measurement up to 2500 pe-
- Measured coincidence with SiPM : 200 ps
- Startup Weeroc <http://weeroc.com/> created from OMEGA for industrial applications contact person : [Julien Fleury@weeroc.com](mailto:Julien.Fleury@weeroc.com)

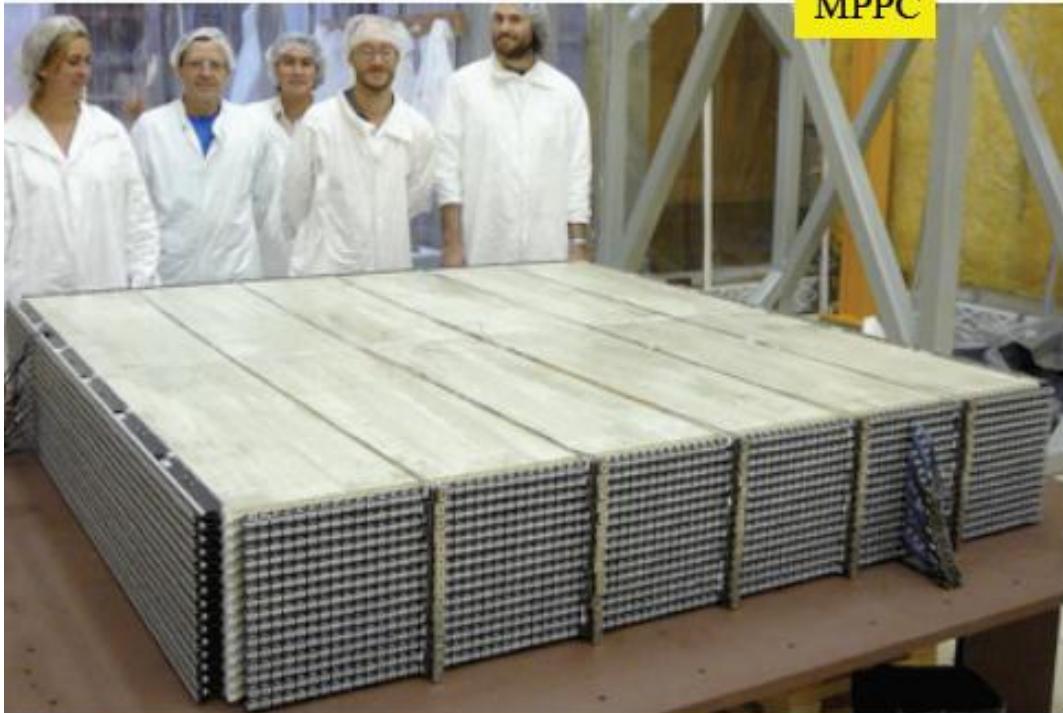
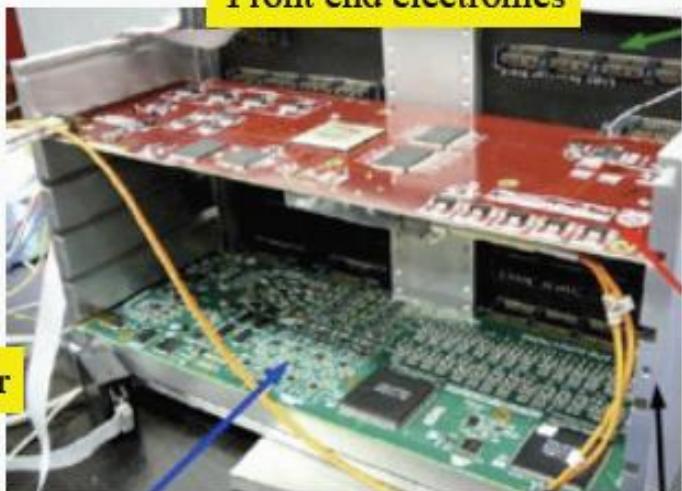


T2K SiPM FGD

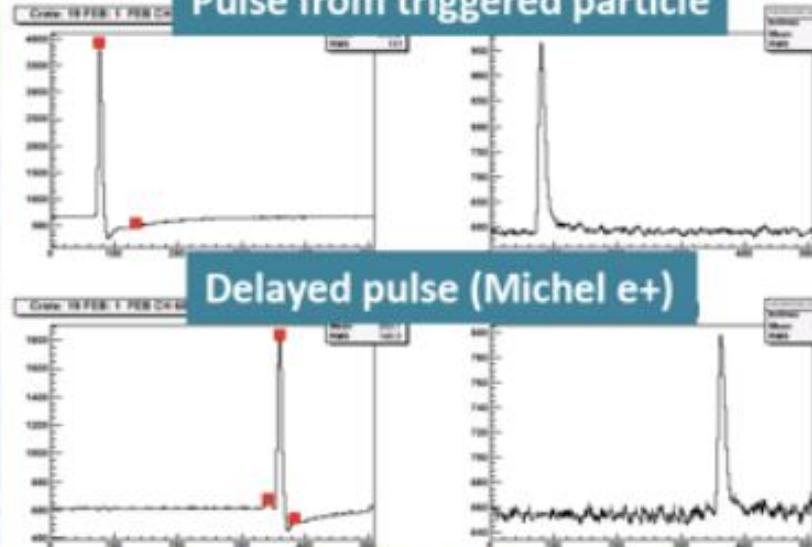
Extruded scintillator



Front end electronics



Pulse from triggered particle



8.5k ch of 50MHz waveform

AFTER: Asic For TPC Electronic Read-out

Technology: AMS CMOS $0.35\mu\text{m}$

Area: $7546\mu\text{m} \times 7139\mu\text{m}$

LQFP 160 pins; Plastic
dimensions: $30\text{mm} \times 30\text{mm}$

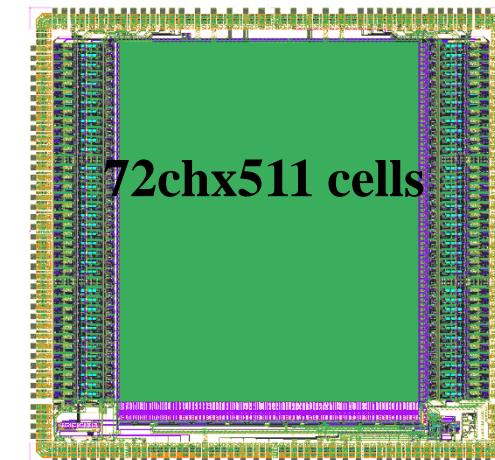
thickness: 1.4mm

pitch: 0.65mm

Number of transistors: 400,000

Power consumption: 5-7 mW/ch

6000 chips manufactured and tested

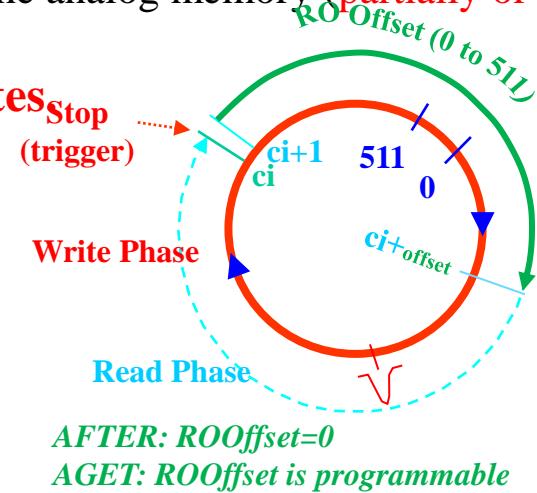
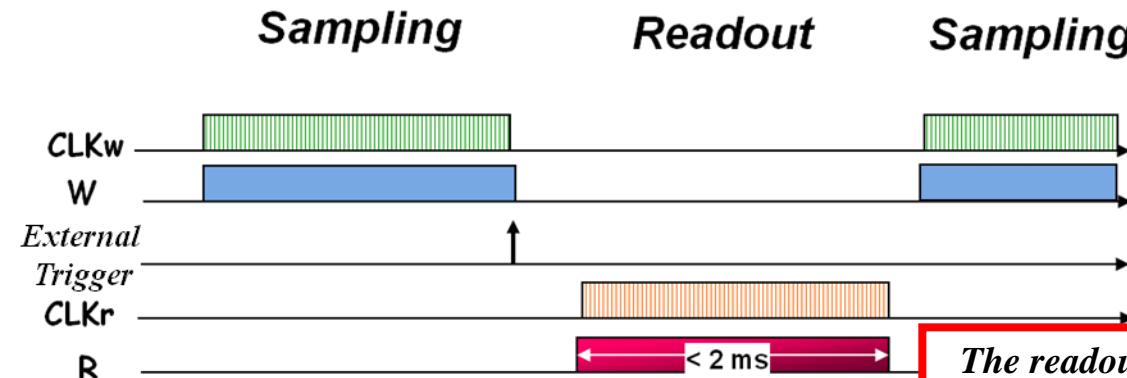


Purpose:

- Collect, preamplify and shape of the detector signal.
- Continuously sample the shaped signal in an 511-cell analog circular buffer (1MHz to 100MHz rate)
- After the sampling has been stopped by an external request, read back the analog memory (**partially or totally**) at a rate up to 20 MHz.

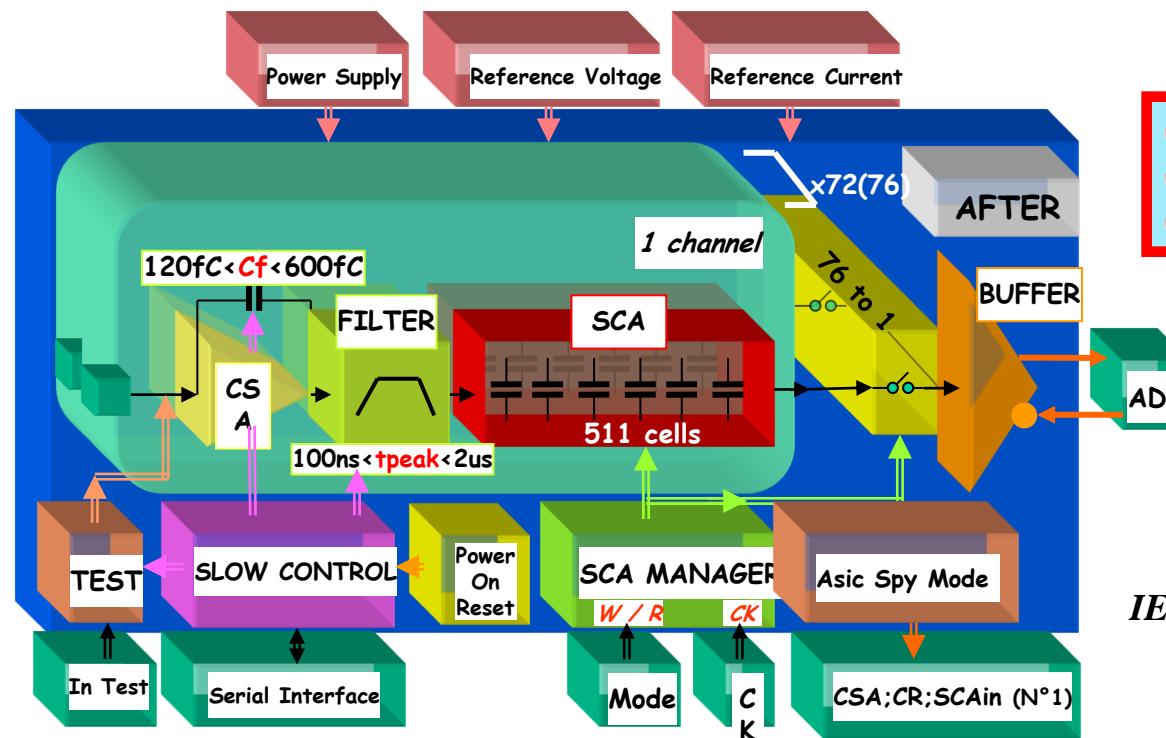
⇒ Allows to de-correlate the sampling and digitization rates

⇒ An oscilloscope on each channel.



The readout time is proportionnal to the number of sample read : 2ms is for 511 cells

AFTER Main Features: 72 low noise FE channels associated with a 511-cell SCA



IEEE Trans. Nucl Sci, June 2008

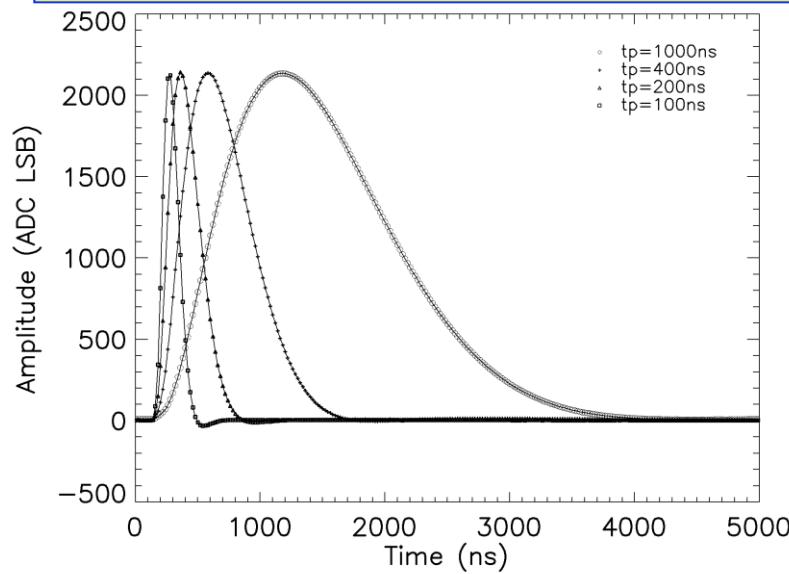
Main features:

- **Input Current Polarity:** positive **or** negative
- **72 Analog Channels**
- **4 Gains:** 120fC, 240fC, 360fC & 600fC
- **16 Peaking Time values:** (100ns to 2μs)
- **511 analog memory cells / Channel:**
Fwrite: 1MHz-100MHz; Fread: 20MHz

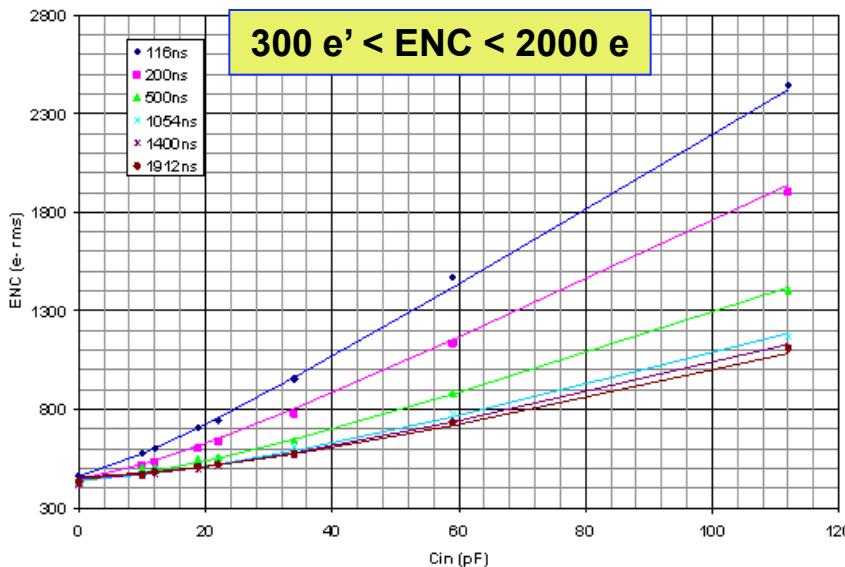
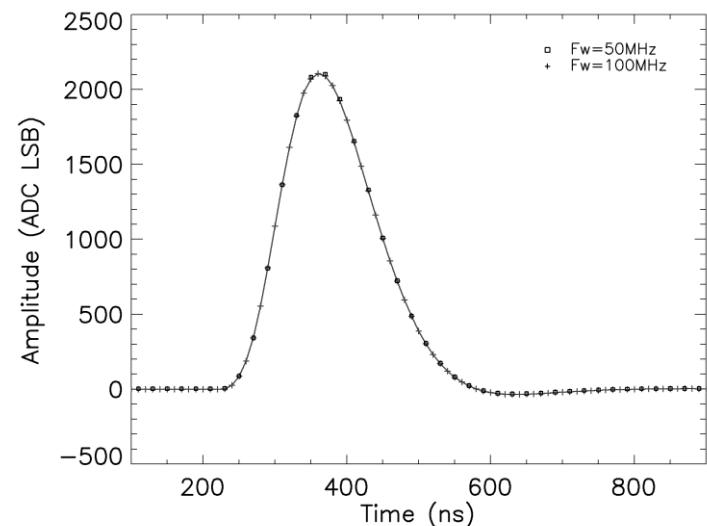
- **Optimized for 20-30pF detector capa**
- **12-bit dynamic range**
- **Slow Control**
- **Power on reset**
- **Test modes**
- **Spy mode on channel 1:**
CSA, CR or filter out

Pulse Shape + linearity

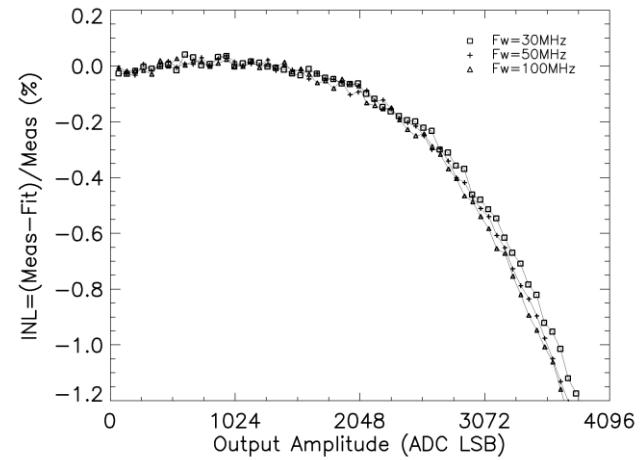
Digitized signal with various peaking time



Perfectly working for a 100MHz wck

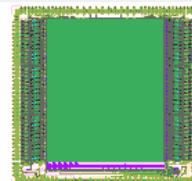


Integral Non Linearity <1.2%



The children of AFTER

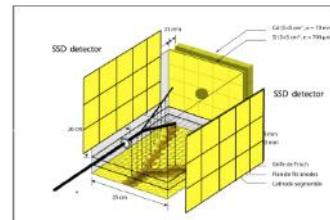
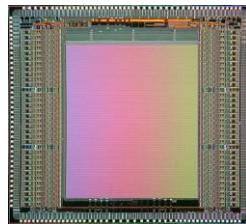
AFTER (T2K)
120K channels



Similar FE + SCA architecture

GET (ANR):

Generic electronics for nuclear physics
(with GANIL, CENBG, NSCL)



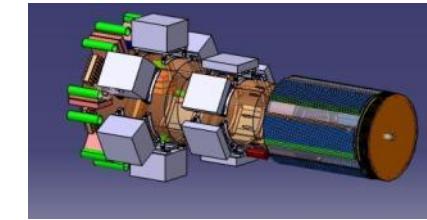
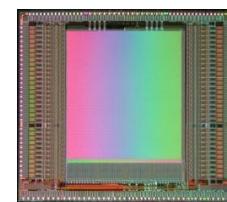
AGET chip:

Auto-trigger, Multiplicity output, 1th/channel

On-chip zero suppress,

Target: ~30 000 –channel active target TPC

CLAS12 (Jefferson Lab):
Trajectographe Micromégas (2014)
30 000 voies.



