OMEGA SiPM readout ASICs

SiPM workshop Bari 2-4 oct 2019

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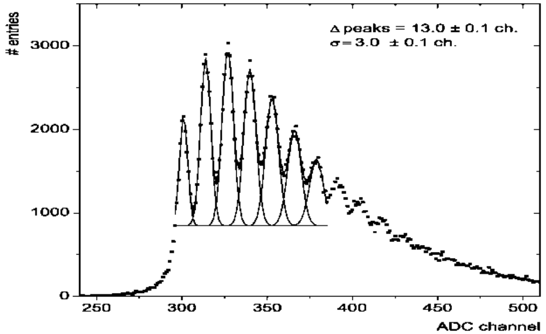
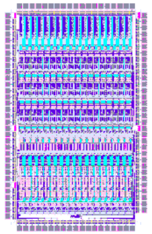
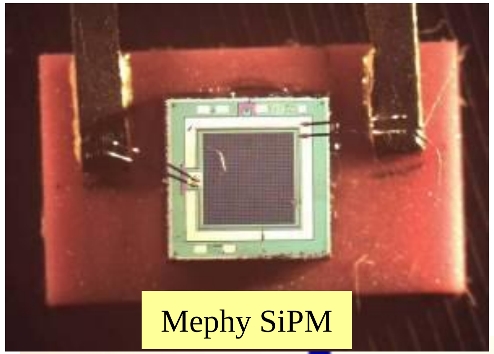
A bit of history : CALICE AHCAL physics prototype (2004)

- Hadronic calorimeter prototype for the ILC : 1 cubic metre, 38 layers, 2cm steel plates
- 8000 tiles with SiPMs fabricated by MePHY group
- First ASIC to read SiPMs : FLC_SiPM 18ch

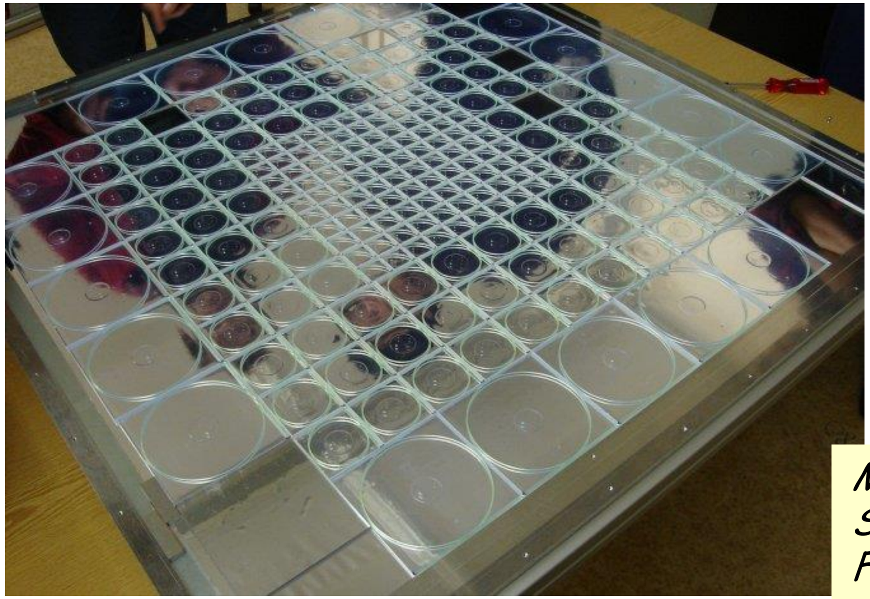


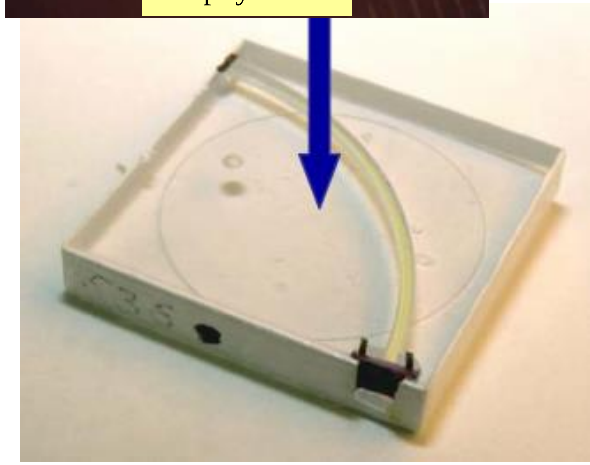


FLC_SiPM ASIC



Mephy SiPM



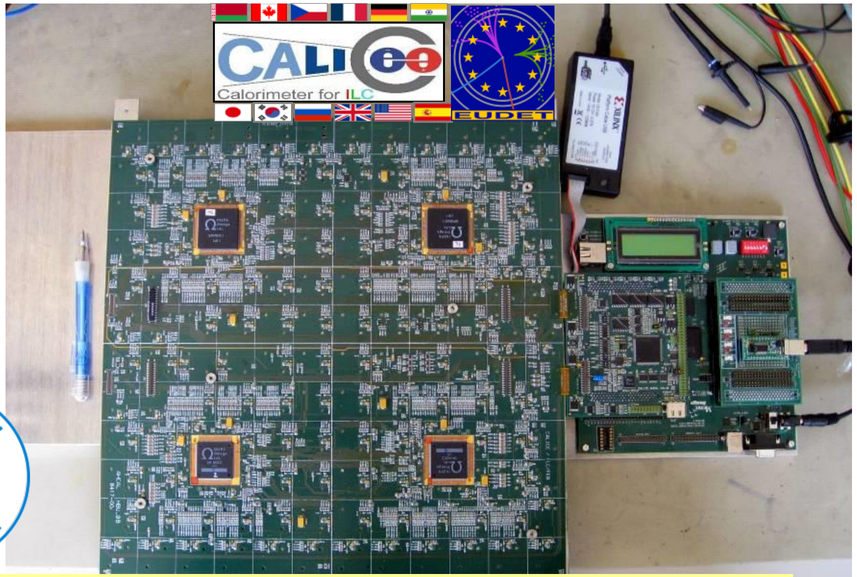


Mechanics and front end boards: DESY
SiPM : Mephy Pulsar Moscow
Front end ASICs: LAL

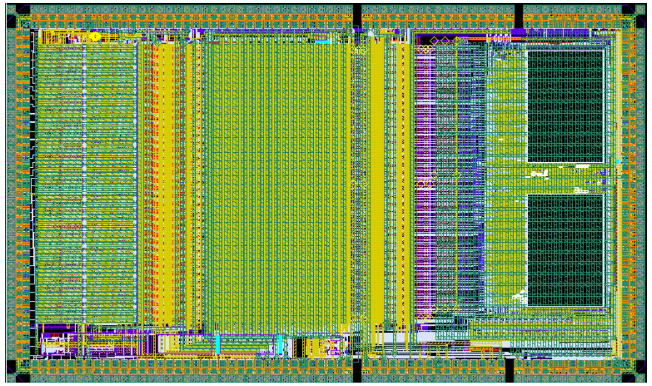
Evolved into SPIROC for ILC calorimetry

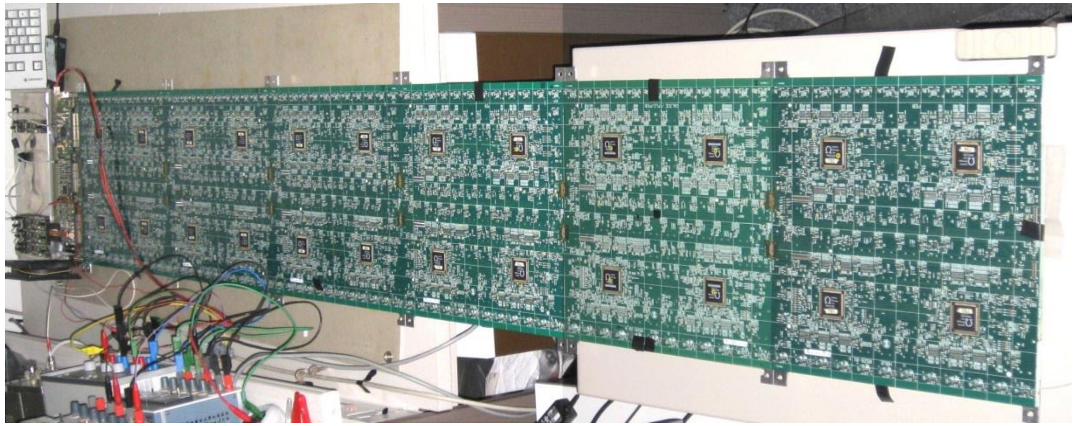
- SPIROC : Silicon Photomultiplier Integrated Readout Chip
  - Developed to read out the analog hadronic calorimeter for CALICE (ILC)
  - DESY collaboration (EUDET project)
  - Chip embedded in detector : low power !

- 36 channels autotrigger 15bit readout
  - Energy measurement : 15 bits in 2 gains
  - Autotrigger down to ½ p.e.
  - Time measurement to ~1ns
  - Power dissipation : 25µW/ch (1% power pulsed)



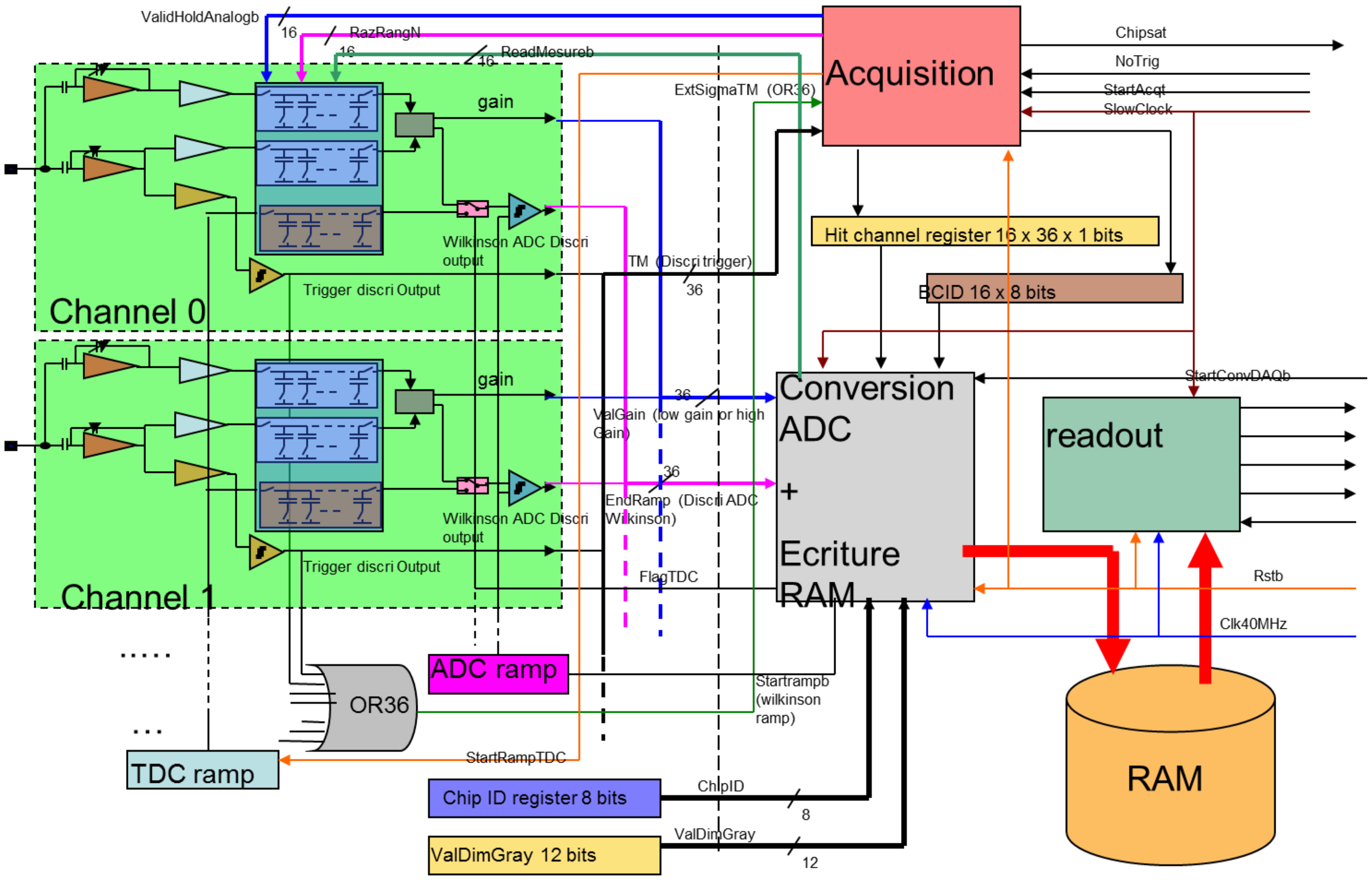
$(0.36m)^2$ Tiles + SiPM + SPIROC (144ch)





SPIROC architecture

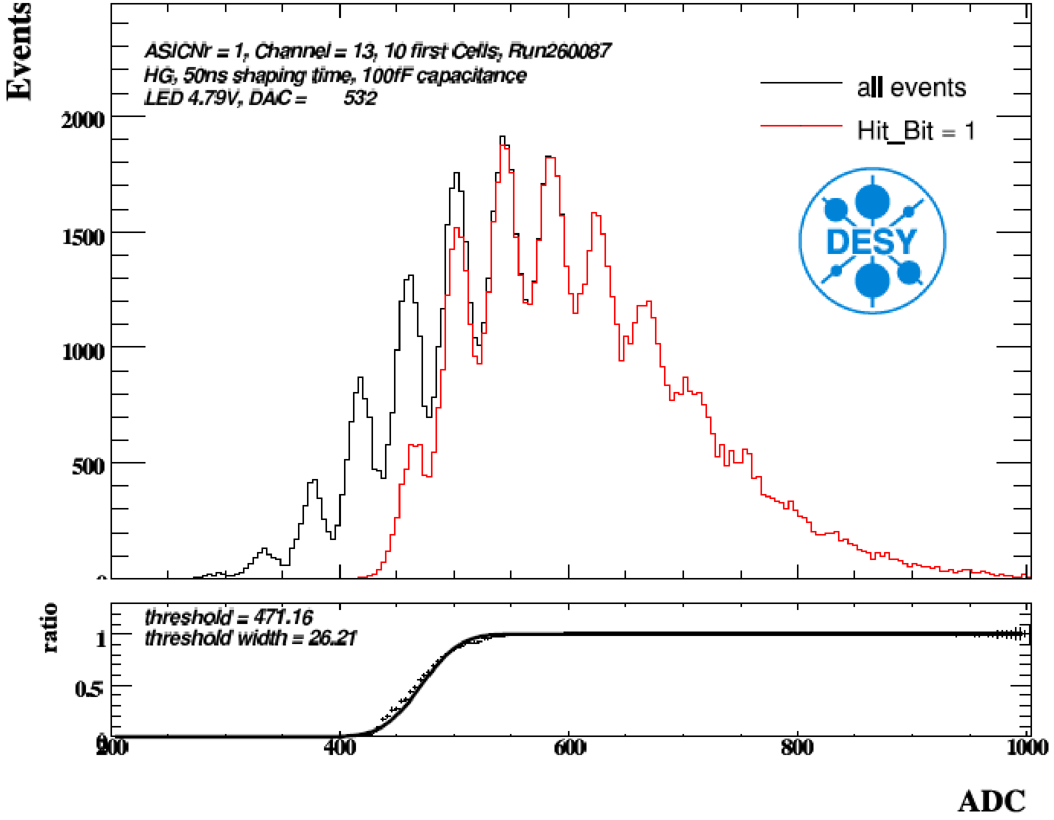
- Dual-gain voltage amplifier
  - Variable gain for HG and LG
- 8-bit input DAC
- 25-50 ns shaping
- Auto-trigger
- 16 bit analog memory
- 2x12 bit Wilkinson ADC
- 12 bit TDC
- 0.5% Power pulsing
  - 5 mW -> 25 µW



