Electronics for Photodetectors

Jean-Francois Genat

LPNHE Paris

New Developments In Photodetection

July 4th-8th 2011, IPN Lyon

genat@in2p3.fr
331 44 27 22 37

Thanks to

Christophe de la Taille
Jacques Lecoq
Eric Oberla
Eric Delagnes
Hervé Grabas
Dominique Breton
Thanh Hung Pham
Hervé Lebbolo
Kholdoun Torki

and many others…

- **Introduction**

- **Contexts**

  - **High Energy Physics**
  - **Space, Medical**

- **Photodetectors**

  - **Vacuum**
  - **Solid state**

- **Photodetectors Electronics**

  - **Technologies,**
  - **Photon counting**
  - **Amplitude, charge**
  - **Imaging**
  - **Timing**
  - **3D integration**

- **Conclusion**

Introduction

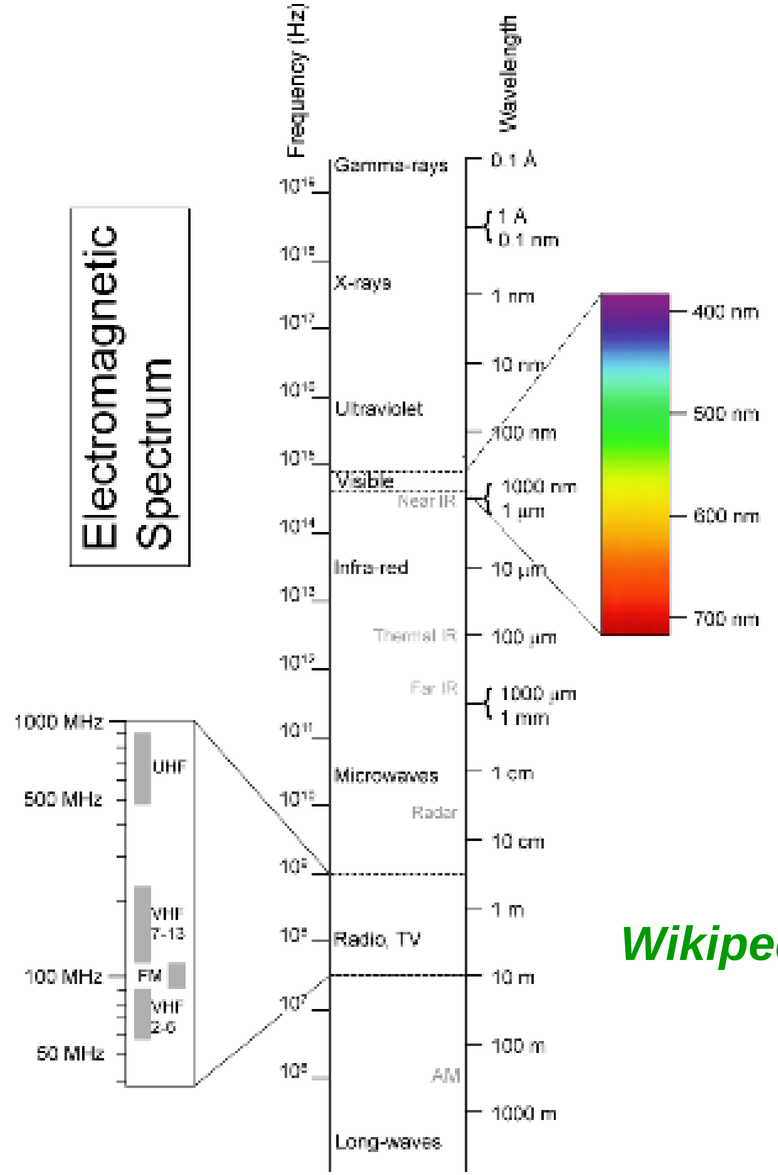
Electromagnetic wave = photon

- **Electromagnetic wave:**
  Wavelength λ, Maxwell's equations

- **Photon:**
  Photon wavelength hc/λ
  Schrodinger's equation

(Electromagnetic field)^2 :
photon's probability of presence

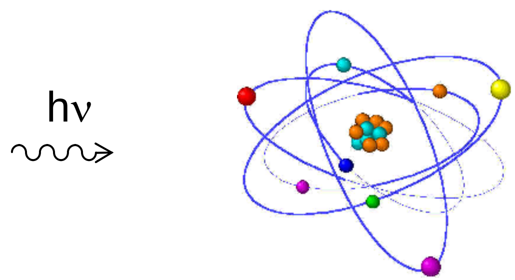
1eV Near | 1.2µm Infra-red | 2.4^{14} Hz photon



Wikipedia

http://www.cft.edu.pl/~birula/publ/CQO7.pdf

Photon Electron interaction



Photon-atom interaction:

- **No absorption : Rayleigh elastic scattering** **no electron ejected**

- **Energy change, absorption:**

  - **Compton effect:** **photon scattered with wavelength change electron ejected**

  - **e+ e- pairs generation (γ rays): 2 x 511 keV minimum energy**

« Shower » in a « radiator » measured in a (photo)-detector

Photo-detectors

Vacuum devices

- *Photo-Multipliers Tubes (PMTs)*
- *Hybrid Photo-diodes (HPDs)*
- *Micro-Channel Plates (MCPs)*

Solid state devices

- *Charge Coupled Devices (CCDs)*
- *Avalanche Photo-diodes (APDs)*
- *Silicon Photo-multipliers, (SiPMs, Geiger mode APDs)*
- *Monolithic Active Pixel Sensors (MAPS, CMOS Silicon)*

Hybrids

- *Hybrid APDs (HPD/APD)*
- *Electron Bombarded CMOS (HPD/MAPS)*

Vacuum and Solid-state

Vacuum devices

Current signal from electrons in vacuum

- ***Large area, large fill factor, poor QE***
- ***Full-custom Photo-cathode***
- ***Electron multiplication, high gain, fast***
- ***Low noise (photo-cathode noise)***
- ***Some sensitivity to magnetic fields (depends on device)***
- ***Readout with external ASICs***

Solid state semi-conductor devices

Current signal from e-/holes + avalanche in ½ conductor

- ***Size limited to a wafer, limited filling factor, high QE***
- ***Spectral response of ½ conductor (Si, GaAs, HgCdTe…)***
- ***Multiplication in high electric fields (depleted PN junctions)***
- ***Noisy due to reverse currents avalanches***
- ***Noise very sensitive to irradiation***
- ***No sensitivity to magnetic field***
- ***Readout easy to integrate + 3D availability***

Devices

Vacuum devices

Photo-multipliers
Hybrid photo-diodes (HPDs)
Electron bombarded CMOS
Micro-Channel Plates

Solid state (semi-conductor) devices

Avalanche Photo-diodes
Silicon PMs

Hybrids

Electron bombarded Silicon

Vacuum devices
Single photo-electrons signals

Silicon Photo-Multipliers (SiPM), Micro-channel Plates (MCP)

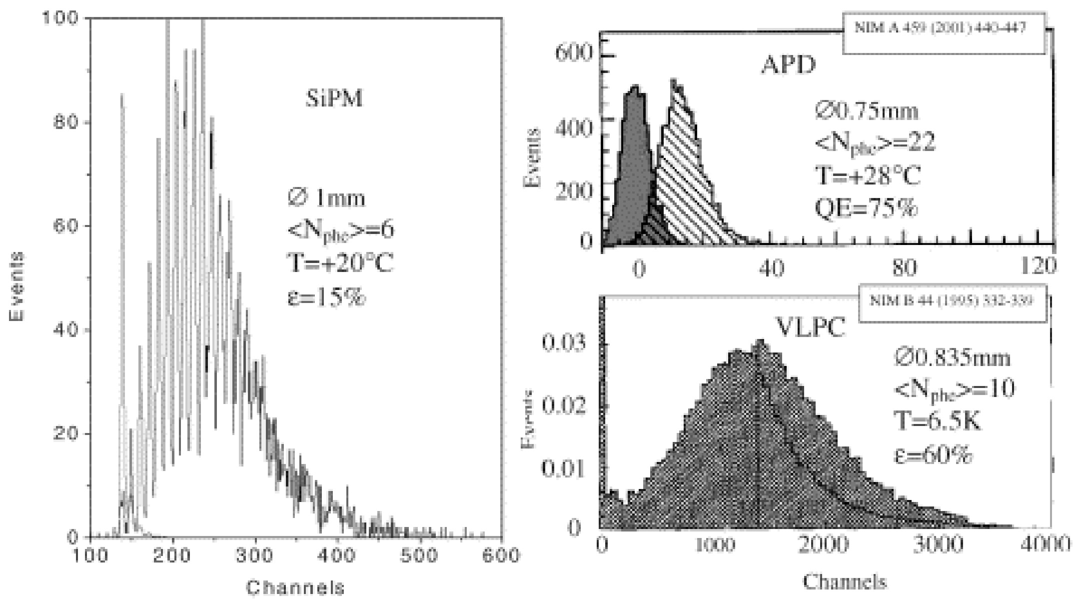
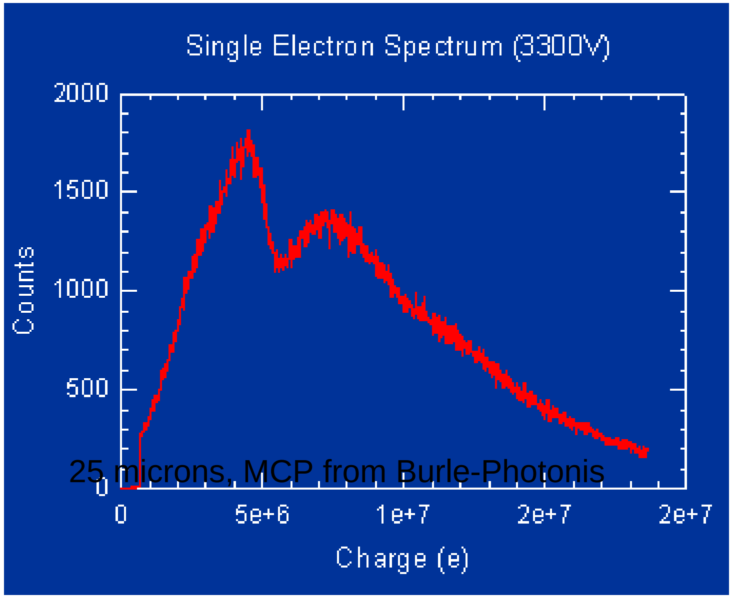


Fig. 3. SiPM application for sci fiber MIP detection (at room temperature): comparison with APD [6] (room temperature) and VLPC [7] (6.5°K).



Silicon PMs From B. Dolgoshein et al.

25 μm MCP from P. Hink (Burle-Photonis)

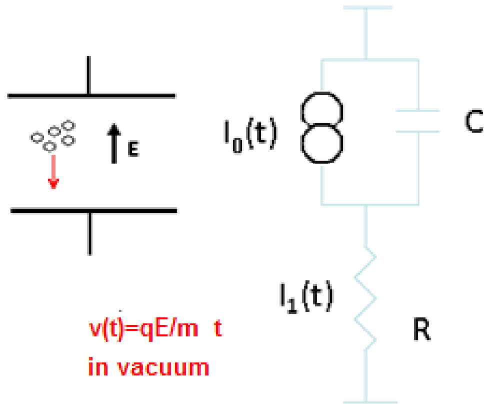
Signal development

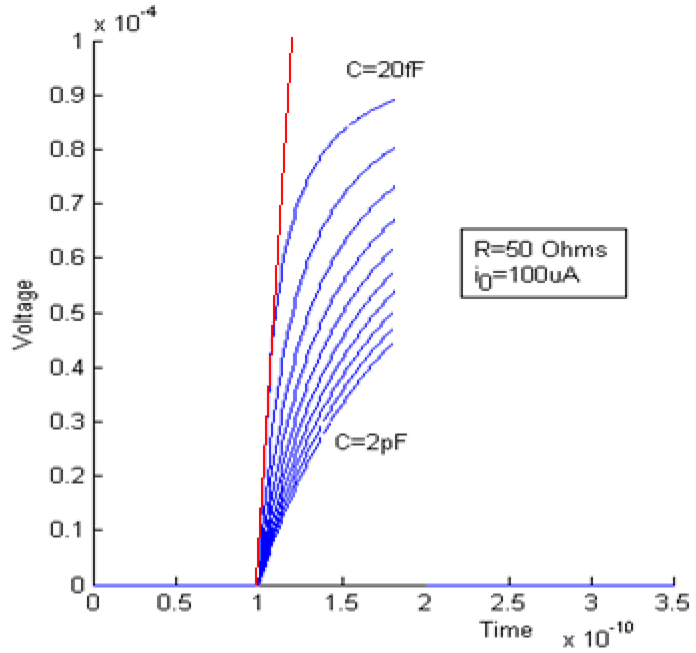
Effect of first order passive:

$$i_0(t) = q\, n(t)\, v(t)$$

Step response:

$$i_1(t) = i_0[1 - \exp(-t / RC)]$$





- Current signals occur as long as charges move in the detector gap

Rise time is RC dependent at first order sets the electronics bandwidth for timing

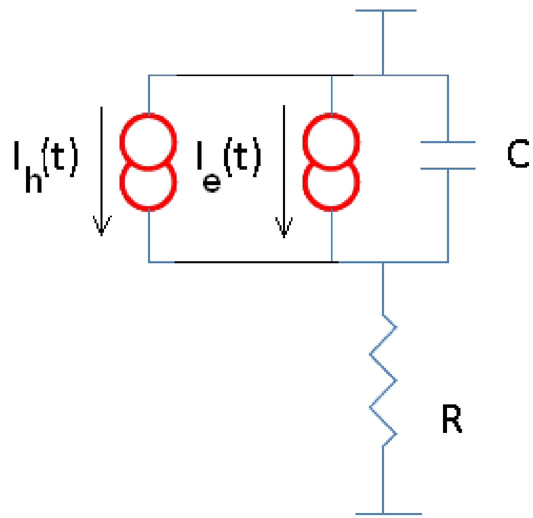
Serial noise proportional to C

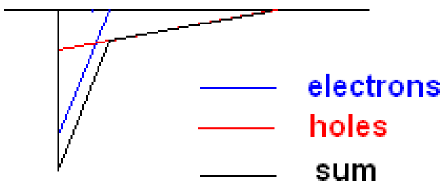
R small, 50 Ω or less if a common base preamp is used

Electronics should not increase C (cables, connectors...)

C is the capacitance seen during the rising edge (not a full coaxial cable length)

Signal development (½ conductor)





Two types of carriers:

- **Electrons**
- **Holes, 3 times slower in silicon**
- **75 electrons-holes in one micron**

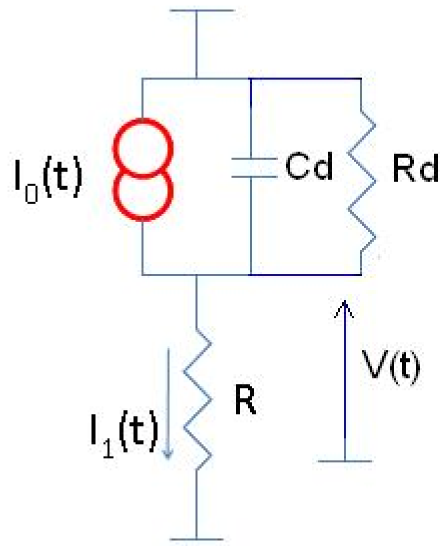
- **APDs and SiPMs:**

  - **Avalanche process is very fast,**
    RC is observed in practice

  Reduce R using a transimpedance or a current conveyor input stage

$$i_1(t) = [(i_e(t) + i_h(t)]\,[1 - \exp(-t / RC)]$$

Electronics and Signal Processing



Detector model

- **Not much amplification needed with PMTs, MCPs, SiPMTs**
  1 electron is 5mV in 50Ω with a detector gain of 10^{6-7}
  Or current conveying using common base input stage

- **Amplification for 10^3 to 10^6 detector gains of (G)APDs, CCDs**

- **Filtering: "Pulse shaping" to remove amplifier noise out of the signal's frequency content**

- **Digitization: Convert to a sequence of numbers using ADCs**

- **Feature extraction: get time, amplitude, charge…**
  Can digital filter as well, remove pedestals

- **Send results to user: normalize, compress, error recover…**

- Introduction
- Contexts
  - High Energy Physics
  - Space, Medical
- Photodetectors
  - Vacuum
  - Solid state
- Photodetectors Electronics
  - Technologies
  - Photon counting
  - Amplitude, charge
  - Imaging
  - Timing
  - 3D integration
- Conclusion

High Energy Physics: Calorimetry

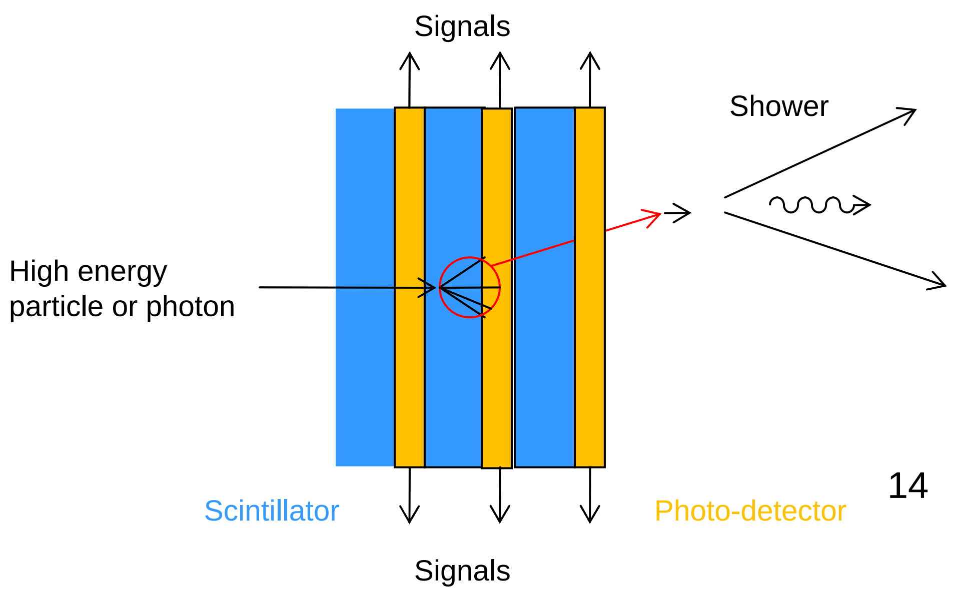
Calorimetry:

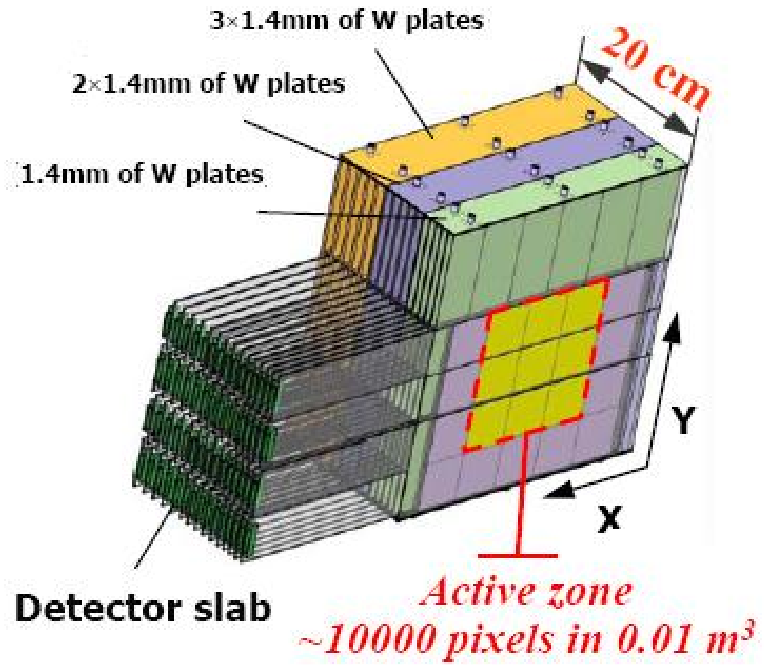
Showers develop in heavy materials Lead glass, Tungsten…

- High energy particles converted in scintillators into « showers »

- Photo-detectors convert photons into electrical signals

- Large dynamic range > 16-bit
Showers are analysed and reconstructed





Calice

ATLAS Hadron Calorimeter
ATLAS TileCal

Constraints for the front-end electronics

- **Photo-multipliers rise time : 5 ns**
- **Least significant charge: 25 fC (20 MeV muon)**
- **Largest charge: 1.6 nC**

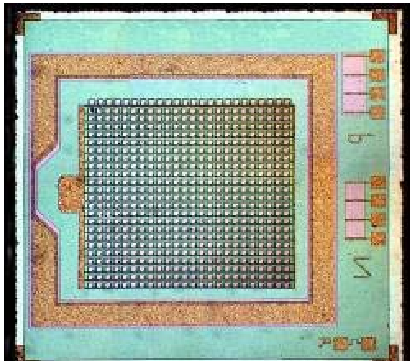
- **For noise and LSB of 12,5 fC**
- **The corresponding currents are:**
  - **625 nA LSB**
  - **Max: 40mA**

Large dynamic range, 16-bits

A multi-gain design is required

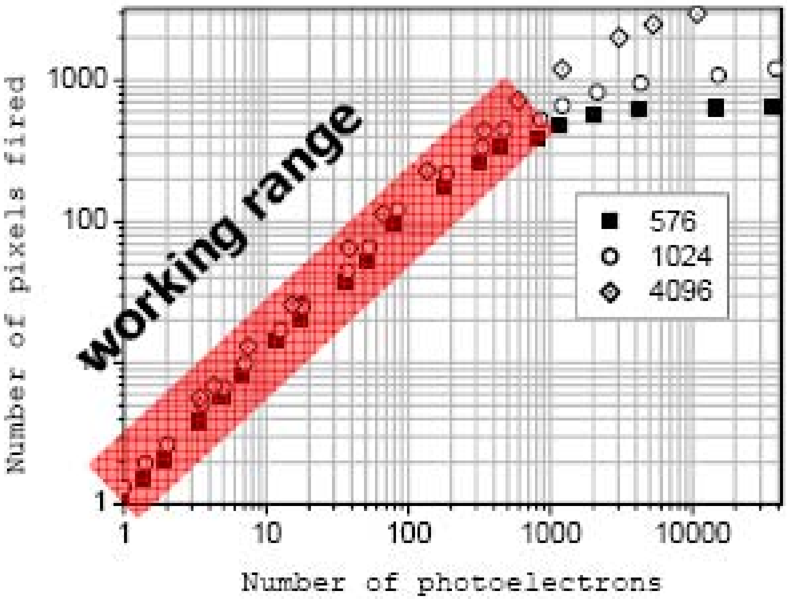
New photo-detectors for Calorimeters
Solid-state

- **Array of avalanche photo diodes: "digital" photon detection**
  - **Array can be 0.5x0.5 up to 5.0x5.0 mm^2**
  - **Pixel size can be 10 up to 100µm**



- **All APDs connect to a single output**
  - **Signal = sum of all cells**

- **Advantages over HPDs:**
  - **28% QE (x2 higher) and 10^6 gain (x500 higher)**
  - **More light (40 pe/GeV), less photo-statistics broadening**
  - **Very high gain can be used to give timing shaping/filtering**



New photo-detectors for Calorimeters Solid-state

- Reverse biased PN junction operated over breakdown voltage;
  Geiger Avalanche triggered by the incoming photo-electron in the high electric field.