ASIC DREAM:

Deadtime « free » architecture,

L0 latency + event buffer

Auto-triggering capabilities

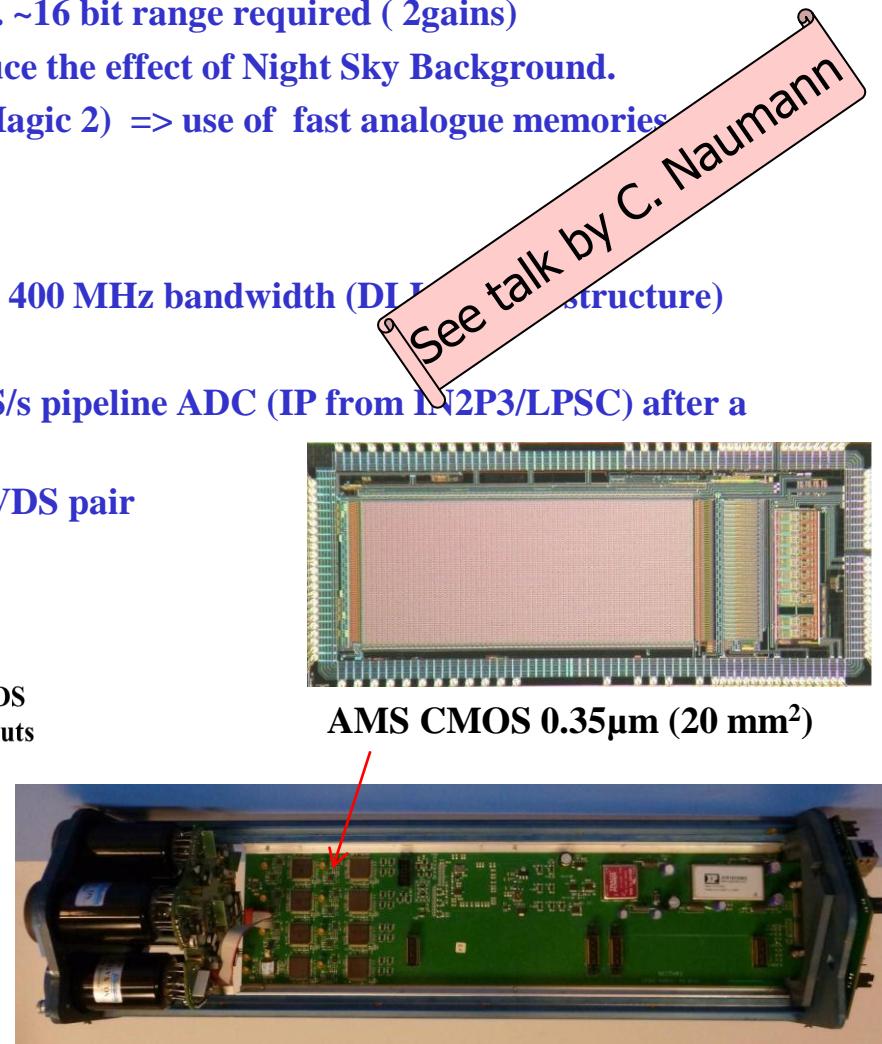
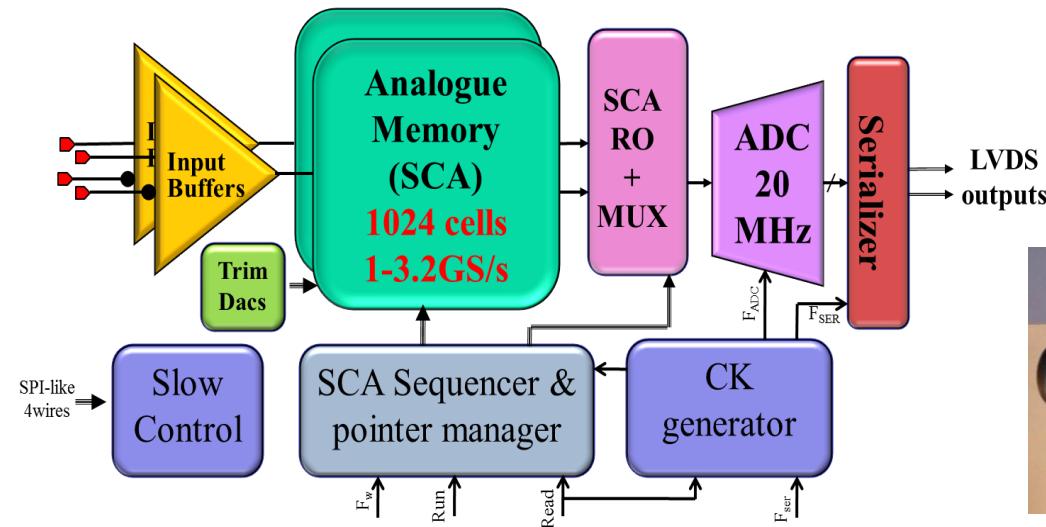
New common features:

- Possibility to bypass CSA and/or shaper to connect directly an external front-end or (photo)-detector &
- programmable gain & for each channel

- project of a large Atmospheric Cherenkov Telescope Array.
 - 100 telescopes with each more than 1000 PMT. ~16 bit range required (2gains)
 - Need for fast integration time (typ 6ns) to reduce the effect of Night Sky Background.
 - Use of low cost and proven solutions (HESS, Magic 2) => use of fast analogue memories Buffer.

NECTAr;

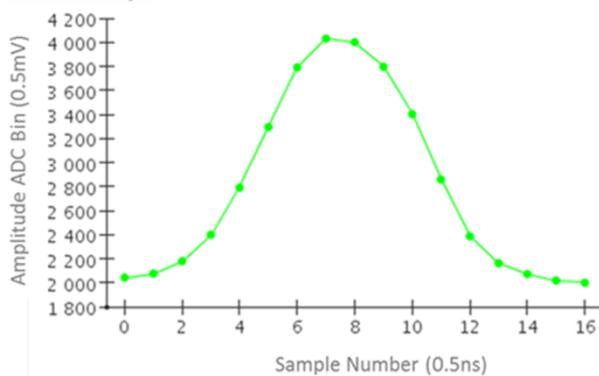
- 2 differential channels of 1024 cells SCA with 400 MHz bandwidth (**DLL**)
 - Sampling rate in the 1-3GS/s range.
 - Digitization of a window of interest by a 20 MS/s pipeline ADC (IP from **IN2P3/LPSC**) after a trigger is received.
 - Serialization of ouput data @120MHz on 2 LVDS pair



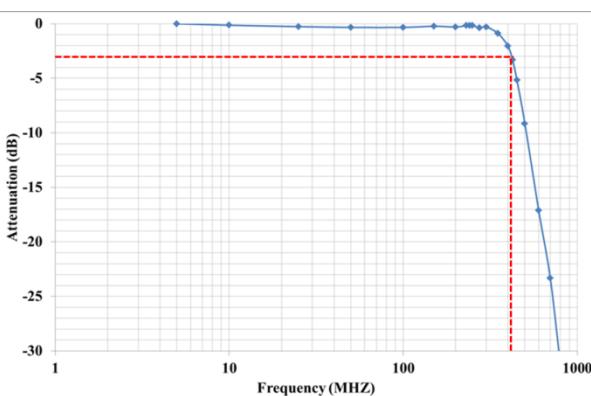
7-pixel NECTAR Module (Ethernet, single voltage supply, autonomous)

NECTAR performance (measured on the NECTAR module)

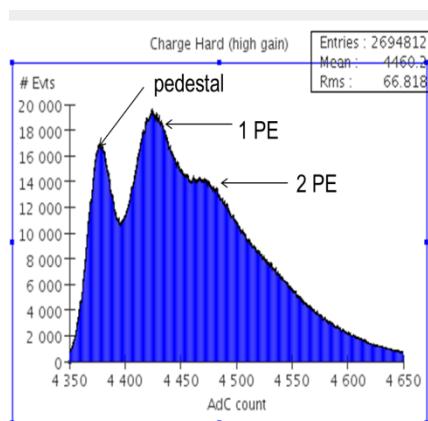
saclay



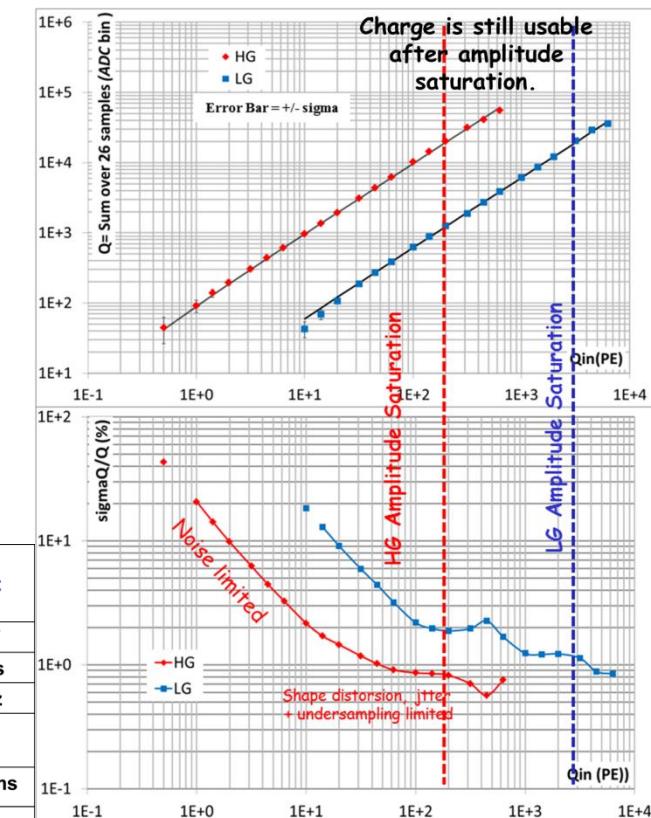
Photoelectron signal digitized by NECTAR: 2.4ns FWHM, half range pulse sampled @2 GS/s



-3dB Bandwidth is larger than 400 Mhz
For 0.8V peak-peak sinewave



Photoelectron Spectrum with Hamamatsu R9619mod PMT (2^{E5} Gain + on board HG=16)



Charge Scan & Q resolution with simulated PE pulses, 2GS/s (the 2 Nectar channels are connected respectively to ampli with gain 1 and 16) .
More than 10,000 usable range

| | Nectar0 performance | Unit |
|--|----------------------------|---------|
| Power Consumption | < 300 | mW |
| Sampling Freq. Range | 0.5- 3.2 GS/s | GS/s |
| Analog Bandwidth | >400MHz | MHz |
| Read Out time for a 16 cell event (2 gains 1- cells) | <2 | μs |
| ADC LSB | 0.5 | mV rms |
| Total noise (unchanged with frequency) | < 0.8mV | mV rms |
| Maximum signal (limited by ADC range) | 2V | V |
| Dynamic Range | >11.3 | bits |
| Crosstalk | 4 | per mil |
| Relative non linearity (integral) | <2% (quasi DC) | % |
| Sampling Jitter | < 40 rms (from resolution) | ps rms |

NINO

Chip designed by CERN group for ALICE TOF RPCs

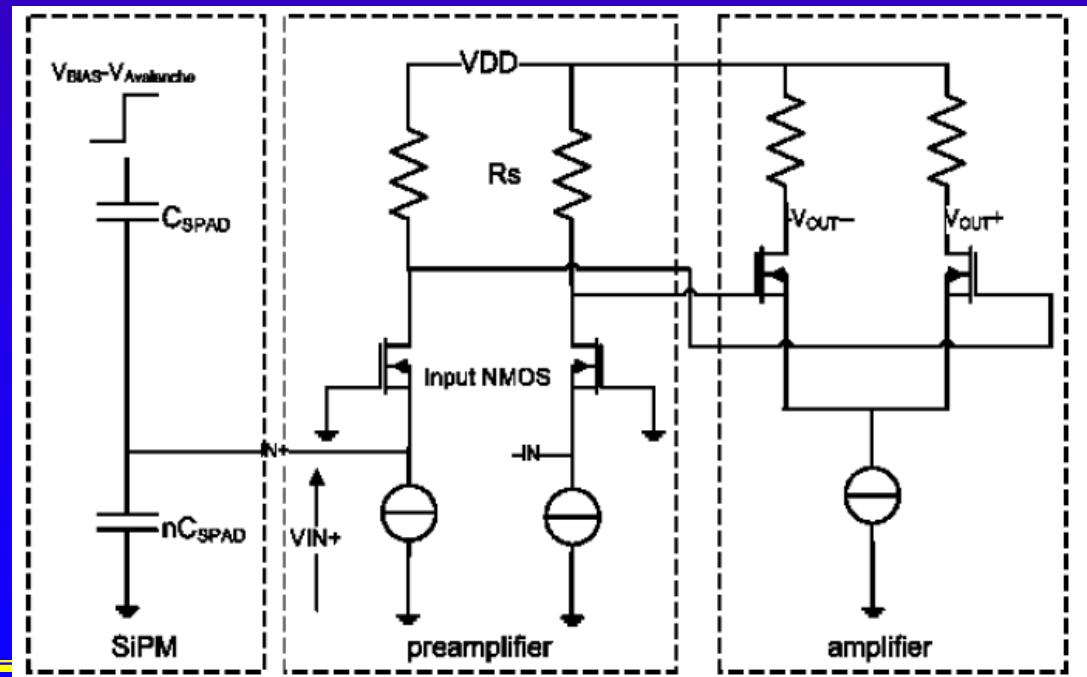
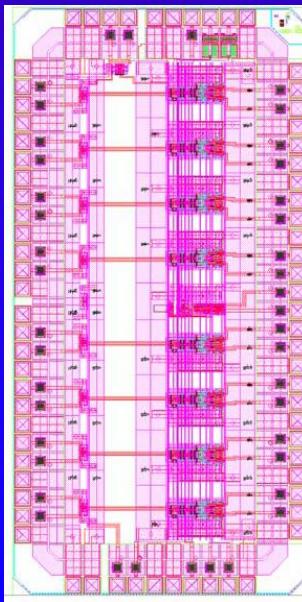
[F. Anghinolfi, P. Jarron et al. NINO: an ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber, NIM A, 2004, Vol. 533 page 183-187]

8 channels amplifier and discriminator

Common grid current conveyor, high speed differential discriminator

High speed time measurement (10 ps), Amplitude through time over threshold technique

Pd = 25 mW/ch, Manufactured in IBM 0.25 μ m





NINO FOR PET

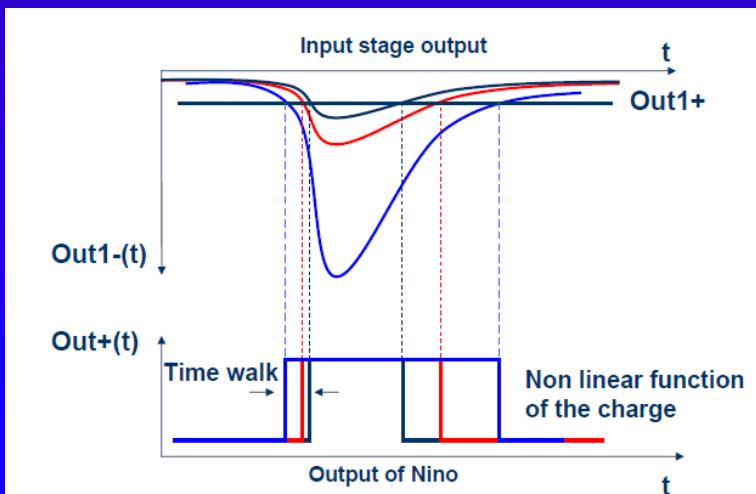
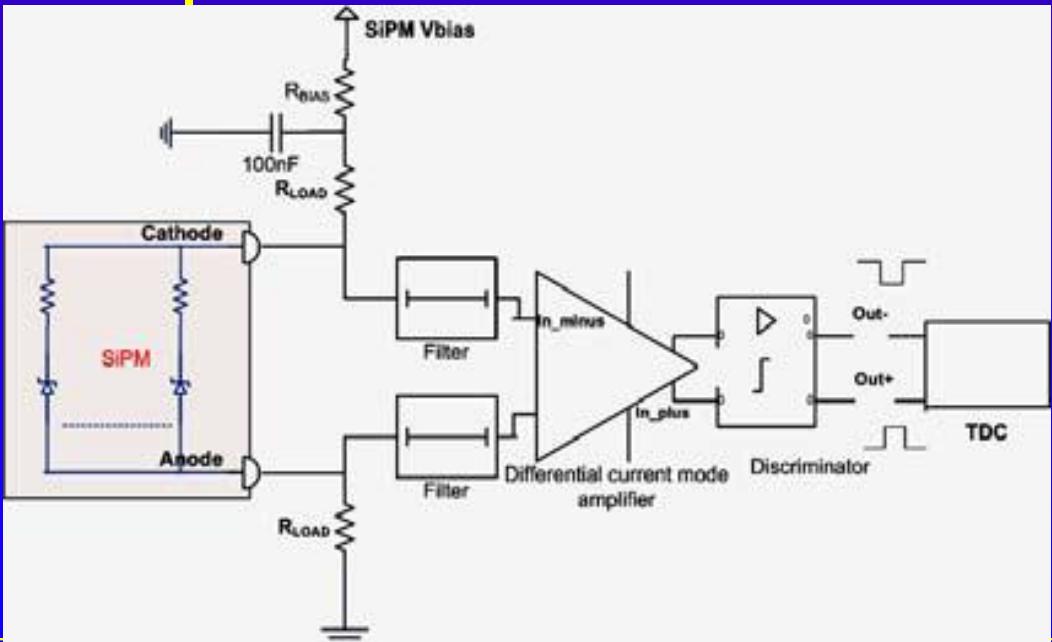


Application for TOF-PET

[P. Jarron, E. Auffray, S.E. Brunner, M. Despesisse, E. Garutti, M. Goettlich, H. Hillemanns, P. Lecoq, T. Meyer, F. Powolny, W. Shen, H.C. Schultz-Coulon, C. Williams - Time based readout of a silicon photomultiplier (SiPM) for Time Of Flight Positron Emission Tomography (TOF-PET) - 2009 IEEE Nuclear Science Symposium Conference Record, p. 1212 and NIM 617 (2010), p. 232]