ASIC

SPIROC performance

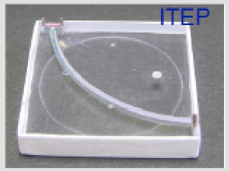
SiPM SPECTRUM with Autotrigger



Progress in SiPM and tiles [F. Sefkow CLIC workshop]

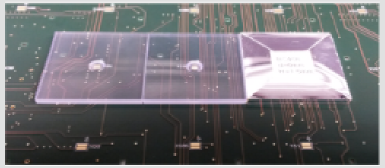
Physics prototype

2006 - 2011



Old ITEP tiles with WLS fibre
1200 px SiPMs

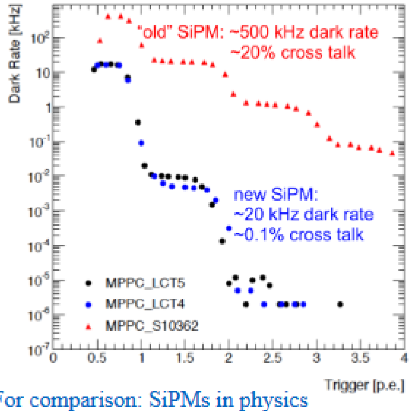
Technological prototype



Surface mounted SiPMs & tiles
- with *MPPC* SiPMs 2700 px

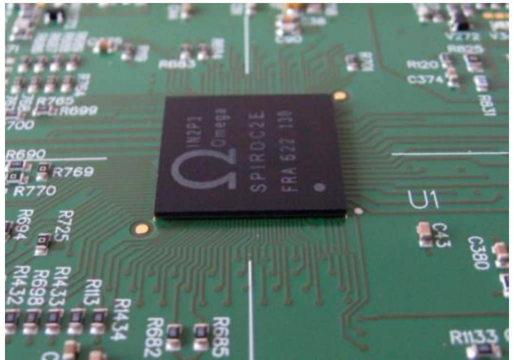
Suitable for automated mass assembly

- SiPMs sensitive to blue light → no need for WLS fibres
- New generation of industrial SiPMs: drastically improved over the past years
  - Dramatically reduced dark rate and increased photon detection efficiency
  - Better signal-to-noise ratio, allows simpler tile design
  - After-pulses and inter-pixel cross-talk largely reduced
  - Noise rate decreases quickly with threshold, much more stable operation
- Excellent uniformity (operating voltage, gain)
  - Simplified calibration
- High over-voltage operation
  - Reduced temperature sensitivity

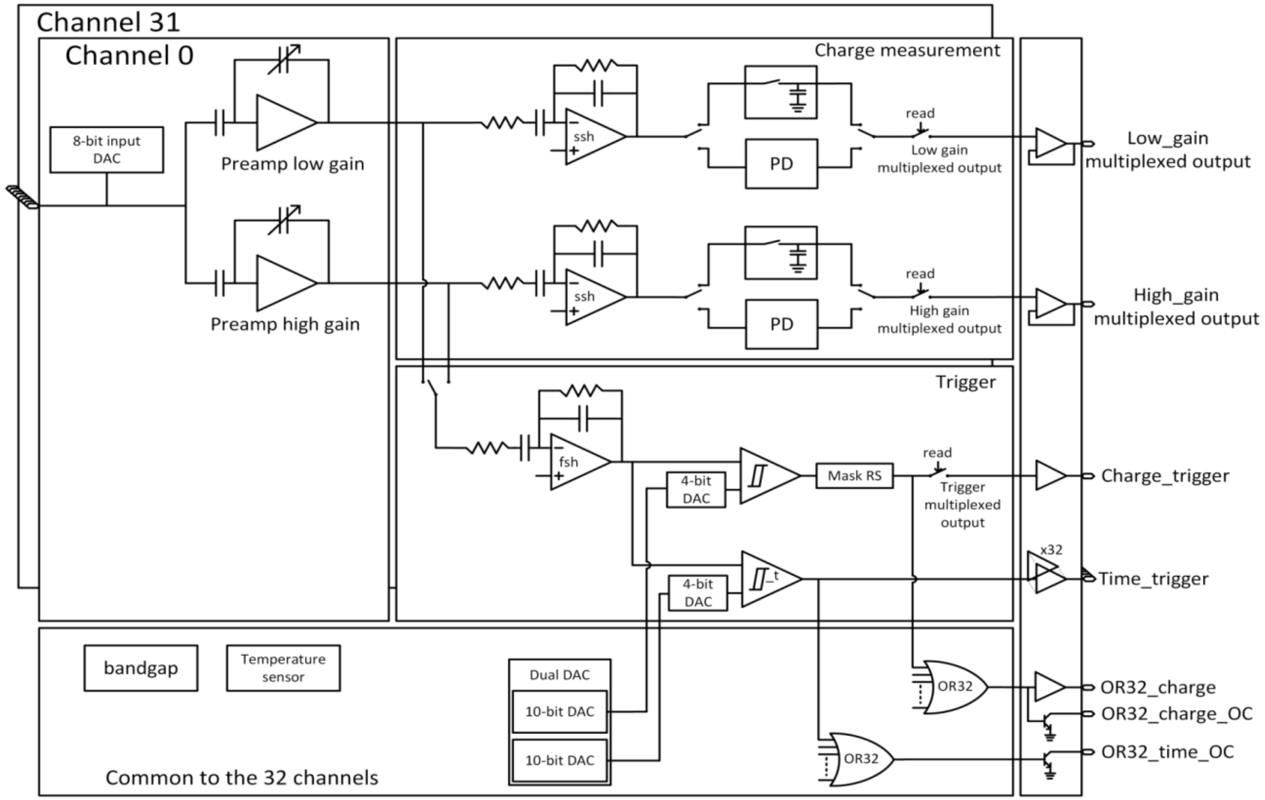


For comparison: SiPMs in physics prototype 2 MHz dark rate, 30% cross talk

New AHCAL prototype   Felix Sefkow   March 8, 2017   4



Variant : CITIROC for CTA ASTRI collaboration

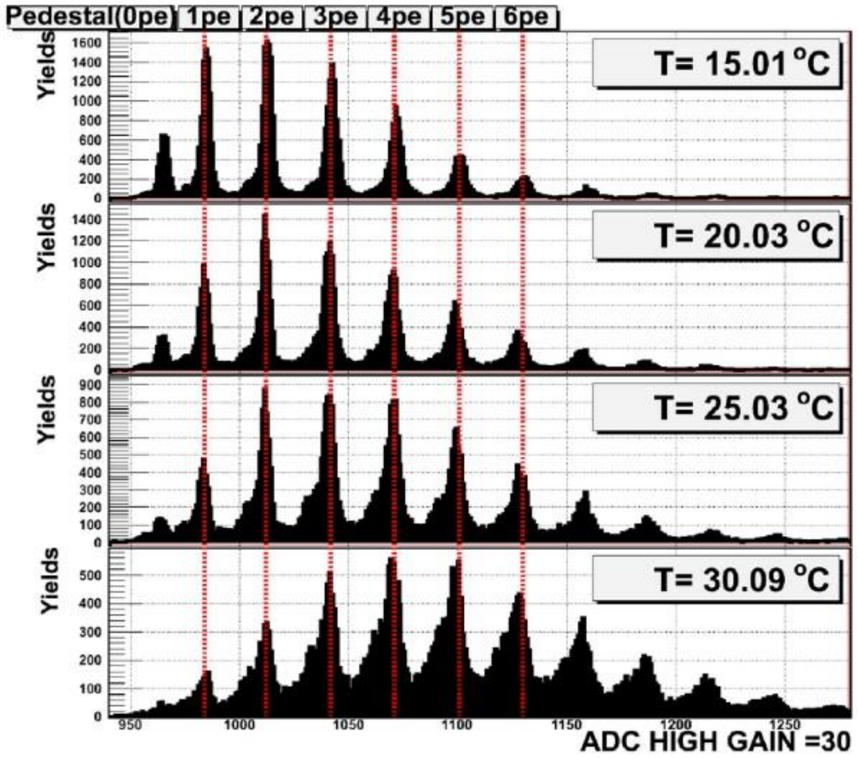


Scientific instrumentation SiPM read-out chip

Detector Read-Out	SiPM, SiPM array
Number of Channels	32
Signal Polarity	Positive
Sensitivity	Trigger on 1/3 of photo-electron
Timing Resolution	100 ps RMS on single photo-electron
Dynamic Range	0-400 pC i.e. 2500 photo-electrons @ 10^6 SIPM gain
Packaging & Dimension	LQFP 160 – TFBGA353

CITIROC performance [ASTRI]

- Extensive tests at INAF Palermo
- Peak sensing allows to capture signals even out of phase



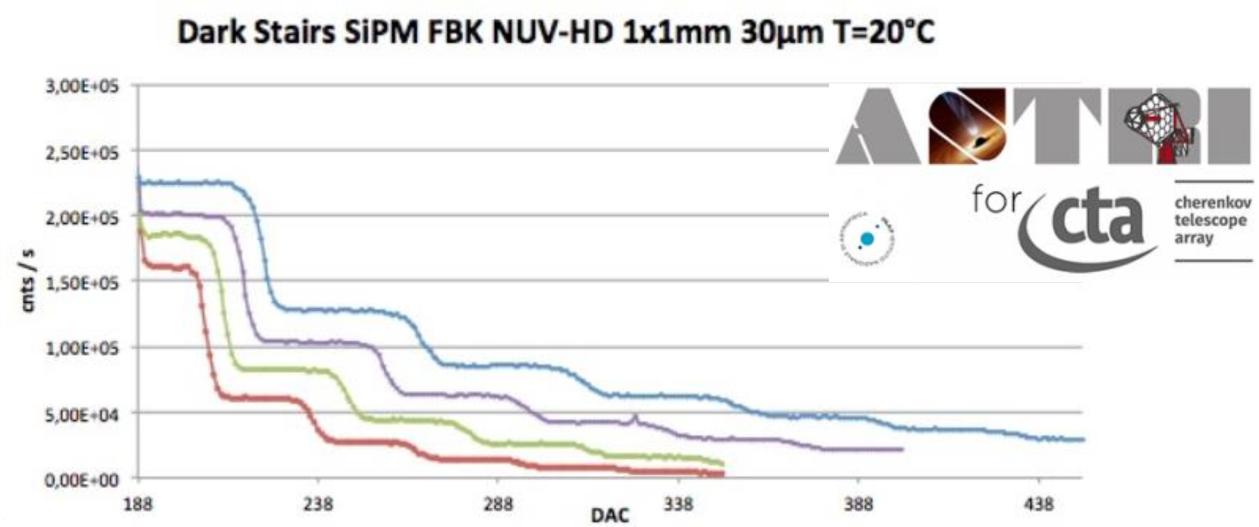
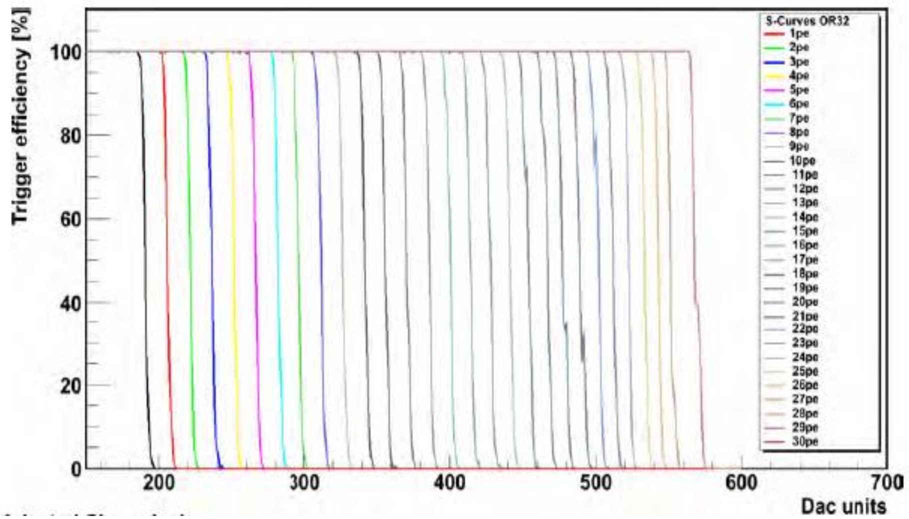
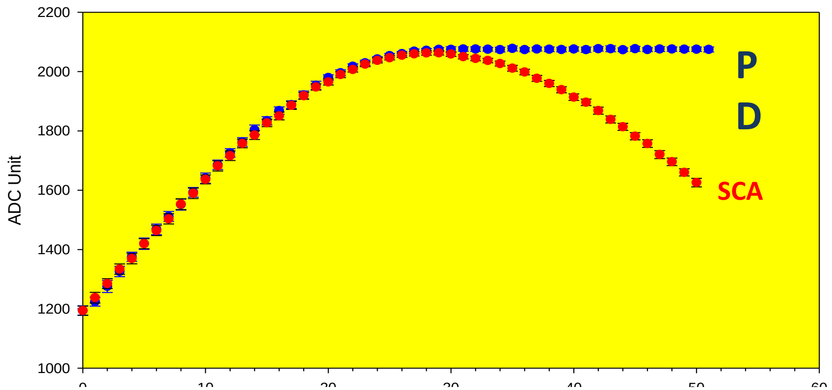


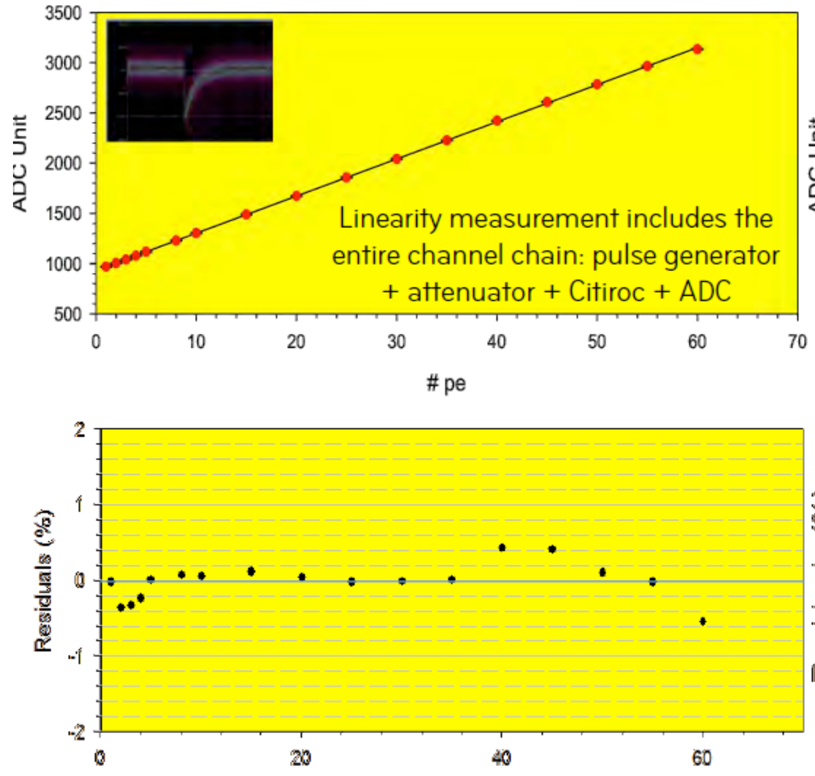
Figure 4. FBK NUV-HD 1×1mm² Staircase at 20°C and at different overvoltages wit the use of the CITIROC.