- Needs « quenching » to stop the current: biasing through a large resistor that drops the voltage (30-50V)

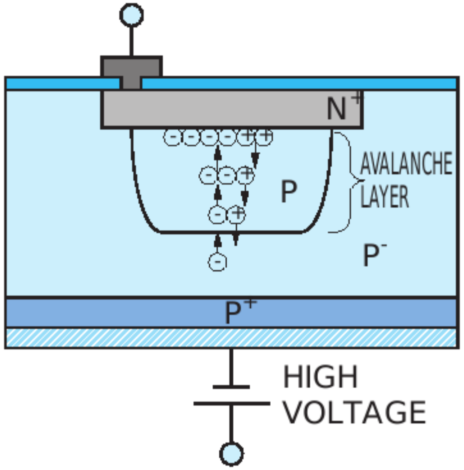
- A SiPM cell comprises several GAPDs having each a quench resistor, all GAPDs tied in parallel: analog sum

- Gain $10^{5\text{-}7}$

- High Quantum efficiency (90%) but poor fill factor (quenching access electrodes)

- High dark counts, optical crosstalk, dead time,

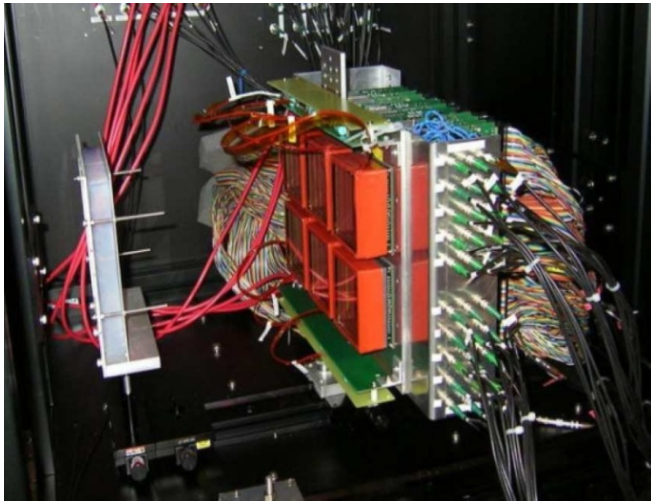
- High Voltage process +CMOS readout (Philips patent)



R. Mirzoyan (MePhy, MPI)

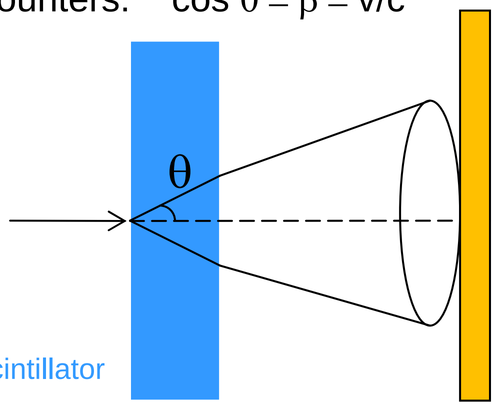
http://heapnet.mppmu.mpg.de/documents/oct_07/03_Photodac-07-Mirzoyan.pdf

High Energy Physics: Particle ID



Particle Identification:

- Cerenkov counters: $\cos \theta = \beta = v/c$



Improved with 100ps resolution Time of Flight

Example:

Fast timing readout using 10 GS/s Analog Memory ASIC (SCA): →

	SPECIFICATION	ACTUAL
Sampling Rate	500 MS/s-17GS/s	2.5 GSa/s-17GS/s
# Channels	4	4
Sampling Depth	256 cells	256 Cells
Sampling Window	$256*(\text{Sampling Rate})^{-1}$	$256*(\text{Sampling Rate})^{-1}$
Input Noise	1 mV RMS	1-1.5 mV RMS
Analog Bandwidth	1.5 GHz	Average 600 MHz
ADC conversion	Up to 12 bit @ 2GHz	Up to ~10 bit @ 2GHz
Latency	2 µs (min) – 16 µs (max)	3 µs (min) – 30 µs (max)
Internal Trigger	yes	yes

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

Space applications

Imagers

Space boarded Telescopes

Need to observe single photons with fair position resolution in all spectral domains, in particular (near to far) infra-red

Pixellated devices such as Charge Coupled Devices, Photo-detectors can be:

- **Silicon in the visible**
- **Compounds materials**
  - **CdTe for soft Xrays**
  - **CdZnTe for hard Xrays**
  - **InGaAs for near IR**
  - **HgCdTe for far IR**

Pixels as small as 5 x 5 μm, can be instrumented.

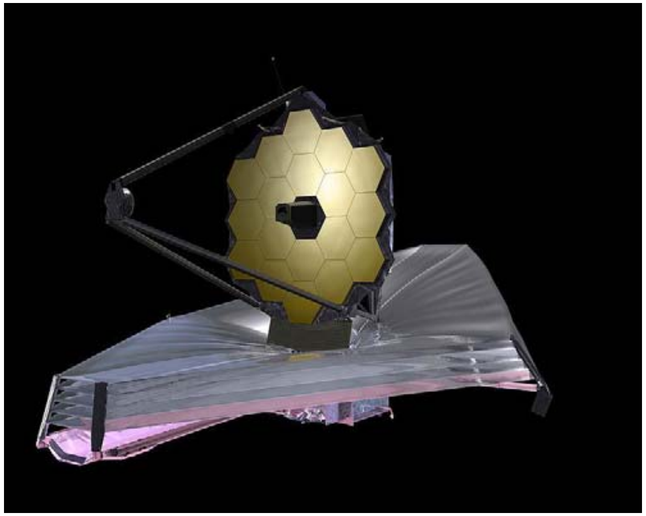
Passive (CCDs) or active (Active Pixel Sensors)

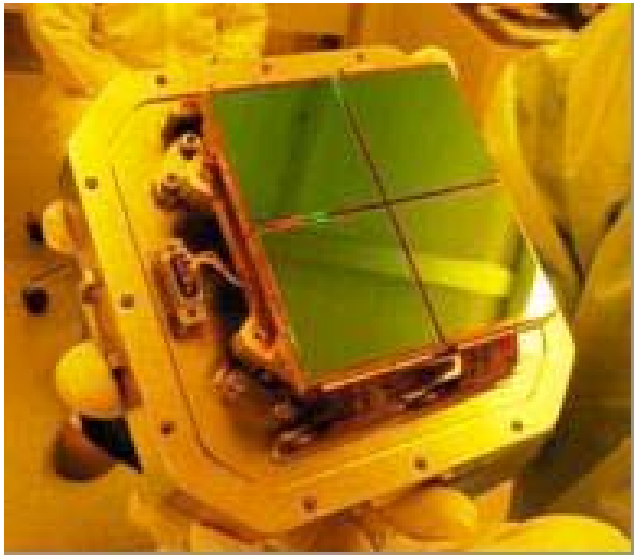
Space boarded X ray detectors for imaging and spectrometry

http://www.jwst.nasa.gov/

« Asynchronous » events (no trigger)

JWST





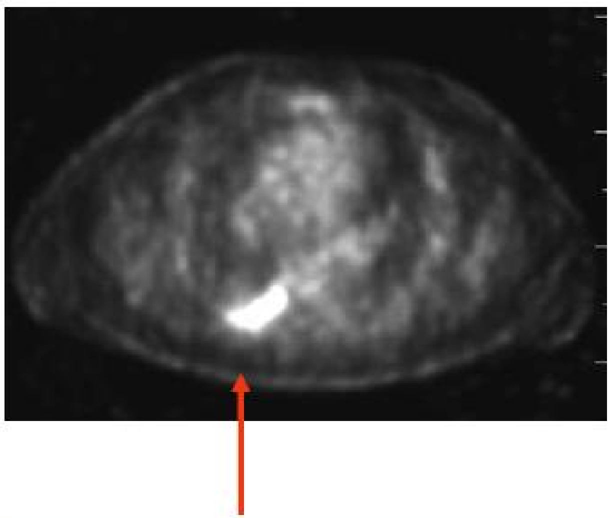
JWST Focal Plane Array

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

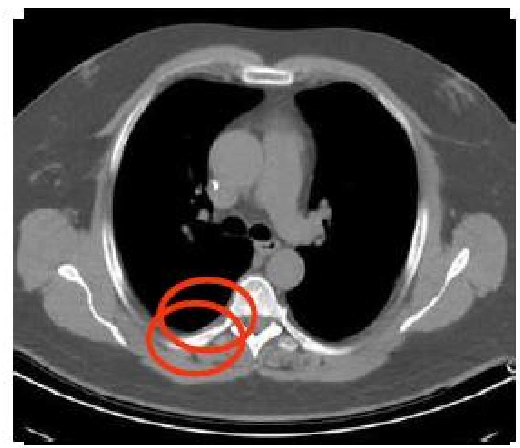
PET CT High/low

3. Résultats
Comparaison d'images: basse dose/haute dose

Emission TEP



Scanner high dose



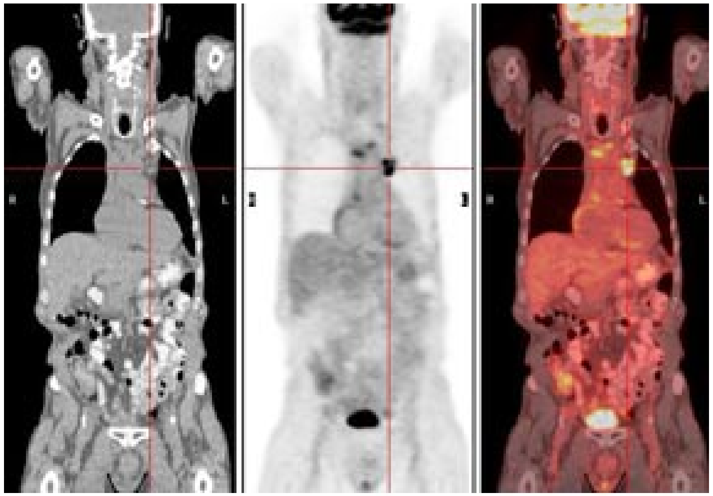
Scanner low dose

10 - Optimisation de la TEP-TDM dans le bilan d'un lymphome- Institut Curie- ROUSSEAU Aline - 13/04/2007

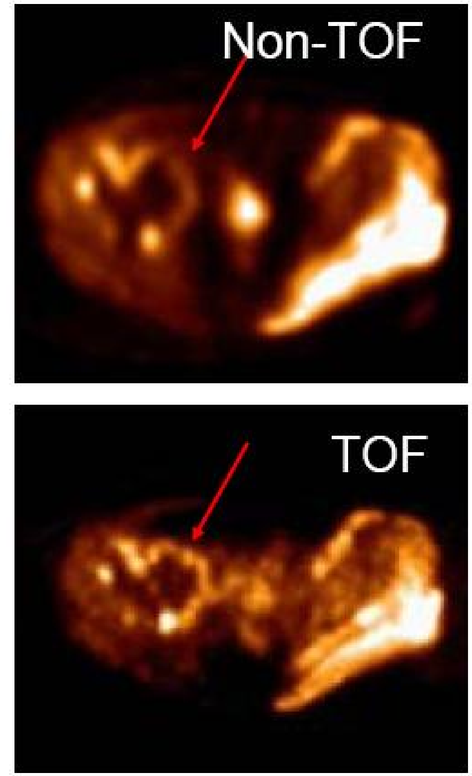
institut Curie

« Asynchronous » events (no trigger)

PET + CT TOF-PET



Combined PET-CT



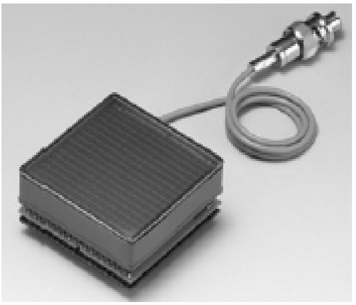
AREVA

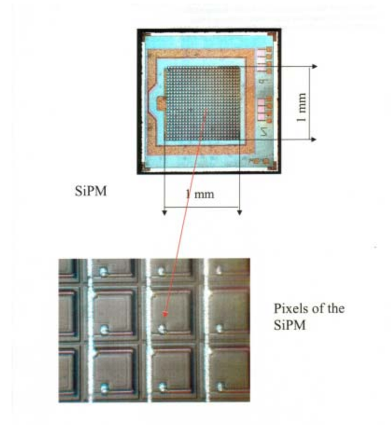
W.W. Moses

« Asynchronous » events (no trigger)

- **Introduction**
- **Contexts**
  - **High Energy Physics**
  - **Space, Medical**
- **Photodetectors**
  - **Vacuum**
  - **Solid state**
- **Photodetectors Electronics**
  - **Components**
  - **Technologies**
  - **Photon counting**
  - **Amplitude, charge**
  - **Imaging**
  - **Timing**
  - **3D integration**
- **Conclusion**

Timing-Imaging Device (visible)

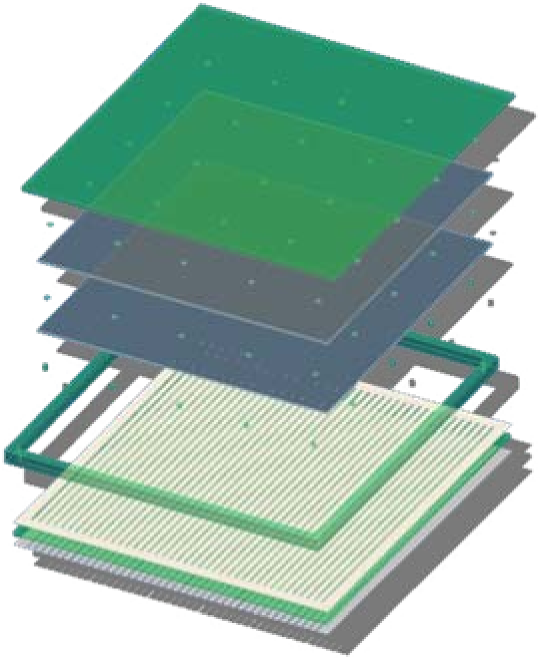




	Multi-anodes PMTs Dynodes	Hybrid Photo-Diodes Electrons on Silicon EBCMOS	Silicon-PMTs Quenched Geiger	Micro-Channel Plates Micro-Pores
Quantum Eff.	25%	25%	90%	25%
Collection Eff.	90%	90%	70%	70%
Gain	10^6	10^{2-4}	10^6	10^6
Rise-time	1-5ns	1-5ns	250ps	50-500ps
Timing resolution (1PE)	150ps	100ps	100ps	20-30ps
Pixel size	2x2mm^2	10x10μm^2	50x50μm^2	1.5x1.5mm^2
Dark counts	1-10Hz/cm^2	1Hz-40kHz/cm^2	1-10MHz/pixel	1Hz-1kHz/cm^2
Dead time	5ns		100-500ns	1μs
Magnetic field	no	1.5T	yes	1.5T
Radiation hardness			1kRad=noisex10	good (glass, Al_2O_3)

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

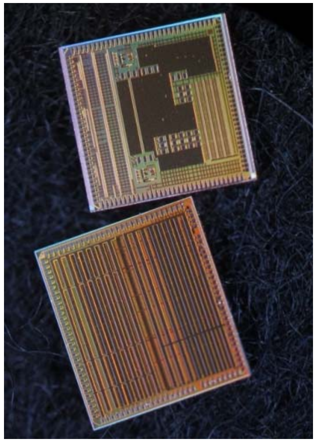
Large Area Micro-Channel Plates

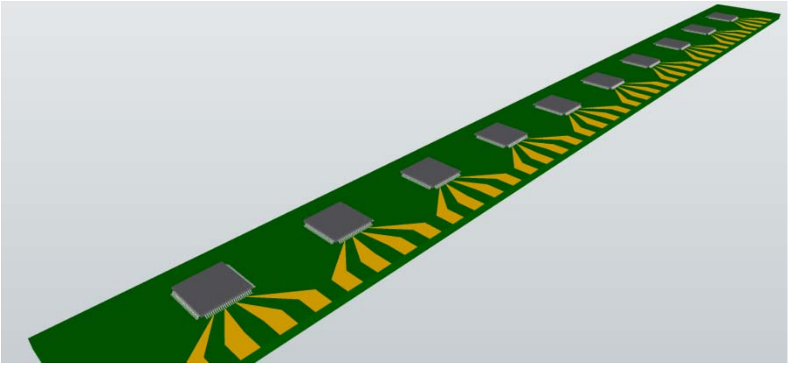


20 x 20 cm^2 MCP structure:

- **Custom photo-cathode**
- **2-plate chevron (high gain)**
- **Transmission line 2D readout**

  limit the number of electronics channels



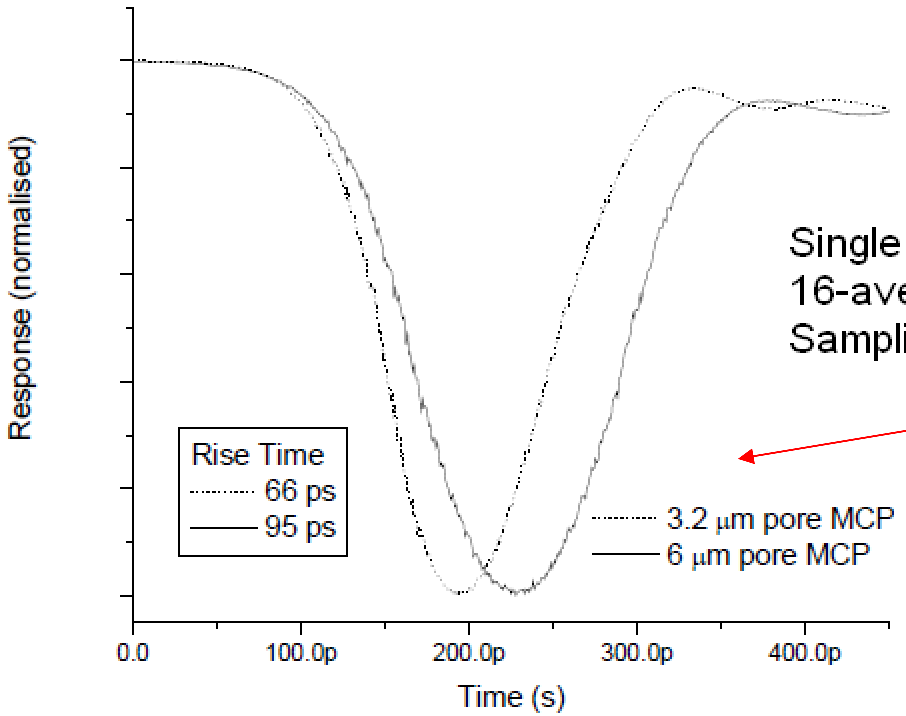


Electronics:

- **GS/s Flipped-Chip ASICs:**

Waveform Sampling + Digital Signal Processing

Micro-Channel Plate Signals



Time response curves for two models of PMT110 with different MCP pore diameters.