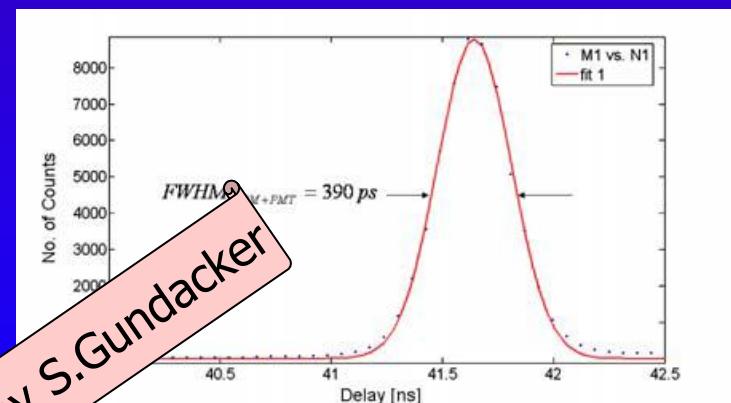
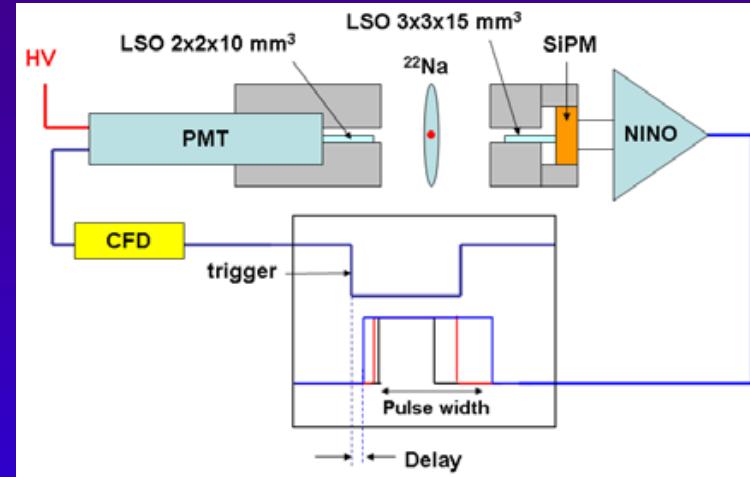
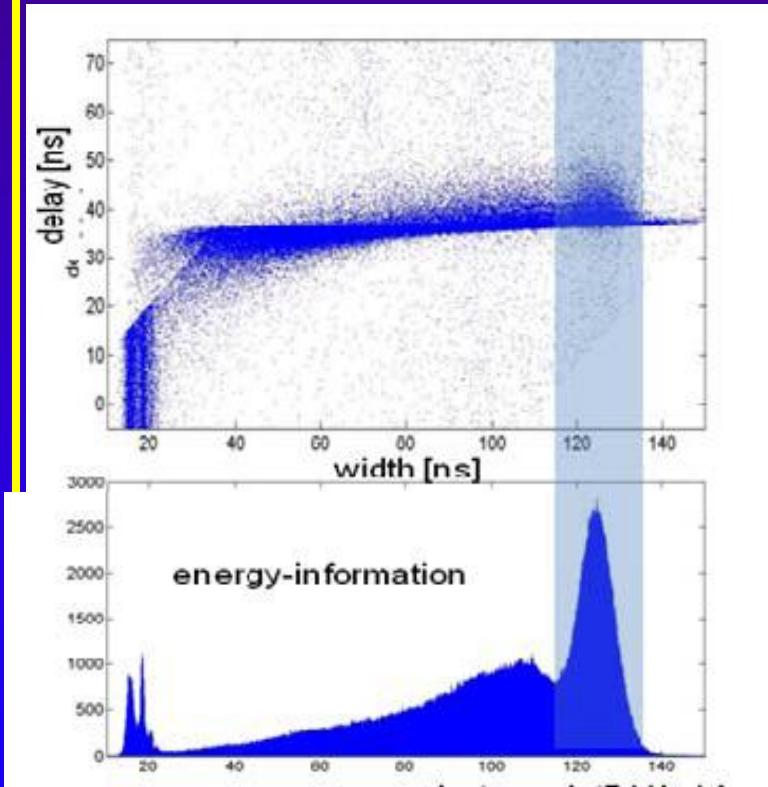
Differential connection of NINO to SiPM

NINO followed by CERN 25 ps HPTDC



PERFORMANCE

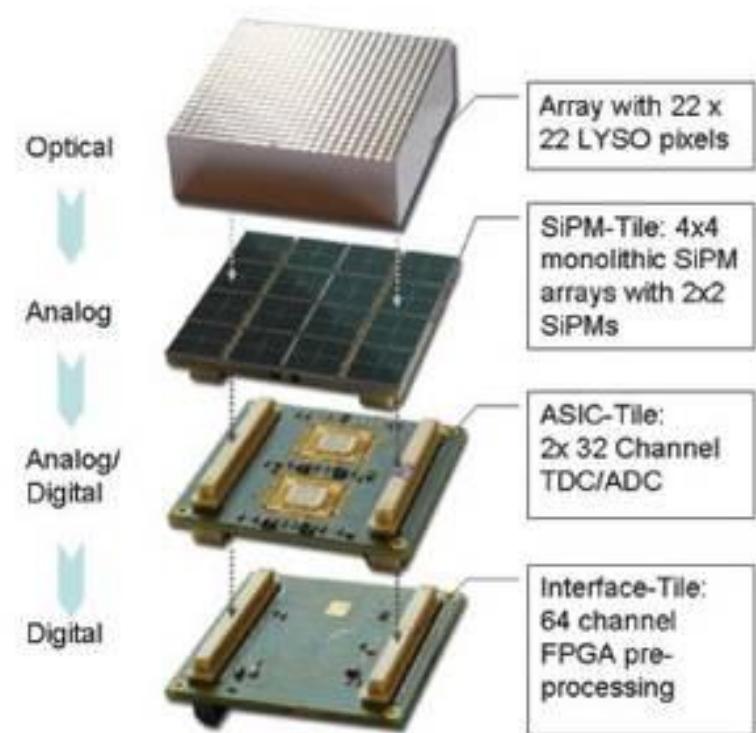
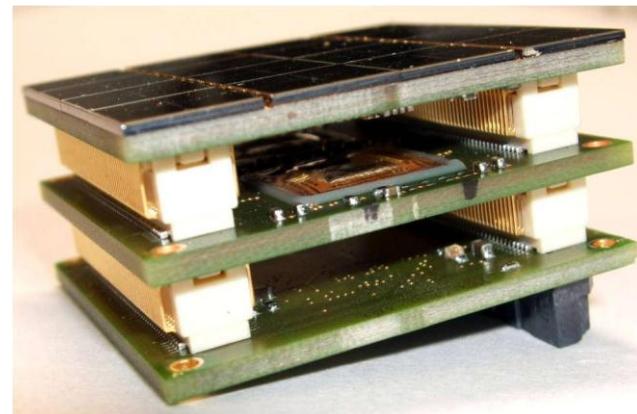
Jitter measured : 390 ps



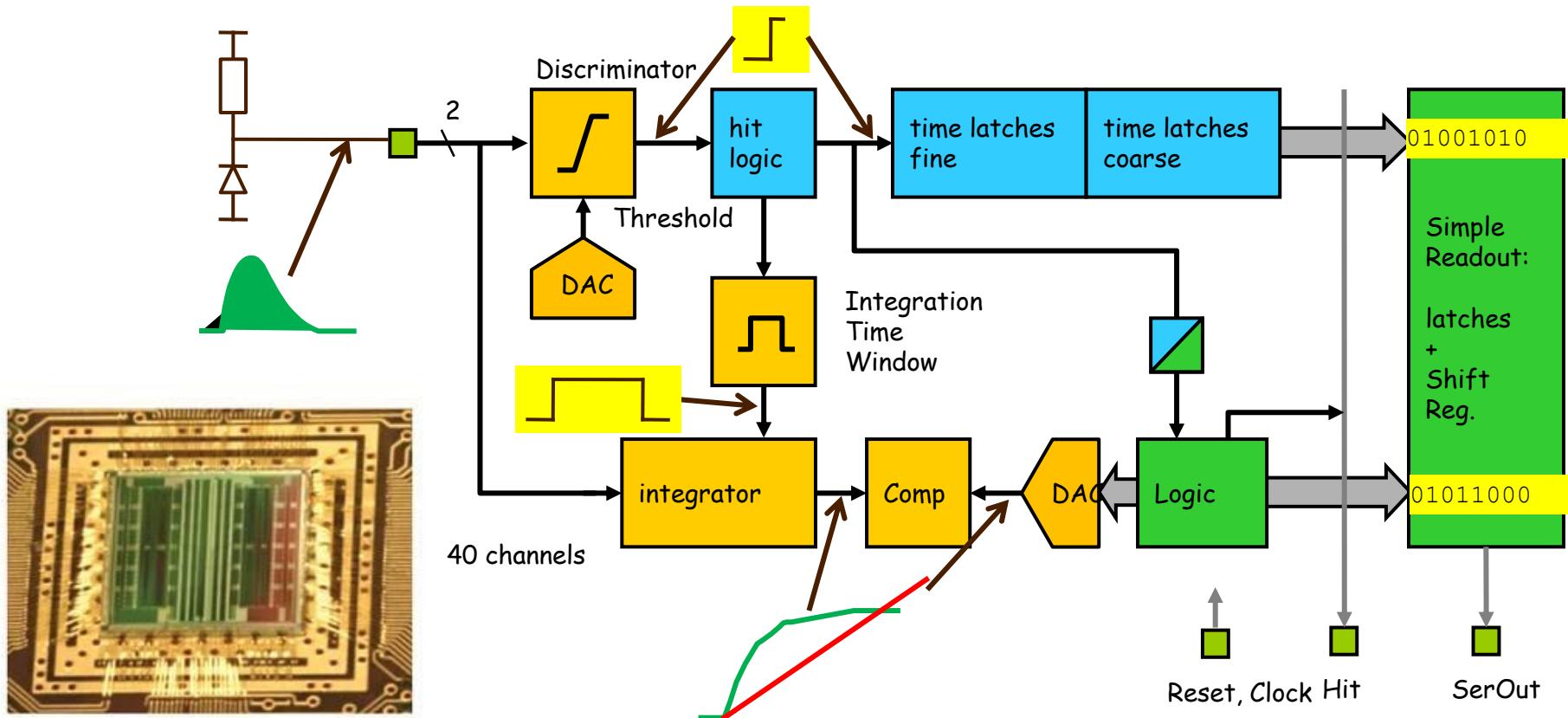
Now in : 32 channels

See talk by S.Gundacker

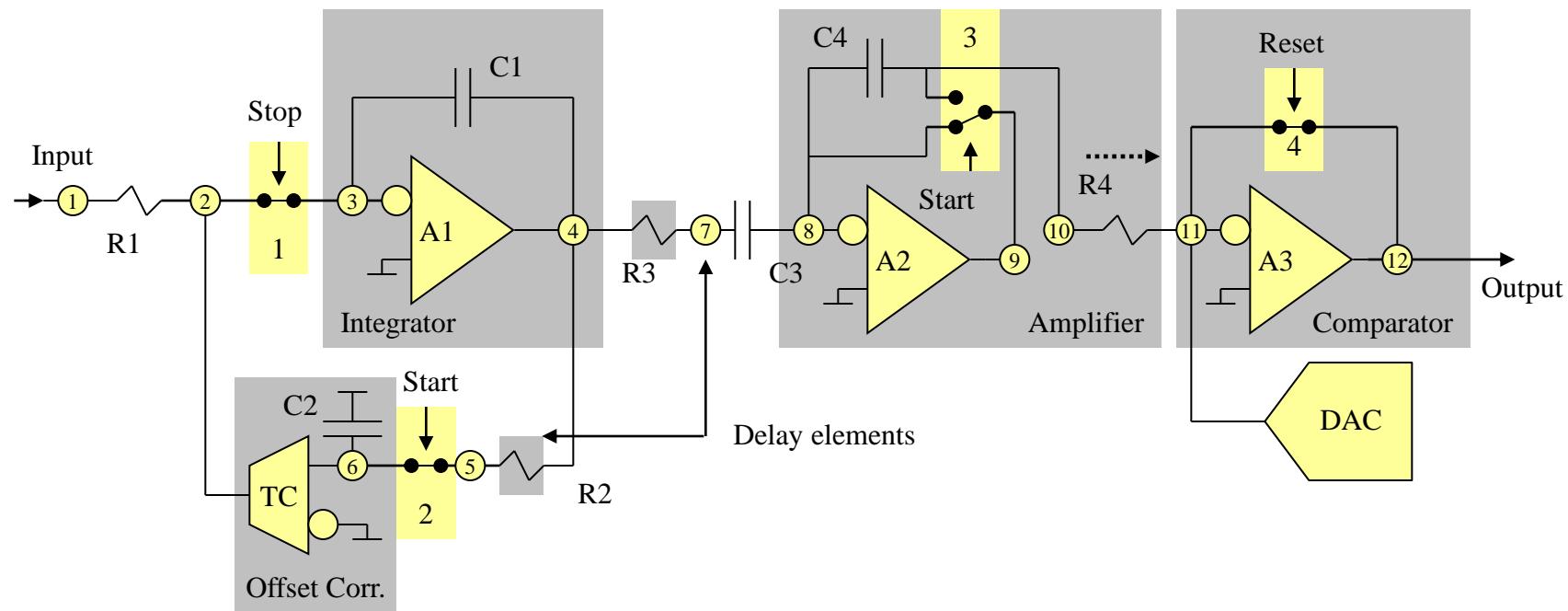
- PET/MRI projekt
 - P. Fischer et al. Heidelberg, Philips, Aachen, FBK Trento
- 40-channel system on chip for readout of the detectors that generate low voltage (several mV) signals
- Combined high precision time (~14 ps) and energy measurements (signal integral = energy)
- Time of flight measurements with energy discrimination
- Particle recognition, by mass measurement
- Medical imaging (SiPM based PET)
- [M. Ritzert...: “*Compact SiPM based Detector Module for Time-of-Flight PET/MR*” on IEE NPS Real Time Conference]



- PETA chip : Positioning, Energy and Timestamping Asic
- P. Fischer, I. Peric, M. Ritzert, and M. Koniczek -Fast Self Triggered Multi Channel Readout ASIC for Time- and Energy Measurement – IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, p.1153
- 40 differential channels that perform **time** and **energy** measurements
- fast **time stamp generators**, that can be synchronized by **in-chip PLL**
- PLL clock frequency is ~770MHz leading to **40ps bin width**

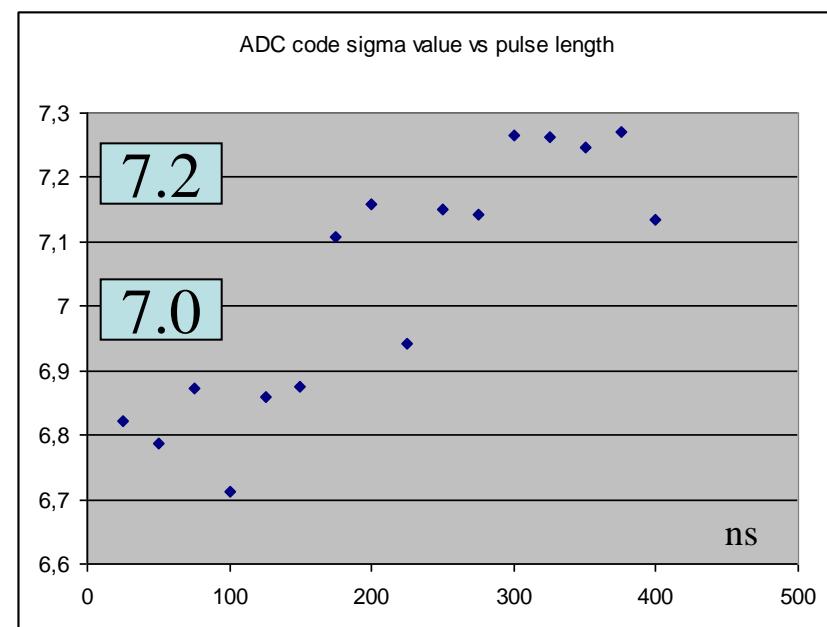
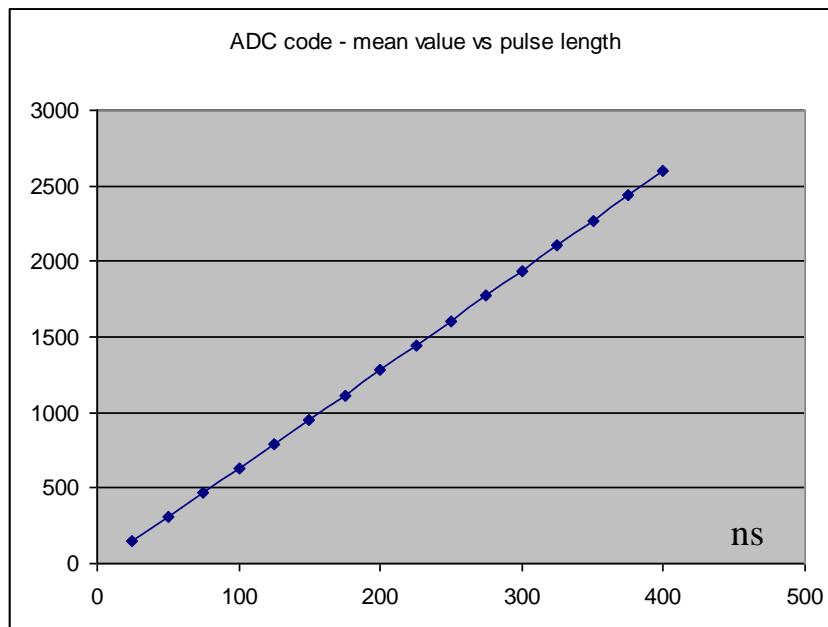


- 1) Input resistor R1 converts the input voltage into current
- 2) A1 - **integrator**
- 3) **Offset correction circuit**
- 4) A2 - **difference amplifier** measures the change of voltage 4 (*integral*) and converts it to current IR4
- 5) A3 - current-mode **comparator** compares IR4 with the DAC current