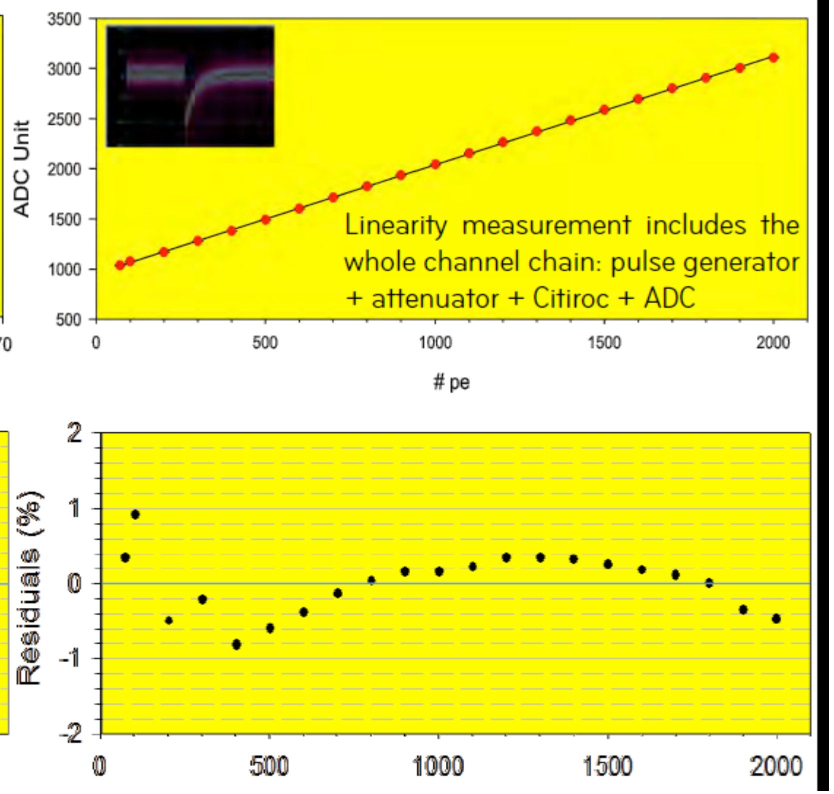


- Linearity
- High Gain 0-60 pe
- Low Gain 0-2000 pe

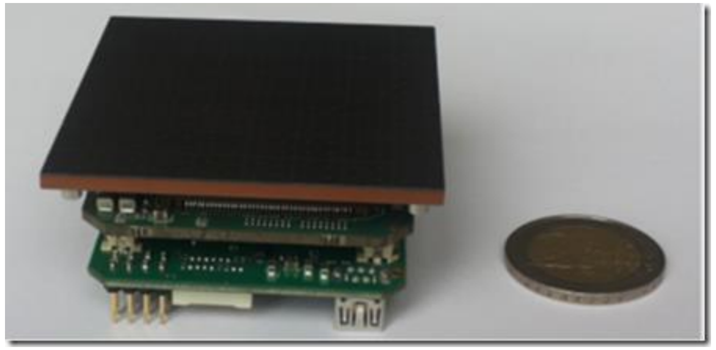


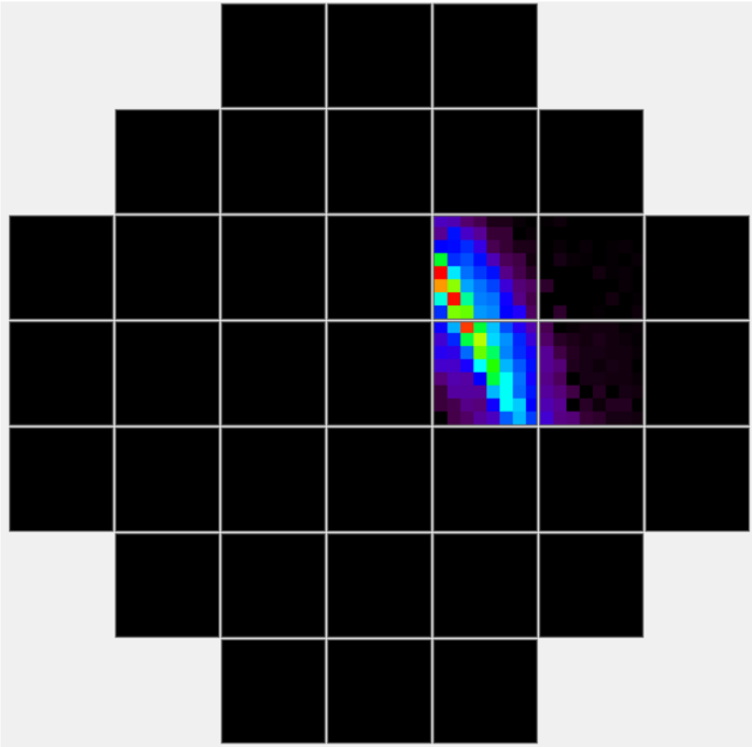
© O. Cataneo INAF Palermo

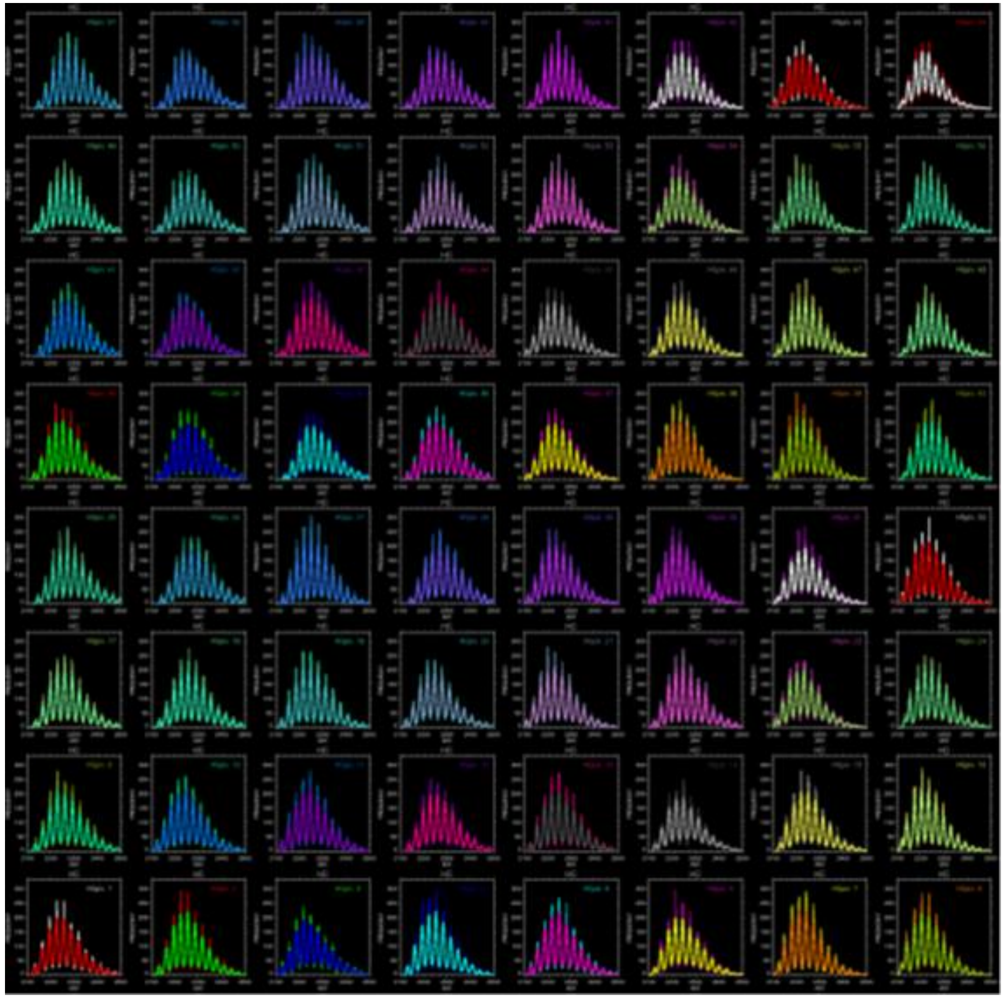




Calibration – one PDM – 64 channels







Courtesy Osvaldo Catalano, IASF Palermo / ASTRI collaboration / CTA

Timing optimization : getting the speed

$$\sigma_t^J = \frac{N}{\frac{dV}{dt}}$$

- Jitter due to electronics noise:
- also presented as j = tr / (S/N)
- dV/dt prop to BW, N prop to √ BW => jitter prop to 1/√BW

⇒ « the faster the amplifier the better the jitter ? »

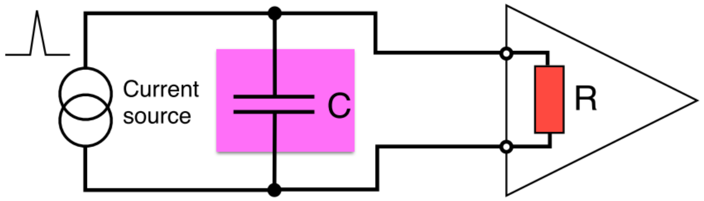
⇒ « High speed preamps need to be low impedance (50 Ω or less) »

NB : tr = $t_{10\text{-}90\%}$ = 2.2 tau.

f_{-3dB} = 1/2πtau = 0. 35 / $t_{10\text{-}90}$

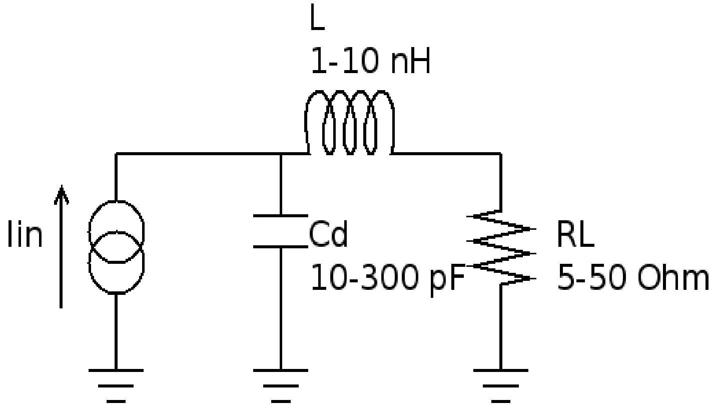
f_{-3dB} = 1 GHz <-> $t_{10\text{-}90\%}$ = 300 ps

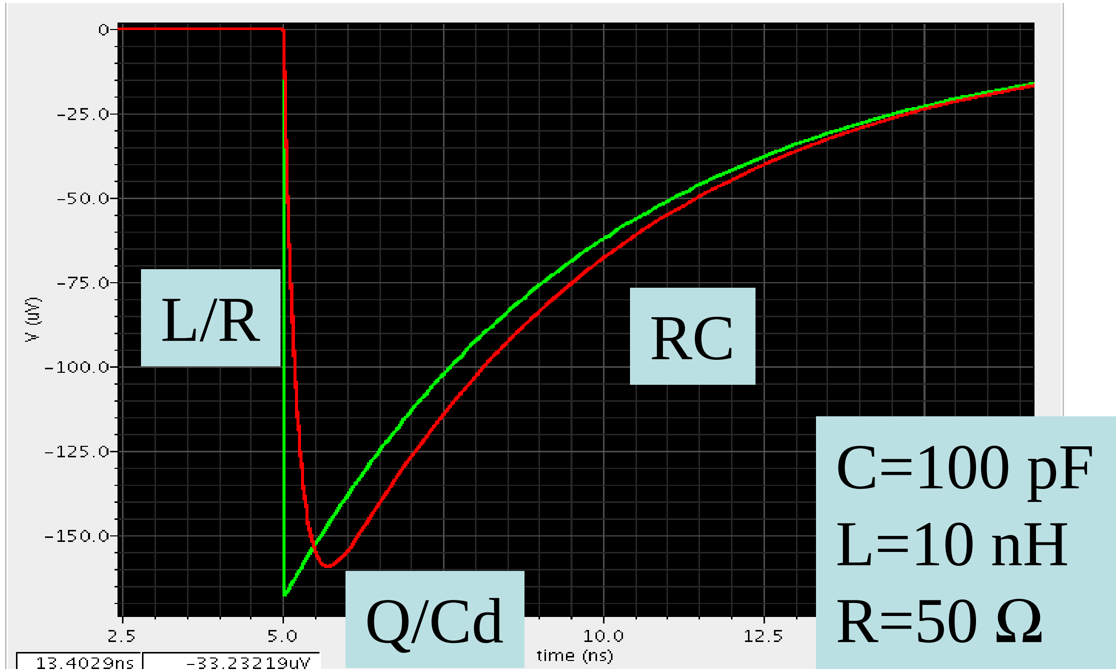
1 ps = 300 µm in vaccum

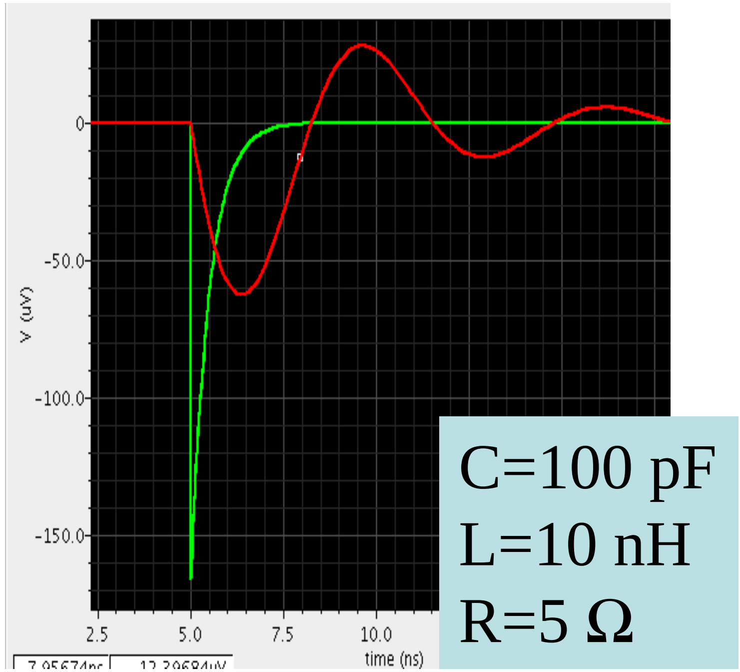


Preamp input impedance : examples of pulse shapes

- SiPM pulse : Q=160 fC, Cd=100 pF, L=0-10 nH, R_{PA}=5-50 Ω
- Sensitivity to parasitic inductance : 1 mm = 1 nH
- Choice of R_{PA} : decay time, stability
- Small R_{PA} not necessarily the fastest
- Convolve with current shape… (here delta)