Single Photon
16-averaged
Sampling: 18 GS/s

From Photek

The fastest photo-detector to date

- Introduction
- Contexts
  - High Energy Physics
  - Space
  - Medical
- Photodetectors
  - Vacuum
  - Solid state
- Photodetectors Electronics
  - Components
  - Technologies
  - Photon counting
  - Amplitude, charge
  - Imaging
  - Timing
  - 3D integration
- Conclusion

APDs

Multiplication initiated by electron-hole, thermally or induced within the APD and accelerated in the high electric field at the APD junction.

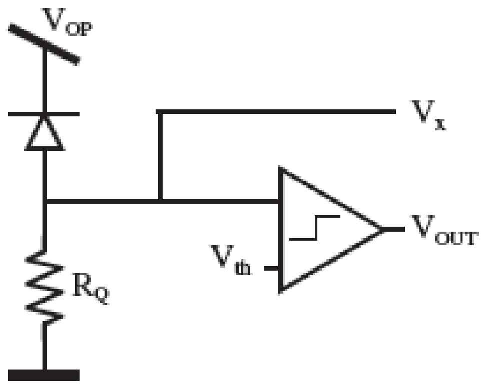
Proportional mode

- Bias: slightly *BELOW* breakdown
- Linear-mode: it's an *AMPLIFIER*
- Gain: limited < 1000

Geiger-mode

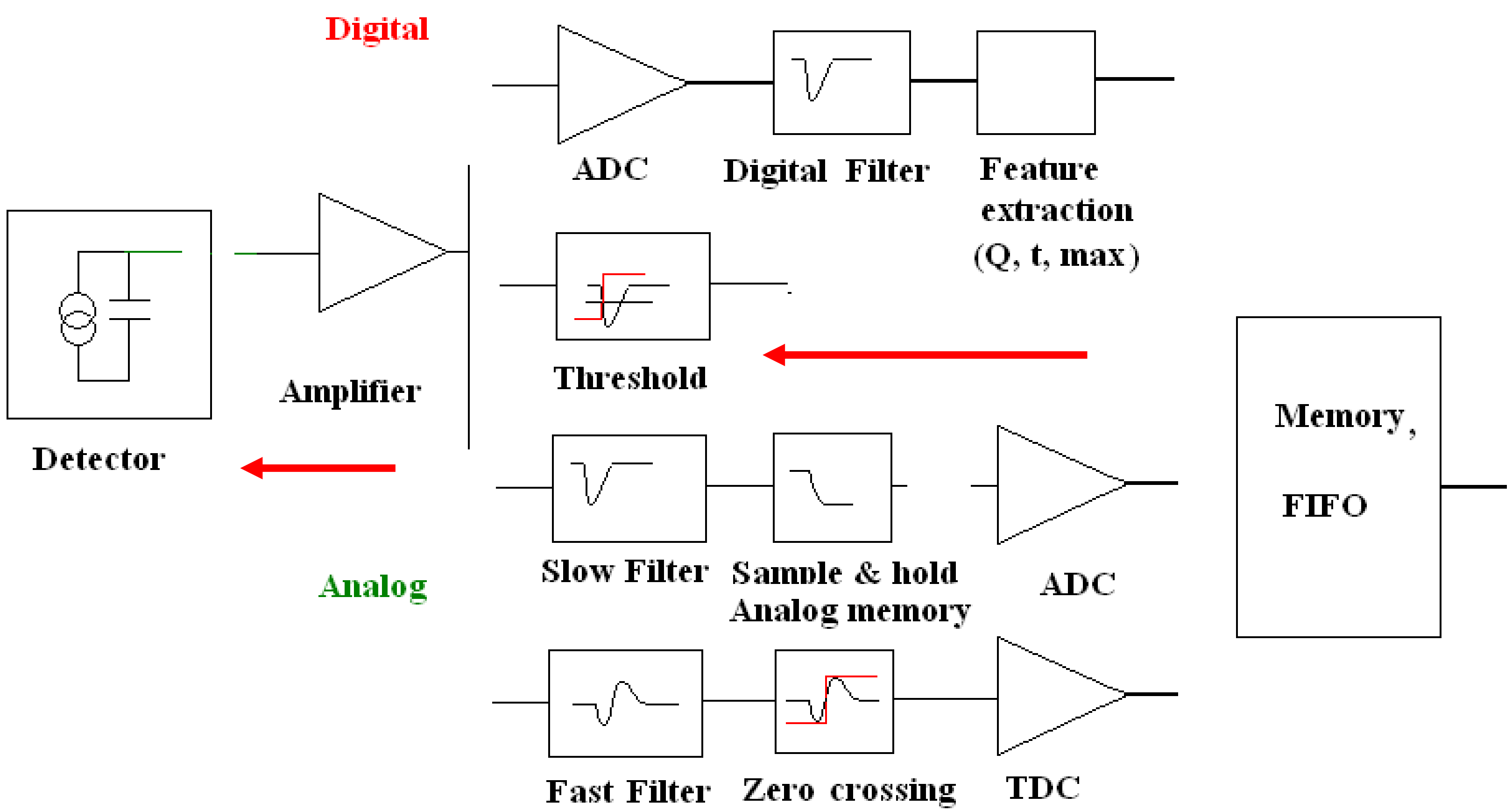
- Bias: *ABOVE* breakdown
- Geiger-mode: it's a *TRIGGER* device!!
- Gain: meaningless ... or "*infinite*" !!

A. Dieguez (U Barcelona)



- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

Typical Readout Components



Present trends: Move ADC to Front-end and Amplifier to Detector

- **Introduction**
- **Contexts**
    - **High Energy Physics**
    - **Space, Medical**
- **Photodetectors**
    - **Vacuum**
    - **Solid state**
- **Photodetectors Electronics**
-
    - **Components**
    - **Technologies**
    - **Photon counting**
    - **Amplitude, charge**
    - **Imaging**
    - **Timing**
    - **3D integration**
- **Conclusion**

Technologies

Best results in analog design:

ASIC implementation at the transistor level

Position resolution requires smaller pixels

Increased on-pixel signal processing up to ADCs

Thinner feature size processes (65nm and less are coming…)

Available technologies:

- **Standard Deep Sub-Micron CMOS down to 65nm**
- **High voltage CMOS**
  - **Large dynamic range readout (but multi-gain possible with std CMOS)**
  - **CCD clocks generation**
- **Silicon Germanium (SiGe) for faster and low 1/f noise applications**
  - **Higher mobility (GBW=300GHz)**
  - **Larger current gain (beta)**
  - **CMOS compatible (0.25 or 0.35µm) for mixed-signal design**

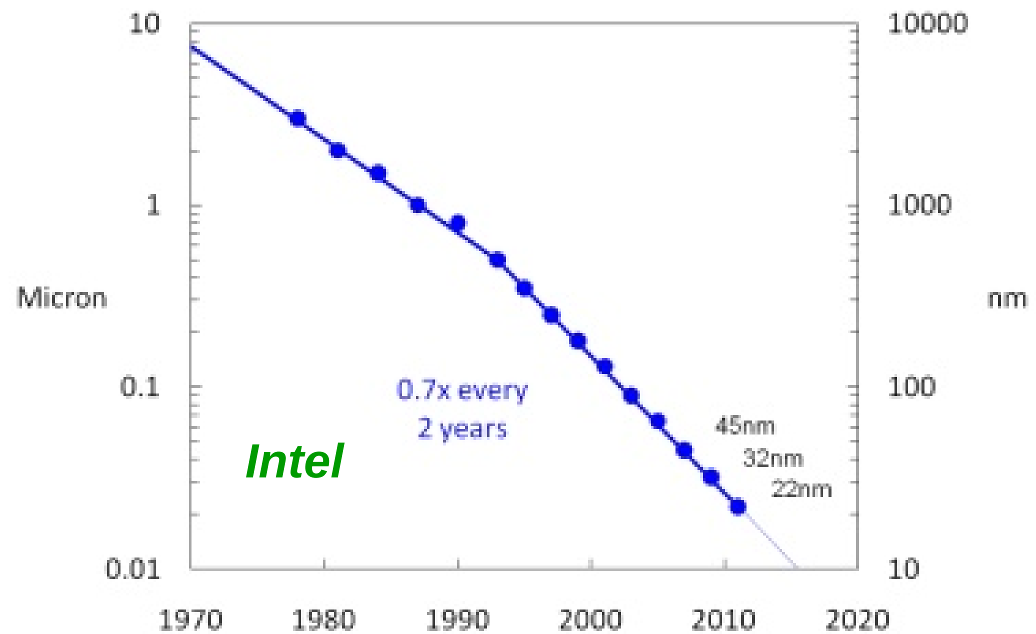
ASICs feature size

The smaller the components, the faster, the less power, the greater density

$BW = 1/2\pi RC$, $W_c = CV^2$ ENC $1/C_{det}$

Reduce capacitances wherever possible

But reduced dynamic range
since voltage supply decreases

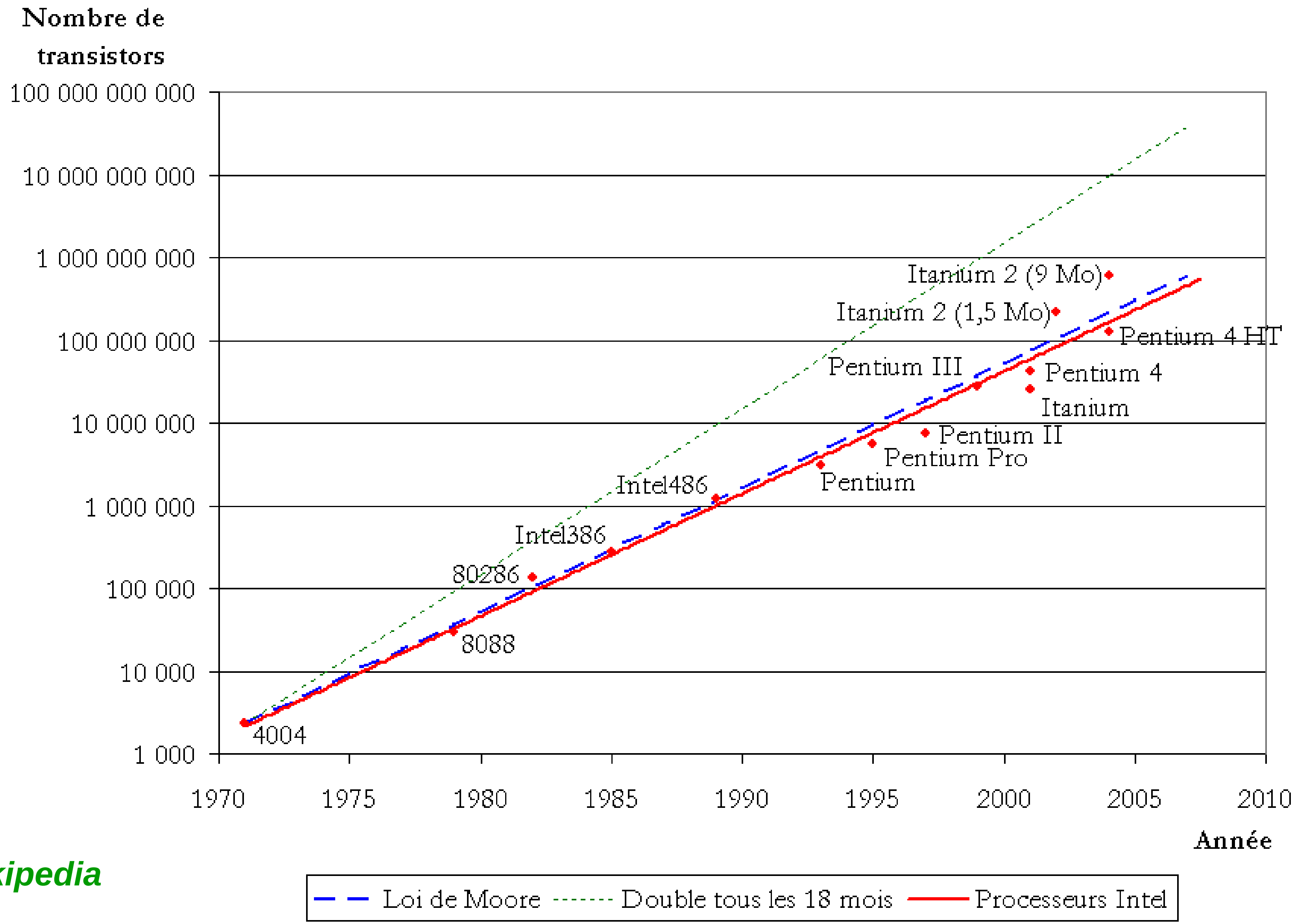


V_{dd} = 1.2-1.6V in 65nm
Multi V_{dd} – Multi V_t technologies

Multi-gain designs

Moore's law: 1968
Computing power will double every two years, for approximately the same cost

ASICs integration level



Wikipedia

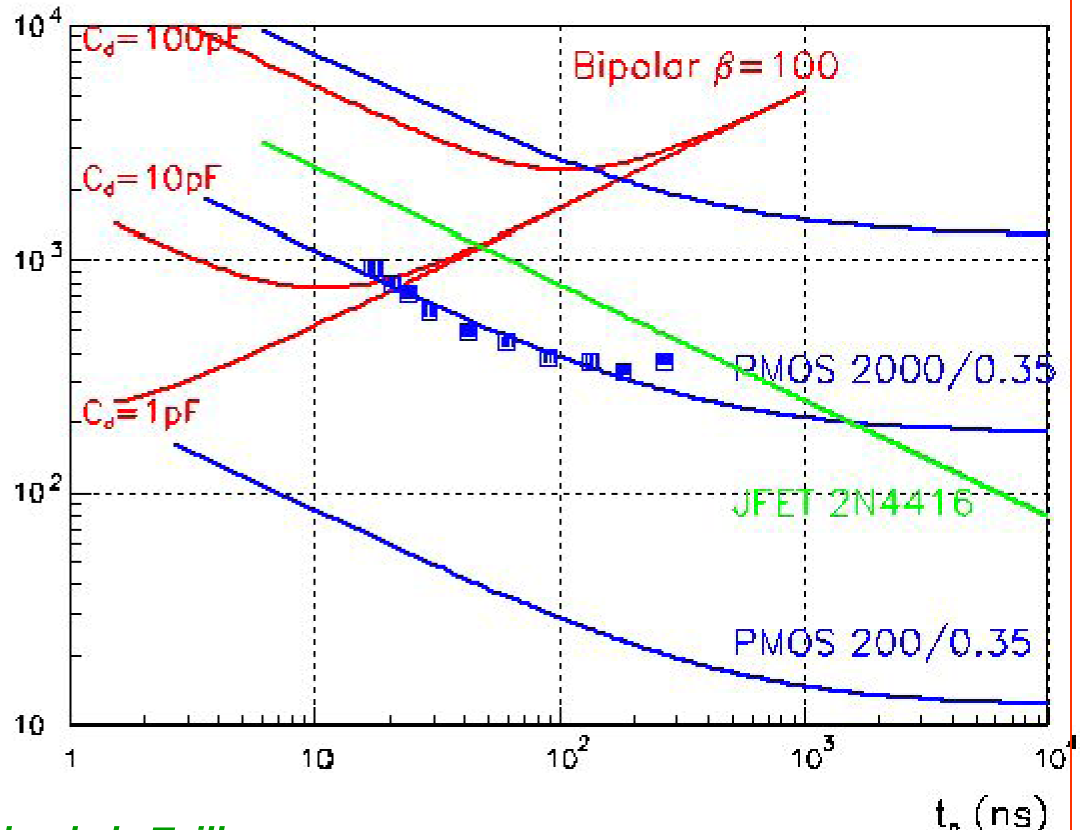
sity:

Noise vs Technology

ENC for various technologies

ENC for Cd=1, 10 and 100 pF at I_D = 500 uA

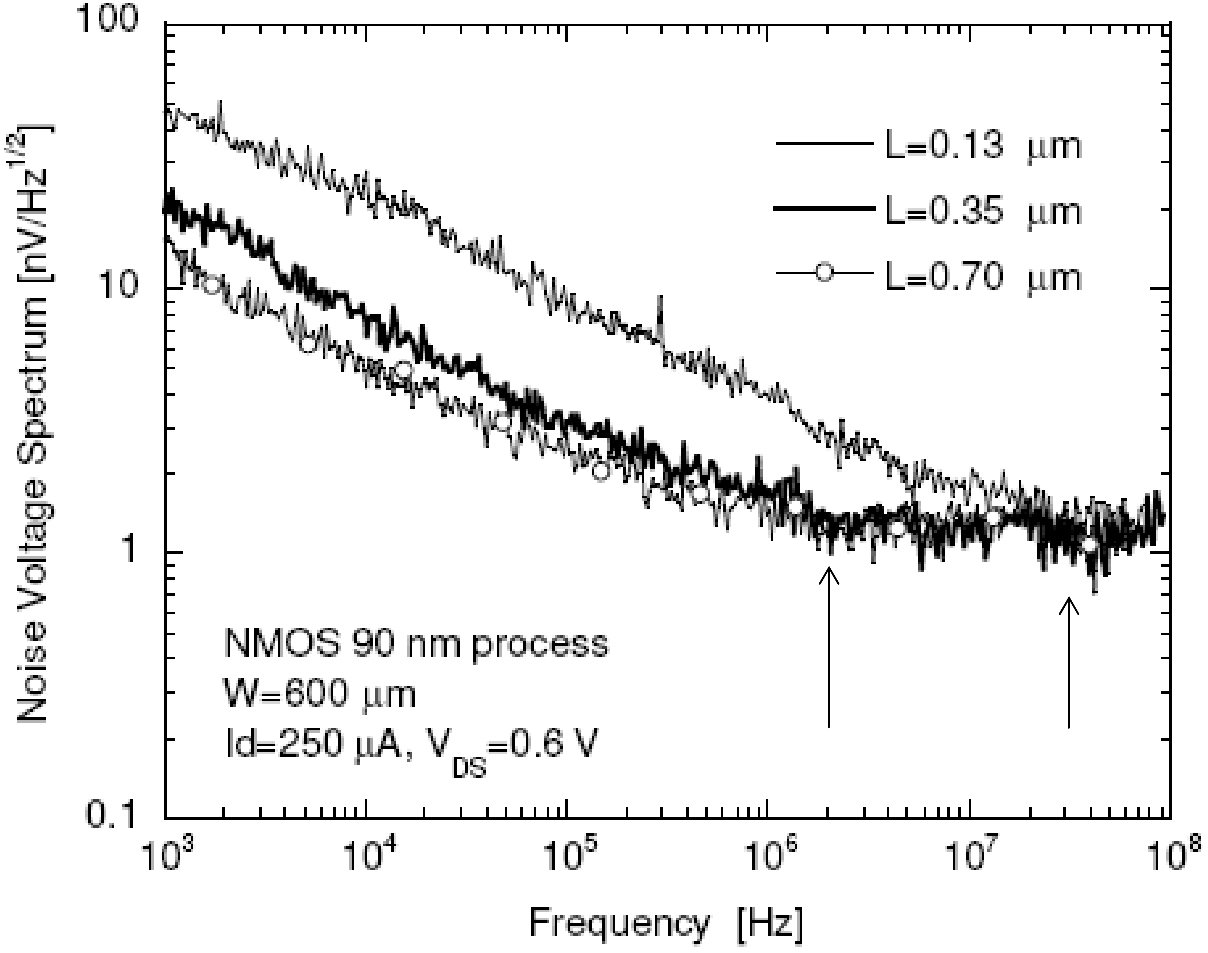
- MOS transistors best between 20 ns - 2 μs