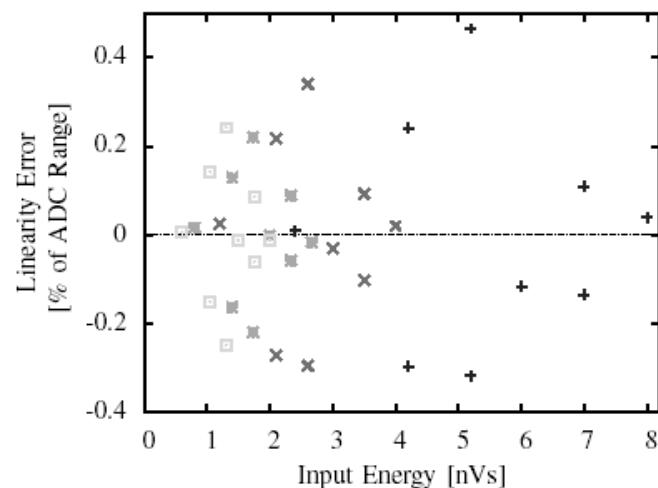


Integral of the input (single ended) pulse with 100mv
Amplitude and variable width

Noise in LSB – full range - 4096



ADC linearity



Fraction of accepted signals at a given threshold setting is measured

Minimum threshold is about 2mV

Noise about **550 μ V RMS**

The chip has been trimmed for minimum noise performances in discriminator

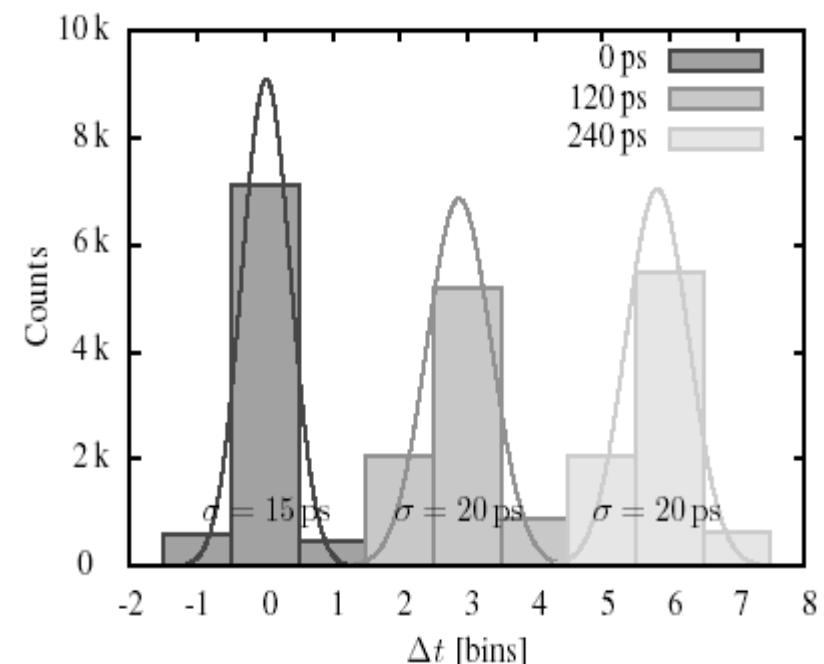
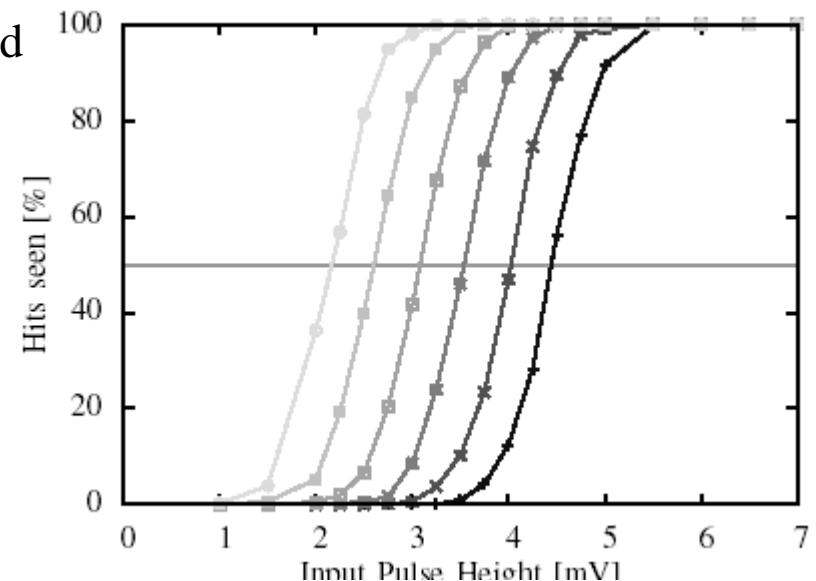
In typical system threshold setting is 5mV with the noise of 800 μ V RMS

Bin width is **41ps**

Pulse generator (Agilent 81110A) with passive attenuators generate 2 pulses with known delays and **amplitudes of 100mV**

Delay between two pulses has been measured

Time measurement resolution is **RMS 14ps** for coincident signals



BASIC32



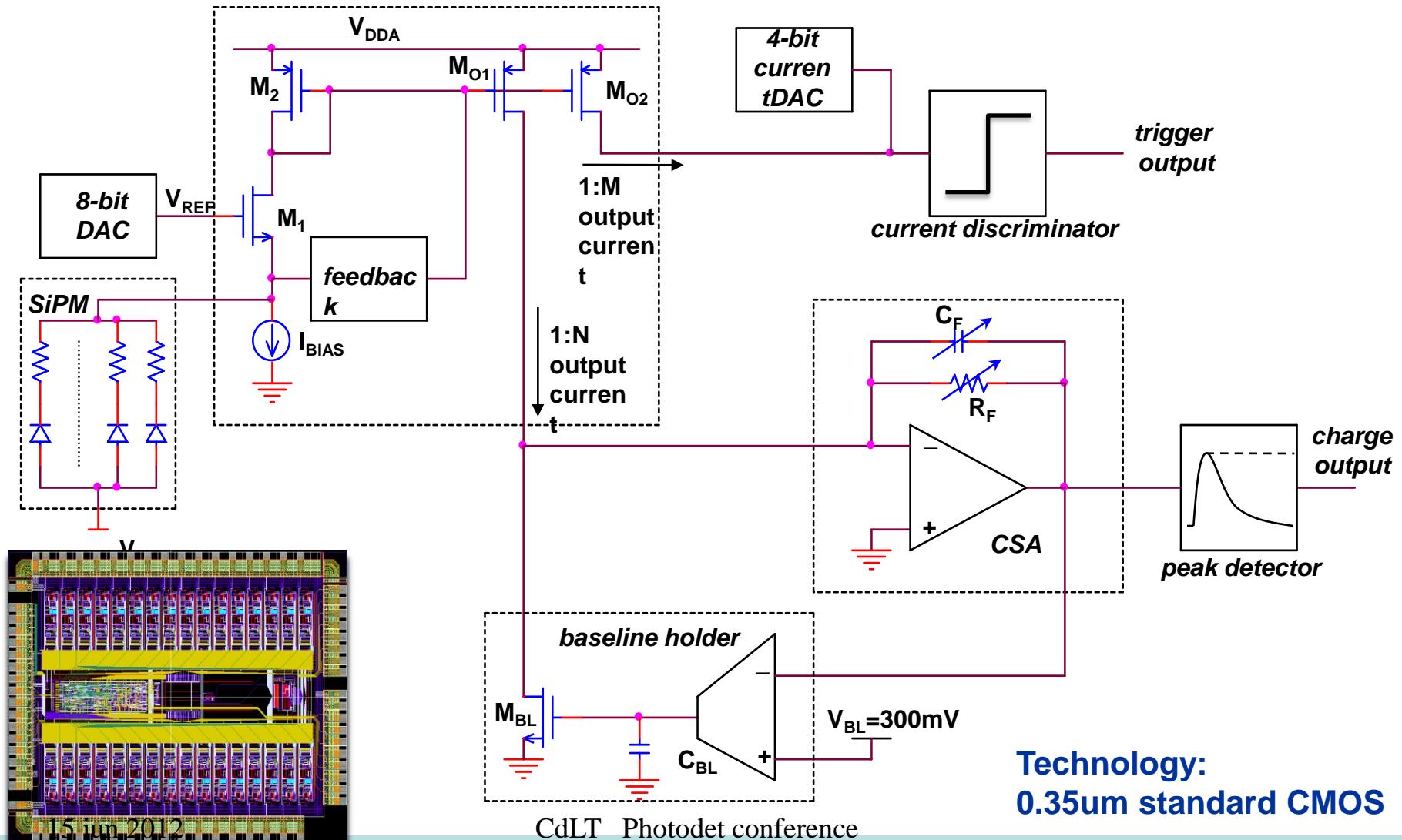
- Politecnico di Bari (F. Corsi, M. Foresta, C. Marzocca, G. Matarrese)
- Universita di Pisa (N. Belcari, M. G. Bisogni, A. Del Guerra, S. Marcatili)

- F. Corsi et al., A “Front--end Electronics for Silicon Photo--Multipliers Coupled to Fast Scintillator”, 2010 IEEE Nuclear Science Symposium (NSS--MIC’2010) Conference Record, Knoxville, TN (USA), October 30-- November 6, 2010.

- 32 channel readout ASIC for PETMRI

- Simultaneous charge and time measurement with current conveyor

Structure of the analog channel



Main features and parameters of the analog channel

Current buffer

- Small signal bandwidth: 250MHz (with a 30pF detector)
- Low input resistance: 17Ω
- Scaling factors: N=10, M= 20
- V_{REF} variable in the range 1V÷2V
- Total current consumption: 800 μ A

Fast Current Discriminator

- Leading edge
- $T_{rise} \approx 300\text{ps}$
- Threshold programmable : 4-bit current DAC from 0 to 40 μ A

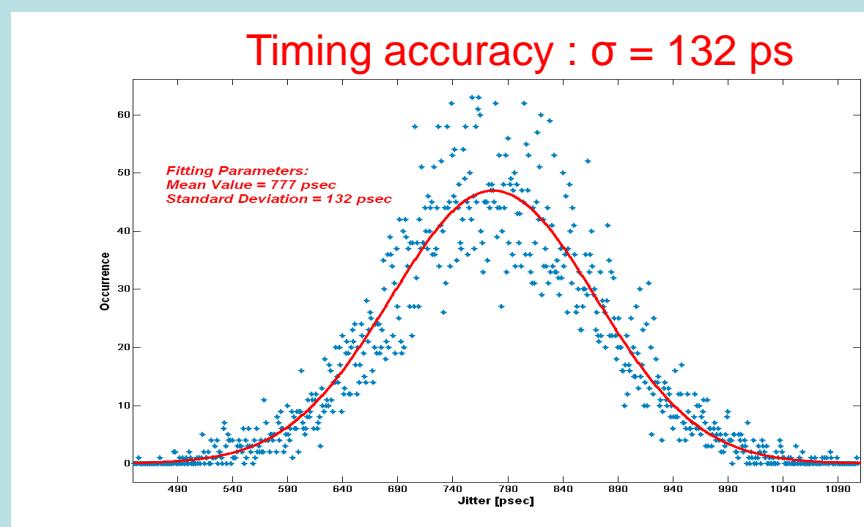
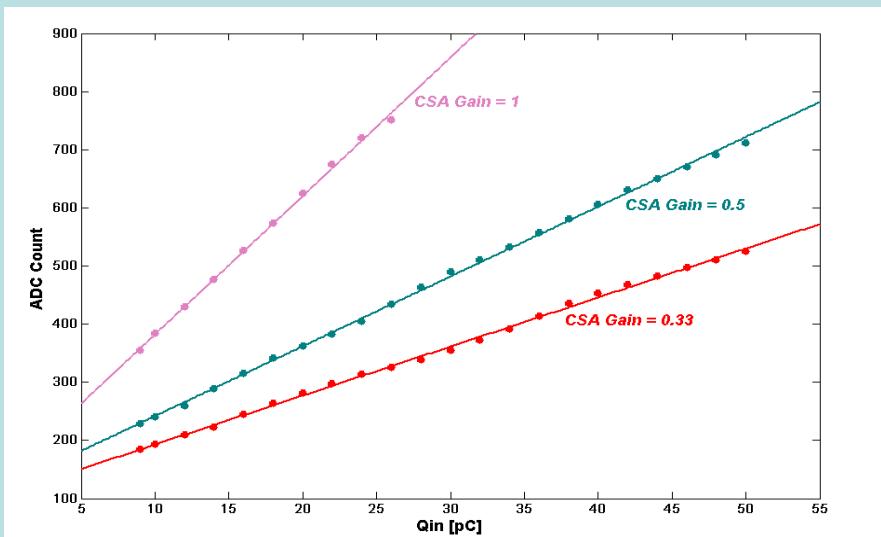
CSA

- Continuous passive reset
- Variable gain: $C_F=1\text{pF}, 2\text{pF}, 3\text{pF}$
- Damping time constant: 200ns
- Output voltage range: 0.3V ÷ 2.7V

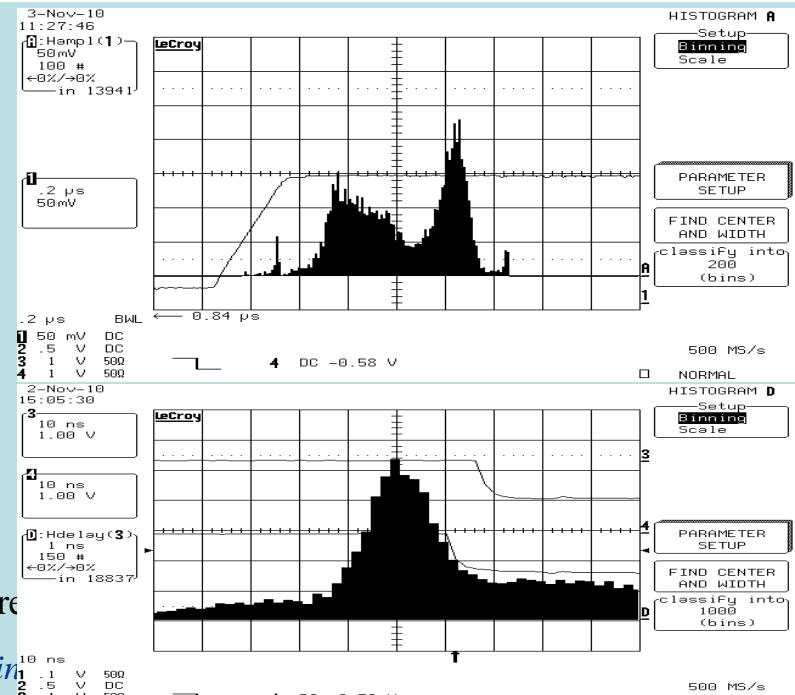
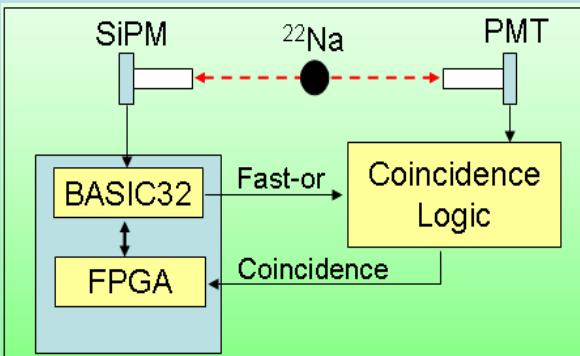
Baseline holder

- Very slow feedback loop
- “Ad hoc” techniques to reproduce large time constants
- Small baseline shifts at high event rates (-1mV @ 100kHz, full dynamic)

Experimental results: injection capacitance, gain , timing



Spectrum with
22Na source
Energy resolution 11%
Time resolution :
1.2 ns FWHM



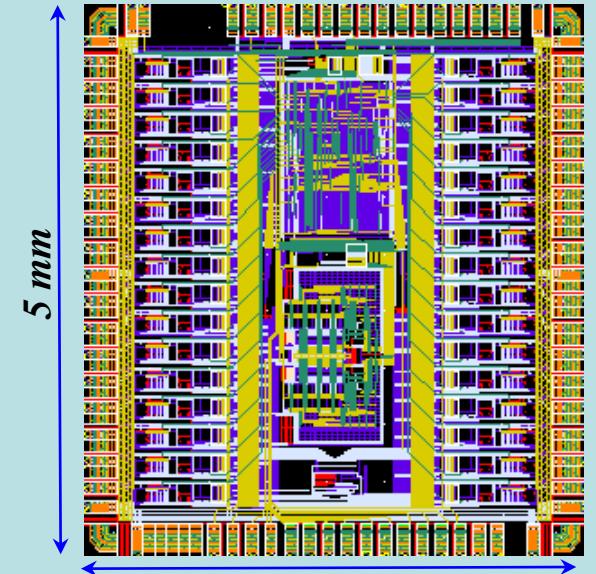
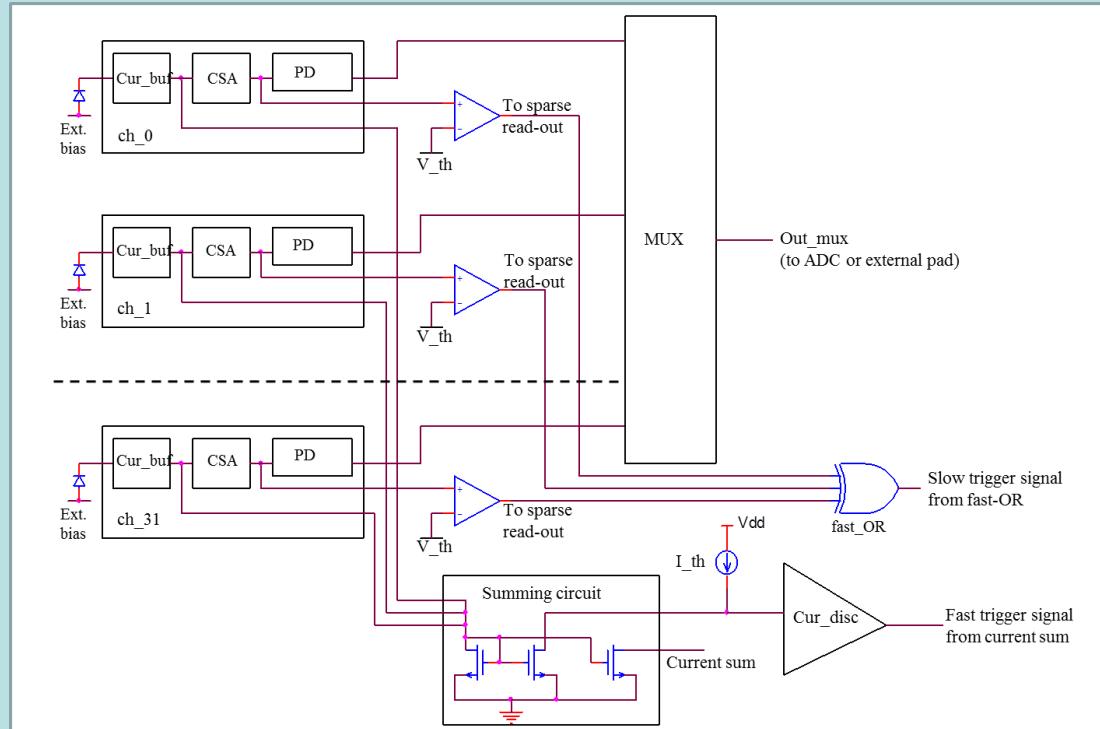
15 jun 2012