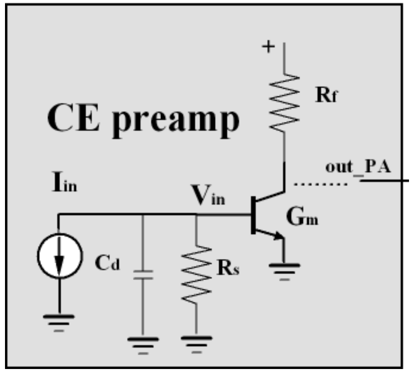




Jitter optimization

- Jitter is given by [details in backup] :

$$\sigma_t^J = \frac{N}{dV/dt} = \frac{e_n}{\sqrt{2t_{10-90\_PA}}} \frac{C_d\sqrt{t_{10-90\_PA}^2 + t_d^2}}{Q_{in}} = \frac{e_n C_d}{Q_{in}} \sqrt{\frac{t_{10-90\_PA}^2 + t_d^2}{2t_{10-90\_PA}}}$$



- Optimum value: $t_{10\text{-}90\_PA} = t_d$ (current duration)

$$\sigma_t^J = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

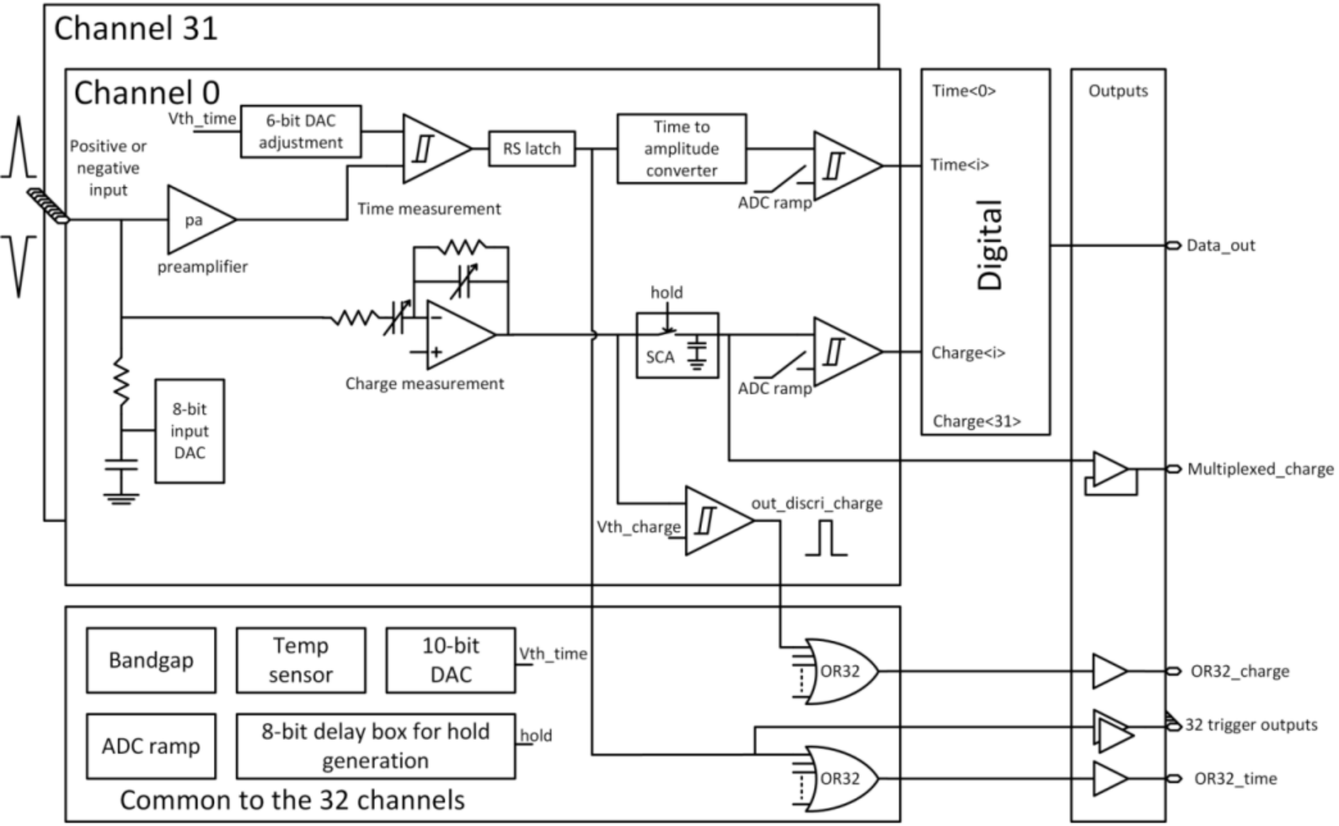
Cd: detector capacitance
$t_{10\_10\_PA}$: rise time of the PA
t_d= drift time of the detector
e_n preamp noise density

Dominated by sensor
Electronics only gives the spectral density of the input transistor e_n

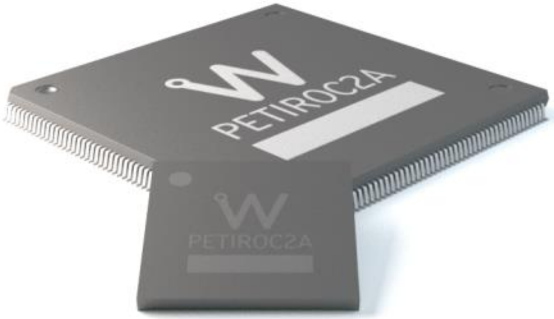
- Gives ps/fC as scales with 1/Qin en~1 nV/

- SiPMs should be particularly good because Qin is large and td is small, but Cd is not so small…
- With SiPM G = 1E6 C_d = 300 pF e_n = 1 nV/√Hz t_d = 100 ps expect : σ = 3 ns/Q(fC)
  - 1 pe = 160 fC => σ = 20 ps/#pe (~60 ps measured)

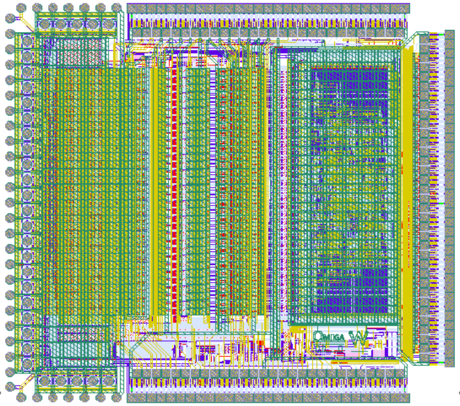
PETIROC2A



SiPM read-out for time-of-flight PET



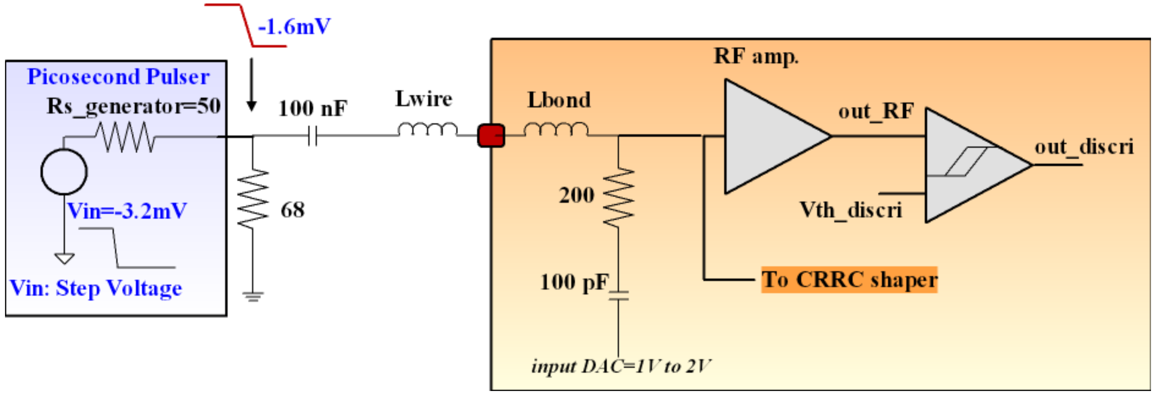
weeroc

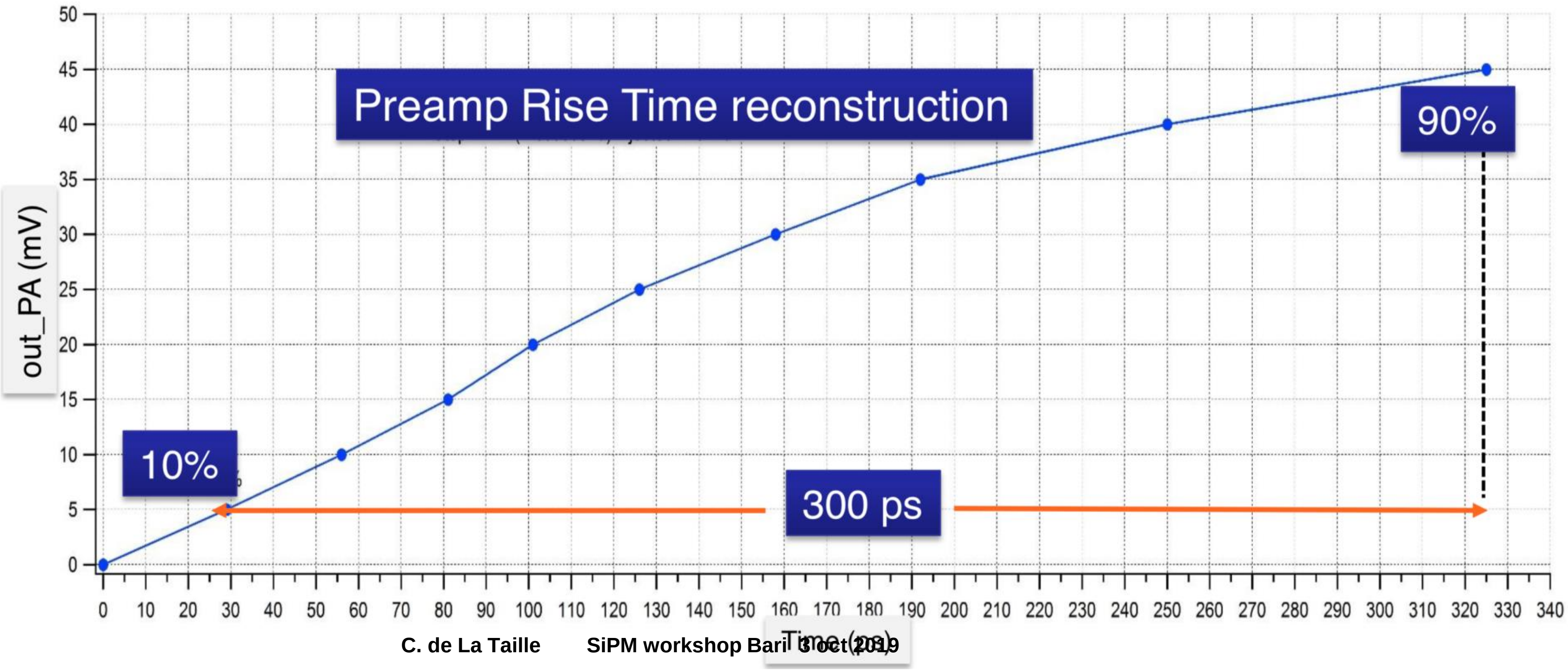


Detector Read-Out	SiPM, SiPM array
Number of Channels	32
Signal Polarity	Positive or Negative
Sensitivity	Trigger on first photo-electron
Timing Resolution	~ 35 ps FWHM in analogue mode (2pe injected) - ~ 100 ps FWHM with internal TDC
Dynamic Range	3000 photo-electrons (10^6 SIPM gain), Integral Non Linearity: 1% up to 2500 ph-e
Packaging & Dimension	TQFP160 – TFBGA353

Petiroc2A bandwidth measurement

- Preamp + discriminator bandwidth
- reconstruction of pulse by discriminator
- **tr 10%-90% = 300 ps,**
- **BW = 0.35 / tr ~ 0.9 GHz**
- can also use BW = 0.1 / ($t_{50\%}$ - $t_{10\%}$)





Petiroc 2A Operation Modes

Omega

Photon Counting

- No system clock in the chip
- Fast preamplifier & fast discriminator
- Programmable threshold
- 32 trigger outputs
- Photon counting on each channel on trigger rising edge
- Time-Over-Threshold possible
- 120 MHz max rate