- **Parameters**
- Bipolar :
  - g_m = 20 mA/V
  - $R_{BB'}$=25 Ω
  - e_n= 1 nV/√Hz
  - I_B=5uA
  - i_n = 1 pA/√Hz
  - C_{PA}=100fF
- **PMOS 2000/0.35**
  - g_m = 10 mA/V
  - e_n = 1.4 nV/√Hz
  - C_{PA} = 5 pF
  - 1/f :

Christophe de la Taille

Noise vs gate length



Noise spectral densities for 90nm at L= 700, 350, 130nm

M. Manghisoni

ASICs Costs

Costs of MPW (Source: Europractice) http://www.europractice-ic.com

Process		Feature	Cost Eur/mm²	
CMOS	180nm		0.6k	UMC
	180nm	HV 50V	1.2k	AMS
	130nm		1.1k	UMC
	90nm		2.8k	
CMOS	350nm	Opto	0.7k	AMS
SiGe	350nm		0.9k	AMS
	250nm	30 GHz	1.9k	IHP
		180	4.4k	
	130nm+ CMOS	300	5.4k	IHP
		400	6.0k	

50-100 parts / MPW run
Some minimum area (25, 16, 12 mm required)

Masks (production): 100-200k

Packaging

Ceramic: 20-30€/chip
Plastic : 2k€ + 1-2 €/chip

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

Photon Counting

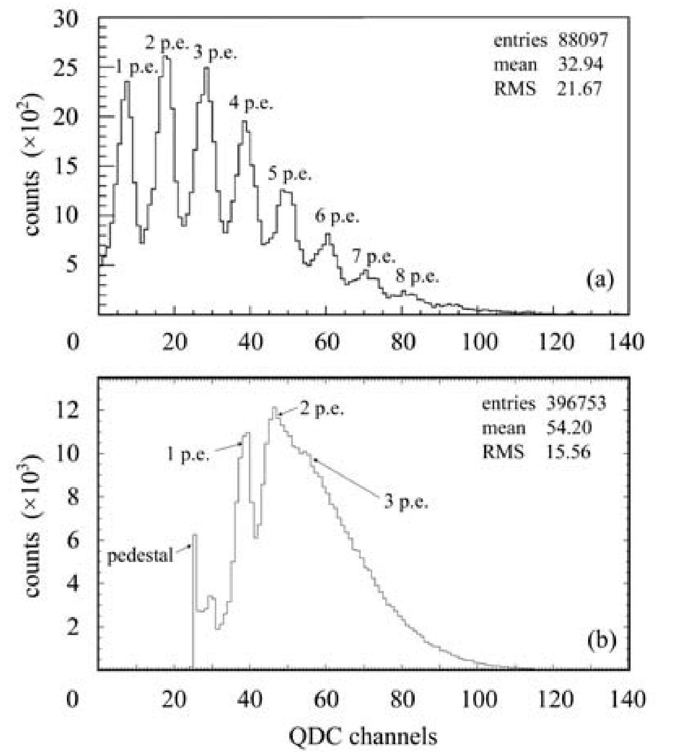
Space and Medical application: no trigger, asynchronous recording
High Energy Physics: a beam synchronous signal is usually available

Visible photons have 1 – 3 eV energy

- **Photo-cathodes have QEs of 30% at best**
- **In semi-conductors, gap is 1.12 eV for Silicon, 1.4 eV for GaAs**

Only 1 electron-hole pair per photon

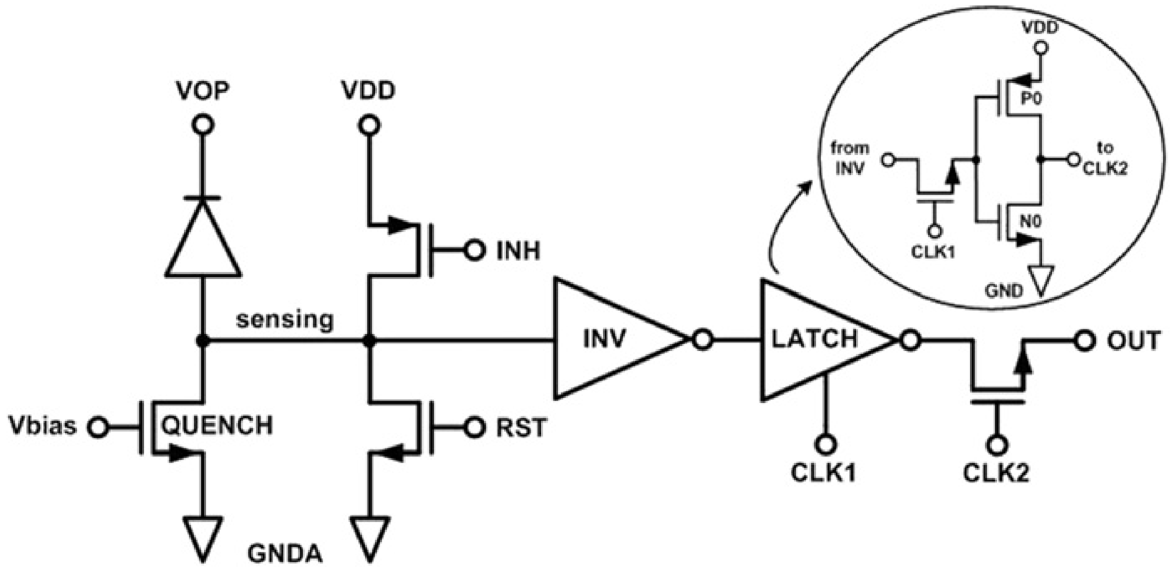
Single photon counting,
noise below 1 electron



Silicon PM and Vacuum PMT responses compared

http://hepnp.ihep.ac.cn/qikan/manage/wenzhang/20110111.pdf

Silicon PMs (Geiger-APDs) readout



E. Villela et al. NIM A 2010
Readout electronics for low dark count pixel detectors

Quenching resistor: high value	**NMOS transistor**
Inhibit / Reset switches	**Switch sensing node to Vdd / Gnd**
Inv	**Shaping to logic levels**
Latch	**Memorize Inv state on clk1**
Clk2	**enable latch on the output bus**

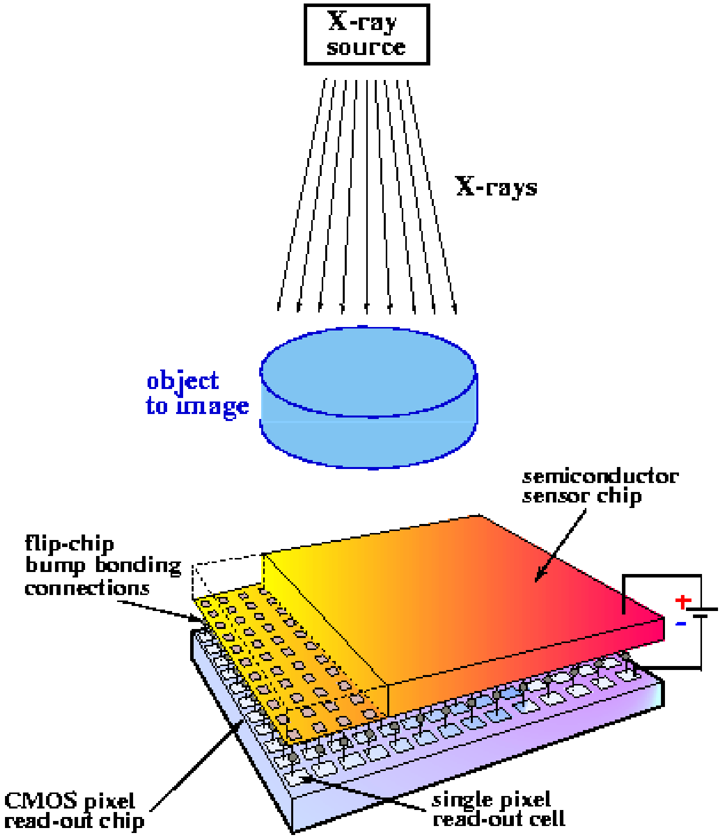
Medipix (EUDET)

MEDIPIX1-3 :

Readout chip to be bonded to an imaging semi-conductor detector (X rays)

- **Asynchronous for photon counting,**
- **Time over threshold provides raw energy estimate**

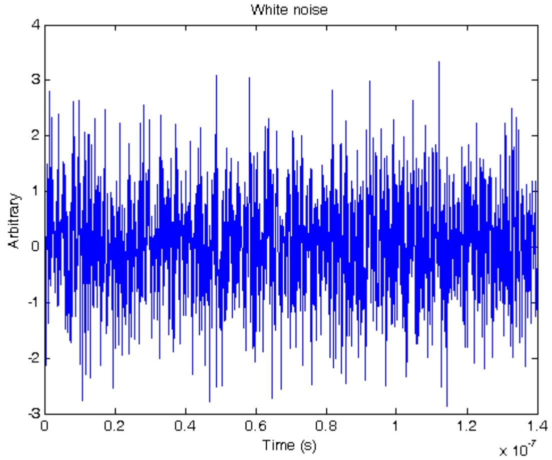
MEDIPIX3: Dead-timeless readout
(two counters, one counts, one is read)



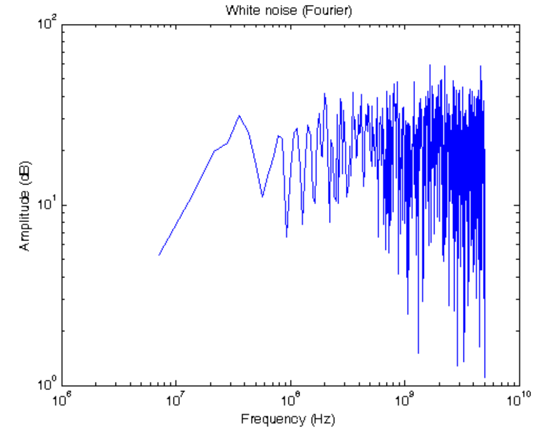
MEDIPIX Website

- **Introduction**
- **Contexts**
    - **High Energy Physics**
    - **Space, Medical**
- **Photodetectors**
    - **Vacuum**
    - **Solid state**
- **Photodetectors Electronics**
    - **Components**
    - **Technologies**
    - **Photon counting**
    - **Amplitude, charge**
    - **Imaging**
    - **Timing**
    - **3D integration**
- **Conclusion**

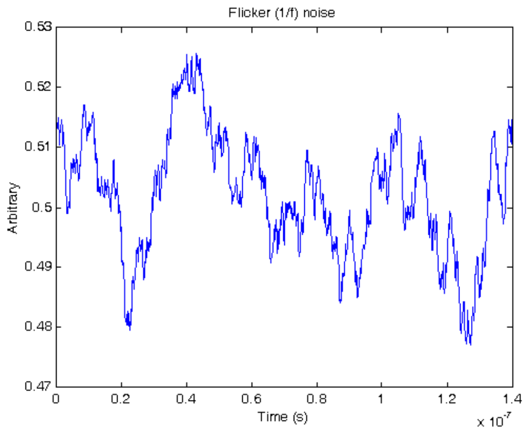
Noise



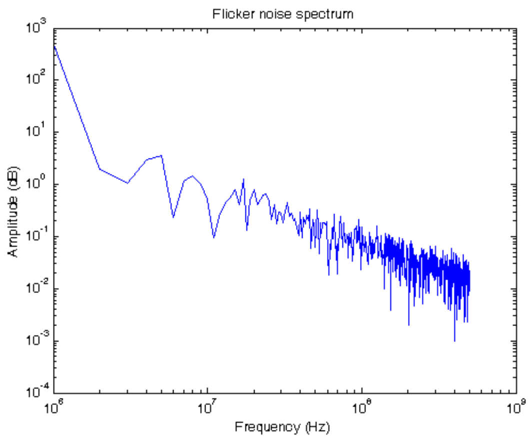
White



Flat spectral density



Flicker (1/f)



Spectral density S_v is 1/f (log scale)

Total voltage squared noise: $V_n^2 = \int S_V(\omega)\, d\omega \,/\, 2\pi$

Equivalent Noise Charge

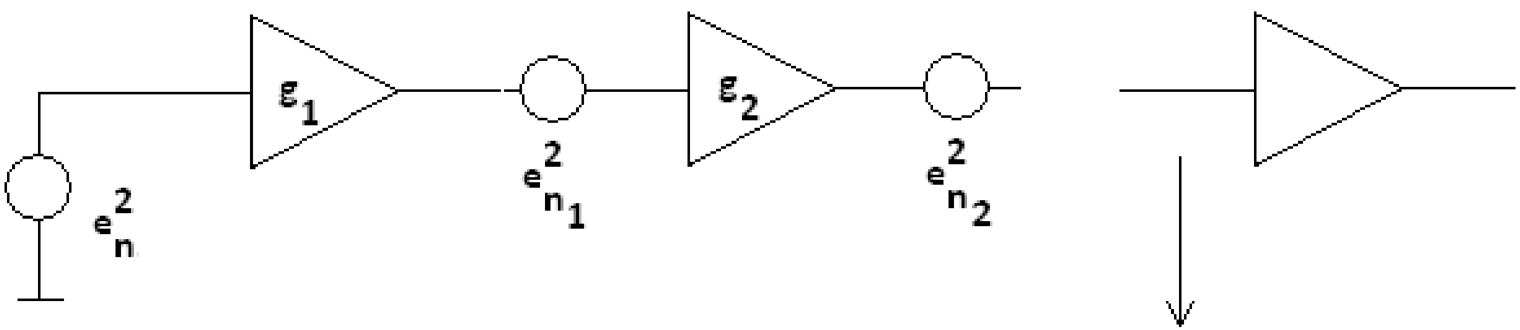
Equivalent Noise Charge:

The charge (in electrons) that produces the same rms output as the noise of the full device with no input signal.

The first stage of the electronics chain is the main contributor to the output noise

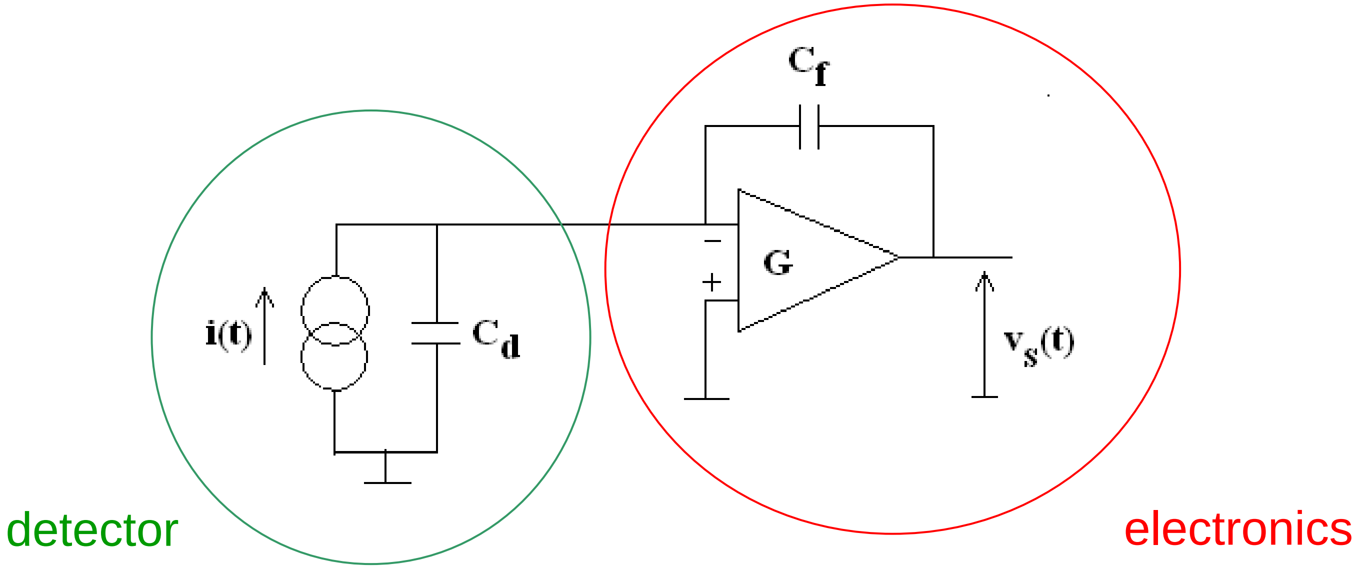
since it is multiplied by the whole gain of the chain.

Subsequent noise contributions are multiplied by the product of last gains only

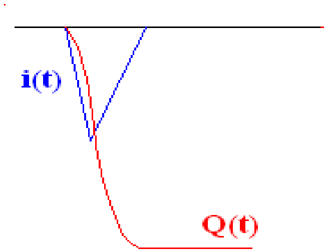


$$g_1^2\, g_2^2\, e_n^2 + g_2^2 e_{n_1}^2 + e_{n_2}^2$$

Amplification: Ideal charge sensitive amplifier



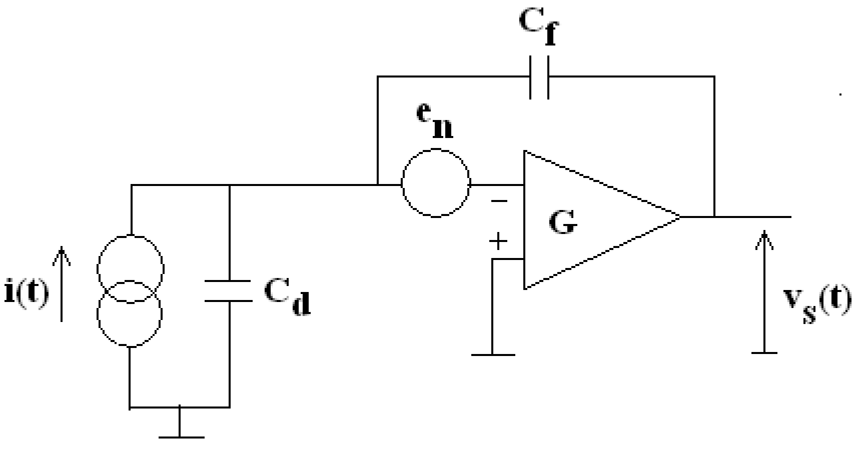
$$v_s(t) = \frac{-\int i(t)\, dt}{C_f + (C_f + C_d)/G} \approx \frac{-\int i(t)\, dt}{C_f} = -\frac{Q(t)}{C_f}$$



Jean-Francois Genat, New Developments in Photo-detection, July 4-8th 2011 Lyon, France

Charge sensitive amplifier
Serial noise

Serial noise: preamplifier
first stage

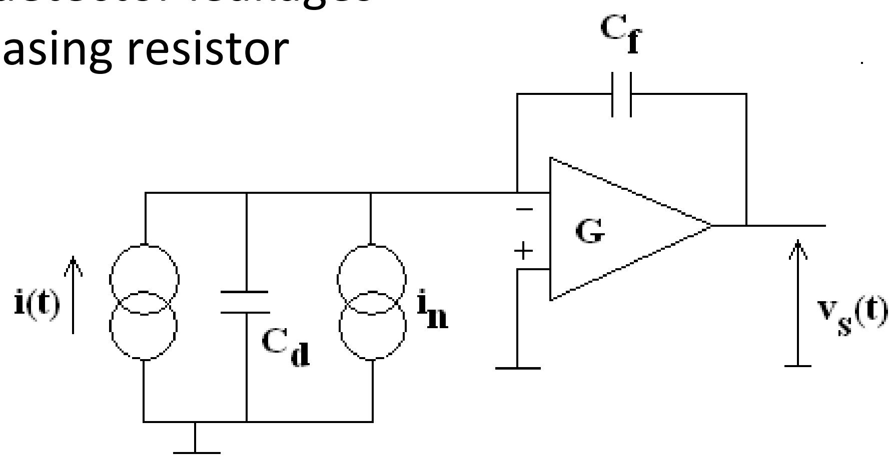


$$v_s(t) = \frac{-\int i(t)\,dt + e_n C_d}{C_f + (C_f + C_d)/G} \approx = \frac{Q(t) + e_n C_d}{C_f}$$

Serial noise is proportional to detector capacitance:
Weighted by C_d/C_f

Charge sensitive amplifier Parallel noise

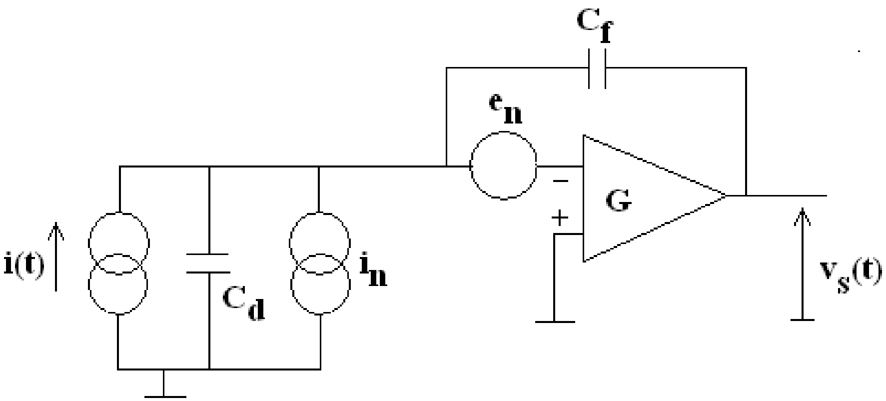
Parallel noise: detector leakages
biasing resistor