CdLT Photodet conference

8th International Meeting

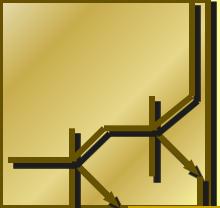
Last version of the ASIC

- Internal 8-bit subranging ADC
- Extended dynamic range (more than 100pC)
- Improved configuration flexibility (524 bits)
- Analog current sum output available
- The internal read-out procedure can be started by the “slow” (fast-OR of the voltage comparators) or “fast” (current discriminator) trigger
- Enhanced and improved management of the external trigger



4.4 mm
Layout of the prototype

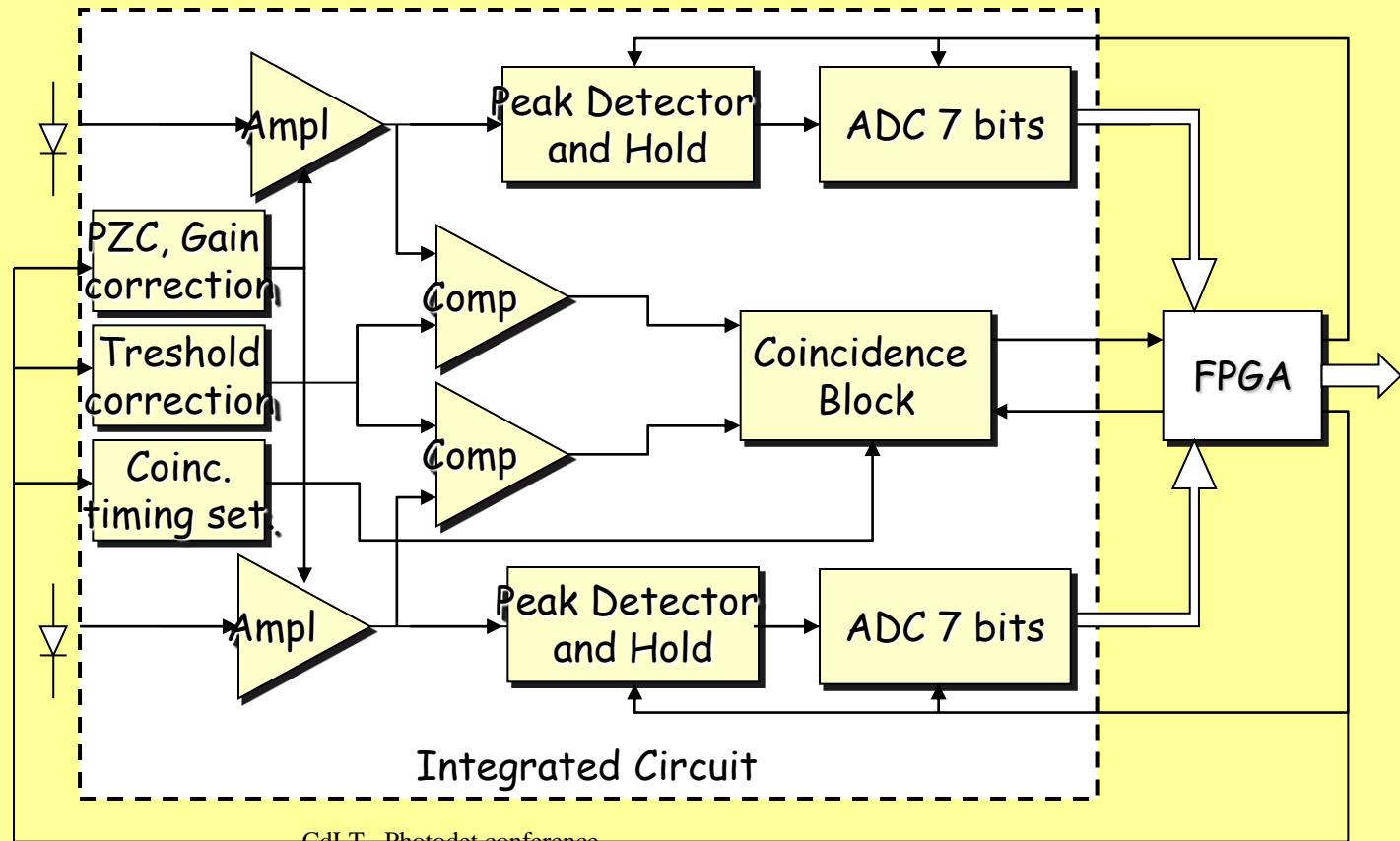
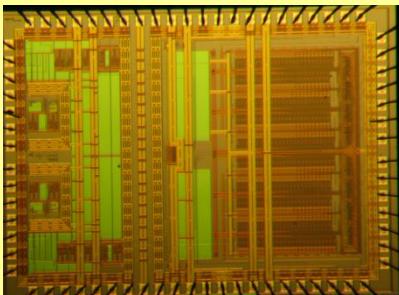
RAPSODI

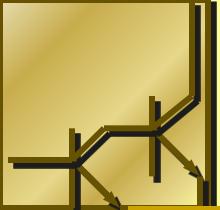


ASIC is a 2 channel SiPM readout chip for energy measurement, made in $0,35\text{ }\mu\text{m}$ CMOS AMS technology (2009)

Each channel measures the amplitude of the signal from SiPM and converts it in 7-bit ADC. The channels can work separately or in coincidence mode.

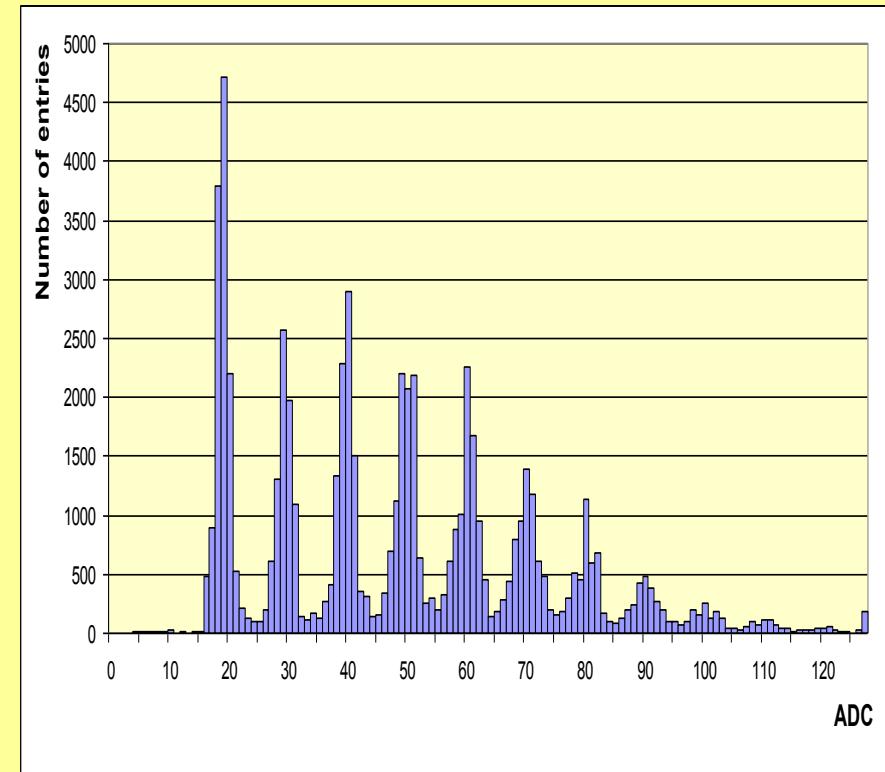
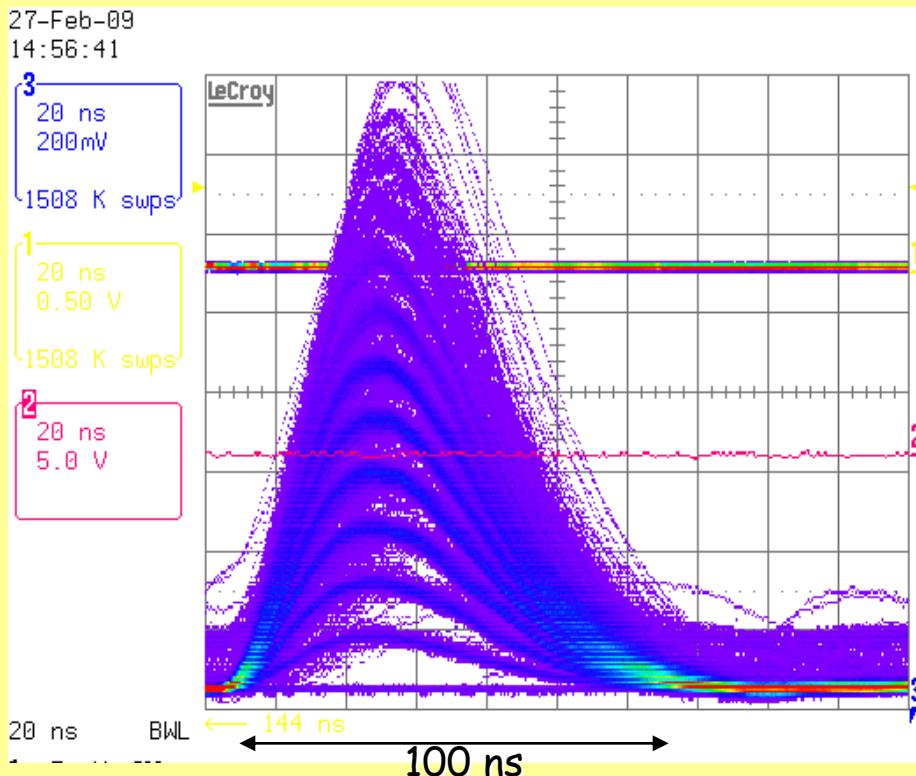
R. Mos, J. Barszcz,
M.Jastrzab, W.Kucewicz,
J. Mlynarczyk, E.Raus, M.
Sapor - Front-End
electronics for Silicon
Photomultiplier
detectors implemented in
CMOS VLSI integrated
circuit - Electrical
Review NR 11a (2010),
p.79





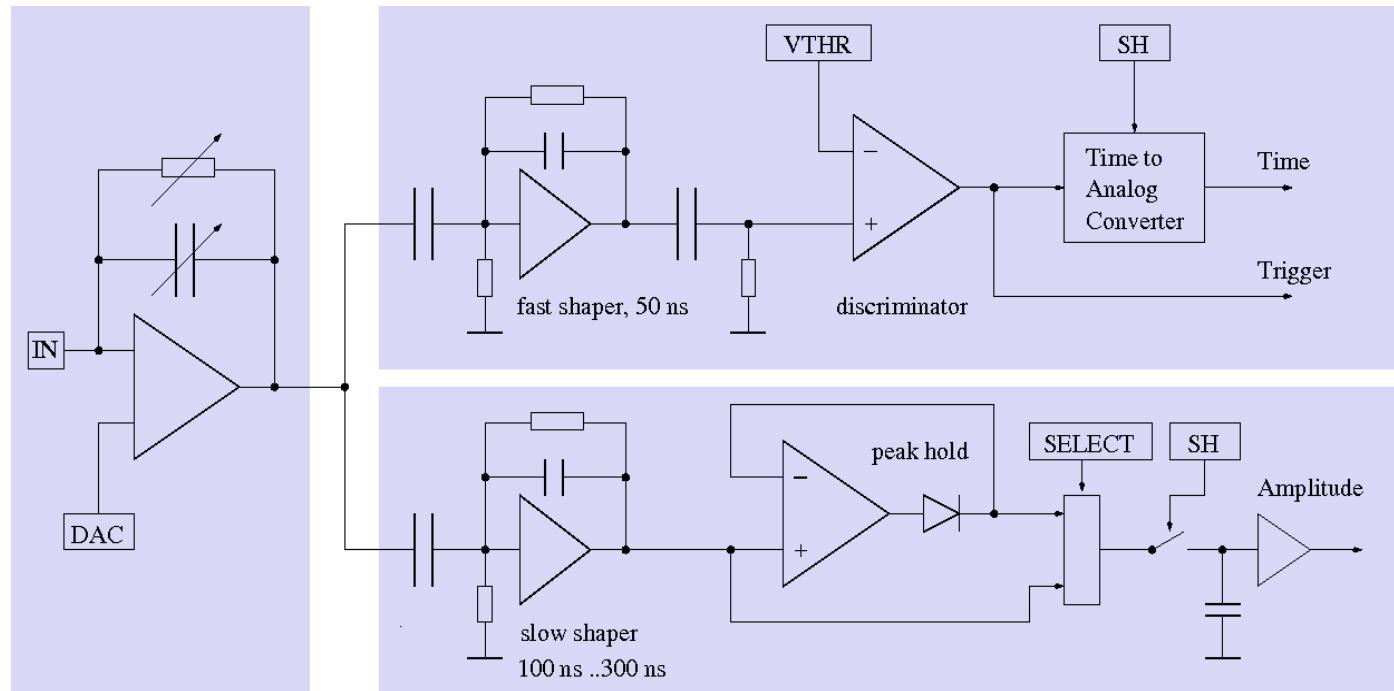
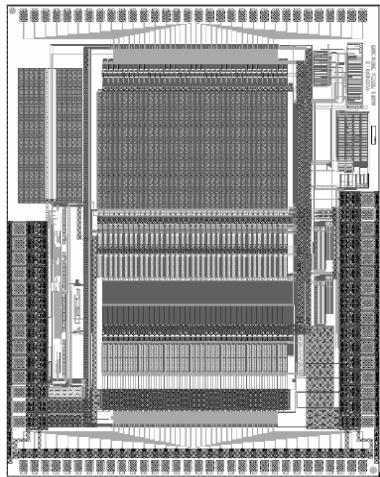
RAPSODI

Sensi SiPM diode, Bias 31V,
Laser 1060nm (12dB; f-100kHz, pulselwidth 4ns)
threshold 0.95V(just above 1 avalanche)



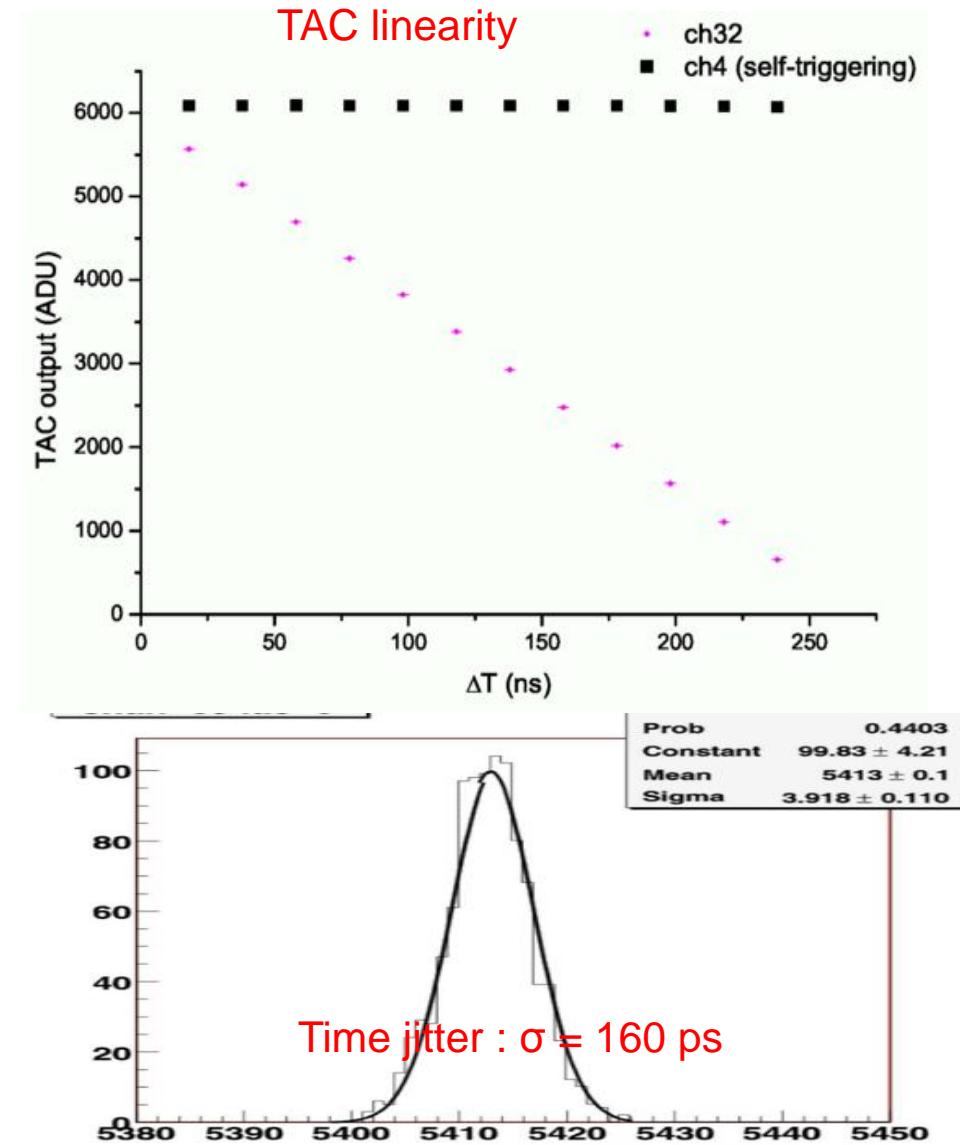
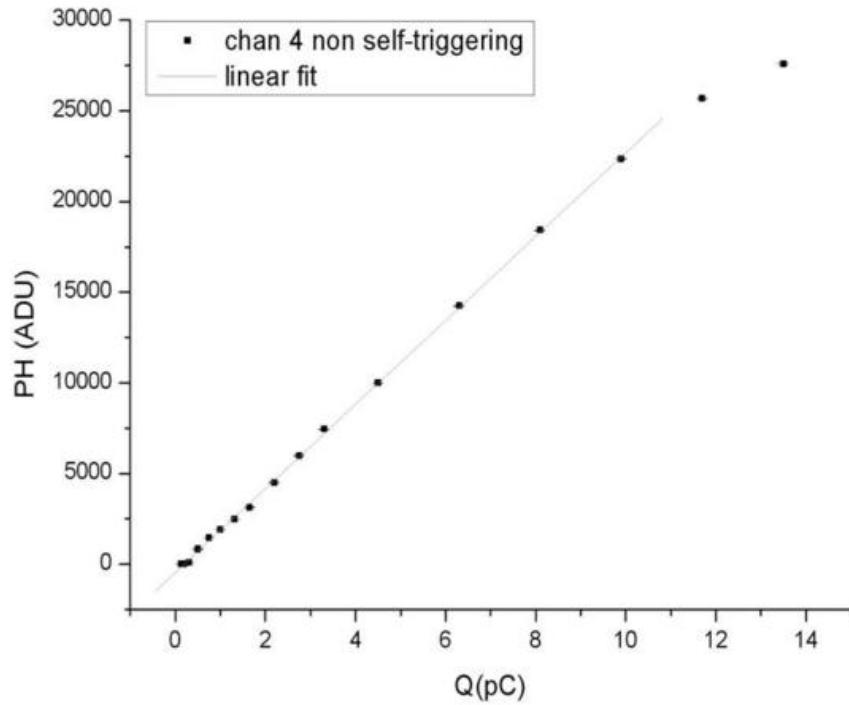
SPIDER VA-TA HDR 16