Analogue Read-out

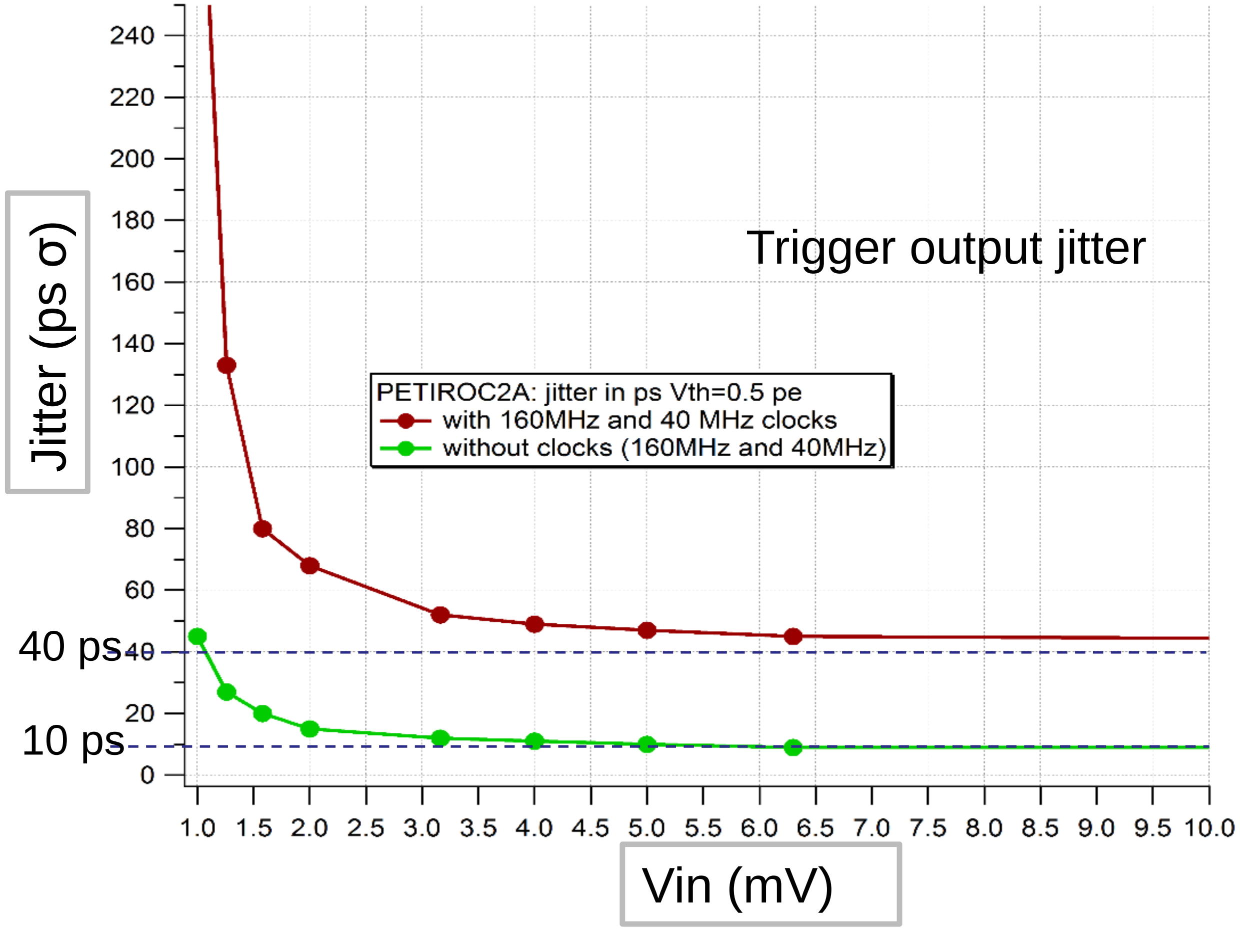
- No system clock in the chip
- Asynchronous
- 32 triggers outputs
- analogue multiplexed output
- Trigger OR, two thresholds
- External TDC and ADC required
- Count rate 500 kCPS

Digital Read-out

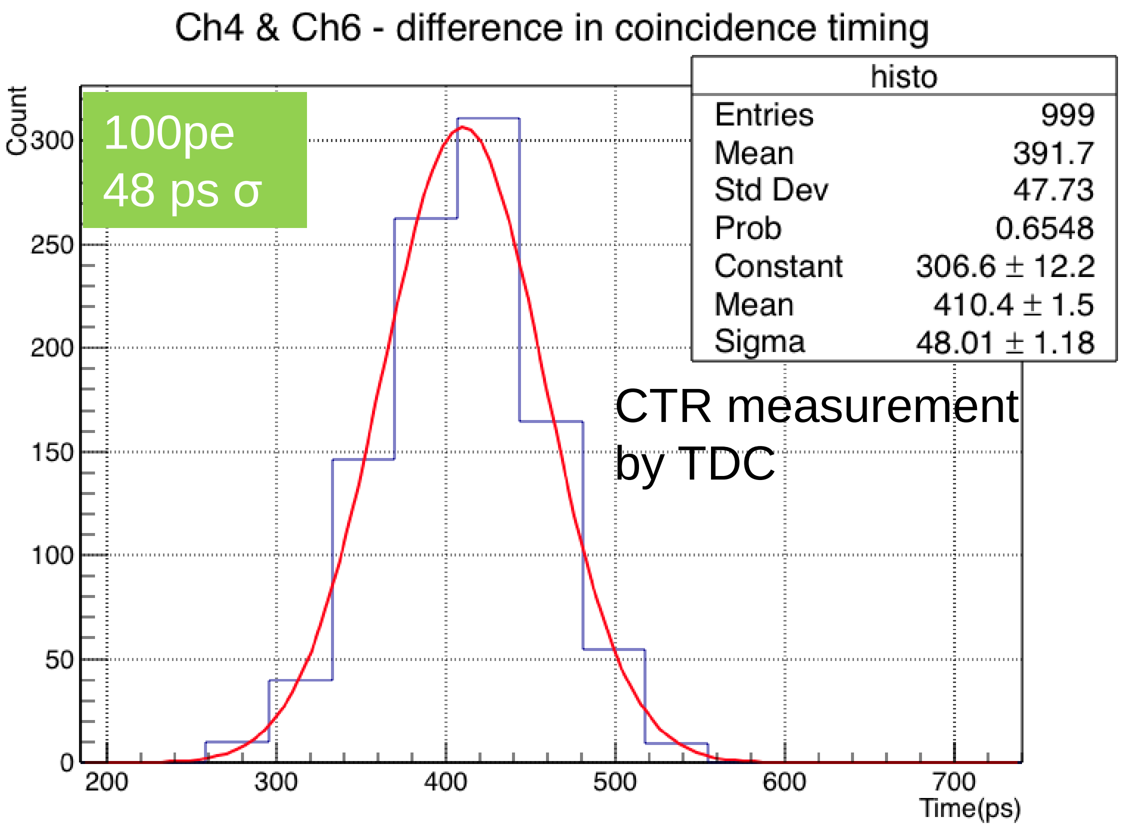
- All conversion inside Petiroc
- One wire serial data out
- Two trigger level
- No zero suppression
- Backend controlled by DAQ
- Count rate 40kCPS

Petiroc2A characterization results - Time

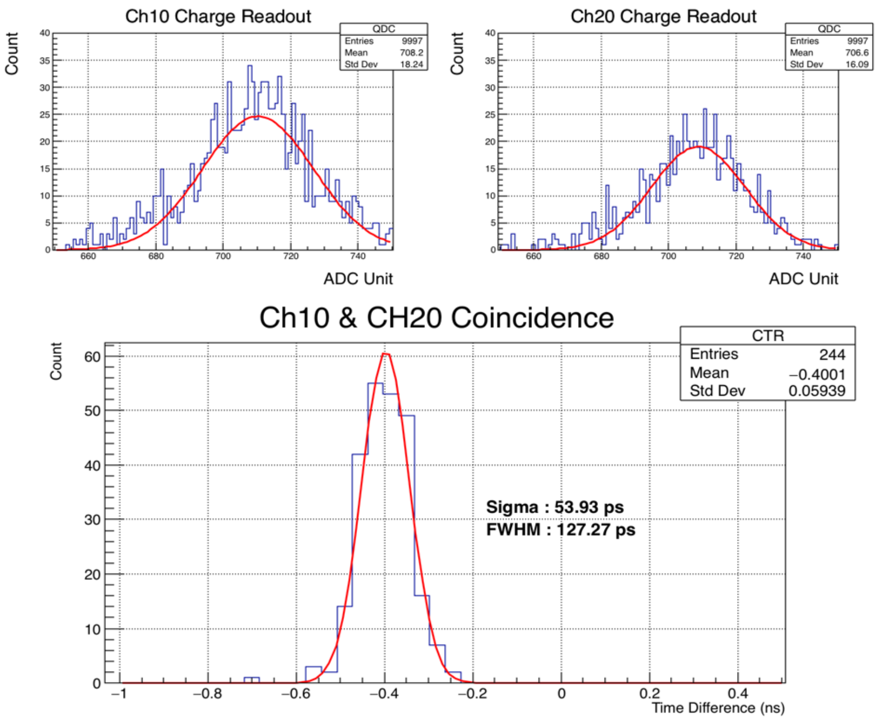
- Jitter vs threshold & pulse injection,
- Clock couplings: through substrate
- Jitter < 40 ps σ for input pulse > 1mV

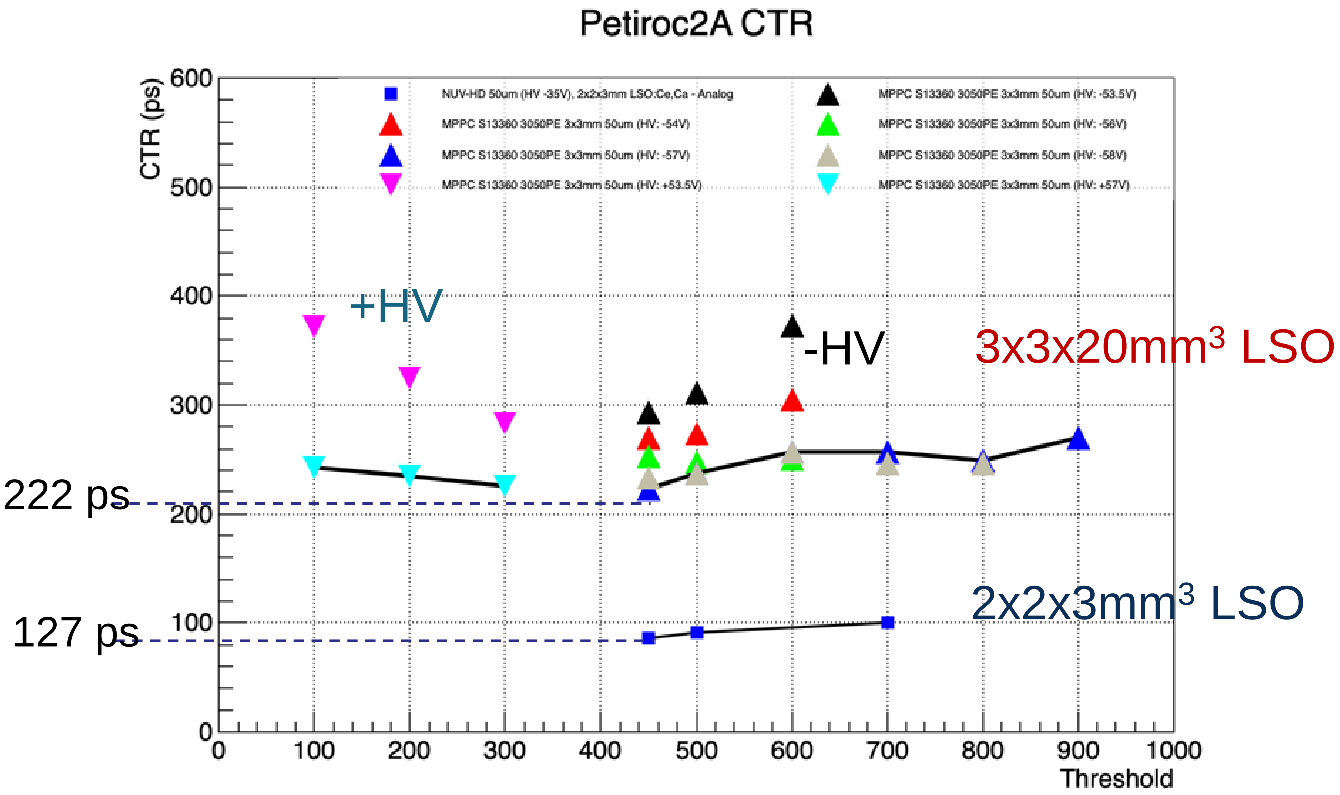


- Coincidence measurement with internal TDC
- Synchronous pulse injection – Ideal case scenario
- Constant term : ~48 ps σ



CTR measurement : Petiroc2A TDC (internal)





NUV-HD & 2x2x3m^3 LSO:Ce,Ca : 127.3 ps FWHM

Source : Na22

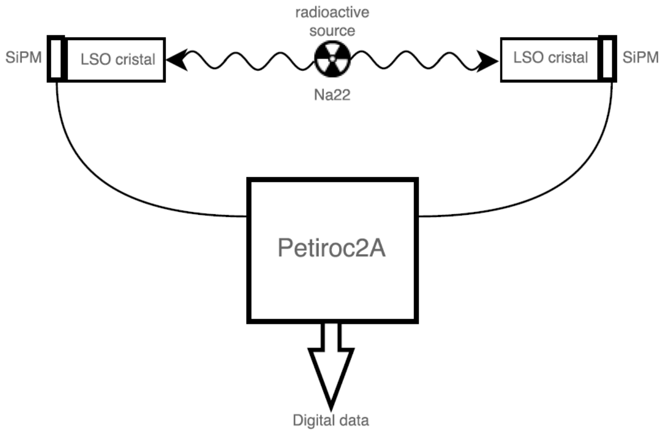
Scintillator : 2x2x3mm^3 / 3x3x20mm^3 LSO:Ce codoped Ca