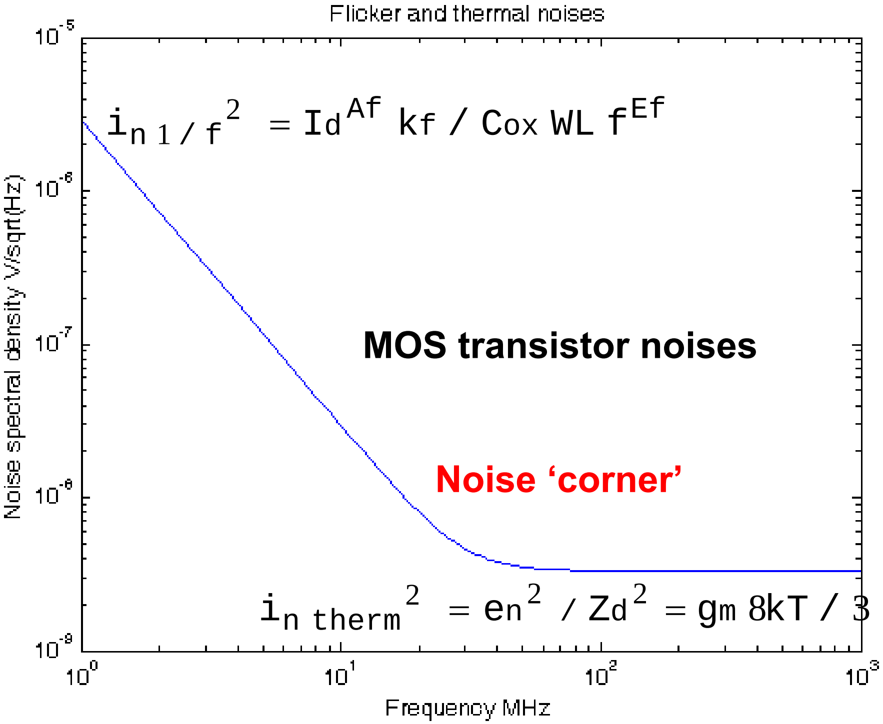


$$v_s(t) = \frac{-\int [i(t) + i_n]\,dt}{C_f + (C_f + C_d)/G} \approx -\frac{Q(t) + \int i_n\,dt}{C_f}$$

Parallel noise integrated adds to signal

Charge sensitive amplifier Total noise





Noise total spectral density :

$V / \sqrt{Hz}$

$$S(\omega) = [i_n^2 + e_n^2 / Z_d^2] / \omega^2 C_f^2 = i_n^2 / \omega^2 C_f^2 + e_n^2\, C_d^2 / C_f^2$$

Parallel noise = $1/\omega^2$ Serial noise flat

$$\text{noise rms} = \sqrt{\int_0^{\infty} S(\omega)\, d\omega / 2\pi}$$

Input transistor sizing

Noise is mainly produced in the input stage, as it is multiplied afterwards by the gain of the other stages
The input transistor is critical

MOS transistor Inversion regimes:

Strong linear : $V_{GS} > V_{th}$ and $V_{DS} < (V_{GS} - V_{th})$

$$I_D = \mu_n C_{ox} \frac{W}{L}[(V_{GS} - V_{th})\, V_{DS} - \frac{V_{DS}^2}{2}]$$

Strong saturation: $V_{GS} > V_{th:}$ and $V_{DS} < (V_{GS} - V_{th})$

$$I_D = \mu_n C_{ox} \frac{W}{L}[(V_{GS} - V_{th})^2 (1 + \lambda(V_{DS} - V_{Dsat}2))]$$

Weak: $V_{GS} < V_{th}$

$$I_d = I_{d0} \exp \frac{V_{gs} - V_{th}}{nV_t}$$

Input transistor sizing

Reduce power going from strong to moderate-weak inversion

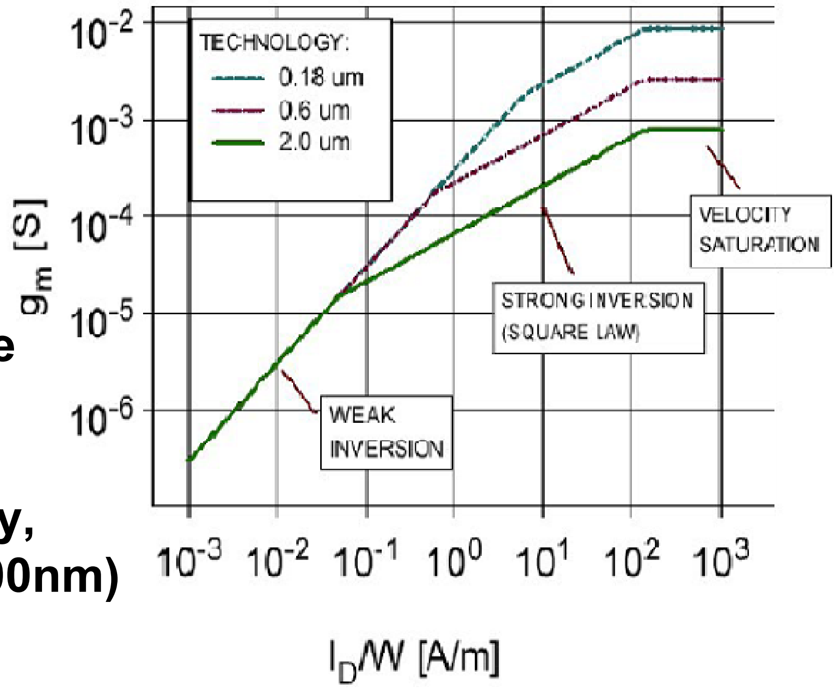
- **Strong inversion: g_m proportional to W/L $\sqrt{I_d}$**
- **C_{gs} proportional to WL**
- **ENC proportional to (Cdet + Cgs)/ $\sqrt{g_m}$**
- **Optimum W/L: $C_{gs} = 1/3\ C_{det}$**
- **Large transistors are easy in moderate/weak inversion at low currents**

Optimum size in weak inversion

- g_m independent of W, L, proportional to I_d

- ENC minimal for C_{gs} minimal, provided the transistor remains in weak inversion

MOSFETs models are pretty accurate today, even for deep submicron processes (L <100nm)



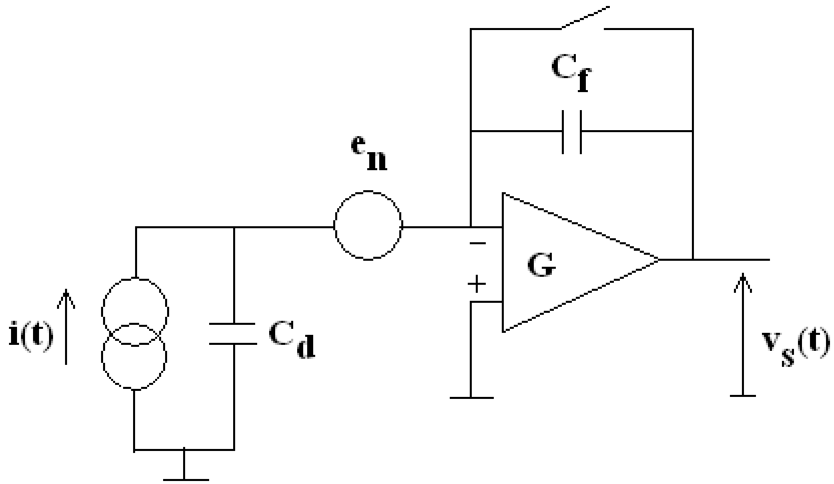
Example: Cd(Zn)Te Xrays detectors readout

16 x 16 pixels readout (camera of 2048 pixels / 8 cm^2)

- **32-channel front-end self triggering**
- **RC^2 shaper**
- **Peak detector**
- **Baseline holder (pulses have a long tail due to slow holes in CdTe)**
- **Variable gain stage, 50, 100, 150, 200 mV/fC**
- **ENC=68 e- at 5.4 μs peaking time and 2 pF input capacitance to achieve 1 keV FWHM energy resolution at 60 keV**
- **1 MeV dynamic range**
- **Discriminator, DAC threshold**
- **AMS 350nm**
- **SEL Radiation hard library**
- **0.8 mW / channel**

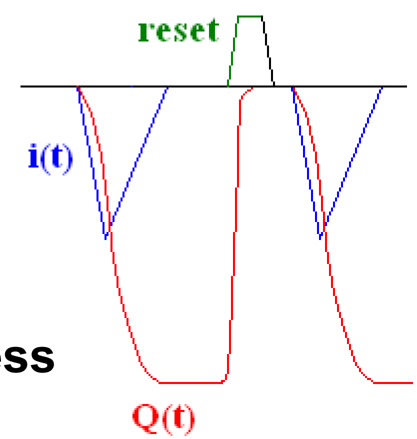
IdEFX Saclay

Charge amplifier reset



detector

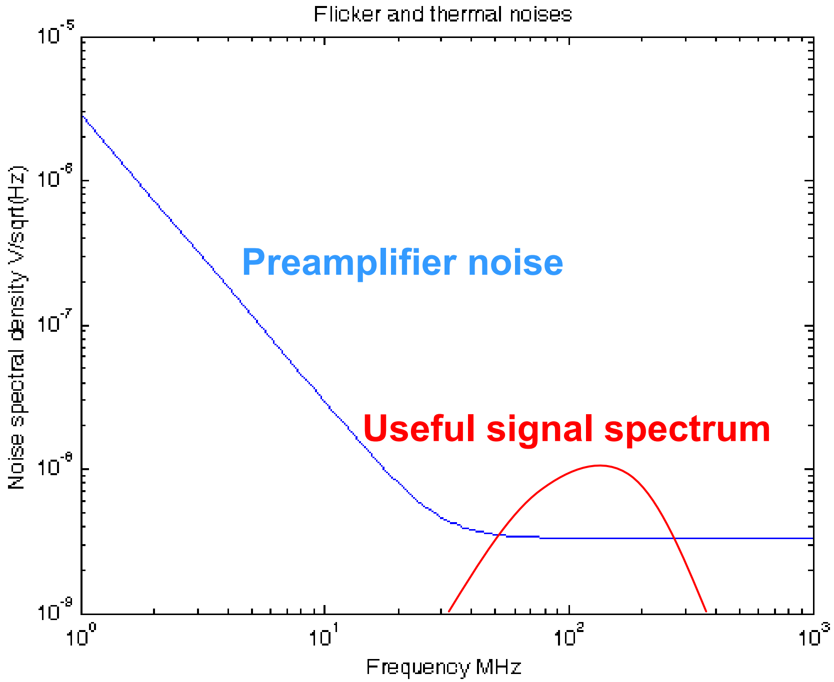
electronics

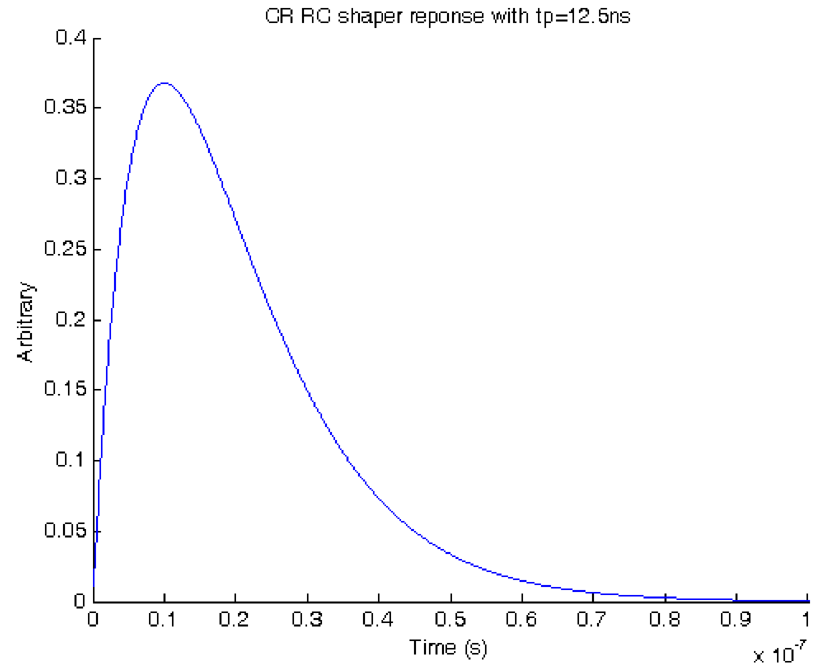


Reset switch:

- **MOS transistor: kT/C noise**
- **Resistance: thermal noise**
- **Optical pulse: needs opto process**

Pulse Shaping





Analog filtering at frequencies that optimize signal/noise
E.g. CR RC, CR RC^2

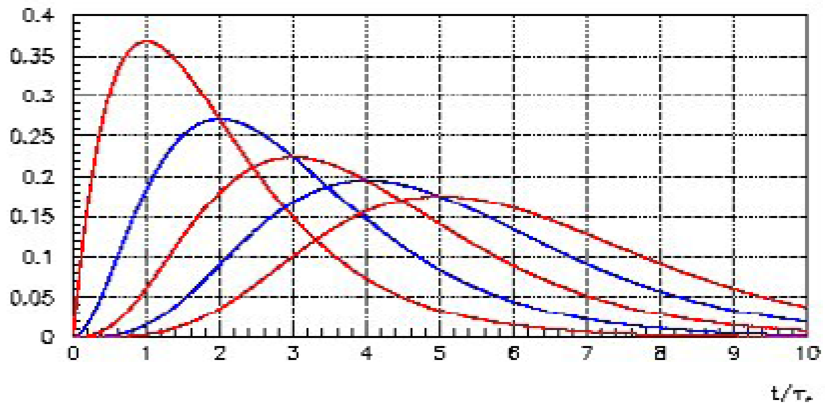
or digitize (if speed and power allow)
Digital filtering

ENC after CR-RC^n Pulse shaping

CR: high pass

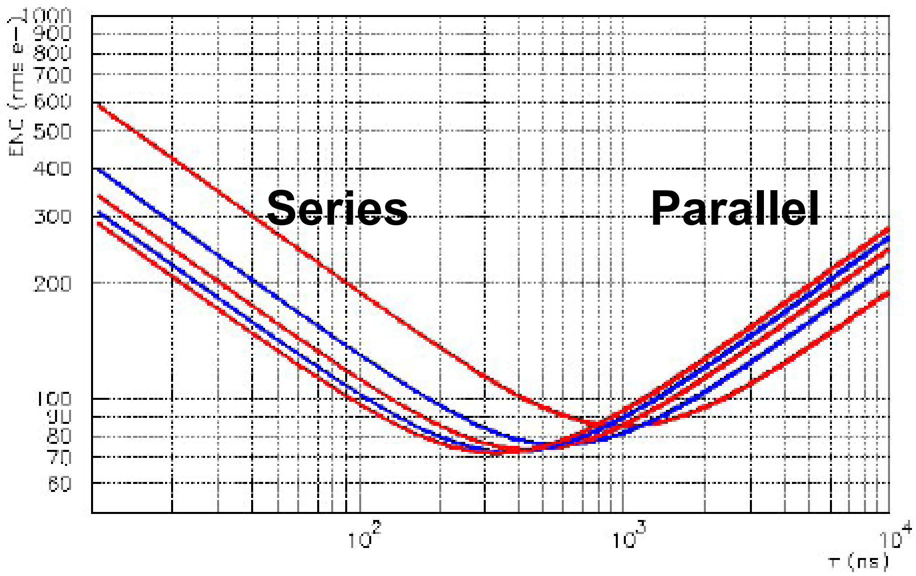
RC^n: low pass

Limit n $\longrightarrow \infty$ is gaussian



Waveform vs shaping time

But higher order filters have drawbacks (noise…)

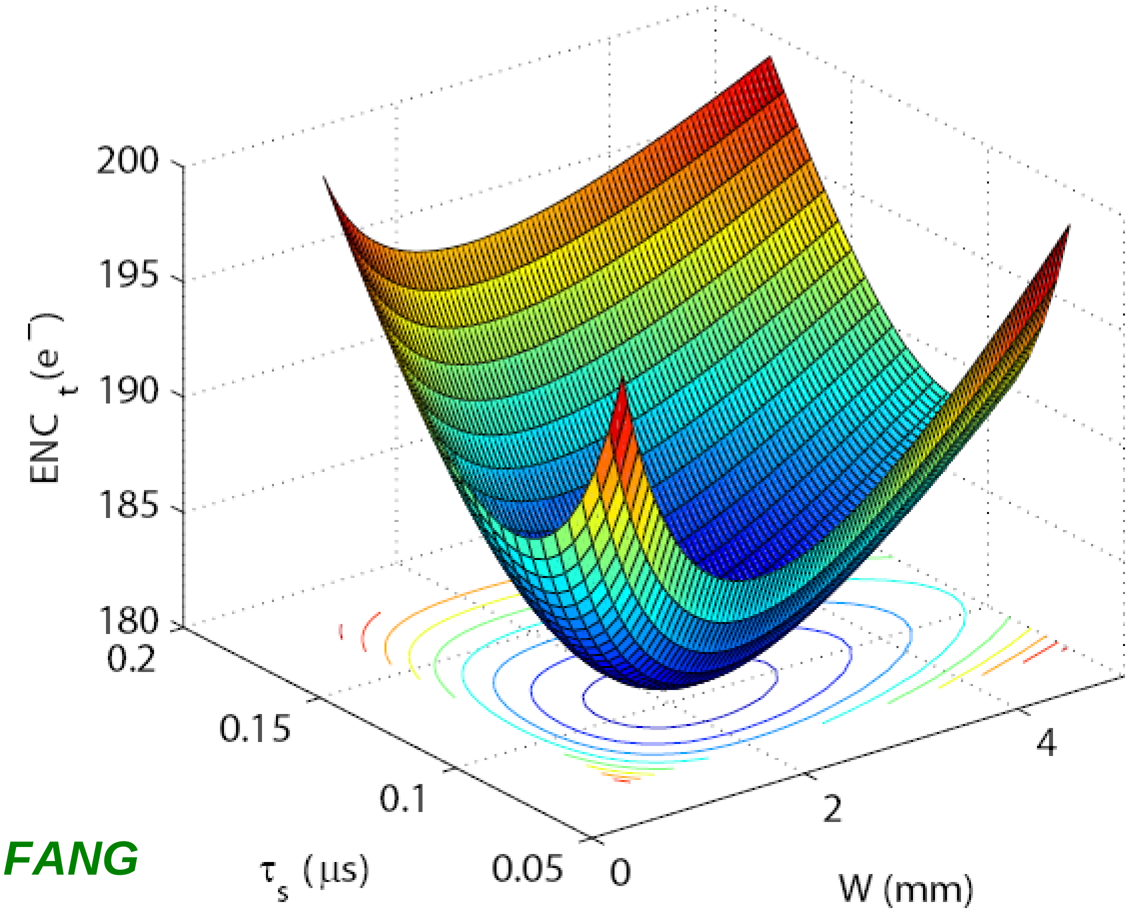


ENC vs shaping time

Series noise in $1/\sqrt{\tau}$ **Parallel noise in** $\sqrt{\tau}$ **1/f noise independent of** τ

ENC optimization in sub-micron CMOS

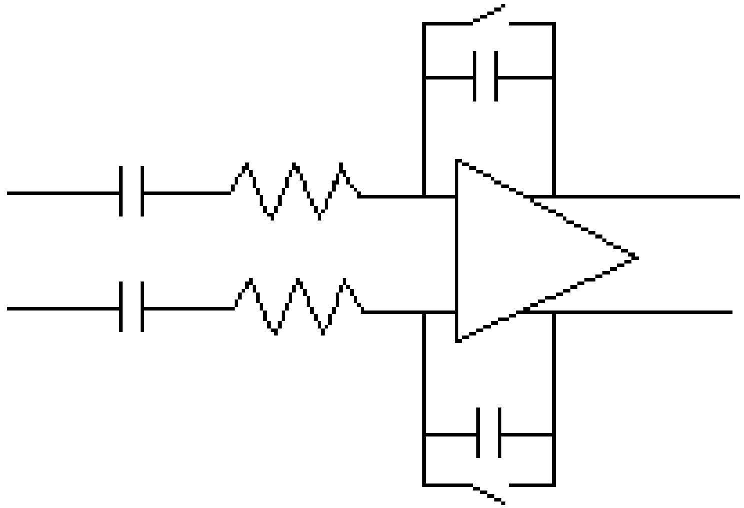
Example: Charge amplifier for Avalanche Photo-Diodes readout