- D. Meier et al. GM-IDEAS Norway, INFN Siena, INFN Pisa
- Chip VATA64-HDR16 was developed for SiPM applied in Ring Imaging Cherenkov Detector of SPIDER (Space Particle IDentifiER) Experiment
- [M.G. Baglieis et al. «A custom front-end ASIC for the readout and timing of 64 SiPM» NIM Nuclear Physics B (Proc. Suppl.) 215 (2011) 344-348]



VA-TA performance

- **Dynamic range : 12 pc**
- **Noise : 1 fC**



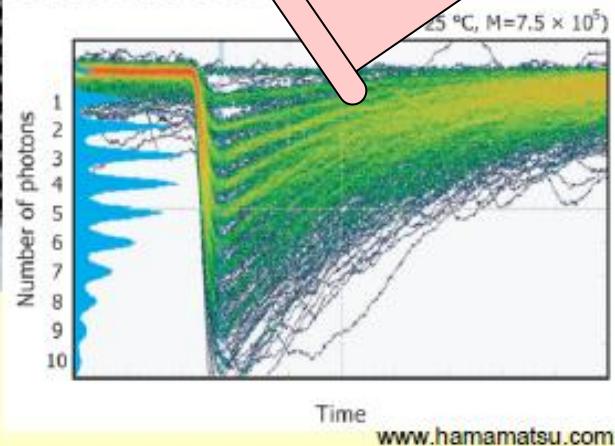
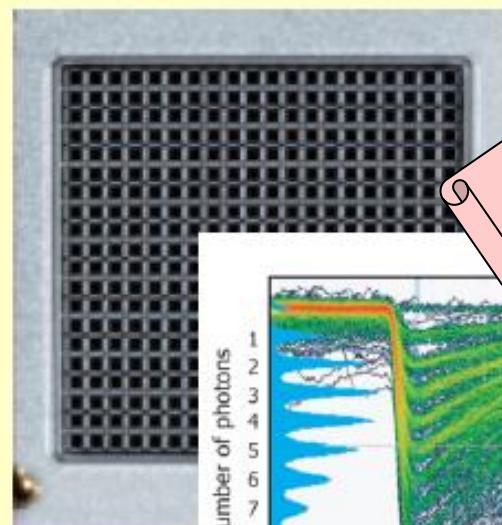
SiPM readout chips

© W. Kucevisz (Krakow)

| Chip name | # of channels | ADC | Power /channel | Dynamic range | Input resistance | noise | jitter |
|---------------------|---------------|-----|----------------|---------------|------------------|---------|--------|
| FLC_SiPM | 18 | n | 10 mW | 100 pC | 50 Ω ext | 15 fC | |
| MAROC2 | 64 | y | 20 mW | 80 pC | 50 Ω | 1 fC | 120 ps |
| SPIROC | 36 | y | 5 mW | 200 pC | 50 Ω ext | 5-10 fC | 100 ps |
| NINO | 8 | n | 30 mW | 300 pC | 20 Ω | 5 fC | 20 ps |
| PETA | 40 | y | 30 mW | 8 bit | 50 Ω ext | x fC | 40 ps |
| BASIC | 32 | y | | 70 pC | 17 Ω | 50 fC | 120 ps |
| VATA64-HDR16 | 64 | n | 16 mW | 15 pC | | 1 fC | 160 ps |
| RAPSODI | 2 | y | 100 mW | 100 pC | 20 Ω | | |

Digital Photon Counting – The concept

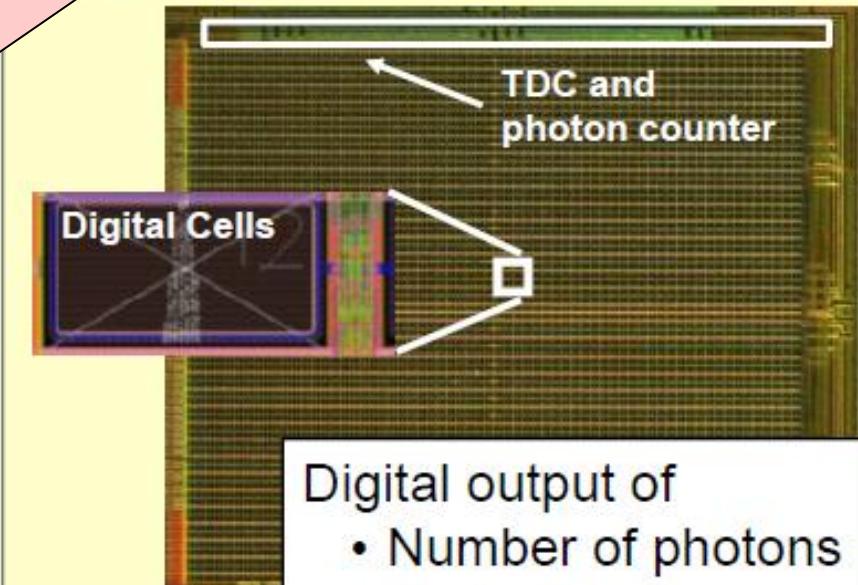
Intrinsically, the SiPM is a digital device: a single cell breaks down or not
analog SiPM



Summing all cell outputs leads to an analog output signal and limited performance

See talks by D. Schaarr
and M. Heller

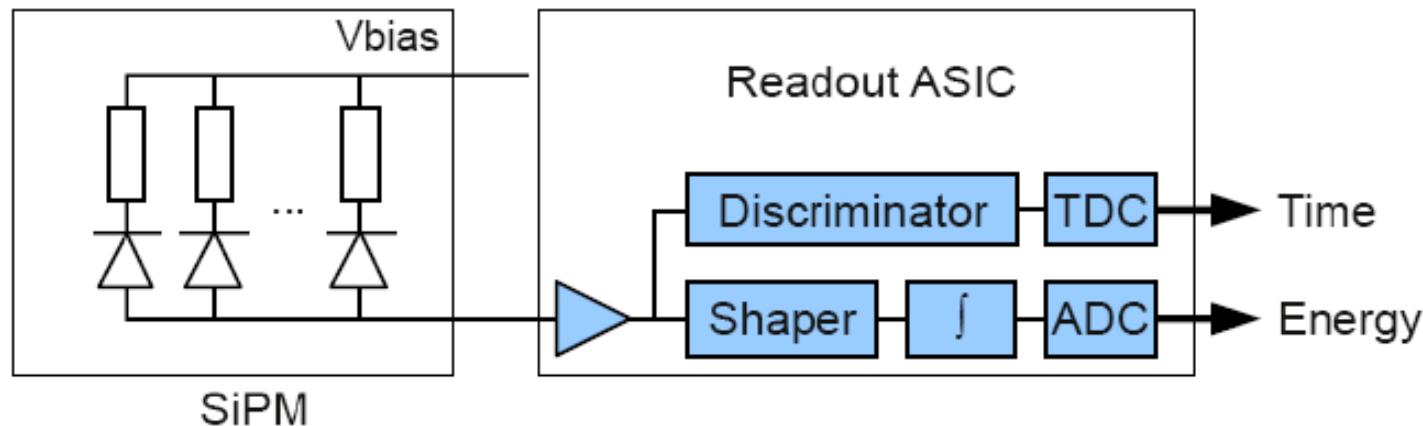
Digital SiPM (dSiPM)



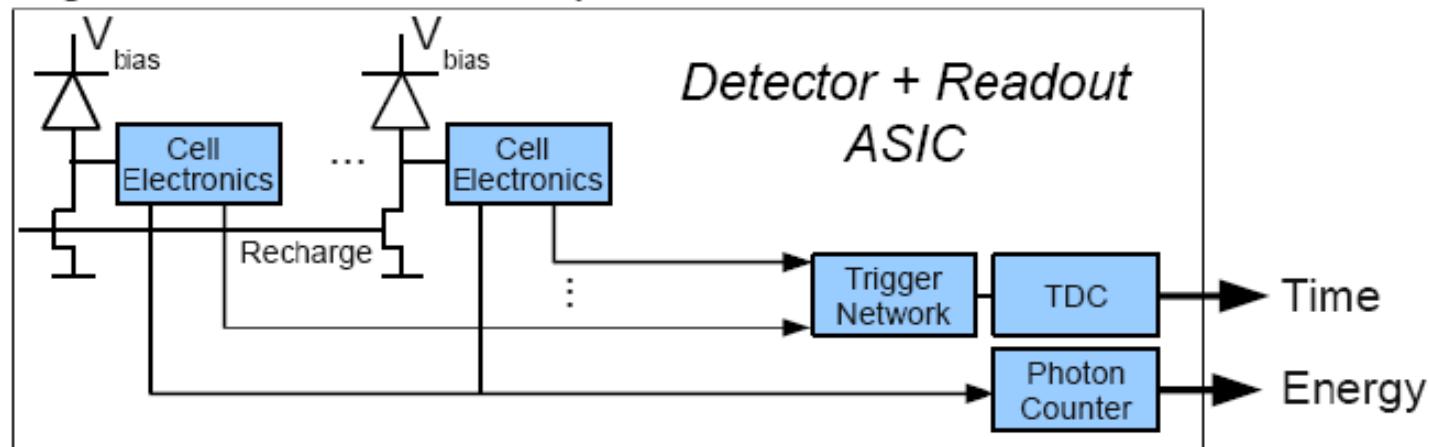
Integrated readout electronics is the key element to superior detector performance

Analog vs. Digital SiPM

Analog Silicon Photomultiplier Detector



Digital Silicon Photomultiplier Detector



Why going from analog to digital SiPM

Fm M. Heller PHOTODET 2012

| Characteristic | dSiPM | aSiPM | APD | PMT |
|--|-----------------------------------|---------------------------|-------------|----------|
| Sensitivity (PDE) | Max. ~70 % tbp | Max ~ 70% tbp | ~ 70% | ~ 35% |
| Intrinsic timing res. | ~ 50 ps | > 150 ps | ~ 1 ns | ~ 400 ps |
| CRT on system level (depends also on scintillator) | Pot. ~ 150 ps 250 ps proven | ~ 500 ps in literature | > 1 ns | ~ 500 ps |
| voltage | 35 V | 35-70V | Up to 1500V | 400-800V |

- Advantages of dSiPM wrt aSiPM

- Lower DCR
- Better CRT (triggering on the first photon) → TOF PET
- Afterpulses does not affect the digital sum thanks to active quenching
- No custom electronics needed

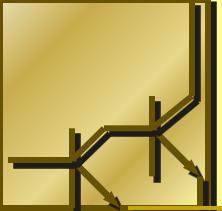
Analog and digital SiPMs

- **Superior timing resolution shown by dSiPM**
 - Gets rid of stray inductance
 - Uses the first photons
- **Is the aSiPM already dead ?**
 - Cost effective solution for large number of channels, with 100 ps
 - Needs dedicated (optimized) readout ASIC
 - Power dissipation and system level issues are easier

Conclusion

- **Spectacular progress of SiPM/MPPC sensors**
 - Larger area, matrixes, lower noise, better PDE...
 - Already equipping large experiments
- **Importance of readout electronics**
 - Timing measurements
 - Large dynamic range measurements
 - high integration => cost reduction
- **Trends for readout electronics**
 - High speed electronics (> GHz)
 - High level of integration (SoC)
 - Integration sensor/readout (digital SiPM)
 - Importance of low power design

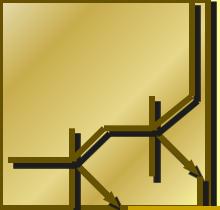
backup



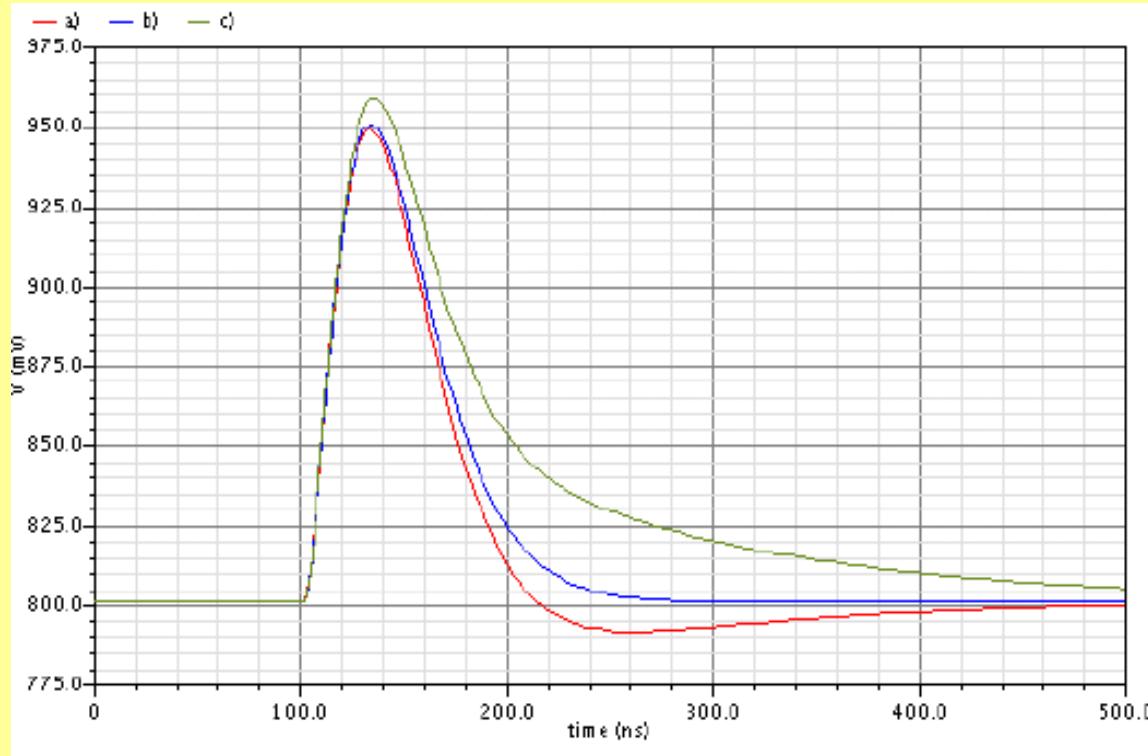
RAPSODI

ASIC developed within the 6 FP RAPSODI for MICROSNOOPER (portable real time meter to detect and identify any type of radiation)

1. R. Mos, J. Barszcz, M.Jastrzab, W.Kucewicz, J. Mlynarczyk, E.Raus, M. Sapor - Front-End electronics for Silicon Photomultiplier detectors implemented in CMOS VLSI integrated circuit - Electrical Review NR 11a (2010), p.79
2. R. Mos, J. Barszcz, M.Jastrzab, W.Kucewicz, J. Mlynarczyk, E.Raus, M. Sapor - Front-end Electronics for Silicon Photomultipliers Implemented in CMOS VLSI - Preceedings of MIXDES 2009, 16th International Conference "Mixed Design of Integrated Circuits and Systems", June 25-27, 2009, p. 266
3. W. Kucewicz, J. Barszcz, J. Juraszek, R. Mos, M. Sapor - The two channel CMOS converter for silicon photomultiplier - Proceedings of ICSES 2008 - International conference on Signals and Electronic Systems : September 14-17, 2008, p. 165



RAPSODI

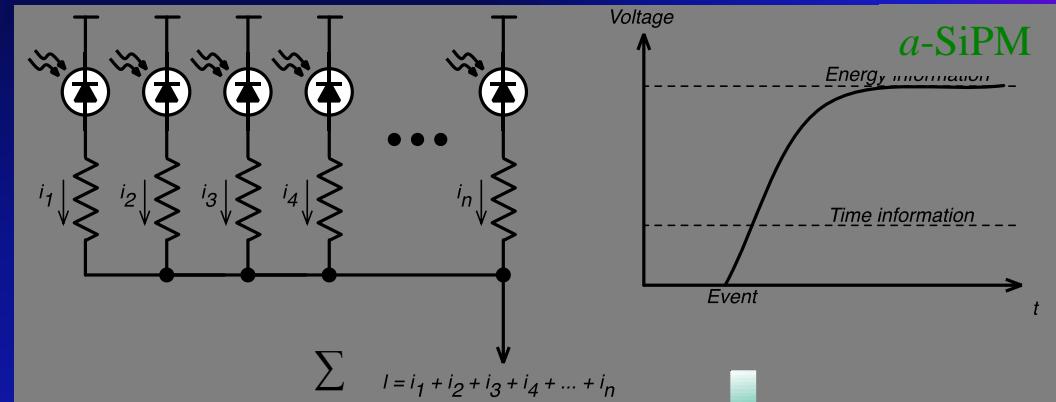


Two stage amplifier allows to switch ranges between 1, 10 and 100 pC.
The PZC block moderate the fallowing edge of the signal.

a-SiPM versus d-SiPM

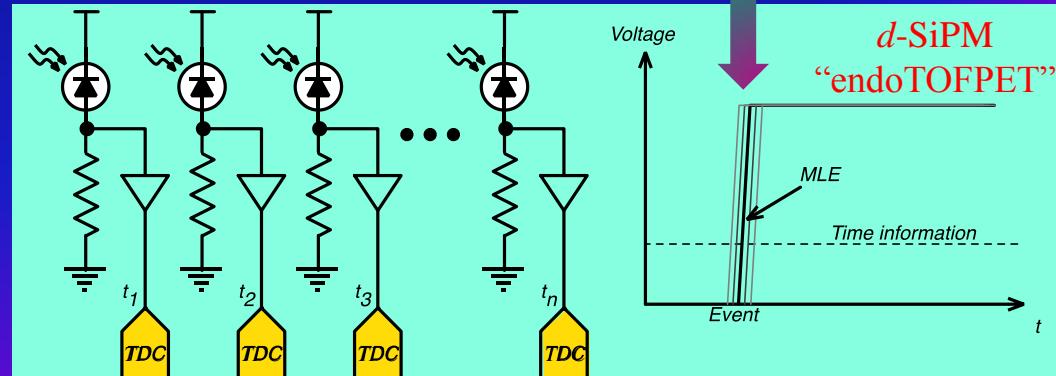
The *a*-SiPM:

- low rise time;
- high capacitance;
- reasonable fill factor (FF);
- mature technology;
- commercially available
- time over threshold discr.
- standard (HP)TDC readout.