SiPM : FBK NUV-HD 4x4 mm^2 40um

Hamamatsu MPPC S13360 3050PE 3x3 mm^2 50um

HV : Various values

Thanks to S. Gundaker and E. Auffray for their help in the measurements



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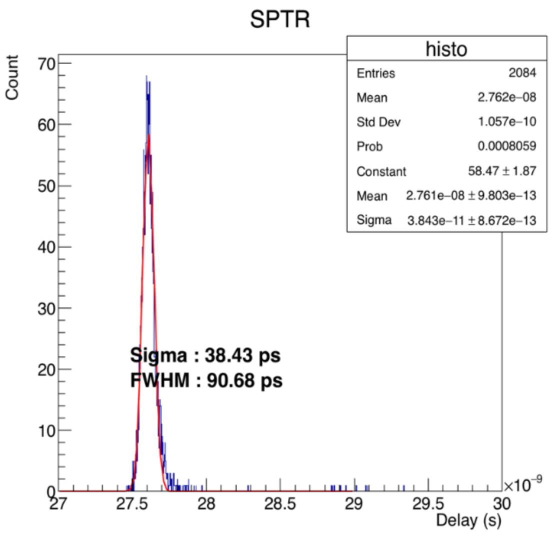
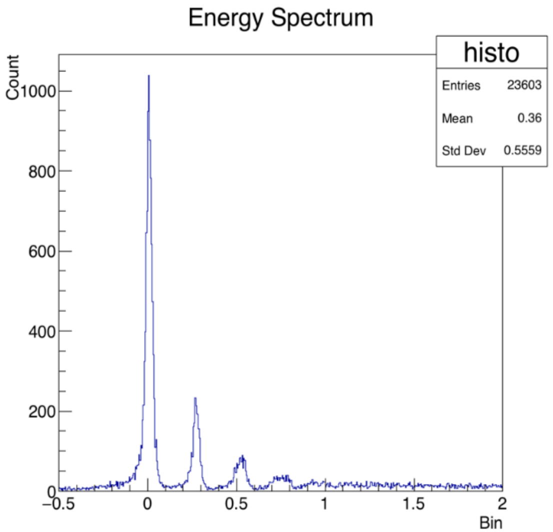
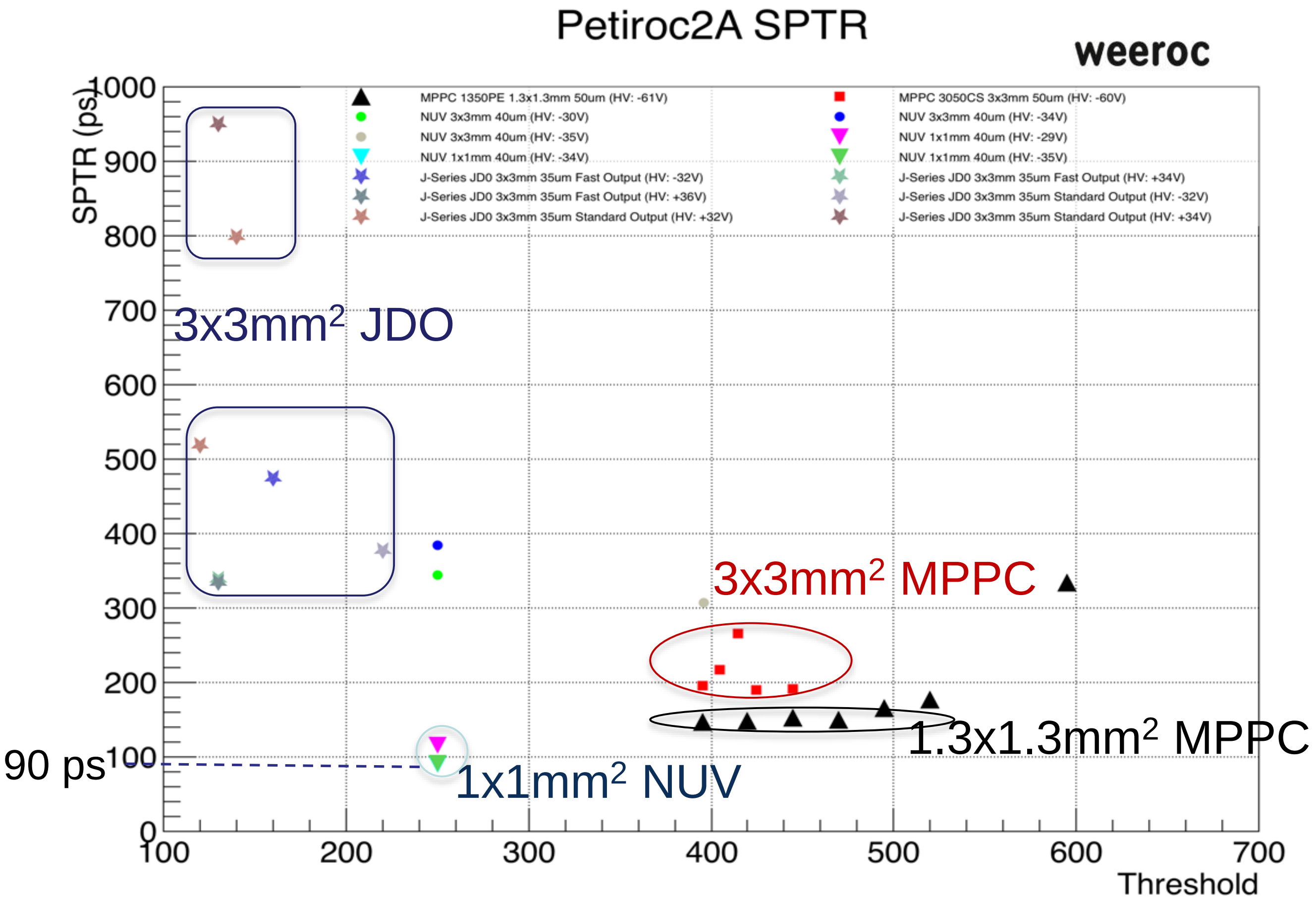
SPTR measurement : Petiroc2A trigger outputs

- SPTR : 90 ps FWHM (40 ps rms)



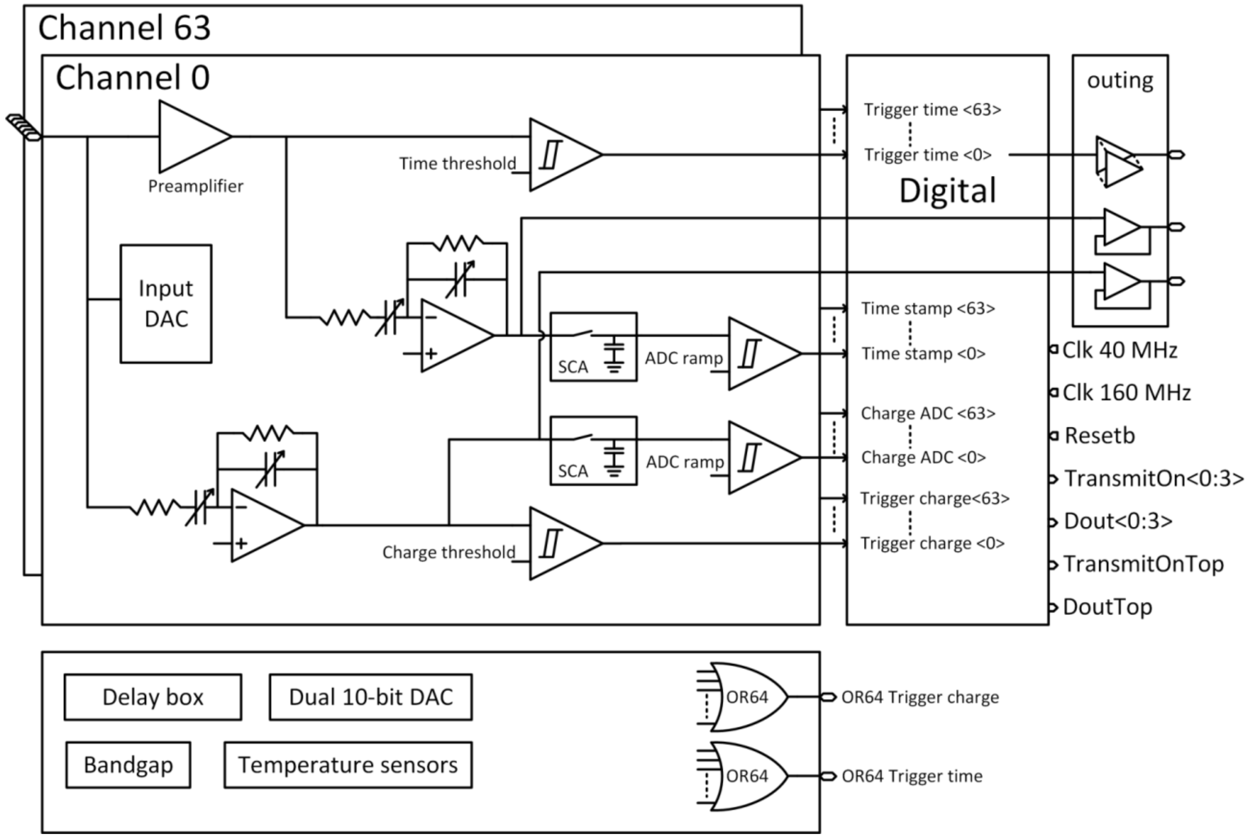


FBK NUV 1x1 mm^2 : 90.7 ps FWHM

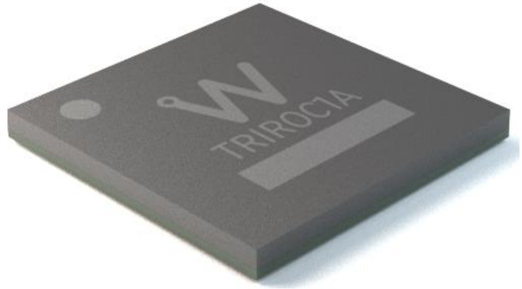


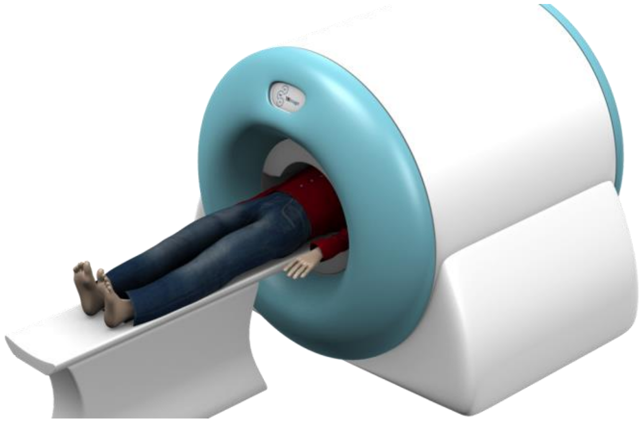
Source : Laser
SiPM : Various model (FBK, Hamamatsu, Sensl)
HV : Various value

TRIROC



All-in-one SiPM read-out for multimodal PET inserts





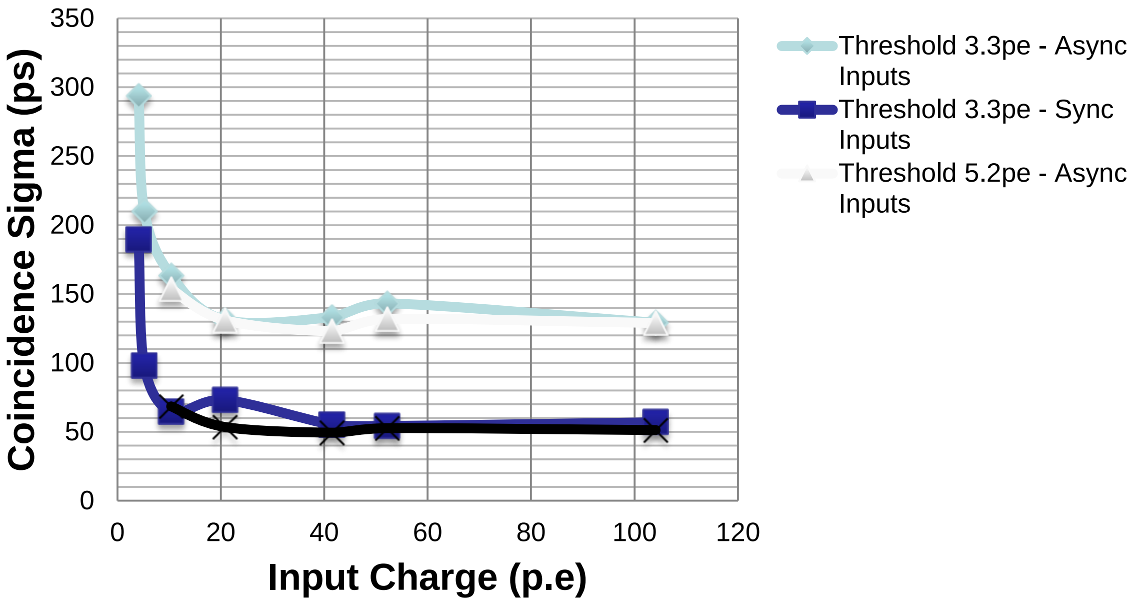
weeroc

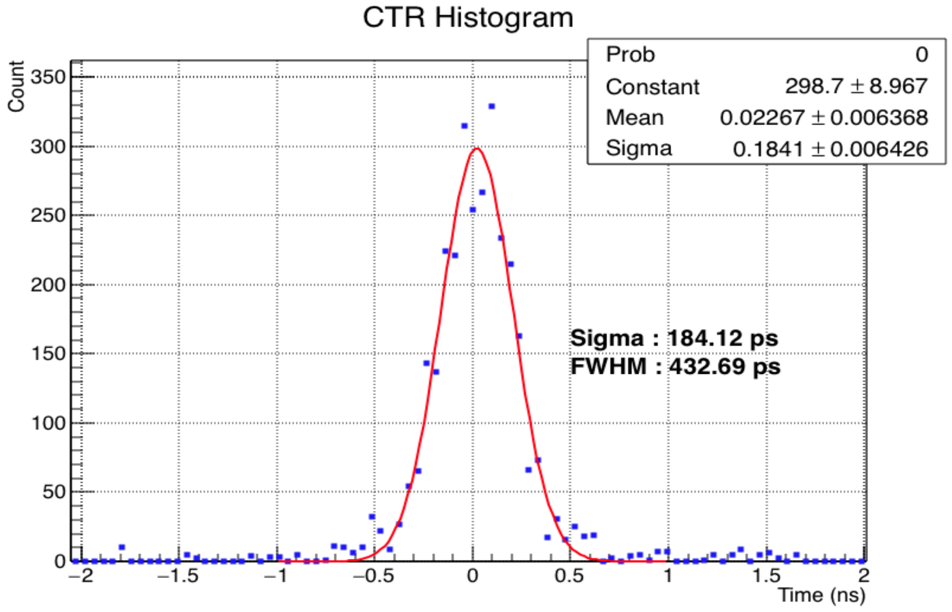
SEVENTH FRAMEWORK PROGRAMME

Detector Read-Out	SiPM, SiPM array
Number of Channels	64
Signal Polarity	Positive or Negative
Sensitivity	Trigger on first photo-electron
Timing Resolution	~20 ps trigger jitter, ~430ps FWHM (internal TDC)
Dynamic Range	3000 photo-electrons (10^6 SIPM gain), Integral Non Linearity: 1% up to 2000 ph-e
Packaging & Dimension	BGA (12x12mm, 393 balls)

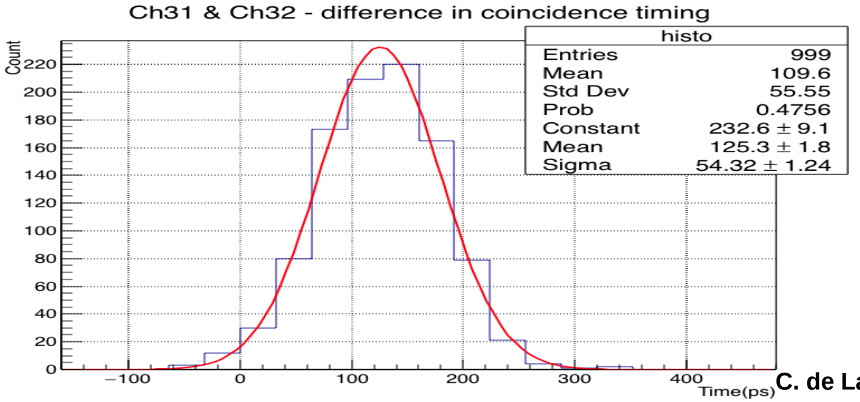
Timing resolution : test pulse and full system CTR