X. FANG

Exemple of noise minimization vs shaping time and width of the input transistor
τ_s = 136ns, W = 2mm

Switched Integration



- Convolution with a window function (Band-pass, Sinc)
- The switch is implemented easily (instead of large resistors)
- Fast reset: no pile-up
- Needs synchronous operations
- Performance similar to CR-RC^n

Transimpedance amplifier

Gain = R $V_s(\omega)/I_{\det}(\omega) = \dfrac{-R}{1+Z_f/GZ_d}$

High counting rate

Typically used for optical link receivers

Easily ringing with capacitive detector

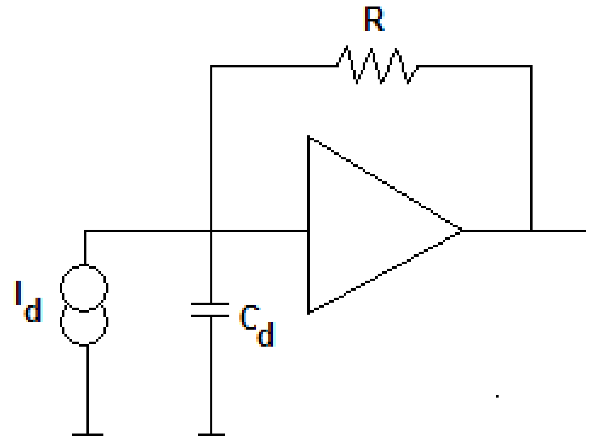
Inductive input impedance L_{eq}= R/ω_c

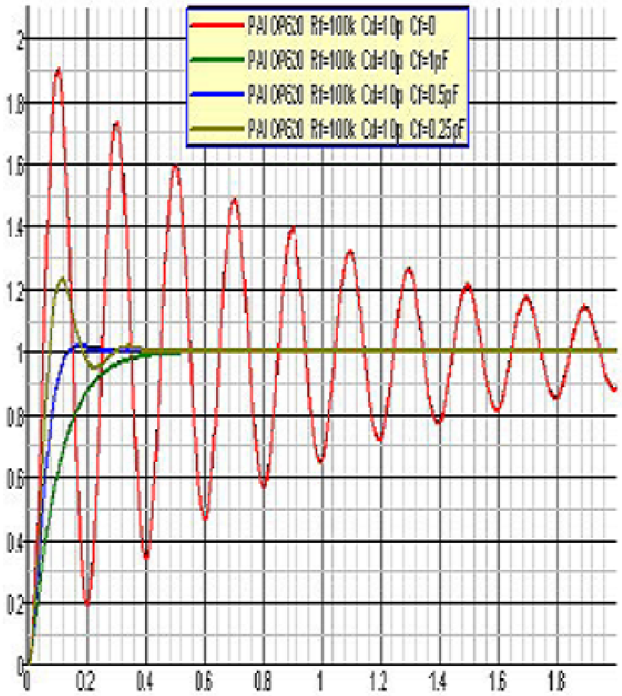
Resonance at : f_{res}= 1/2π $\sqrt{L_{eq}C_d}$

Quality factor: Q = R / $\sqrt{L_{eq}/C_d}$ Q > 1/2 induces ringing

Damping with capacitance $C_f = 2\sqrt{\dfrac{C_d}{RG\omega_0}}$

Easier with fast amplifiers

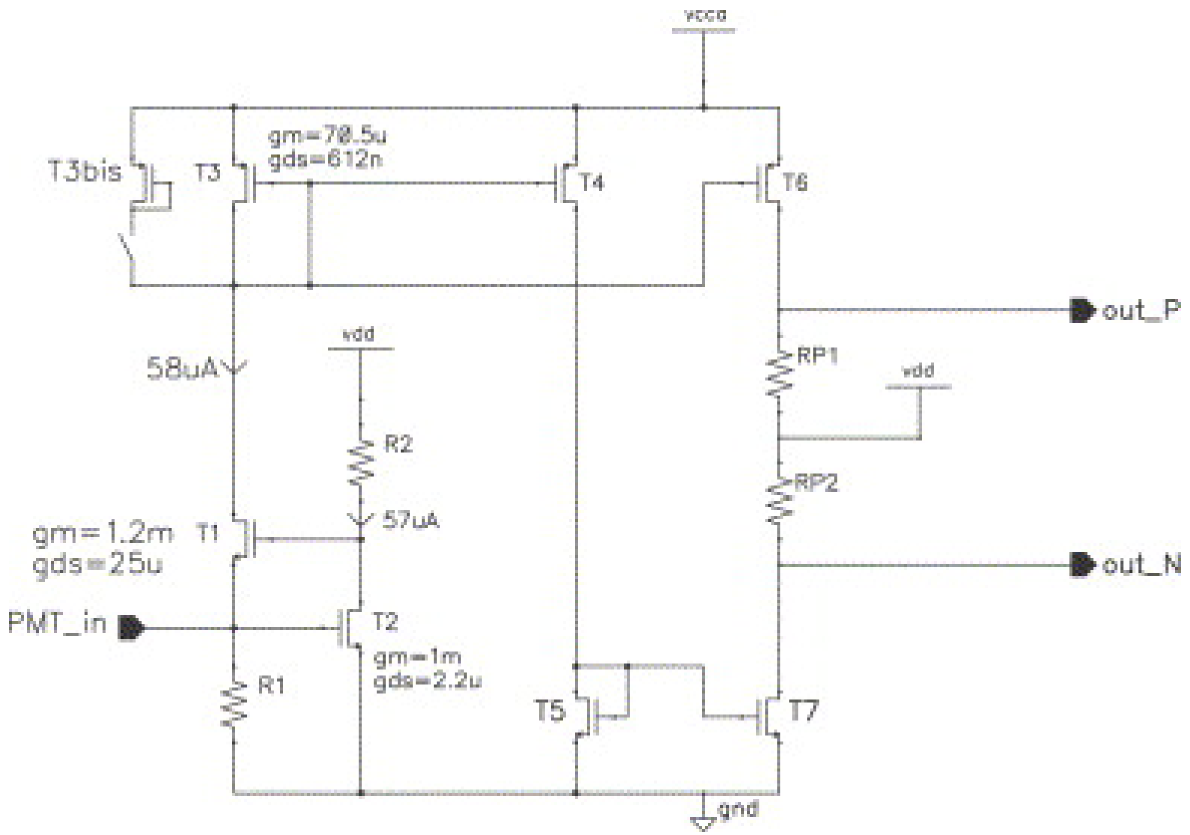




C de la Taille

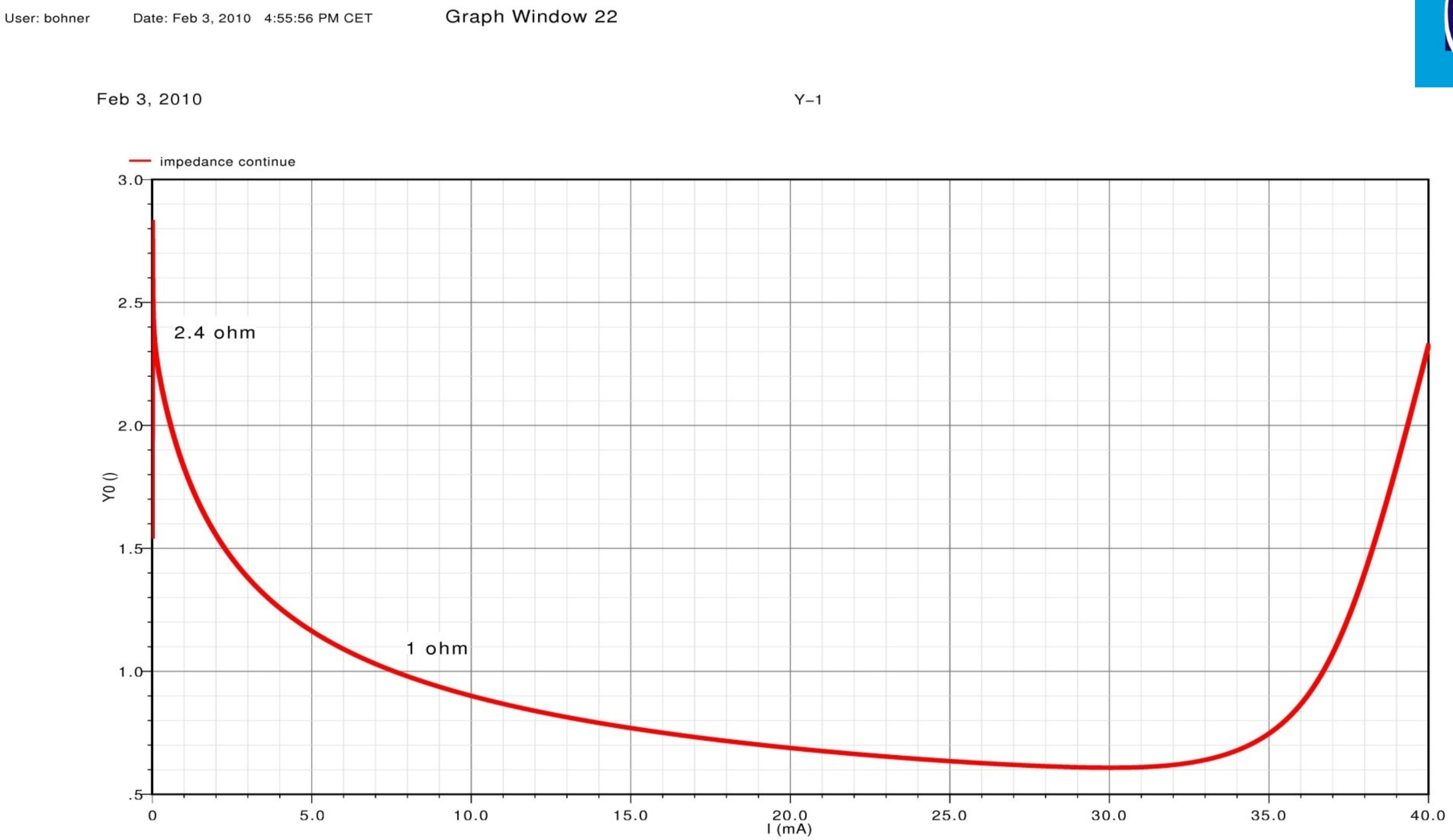
Current conveyor

- **Very low input impedance: less sensitive to crosstalk, electromagnetic interferences**
- **Differential output**



J. Lecoq

Input impedance versus magnitude



J. Lecoq

Charge vs Current preamplifiers

Charge preamps

- **Best noise performance**
- **Best with short signals**
- **Best with small capacitance detectors**

Current preamps

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

C de la Taille

Guidelines for low-noise design

Noise

- **Reduce detector capacitance**
- **Avoid as much as possible connectors and cables, try to digitize on front-end**
- **Increase the first stage gain keeping matching with C_{det}**
- **Shape at the optimum peaking time**

ADCs (see J. Lecoq presentation in 2007)

Ramp ADCs

Convert to time (TDC). Compare level to a ramp until trigger.
Very effective if many channels in parallel (switched capacitors arrays)
A few MHz at more.

- 1 comparator/channel
- 1 common (Gray) counter
- 1 ramp generator

Can be speeded up using an analog feedback from already eliminated codes

Successive approximation (SAR)

Compare level bit after bit to bit-voltages references..
Subtract the winner bit up to LSB.

Faster by N/2N Conversion times 1-10 MHz

- 1 shift register
- 1 digital to analog converter/channel
- 1 subtractor/channel
- 1 comparator/channel

Flash ADCs

Compare level to all possible codings generated from a voltage divider bridge
Very heavy, power hungry, but very effective
GS/s speeds

- 2^N comparators/channels
- Encoding logic

Pipe-line

Digitize on N-bit, subtract DAC encoded result
Multiply residual by 2 to a next identical stage, up to LSB

- N-bit ADC
- 1 multiplication by 2
- 1 comparator

ADCs

it fractional

Pipe-line structure, with two thresholds/bit to manage code borders, delaying decision to the next stage after signal amplified by 2.

Sigma-Delta

Continuously sampling device. One_bit output obtained from comparison between the integral of the previous differences between level and this normalized bit-output. Output oscillates when conversion achieved. Average level of the bits tream is proportional to the input signal level. Low pass filter recovers the digital data in binary format

- **Very accurate (>20-bit)**
- **Very slow (kHz range)**
- **1 integrator, 1 comparator, 1-bit DAC/channel**

These ADC have replaced ramp ADCs
But photo-detection needs mainly ramp ADCs: high channel count to convert in parallel

All ADCs need an input sample and hold device to assert a stable level during conversion

Many hybrid devices, depending on the best case-dependent trade-off between area, power, technology cost e.g. SAR/flash

Photo-detectors

Very application dependent: CCD need parallel operation for column readout, pixels can accomodate one low resolution ADC/pixel

http://www.in2p3.fr/actions/formation/microelectronique07/porquerolpdf2007.pdf

Pulse Sampling ADCs, IPs

Trade-off precision / sampling speed / power

Example:

Discrete ADCs on the market

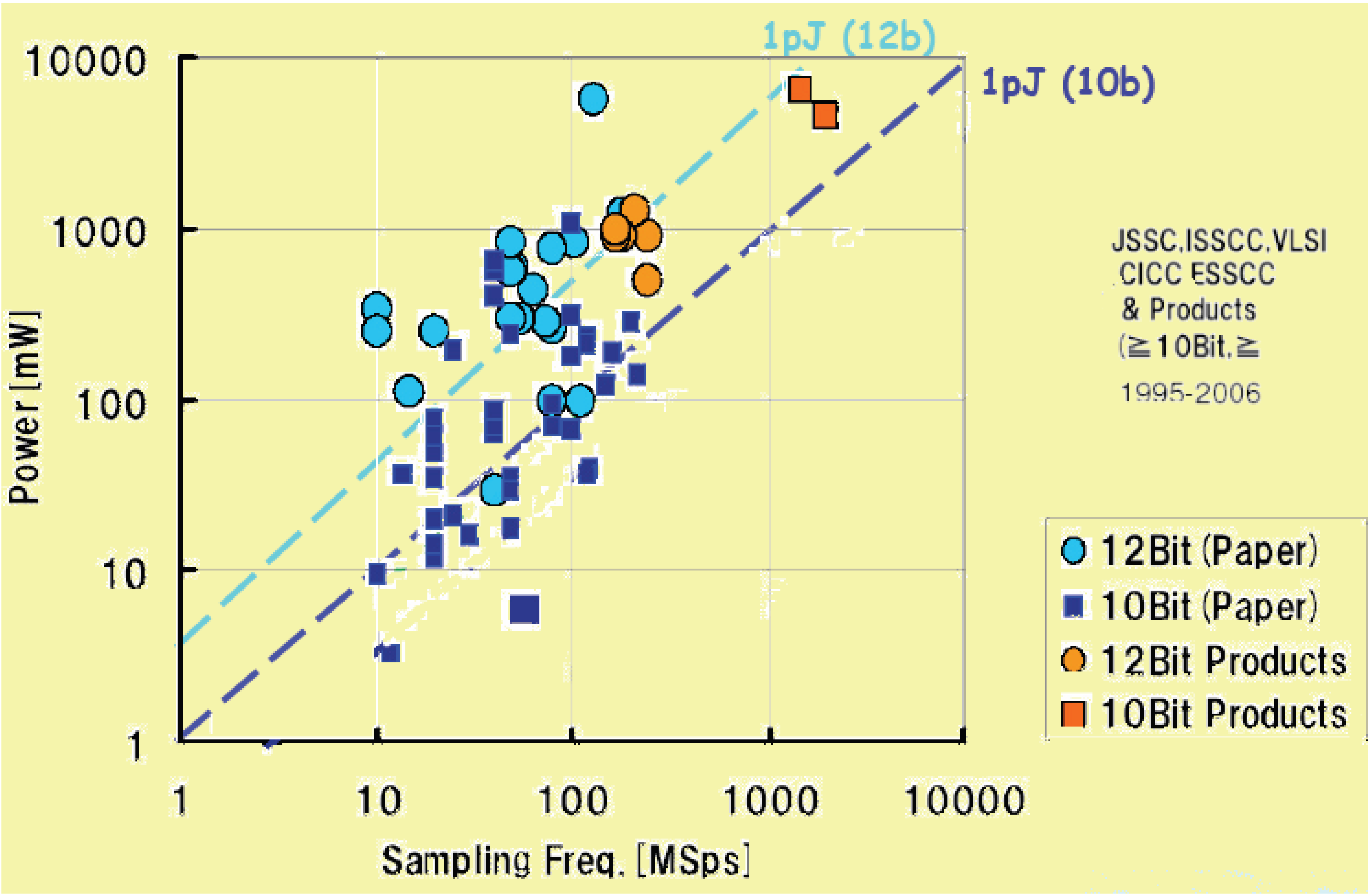
24-b Σ/Δ Dual-slope **16-bit SA + Flash**
12-b 3.6GS/s
8-b 56GS/s

Custom IPs:

AMS 350nm	**12-b 1MHz**		**purchased by IN2P3**
TSMC 130nm	**14-b 150 MHz**	**300mW**	**nSilition (Belgium)**
SOS 90nm	**12-b 220 MHz**	**50mW**	**Anacatum (Sweden)**
Chartered 350nm	**8-b 40 MHz**		**NTLab (Russia)**
IHP BiCMOS 250nm	**14-b 25 MHz**		**NTLab (Russia)**
IHP BiCMOS 250nm	**2x 12-b 8kHz**		**NTLab (Russia)**

TSMC 130nm	**4.25 Gb/s**	**Quad SerDes**	**Mixel (USA)**
TSMC 28nm	**PLL 2-3.6GHz**	**1ps jitter**	**Silicon Creation (USA)**
Chartered 350nm	**PLL 300MHz**		**NTLab (Russia)**

ADCs Power



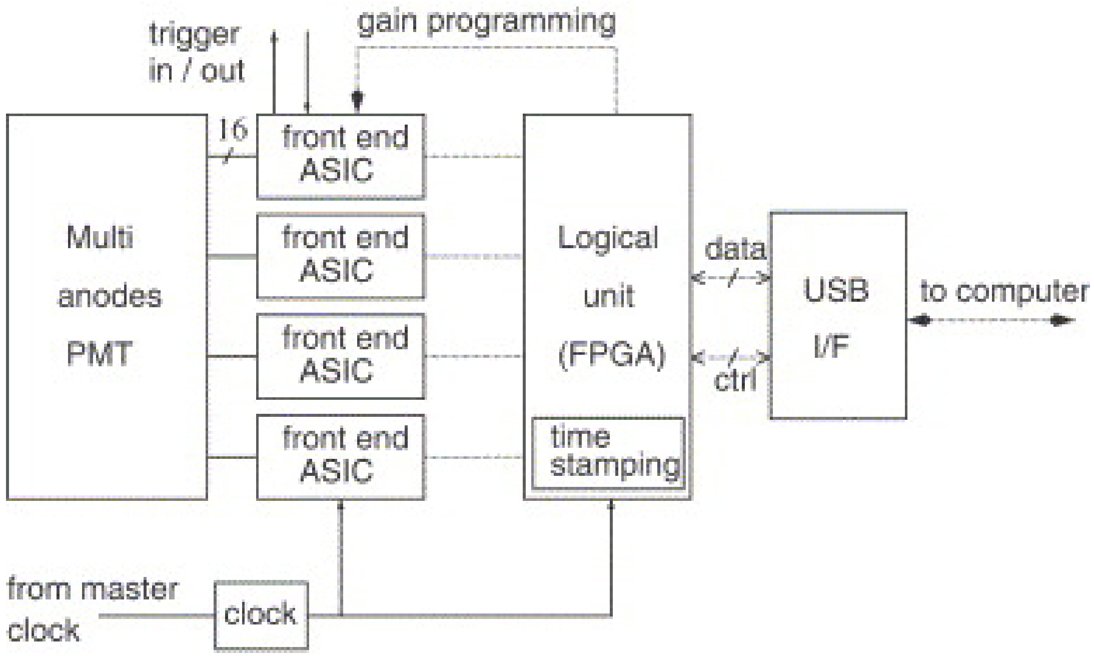
P. O'Connor

Photo-multiplier readout

64-anode MaPMT photo-detector

16-channel ASIC in AMS 350nm
Includes:
- **Input integrator**
- **8_bit ADC**
- **Parallel to Serial conversion**