The *d*-SiPM:

- very low rise time;
- individual SPAD readout
→ single photon counting
→ optimum timing
- high functionality
- ambitious/risky
- novel technology
- optimized for endoscope

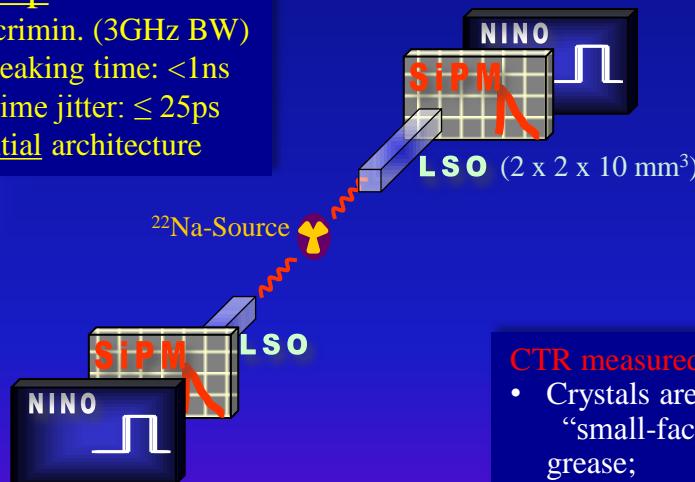


a-SiPM: Test Scenario

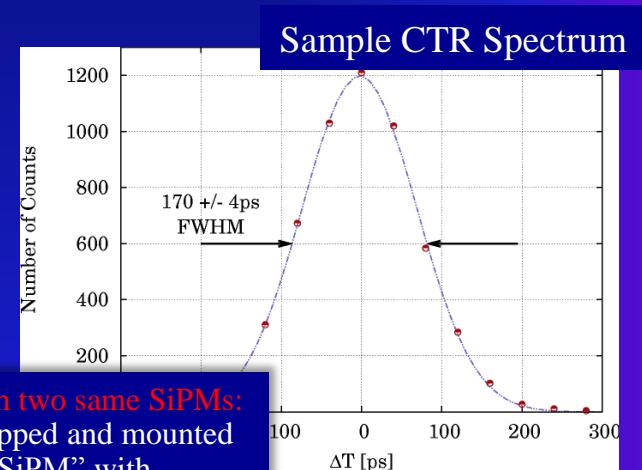
- For an intrinsic SiPM timing evaluation, see poster by Stefan Gundacker/CERN;
- Coincidence time resolution (CTR) measured with scintillating “reference” crystals and the NINO amplifier/discriminator;
- Use high-BW scope (LeCroy DDA 735Zi, 40GS/s) or HPTDC.

NINO chip:

- Fast discrimin. (3GHz BW)
- Signal peaking time: <1ns
- Output time jitter: $\leq 25\text{ps}$
- Differential architecture



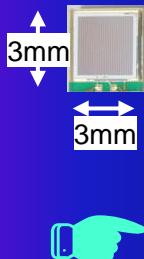
- CTR measured with two same SiPMs:
- Crystals are wrapped and mounted “small-face-to-SiPM” with grease;
 - Spectra are refined through photo-peak selection.



a-SiPM: Evaluation & Selection



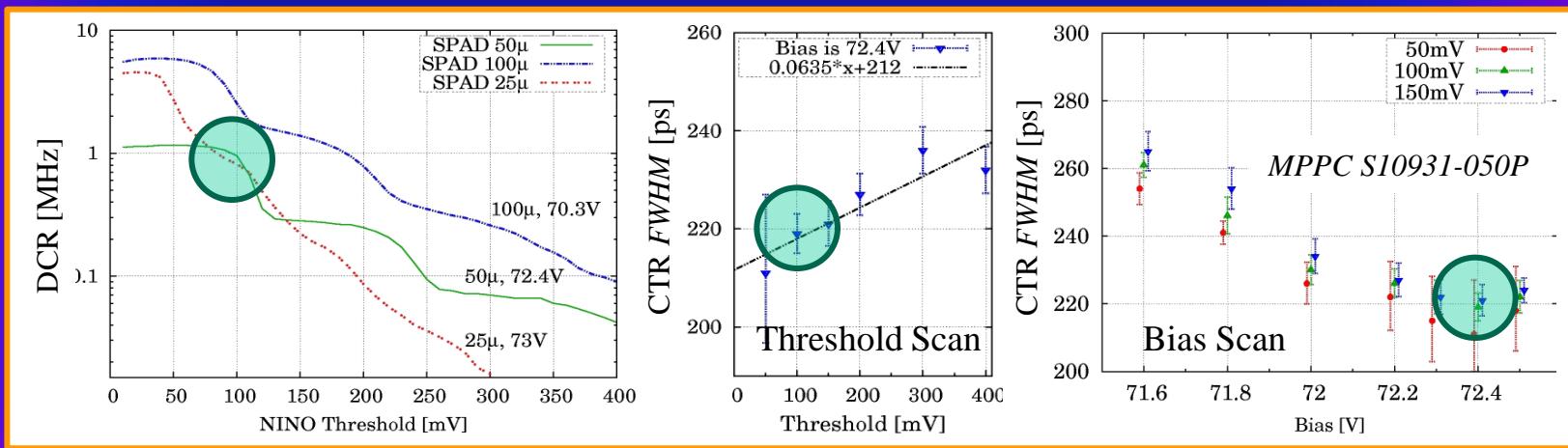
- Suitable SiPMs are commercial MPPCs by Hamamatsu Photonics;
- Evaluation of photodetectors via measurement of the (CTR):



| MPPC S10931- | # SPADs | Fill Factor [%] | $V_{\text{Manuf.}}$ [V] | V_{optimum} [V] | DCR*) [MHz] | NINO Thr. [mV] | CTR FWHM [ps] |
|--------------|---------|-----------------|-------------------------|--------------------------|-------------|----------------|---------------|
| -025P | 14'400 | 30.8 | 71.49 71.44 | 73.0 | 3.2 | 150 | 340±9 |
| -050P | 3'600 | 61.5 | 72.11 72.09 | 72.4 | 1.1 1.0 | 100 | 220±4 |
| -100P | 900 | 78.5 | 70.81 70.87 | 70.3 | 9.0 9.5 | 300 | 280±9 |

Note: Optimization of SiPMs done with non-optimized crystals.

*) DCR = Dark Count Rate



S. Gundacker et al., "A Systematic Study to Optimize SiPM Photo-Detectors for Highest Time Resolution in PET" (TNS-00225-2011)



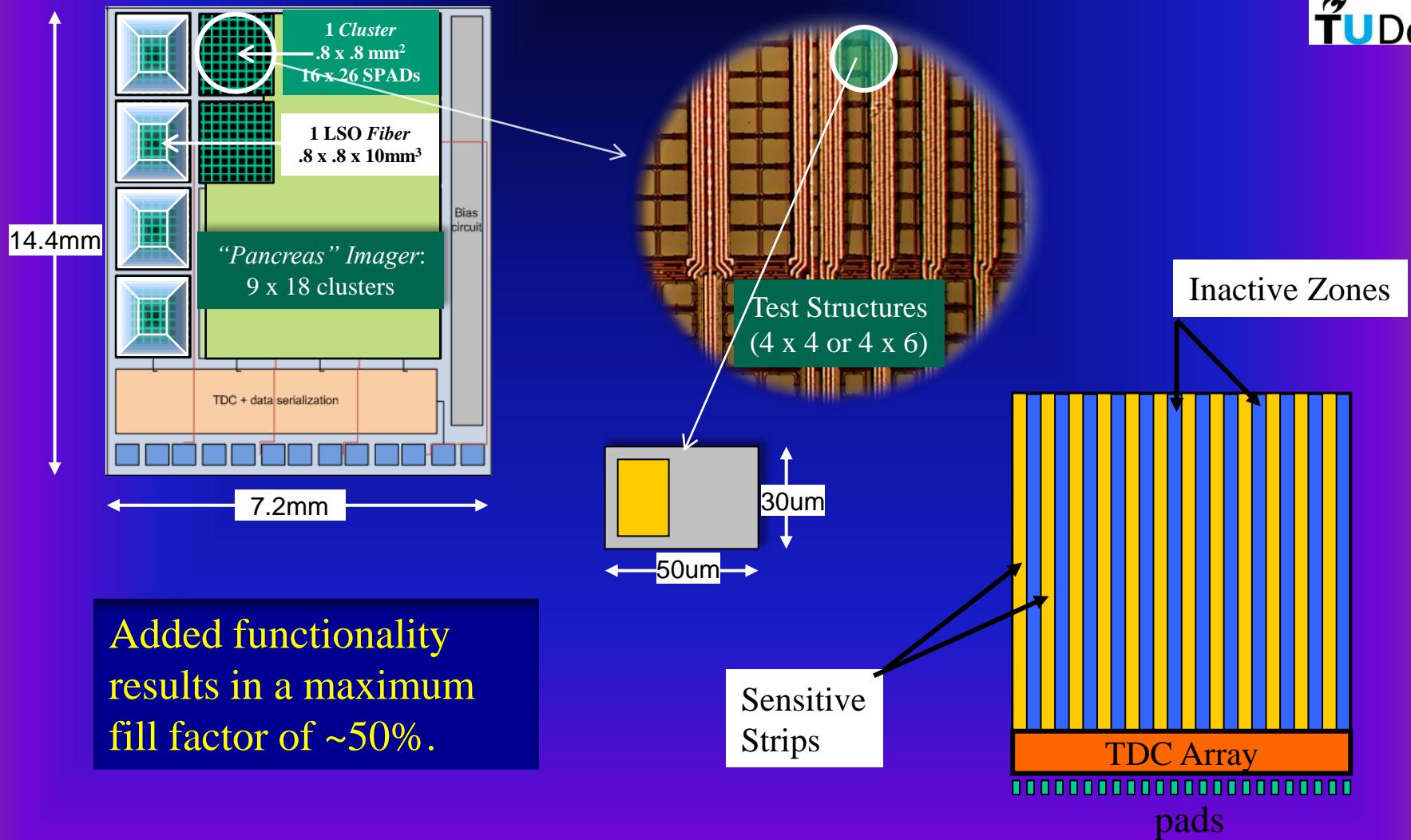
d-SiPM for endo-TOFPET-US



- Capability to gather the statistics of the first individual photons that reach a cluster^{*)};
 - Intrinsically best timing performance → attractive for TOF;
- Balance functionality and PDE;
- Design must adapt to process-specific effects:
 - high DCR from tunneling and trap-assisted noise;
 - after-pulsing;
 - lower PDP than with conventional *a*-SiPMs.
- Requires multi-parameter optimization/simulation.

^{*)} M. Fishburn & E. Charbon, "System Tradeoffs in Gamma-Ray Detection Utilizing SPAD Arrays and Scintillators", IEEE-TNS, VOL. 57, NO. 5, OCTOBER 2010.
S. Seifert et al., "The lower bound on the timing resolution of scintillation detectors", Phys. Med. Biol. **57** (2012) 1797–1814

d-SiPM: Sensor Floor Plan





d-SiPM: Characteristics & Results



| Characteristic Parameters of <i>d</i> -SiPM-“endo-TOFPET-US” Test Structure | | Commercial 1 <i>d</i> -SiPM (Philips) |
|---|------|--|
| Cluster Pitch [μm] | 800 | 4000 |
| # SPADs/cluster | 416 | 6400 |
| Maximum Fill Factor [%] | 50 | 77 |
| PDP [%] @ 430nm | 32 | 31 |
| PDE [%] | 15 | 24 |
| # TDCs / Cluster Column | 48 | 1 |
| # Time Of Arrivals (TOA) / cluster | 48 | 1 |
| TDC Resolution or LSB [ps] | 51.8 | - |
| Clock Frequency [MHz] | 25 | 200 |

First evaluation results:

DCR (0 °C): 25kHz/SPAD → DCR (40 °C): 80kHz/SPAD

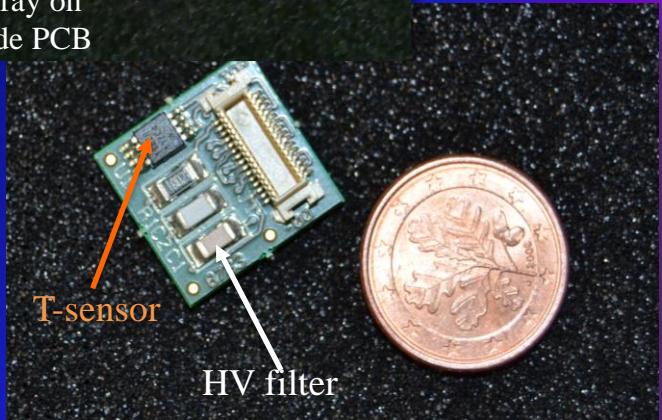
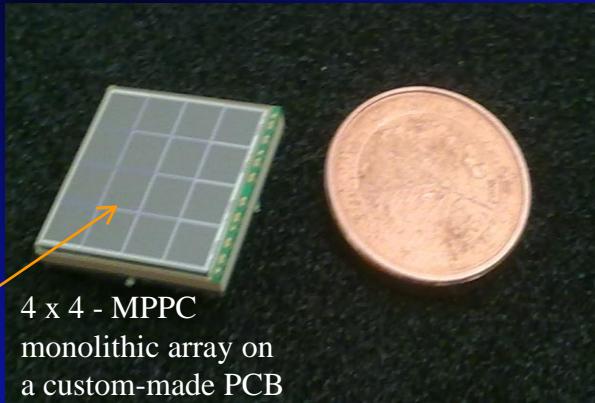
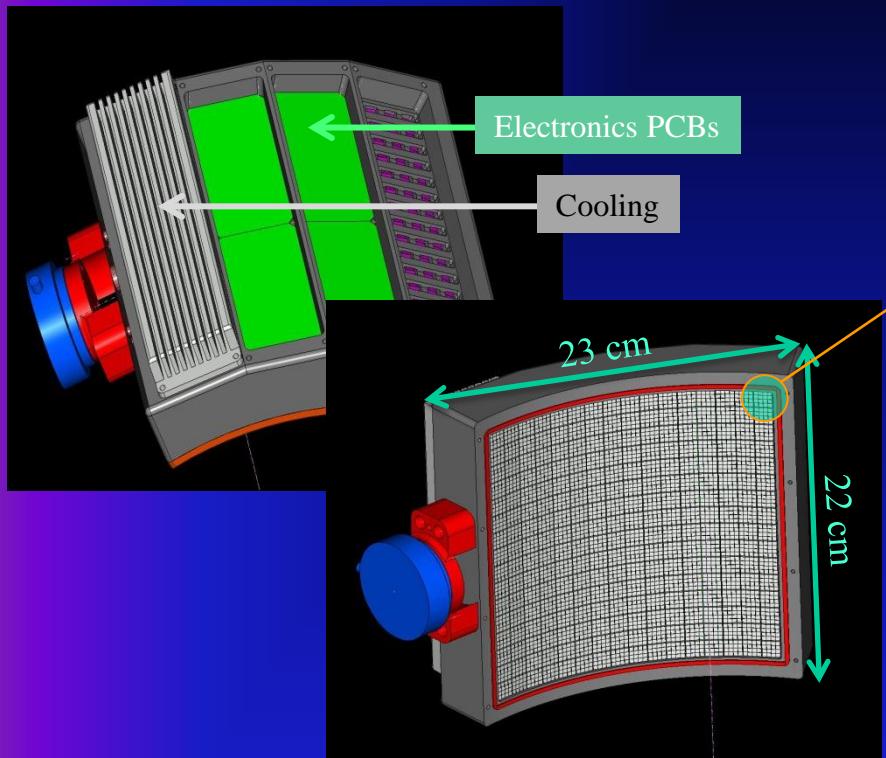
NEED COOLING OF *d*-SiPM!

Masking of noisy pixels (“screamers”): DCR ↓ but also PDE ↓

Lowering excess bias: DCR ↓ but also PDE ↓

Boost PDE optically!

System Integration: External Plate



Sensitive detector: 16 x16 detector units (4096 ch.) with ~100 μ m gap;

Electronics: dedicated readout chips on PCBs (512 ch./PCB) ;

Cooling: detector stabilized to room temperature via Peltier elements (expected 30mW/ch);

Tracking: detector mounted on a robotic arm for mechanical tracking (6D info, <1mm accuracy);

Curved geometry: facing the organ during diagnose ($r = 21\text{cm}$).