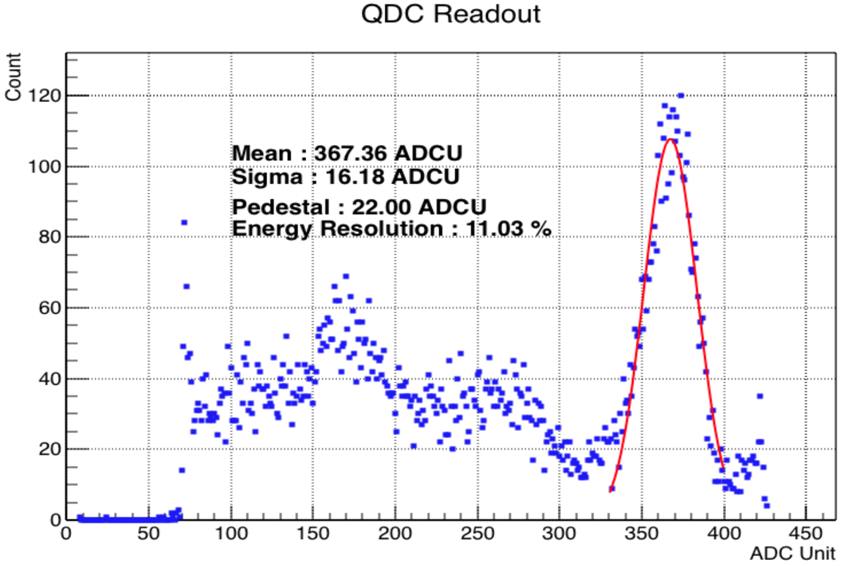
2 channels coincidence





- Two channels of Triroc are fired by fast test pulse
- TDC output is compared
- Sync measurement correspond to perfect calibration
- Async measurement correspond to no calibration

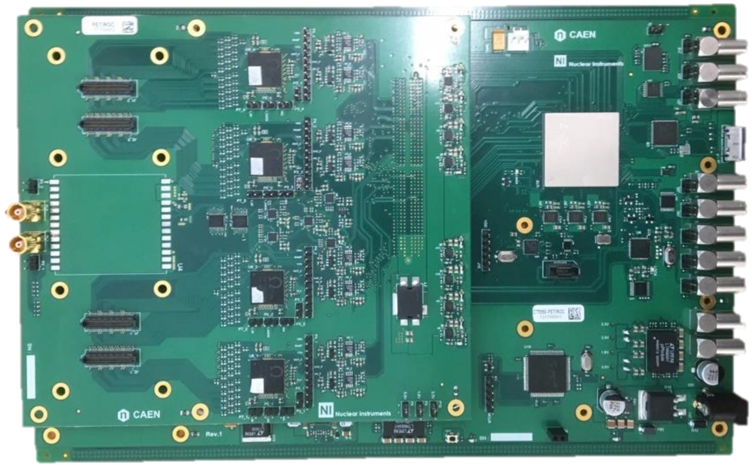


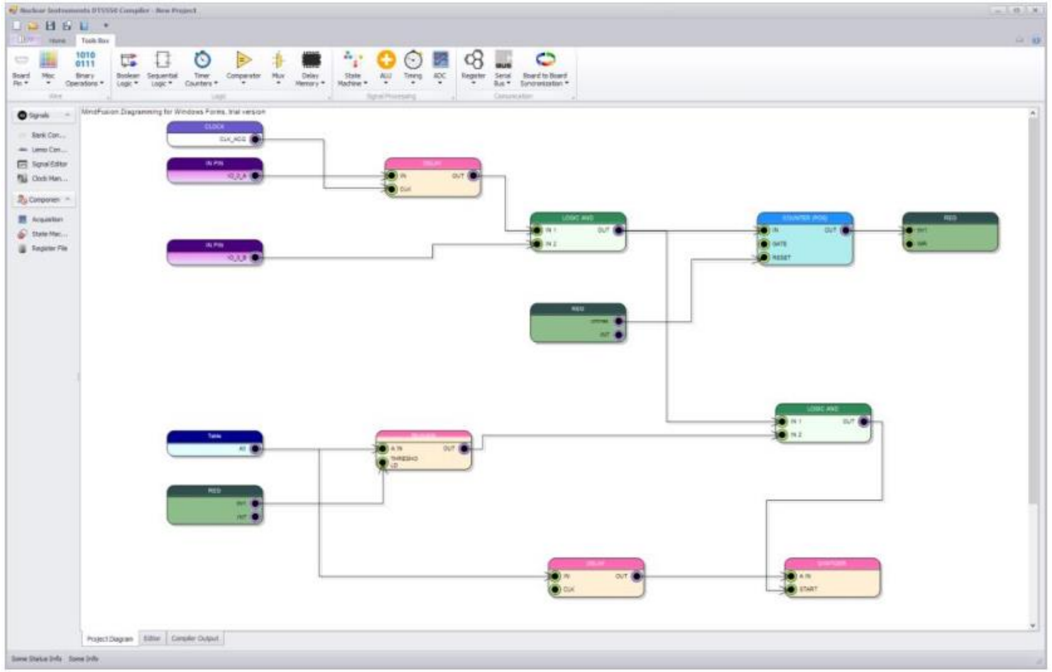


DT 5550W from CAEN

- Transfer to industry

128-channel – 4 Petiroc 2A Hi performance evaluation system
Easy firmware design
Released summer 2017



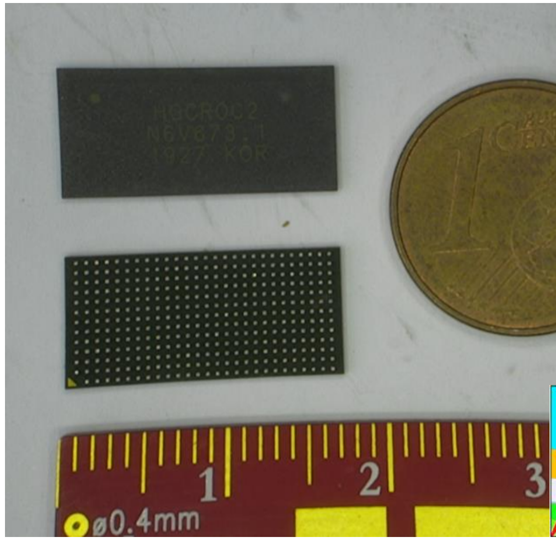


Nuclear Instruments

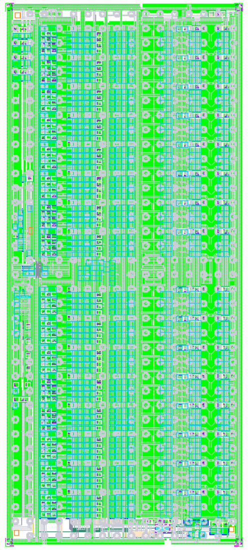
CAEN
Tools for Discovery

coming up : H2GCROC & LIROC

- Omega strongly involved in LHC ATLAS & CMS upgrades
- H2GCROC : Hadronic High Granularity Calorimeter Read Out Chip
  - 78 channels with current conveyor « à la KLAUS [U. Heidelberg] »
  - ADC + TDC
  - Collaboration : AGH, CEA, CERN, Imperial, OMEGA



- LIROC : ATTRACT project for space based LIDAR
  - 64 high speed amplifiers/discriminators « à la petiroc »
  - 1 GHz bandwidth
  - 2 ns double pulse resolution
  - SEU hardened
  - Flip chip on BGA 0.8 mm pitch



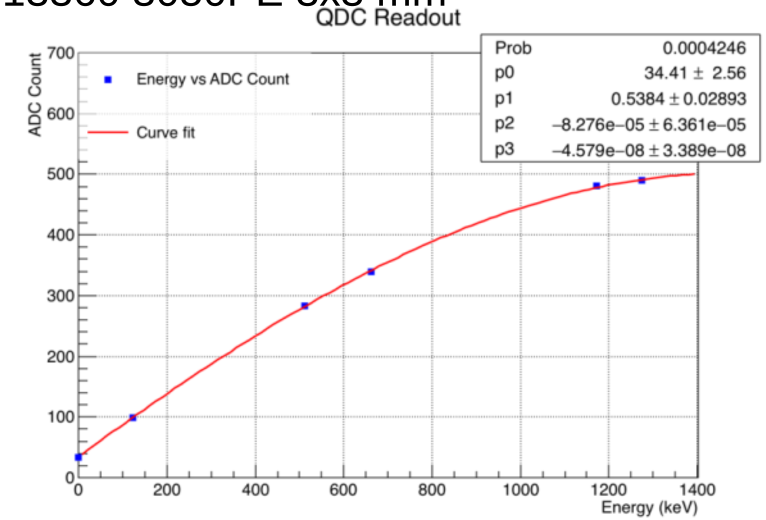
- CMOS 130 nm process rad hard up to 300 MRad

- Several SiPM chips developed at OMEGA for HEP
- SPIROC tested extensively on ILC R&D by DESy et al.
  - Also equips Wakashi detector on T2K
- Variants developed and transfered from HEP to WEEROC / CAEN
  - EASIROC equips E40 experiment in Japan
  - CITIROC equips ASTRI CTA SST, T2K…
- PETIROC and TRIROC developed for PET applications
  - 1 GHz bandwidth for 10-100 ps timing accuracy
- Thousands of chips fabricated in SiGe 350 nm
- Next generation : HGCROC, LIROC, SPACIROC….

backup

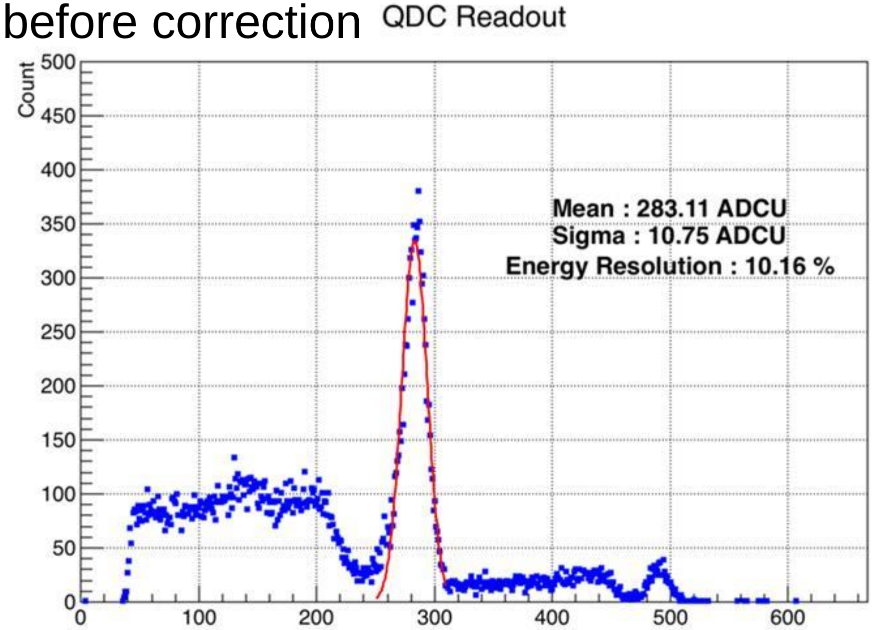
Petiroc 2A energy resolution

Scintillator : 3x3x20mm LSO:Ce codoped Ca (TBC)
SiPM : Hamamatsu MPPC S13360 3050PE 3x3 mm 50um

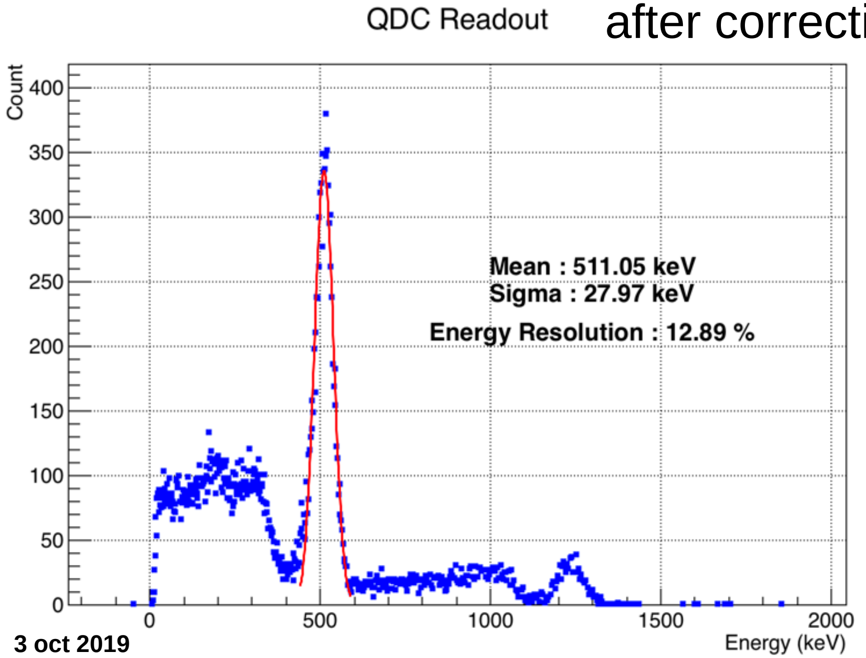


Isotope	Photopeak	energy (MeV)
Na22	1	0,511
Na22	2	1,274
Co60	1	1,173
Co60	2	1,332
Cs137	1	0,662
Co57	1	0,122