J. Lecoq

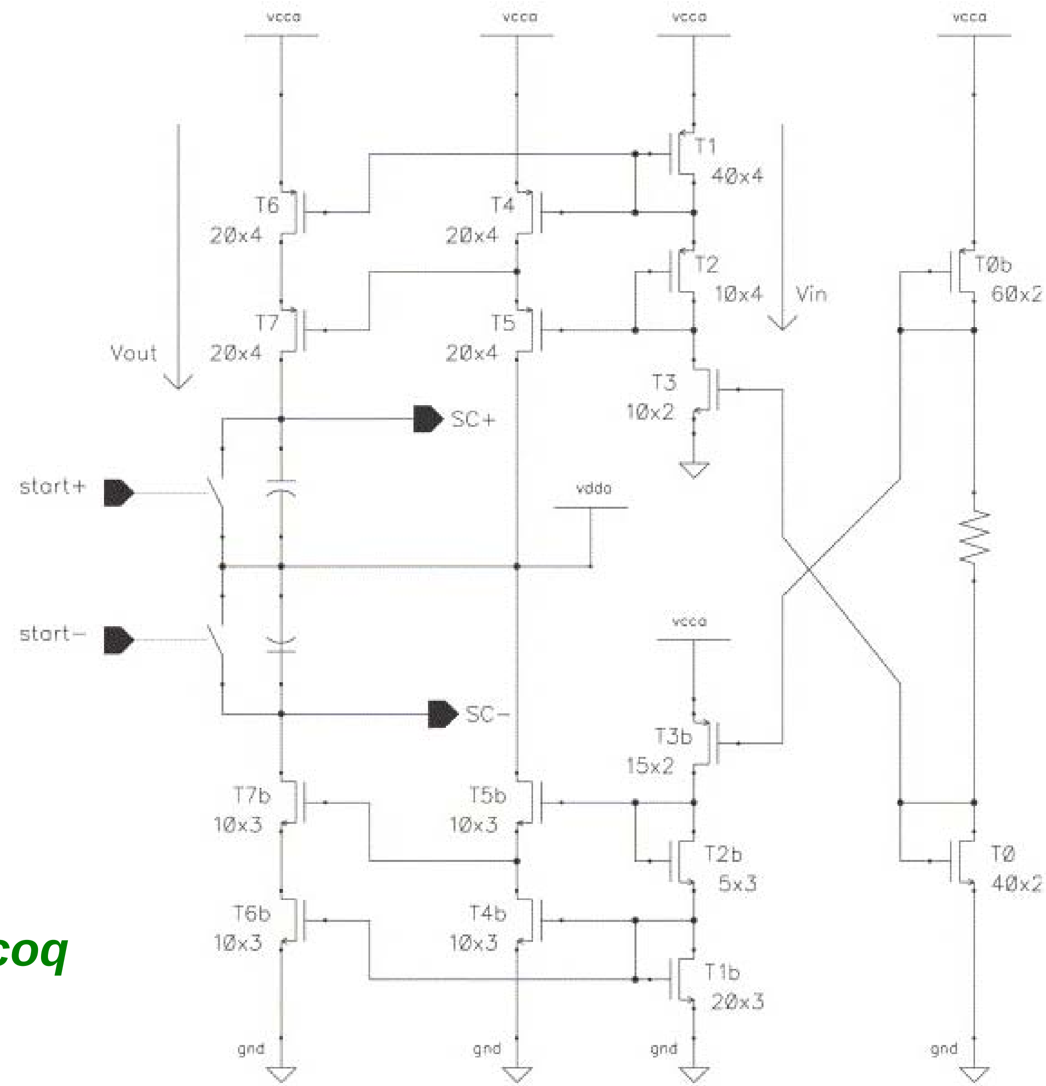


***http://*www.sciencedirect.com/science/article/pii/S0168900206008886#bib3**

CMOS 8-bit ADC ramp generator

- Charge capacitors at constant current
- Cascoded current sources (linearity)
- Two symetric ramps
- 5.12 μs duration
- 4V range
- Linearity 0.085%

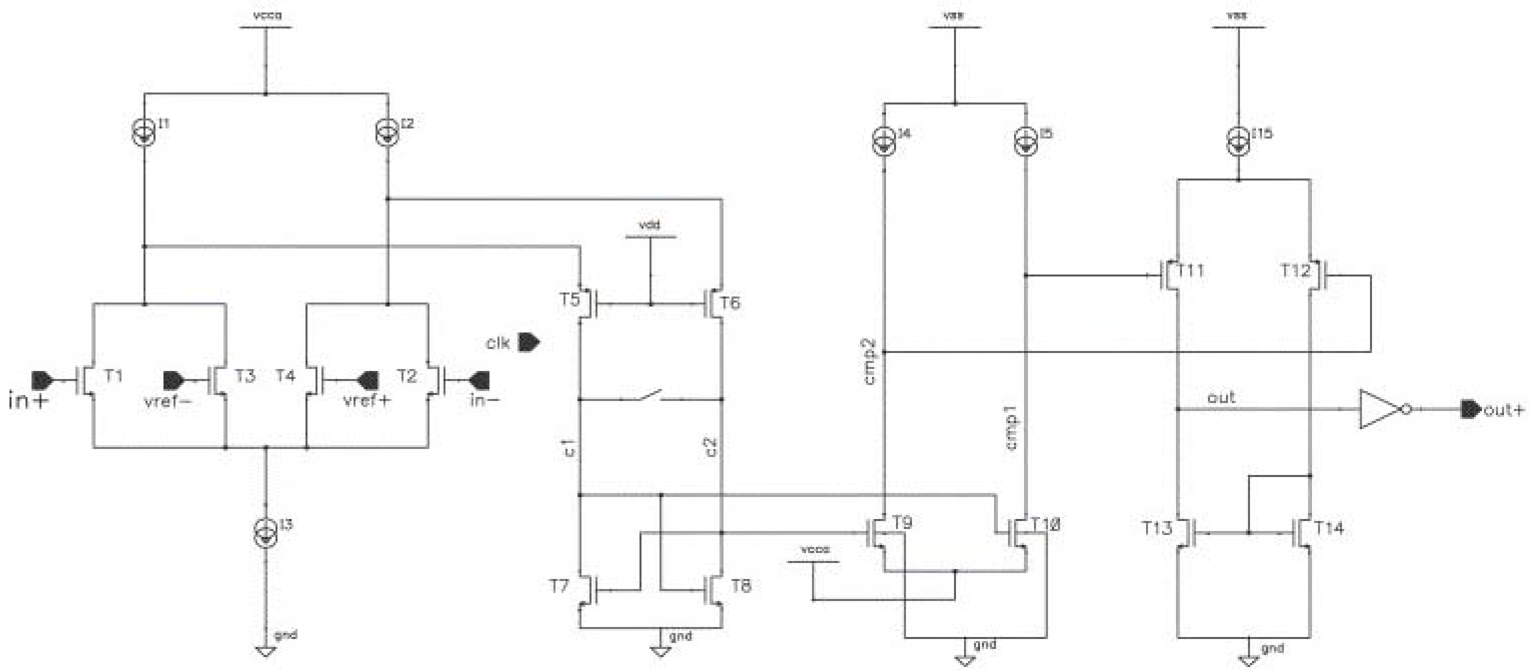
J. Lecoq



CMOS ADC latched comparator

- Differential
- Cascoded
- Positive feedback
- 300 μV sensitivity

J. Lecoq

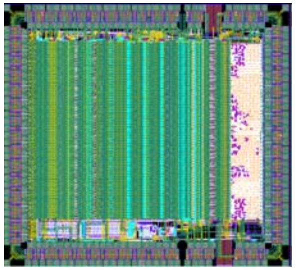


Silicon PMT readout

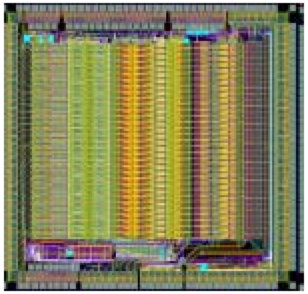
AMS SiGe 350nm technology line from LAL Orsay

C de la Taille

Maroc
- **64-channel photon counting**
- **1/3 Photo-Electron trigger sensitivity**
- **50fC dynamic range**
- **Tunable slow channel for charge**
- **Tunable fast channel for timing**
- **Internal 8-12 ramp ADC**



Easiroc
- **32 inputs**
- **8-bit DAC for gain adjustment**
- **Two control analog channels**
- **Fast trigger channels for timing**
- **Low power: 5mW/ch**



Contact LAL Orsay: P Barrillon

http://www.omega.in2p3.fr
(Need registration)

Full Orsay 0.35μm SiGe line

Chip	Optimized for	#ch	#triggers	Data type	Outputs
MAROC	MaPMT	64	64	Th Q	1 Q analog + dig
SPIROC	SiPM	36		Th Q t	1 Q analog Dig
EASIROC	SiPM	32	32	Th Q	2 Q analog
HARDROC	RPC	64		Th Q	1 Q analog Dig
MICROROC	MicroMegas	64		Th Q	1 Q analog Dig
SKIROC	PIN diodes	64		Th Q	1 Q analog Dig
PARISROC	PMTs Matrix	16	16	Th Q t	Dig
SPACIROC	MaPMT	64	64	Th Q	9 Q

http://www.omega.in2p3.fr

Multi-anode PMT readout (JEM-EUSO)

C. de la Taille

AMS SiGe 350nm technology line from LAL Orsay

Spaciroc **64-channel photon counting for JEM-EUSO**
1/3 Photo-Electron trigger sensitivity
10-1500 PE dynamic range
Tunable slow channel for charge
Tunable fast channel for timing
Internal 8-12 ramp ADC
Low power: 1mW/ch required by the ISS

http://www.omega.in2p3.fr
(Need registration)

Fast Switched Capacitors Arrays (SCA)

- **Fast photo-detectors as Micro-Channel Plates or Silicon Photo-Multipliers signals analysed on-chip as with digital oscilloscopes**

- **Regular PMTs sampled to 13-bit dynamic range (E. Delagnes, D. Breton)**

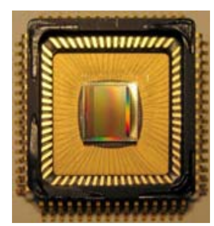
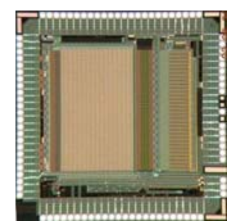
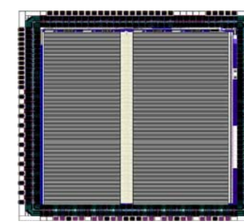
Principle of SCA ASICs:

Write fast (1-10GS/s)
Read as possible (10-100 MHz)
Digitize all caps in parallel with a ramp ADC
Input discriminator as trigger to stop sampling

Limitations:

Random noise
Sample aperture jitter
Sampling timebase jitter

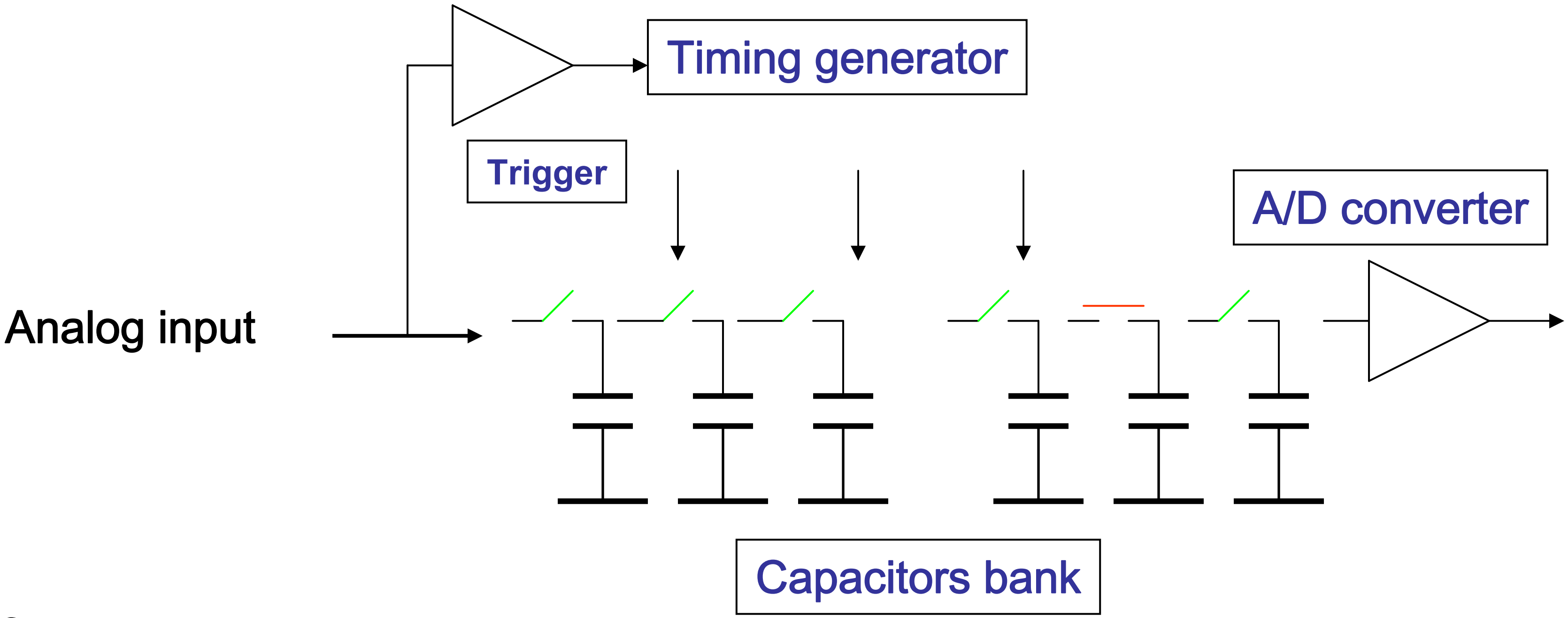
Key component of digital scopes

Examples:

DRS4	**S. Ritt (PSI)**	**6GS/s**	**850 MHz**	**250nm**
SAM	**D. Breton, E. Delagnes (France)**	**3GS/s**	**300 MHz**	**350nm**
LAB	**G Varner (Hawaii)**	**6GS/s**	**900 MHz**	**250nm**
PSEC	**H Grabas, E. Oberla (Chicago)**	**15GS/s**	**600 MHz**	**130nm**

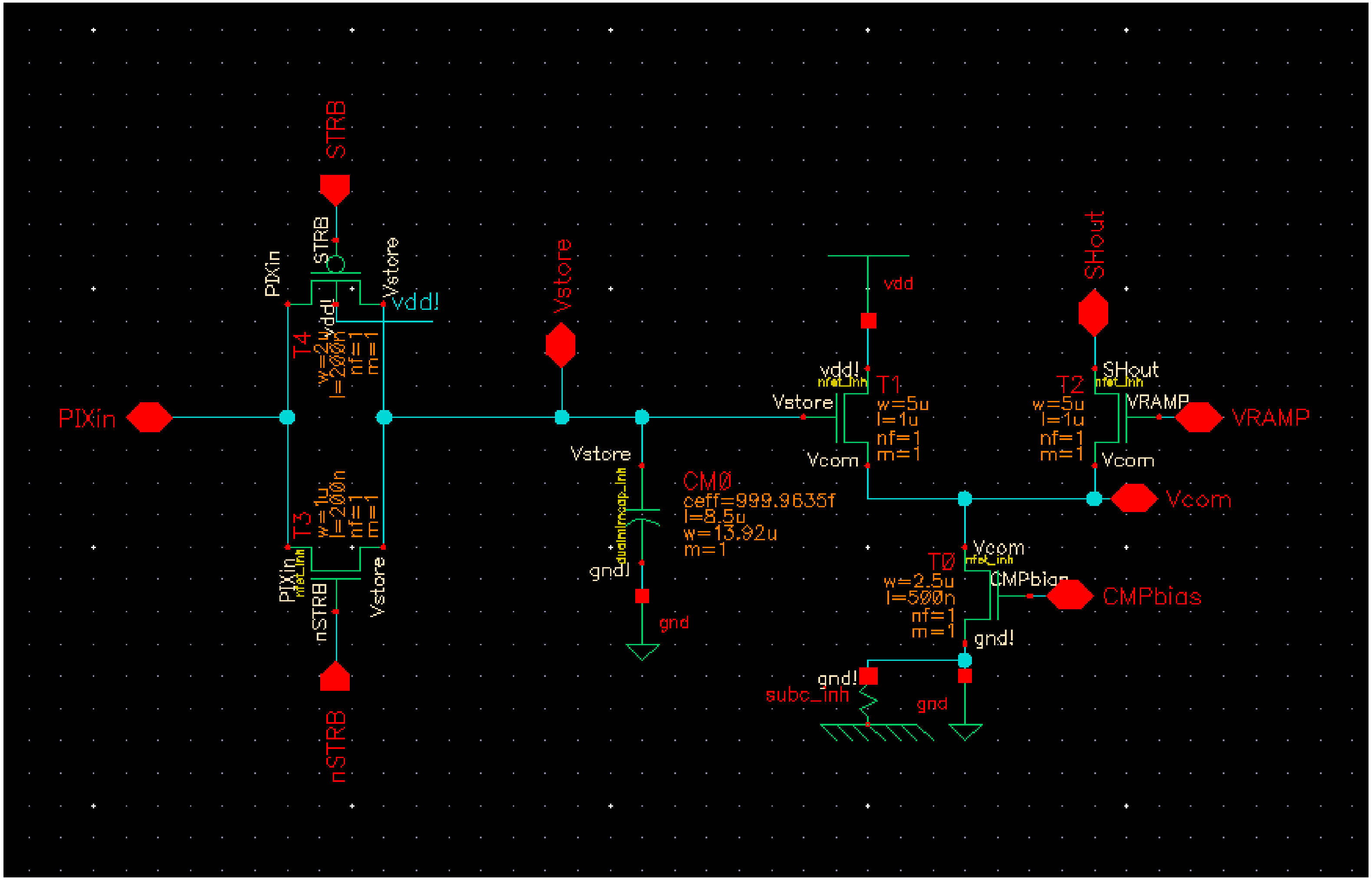
SCAs



Main features:

- **Sampling frequency**
- **Analog bandwidth**
- **Analog dynamic range (ADC bits)**
- **Depth**
- **Readout frequency**