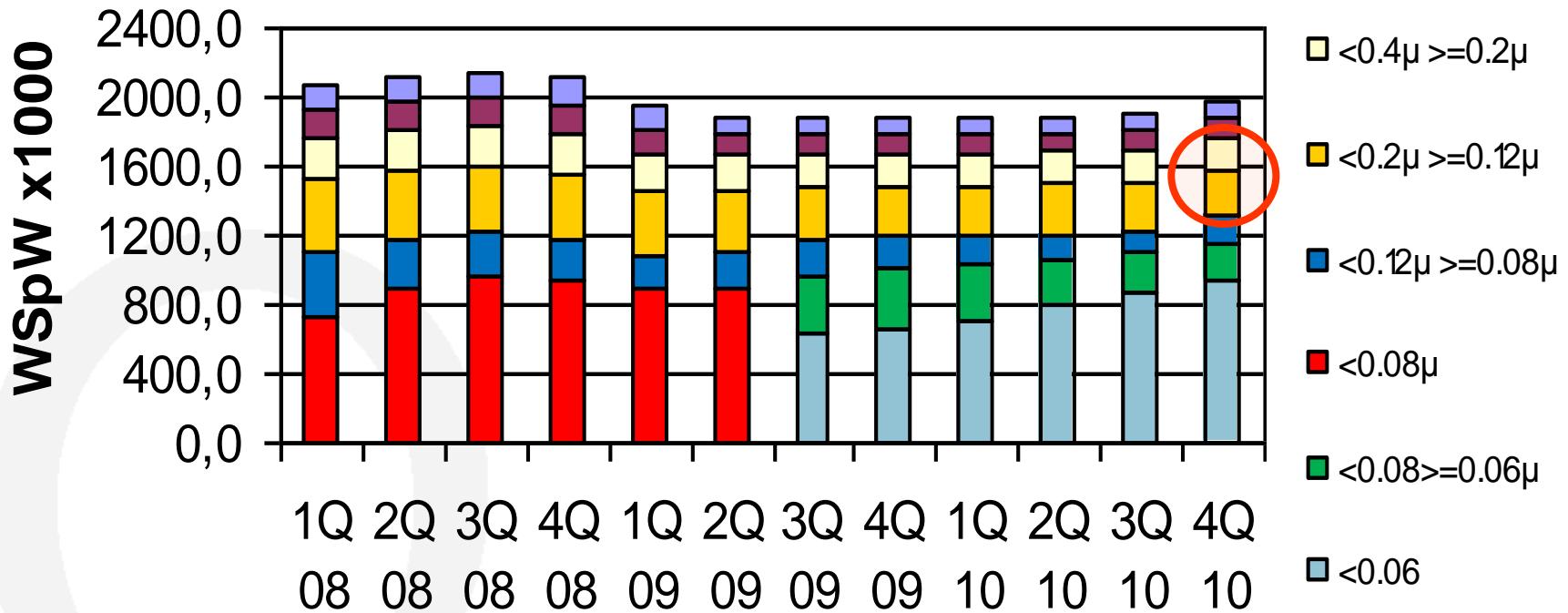


Summary



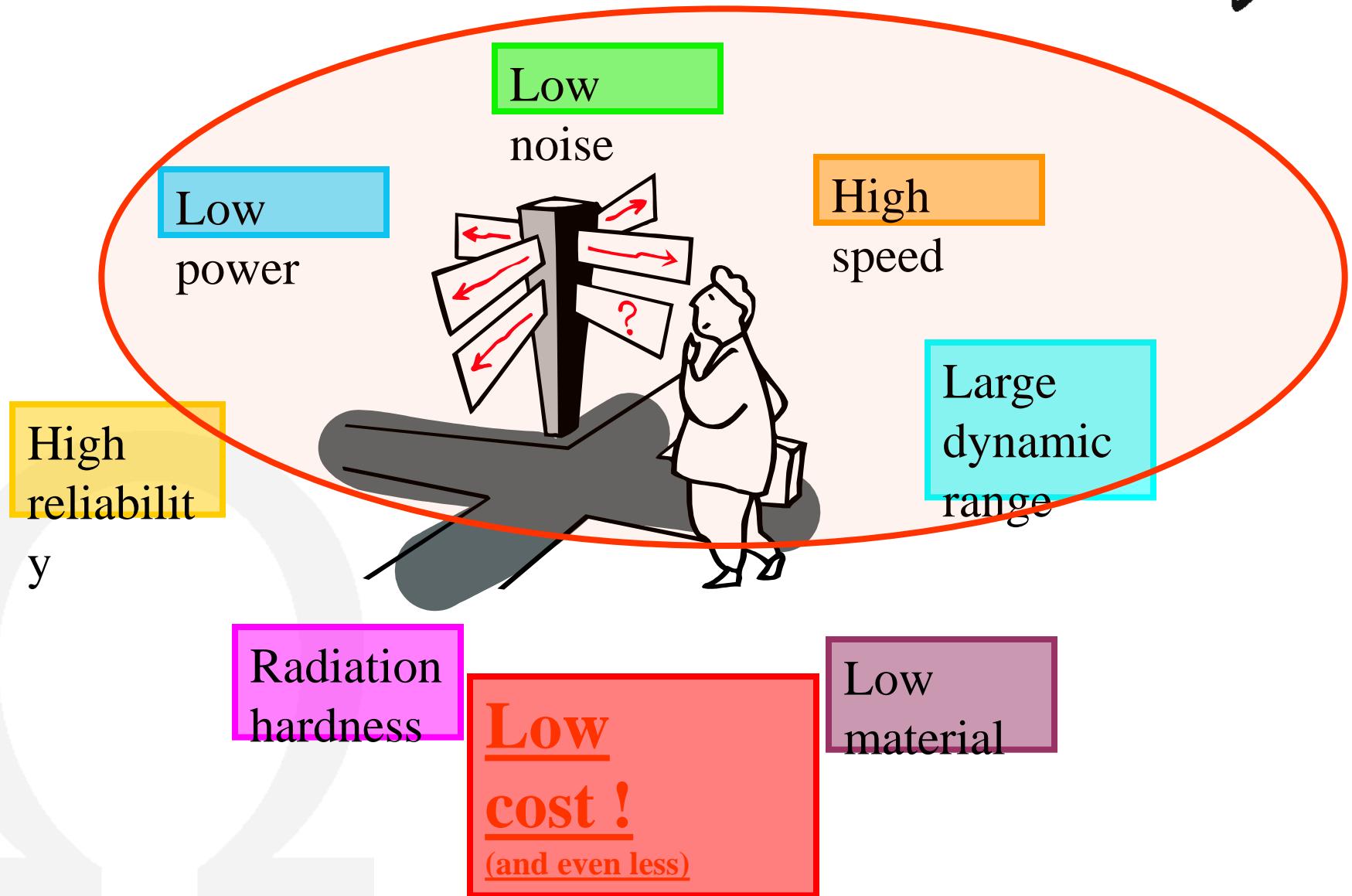
- Frontline research in the domain of:
 - digital photodetectors;
 - scintillators & optical systems;
 - medical instrumentation.
- Large knowledge and technology transfer between HEP, industry and medicine;
- Defines a roadmap for the development of a new generation of multimodal endoscopic probes.
- Thanks to the endo-TOFET and PicoSEC-Coll.
- We still seek ESR applications for the Marie-Curie ITN
 - Please contact us or our Marie-Curie-Homepage:
 - <http://picosec.web.cern.ch/picosec/home.html>

MOS Capacity by Dimensions



Readout electronics : requirements

Omega

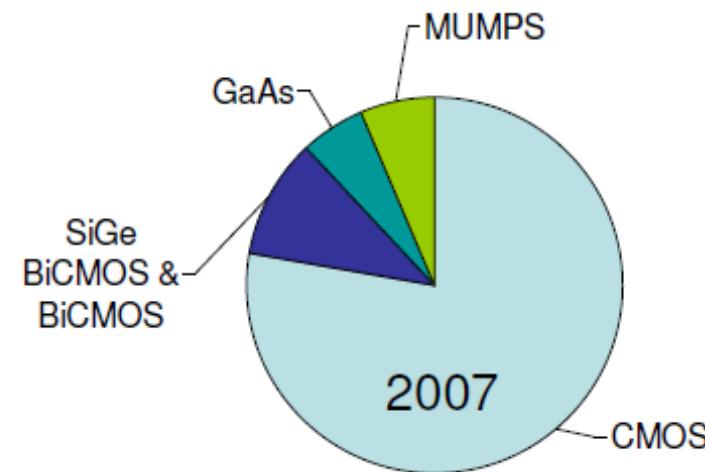
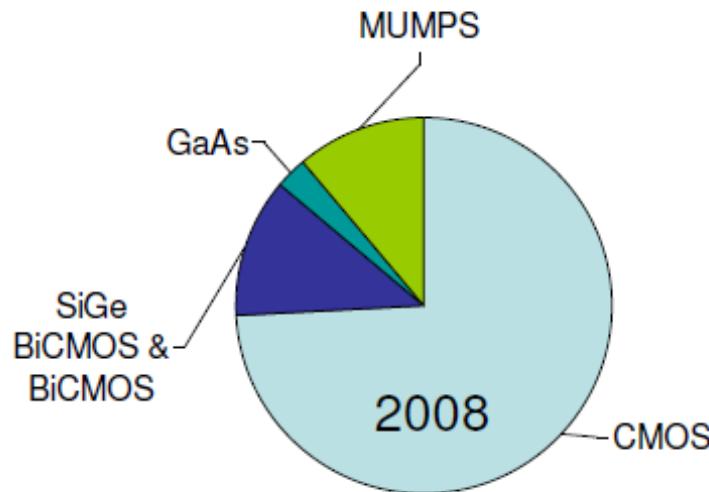
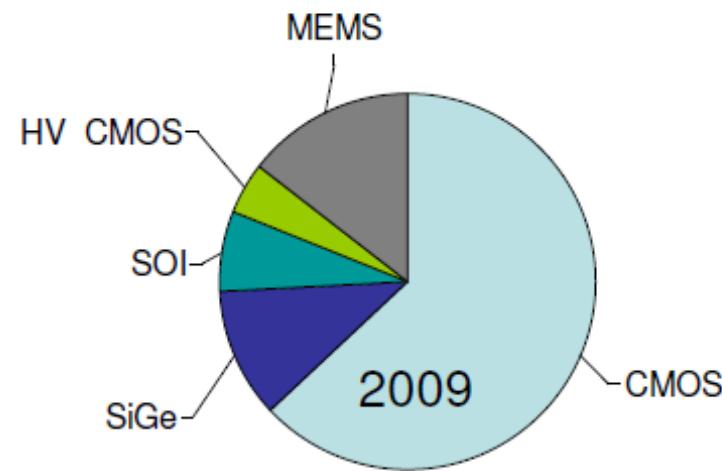
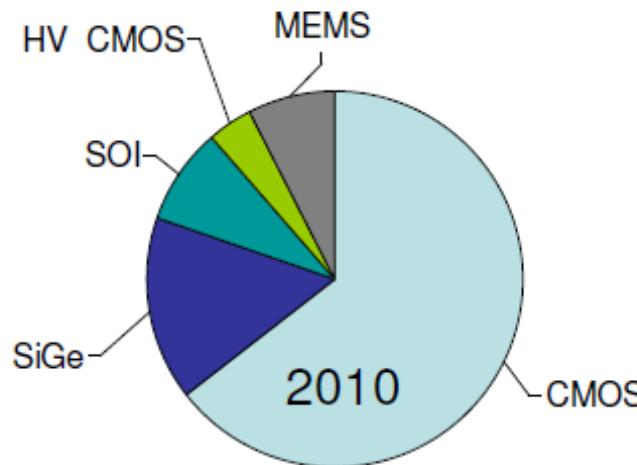


Example of prices, prototyping

| | | | |
|----------------|-----------|---------|-------------------------|
| CMOS | .35 μ | AMS | 650 €/mm ² |
| CMOS opto | .35 μ | AMS | 810 €/mm ² |
| CMOS HV | .35 μ | AMS | 1000 €/mm ² |
| CMOS | 130nm | ST | 2200 €/mm ² |
| CMOS | 65 nm | ST | 7500 €/mm ² |
| CMOS | 40 nm | ST | 15000 €/mm ² |
| SiGe BiCMOS | .35 μ | AMS | 890 €/mm ² |
| SiGe:C BiCMOS | 130nm | ST | 3500 €/mm ² |
| SOI | 130nm | ST | 4000 €/mm ² |
| SOI | 65nm | ST | 9500 €/mm ² |
| Poly-SOI-Metal | MUMPS | MEMSCAP | 3700 €/cm ² |

http://cmp.imag.fr/aboutus/slides/Slides2011/02_Runs_2011.pdf

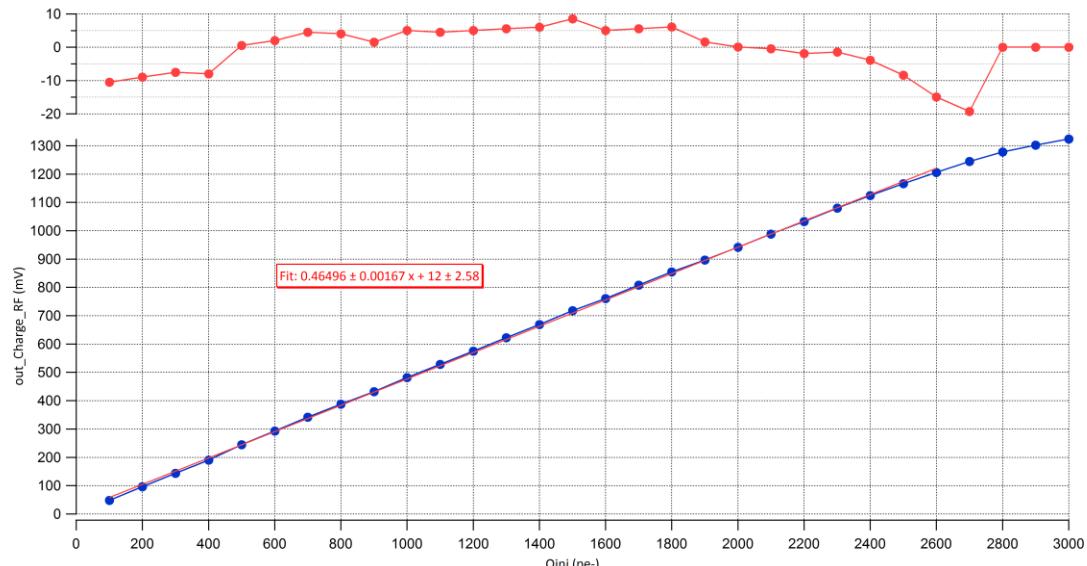
Circuits per technology, evolution



New R&D developments: PETIROC

Omega

- SiPM readout in 0.35 μ m SiGe, for TOF PET MRI and pre clinical applications,
- 12 channels with 3 different architectures (end of 2011)
- High bandwidth preamp (GBWP> 10 GHz), <3 mW/ch, internal TDC (step=25 ps)
- Dual time and charge measurement up to 2500 pe-



- Good testbench performance: **jitter < 10 ps rms**
- Patented input stage for dual time and charge measurement
- Strong industrial interest
- Test boards with bonded die available for academic applications
- 16 channels chip to be submitted
- Startup Weeroc <http://weeroc.com/> created from OMEGA for industrial applications contact person: Julien Fleury

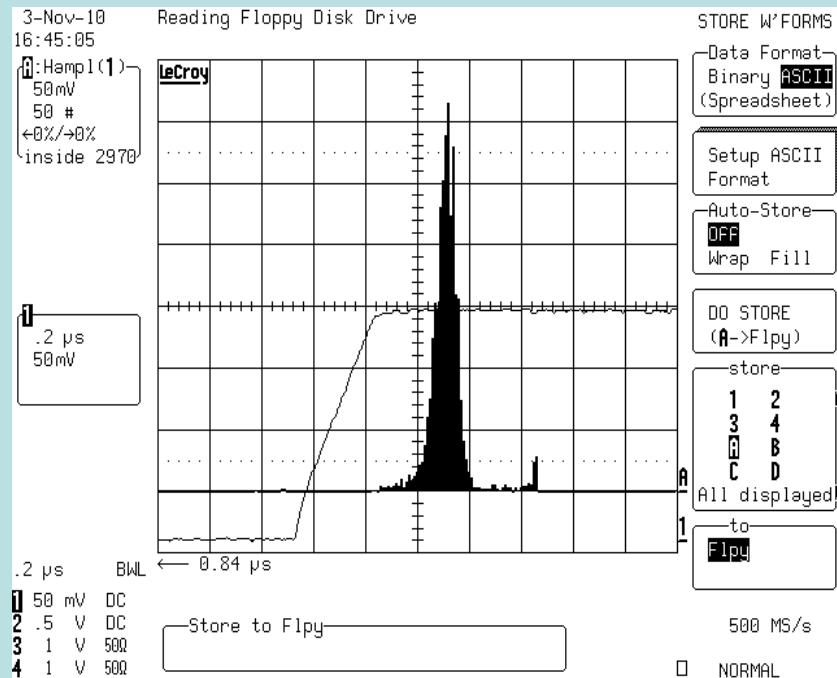


Omega

ROC family

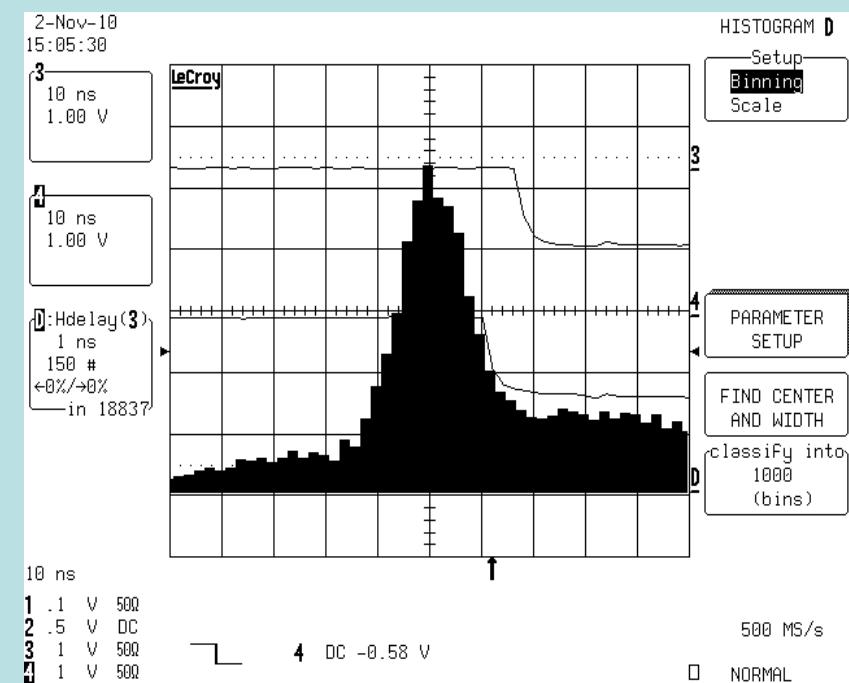
| | MAROC | SPIROC | EASIROC | HARDROC | MICROROC | SKIROC | PARISROC | SPACIROC |
|---------------------|--|---|--|---|---|---|--|------------------------------|
| Technology | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe | 0.35µ SiGe |
| Packages available | •Naked •QFP240 | •Naked •TQFP208 | •Naked •TQFP160 | •Naked •TQFP160 | •Naked •QFP160 | •Naked •QFP240 | •Naked •QFP160 | •Naked •CQFP240 |
| Detector compliant | PMT, MAPMT, PMT, MAPMT, PMT, MAPMT, PMT, MAPMT, SiPM, µmegas, SiPM, µmegas, SiPM, µmegas, SiPM, µmegas, RPC, RPC, GEM, PIN RPC, GEM, PIN | | | | | RPC, GEM, PIN | PM matrix | MAPMT |
| Optimized for | MAPMT | SiPM | SiPM | RPC | µmegas | PIN | PM matrix | MAPMT |
| Number of channels | 64 | 36 | 32 | 64 | 64 | 64 | 16 | 64 |
| Kind of measurement | •Threshold •Charge | •Threshold •Charge •Time | •Threshold •Charge | •Threshold •Charge | •Threshold •Charge | •Threshold •Charge | •Threshold •Charge •Time | •Threshold •Charge |
| Outputs | 64 triggers, 1 mux charge (analogue), 1 mux charge digitized | 1 digital formatted output, 1 mux charge (analogue) | 32 triggers, 2 mux charge (analogue), 1 mux trigger | 1 digital formatted output, 1 mux charge (analogue) | 1 digital formatted output, 1 mux charge (analogue) | 1 digital formatted output, 1 mux charge (analogue) | 16 triggers, 1 digital formatted output, 1 mux trigger | 64 triggers, 9 mux charge |
| Input Polarity | Negative | Positive | Positive | Negative | Negative | Positive | Negative | Negative |

Measurements of SiPM in coincidence with a PMT (II)



Energy spectrum of ^{22}Na

- Threshold increased to get rid of the Comptons:
energy resolution $\cong 11\% \text{ FWHM}$



Timing accuracy of the fast-OR signal vs
the trigger provided by the PMT

- Low threshold level:
timing accuracy $\cong 1.2 \text{ ns FWHM}$