Na22 spectrum before correction

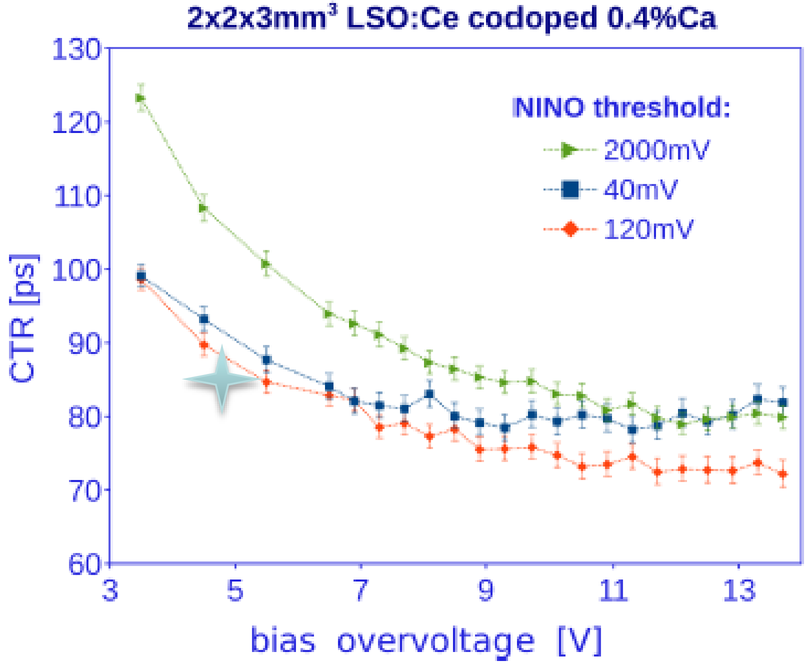


Na22 spectrum after correction

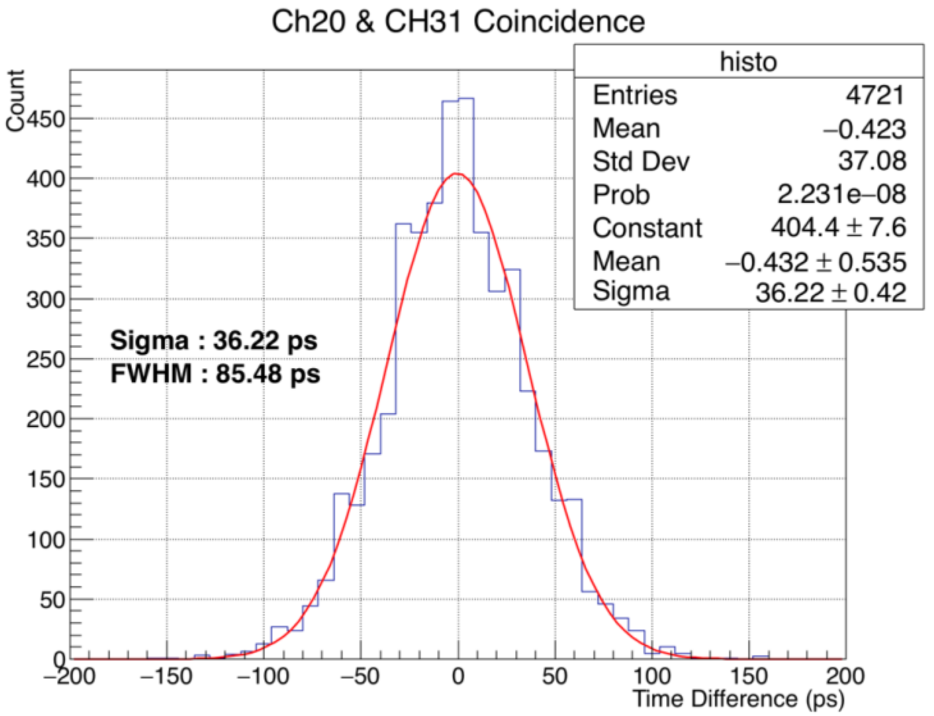


Petiroc 2A – CTR measurement, analog mode

Petiroc2A Threshold	Digital Part	CTR (FWHM)
450	OFF	85.48 ps
500		91.91 ps
700		100.57 ps
450	ON	125.07 ps
500		104.07 ps

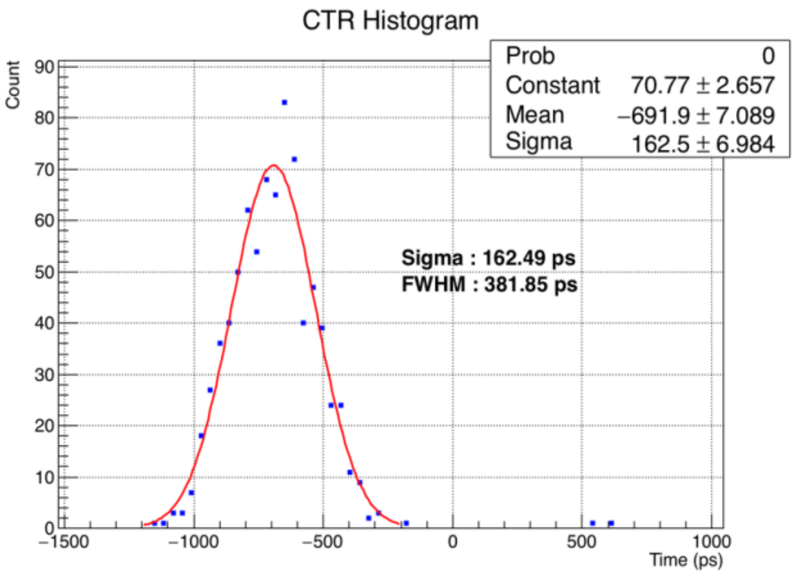


State of the art timing in TOF-PET detectors with LuAG, GAGG and L(Y)SO scintillators of various sizes coupled to FBK-SiPMs
S. Gundacker & Al, CERN

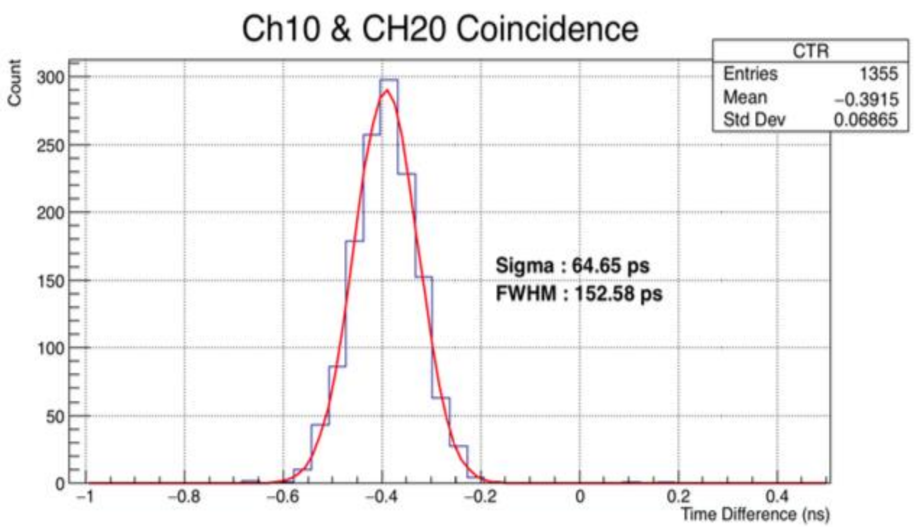


Source : Na22
Scintillator : 2x2x3mm LSO:Ce codoped Ca
SiPM : Advansid/FBK NUV-HD 40um
HV : 35V
FWHM : 85ps

Petiroc 2A – CTR measurement : digital mode



Source : Na22
Scintillator : 3x3x20mm LSO:Ce codoped Ca
SiPM : MPPC S13360 3050PE 3x3 mm 50um
HV : 54V
FWHM : 380ps

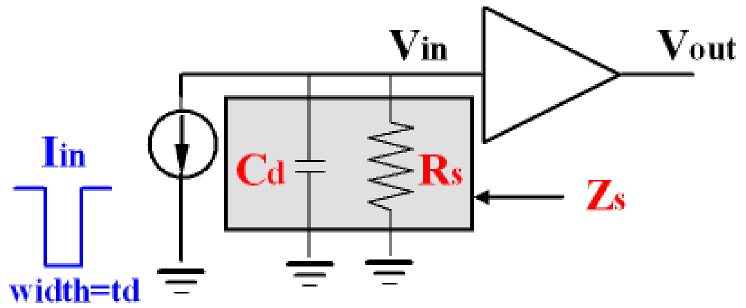


Source : Na22
Scintillator : 2x2x3mm LSO:Ce codoped Ca
SiPM : Advansid/FBK NUV-HD 40um
HV : 35V
FWHM : 220ps

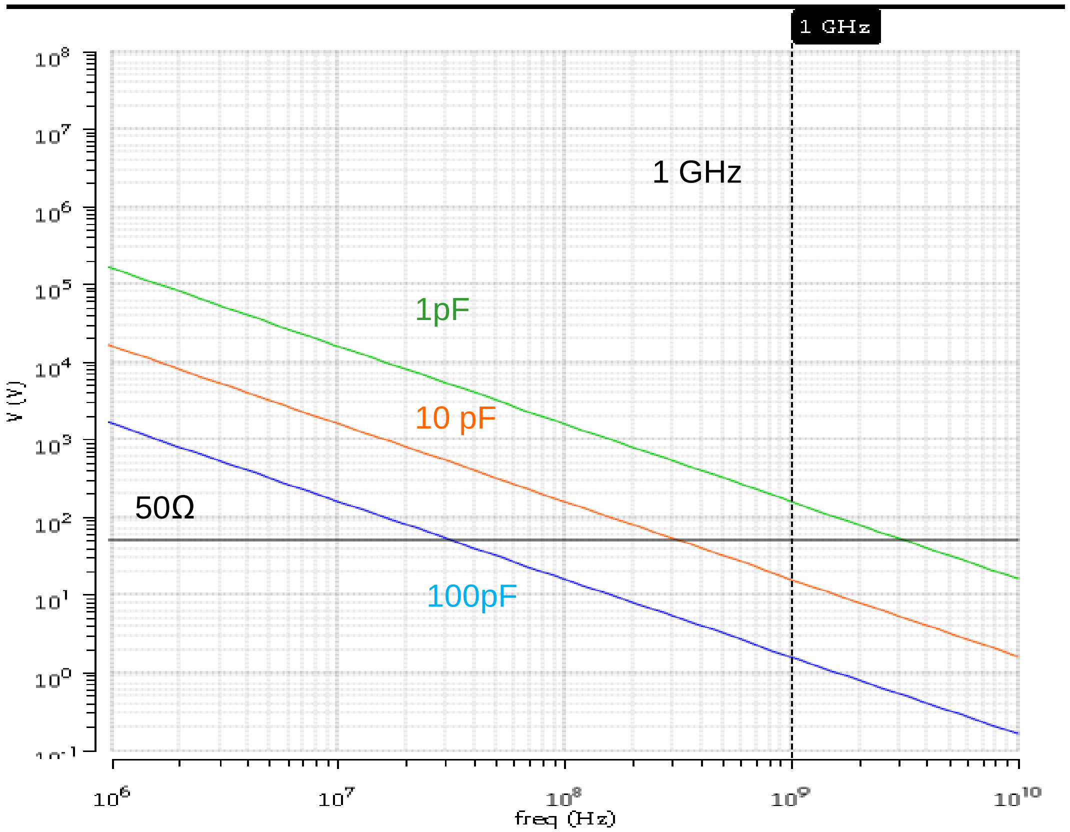
Full system Coincidence Timing Resolution including all errors : from Crystal to data processing in Computer

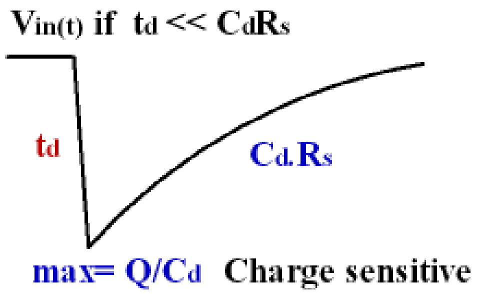
Detector impedance and input voltage

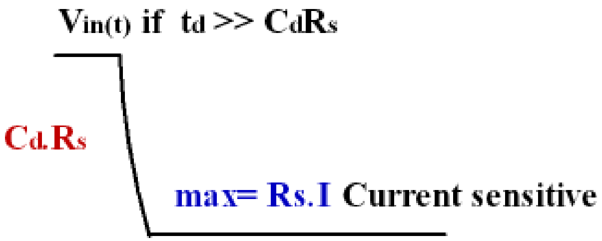
- 1 GHz, Cd=few tens of pF, input signal width <1ns
- Cd>1 pF, Zs@1GHz dominated by Cd
- Rise time: tr= td when td<< $R_S\,C_d$ and tr= $R_S\,C_d$ when td>> $R_S\,C_d$



At HF : difficult to beat the capacitance => signal integrated on Cd



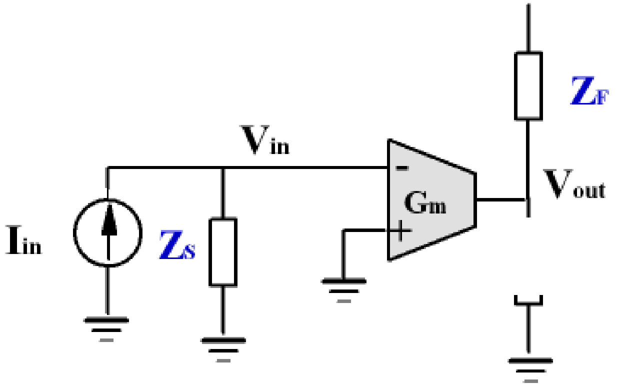




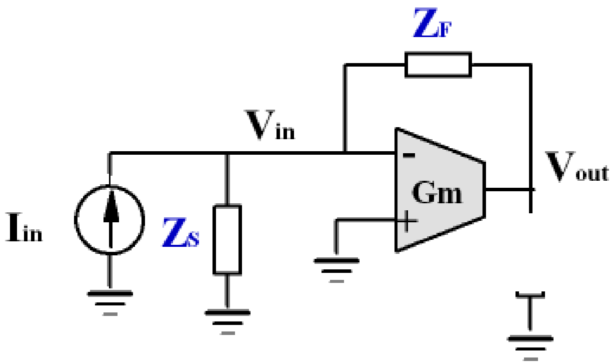
High speed amplifiers

- Response to very short pulse

- Broadband
  - Zin=Rs (50 Ohm)
  - Vin = Q/Cin
  - $V_{OUT} = -G_m R_F \frac{Q_{IN}}{C_d}$



- Transimpedance
  - Zin ~ Zf/G ~ 1/gm
  - $V_{OUT} = \frac{\frac{1}{G_m} - R_F}{1 + j\omega \frac{C_d}{G_m}} I_{IN} \approx -G_m R_F \frac{Q_{IN}}{C_d}$

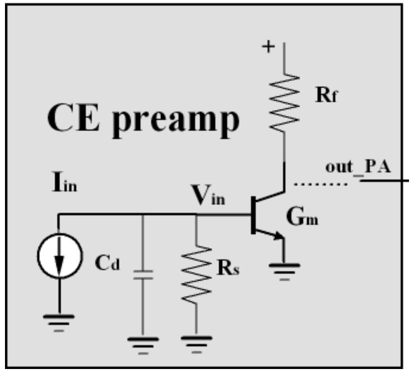


- Same response at High Frequency
- For highest speed : go to broadband. Faster, less stability issues

High speed amplifiers

- Jitter is given by [details in backup] :

$$\sigma_t^{\,J} = \frac{N}{dV/dt} = \frac{e_n}{\sqrt{2t_{10-90\_PA}}}\frac{C_d\sqrt{t_{10-90\_PA}^2 + t_d^2}}{Q_{in}} = \frac{e_n C_d}{Q_{in}}\sqrt{\frac{t_{10-90\_PA}^2 + t_d^2}{2t_{10-90\_PA}}}$$



- Optimum value: $t_{10\text{-}90\_PA} = t_d$ (current duration)

$$\sigma_t^{\,J} = \frac{e_n C_d}{Q_{in}}\sqrt{t_d}$$

Cd: detector capacitance
$t_{10\_10\_PA}$: rise time of the PA
t_d= drift time of the detector
e_n preamp noise density

Dominated by sensor
Electronics only gives the spectral density of the input transistor e_n

- Gives ps/fC as scales with 1/Qin

- Electronics noise e_n given by the input transistor transconductance g_m:

$$e_n = \sqrt{\frac{2kT}{g_m}} \approx \frac{2kT}{\sqrt{qI_D}}$$