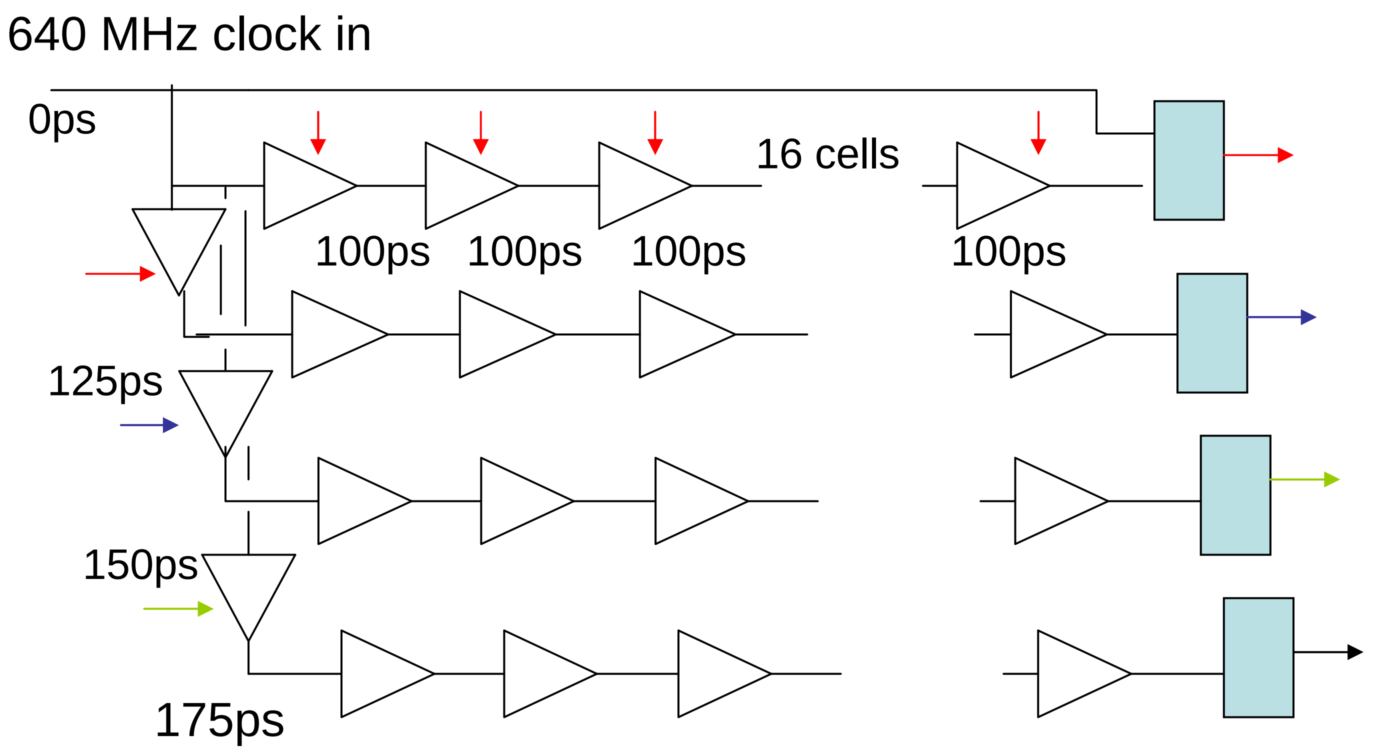
SCA sampling cell



L. Ruckman

Sampling cell + ADC comparator

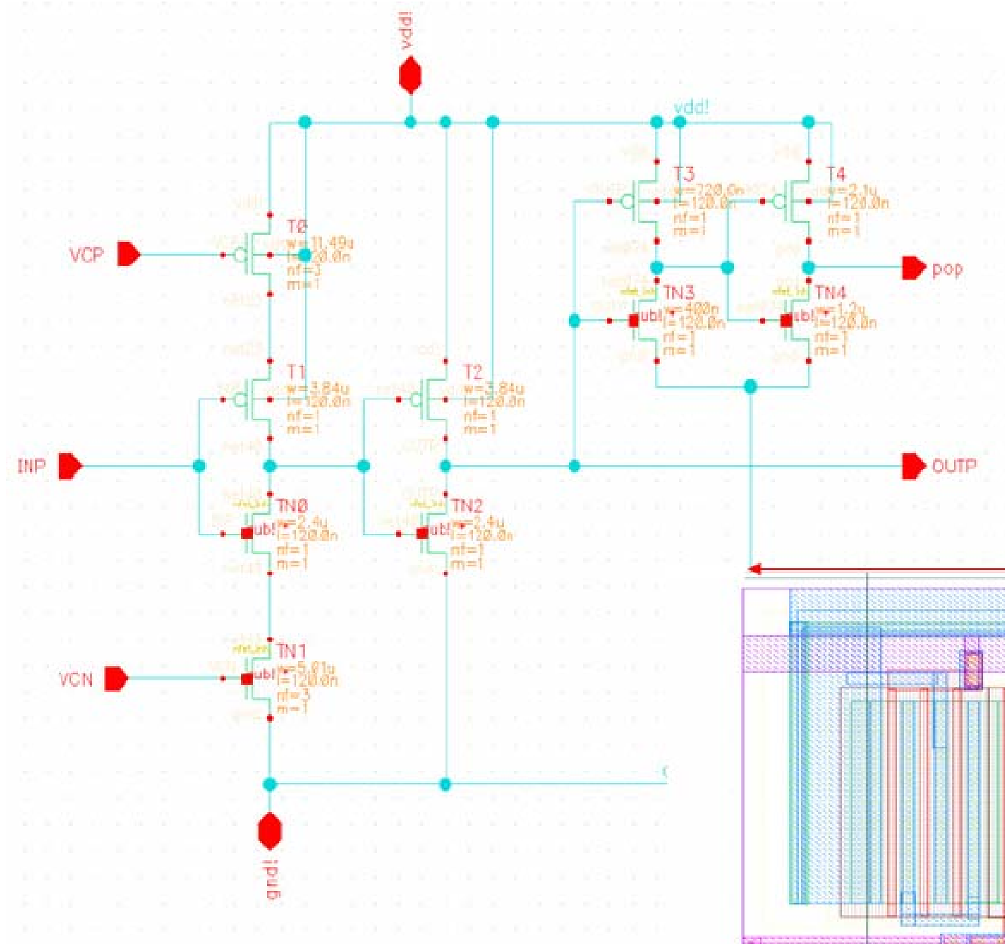
40 GS/s Timing generator

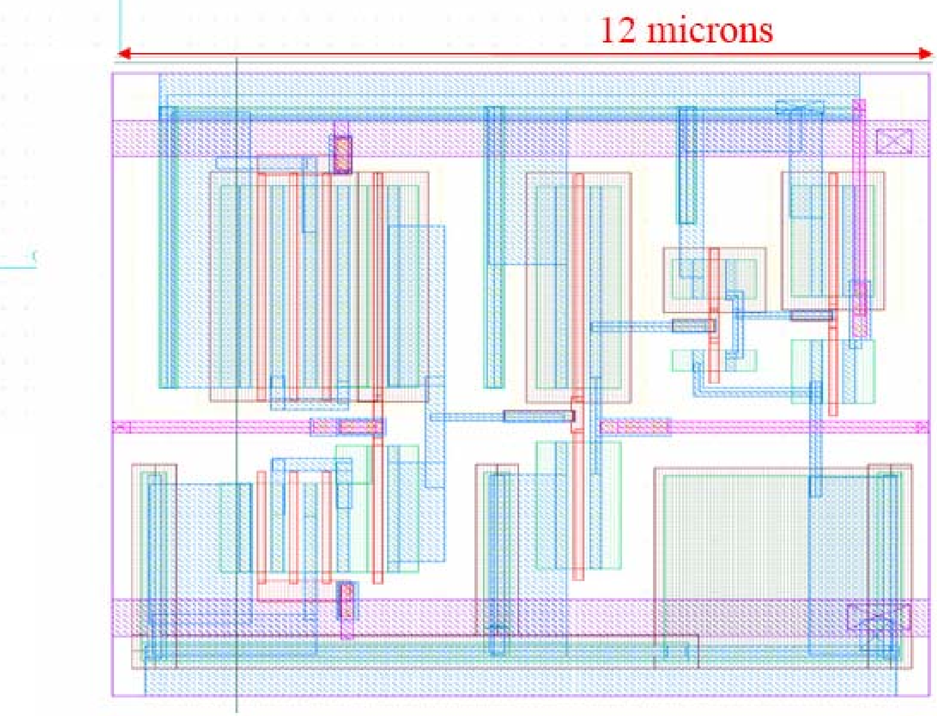


16 x 4 = 64 cells, 25ps step delays

J. Christiansen (CERN)

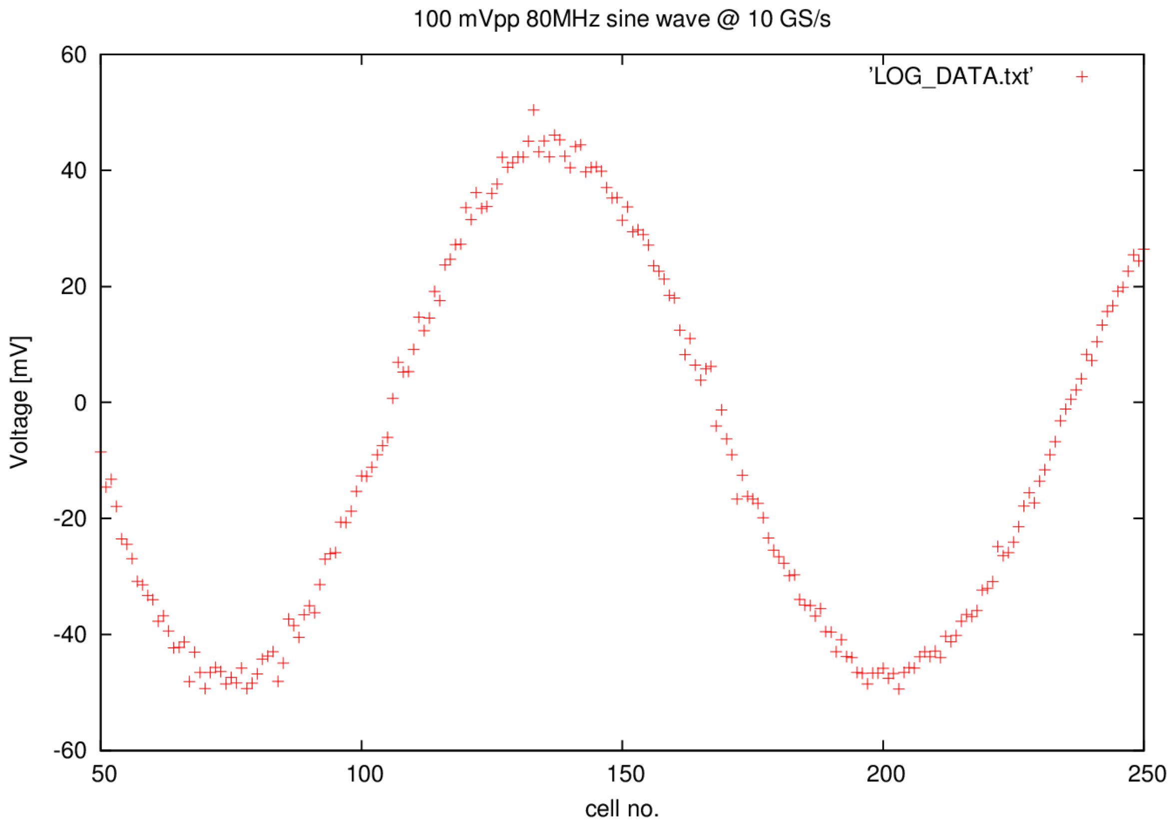
15 GS/s Timing generator





Voltage controlled delay cell
IBM 130nm

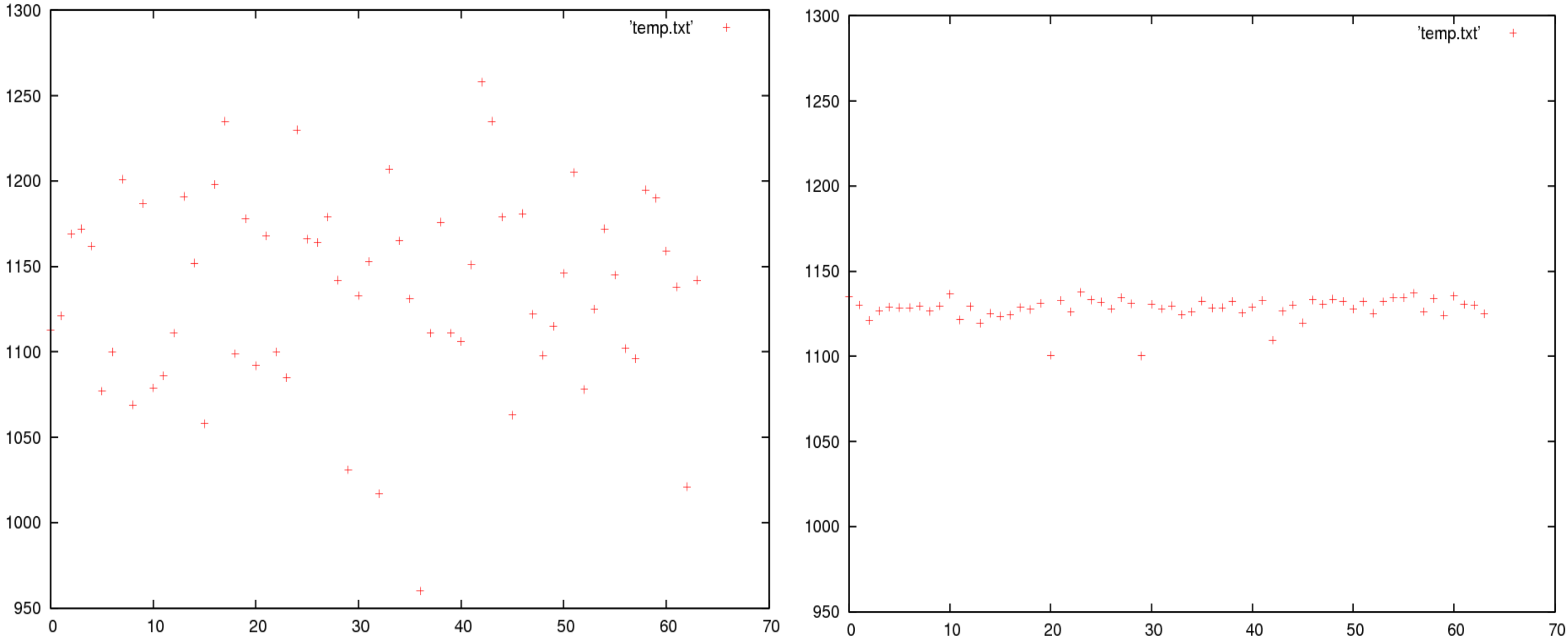
80 MHz sine wave sampled at 10GS/s



80 MHz, 100 mV pp sine wave sampled at 10 GS/s, after on-chip digitization and offset corrections

Eric Oberla (Univ Chicago)

SCA Offsets distribution



Sampled DC value before and after offsets subtraction

Offsets due to voltage threshold spreads (fixed pattern)

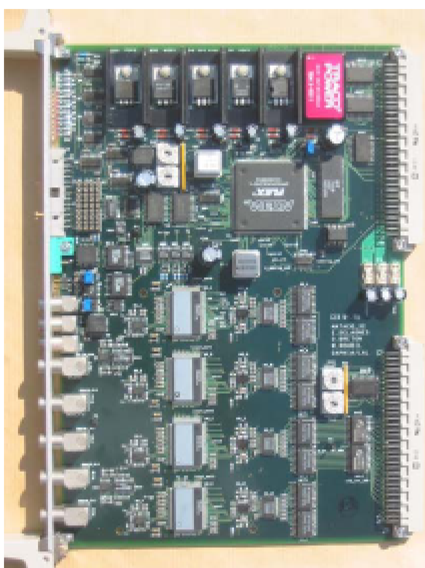
Eric Oberla (Univ Chicago)

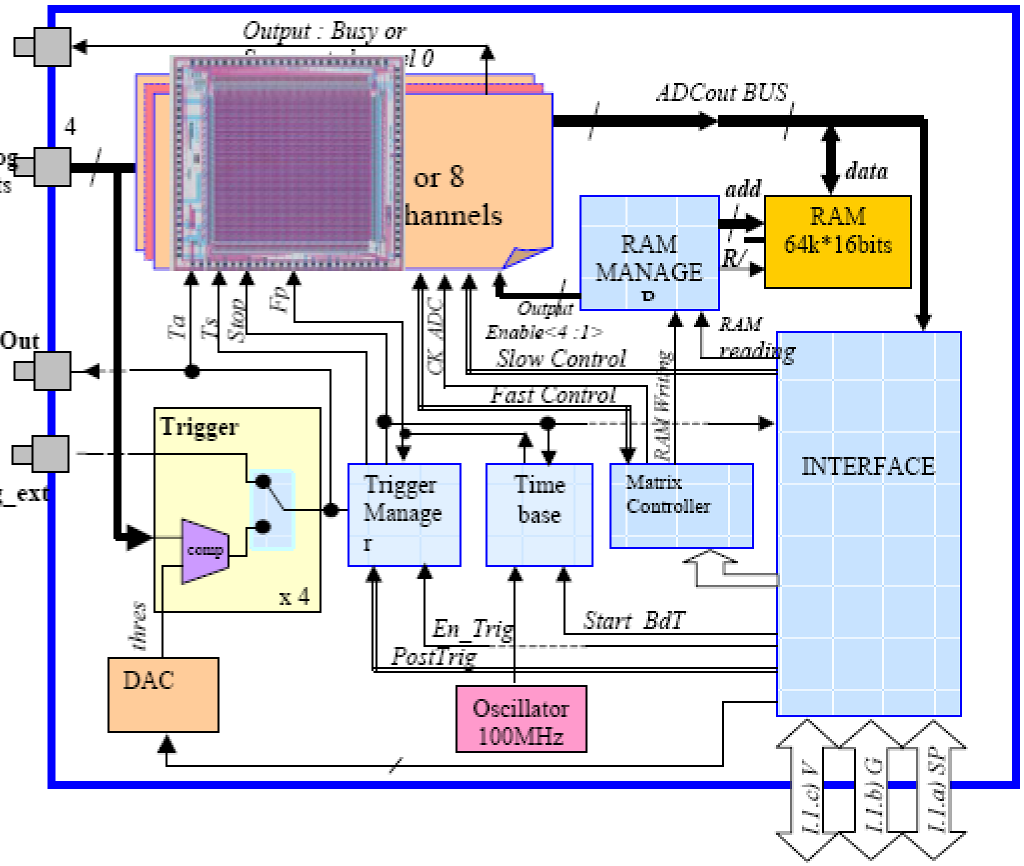
VME board equipped with SCA chips

Pipeline 12b 2GHz

©D. Breton

- MATACQVME
  - VME board with 4-8 channels
  - 2 GHz - 12 bits
  - Auto-trigger mode
  - Sold by CAEN





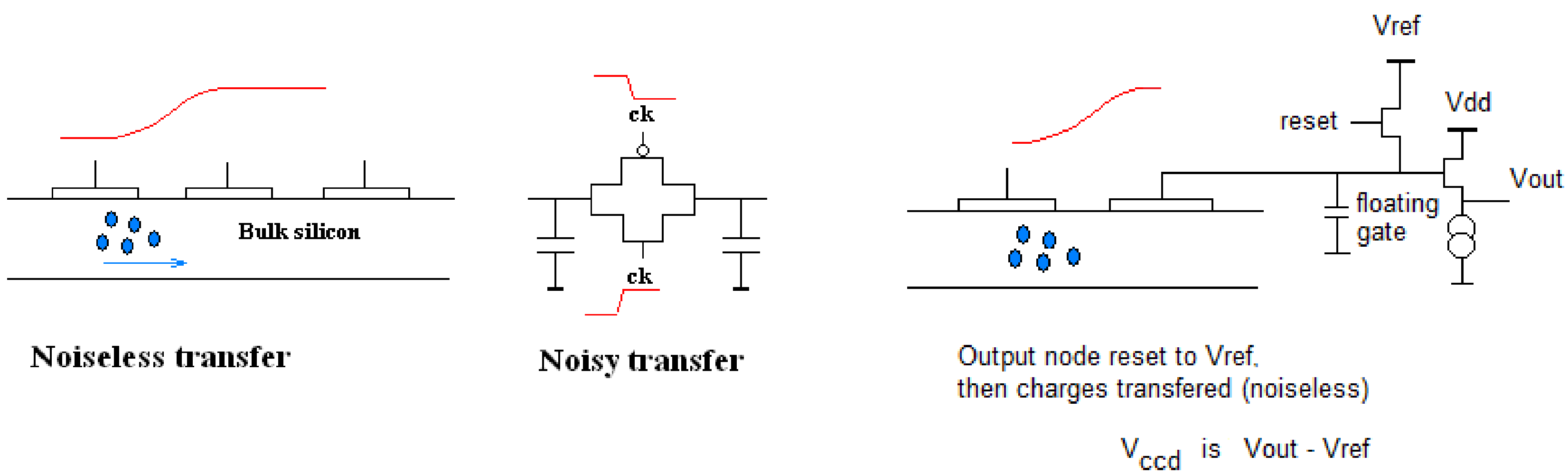
D. Breton, E. Delagnes

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

Charge Coupled Devices (CCD)

Set of electrodes on top of high resistivity silicon, top or backside illuminated
Scientific CCDs: huge dynamic range (16-bit), single electron sensitivity if cooled.

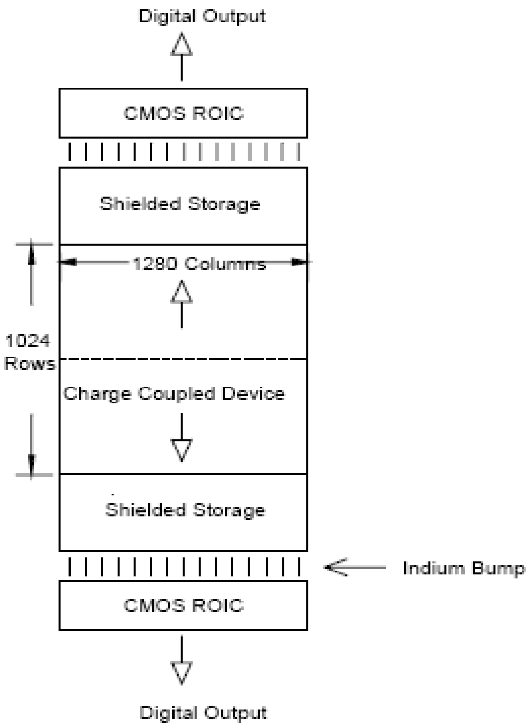
Pixels are readout serially with fast amplifiers (one per electrodes array)
Charge shifts horizontally into vertical registers which are readout serially.



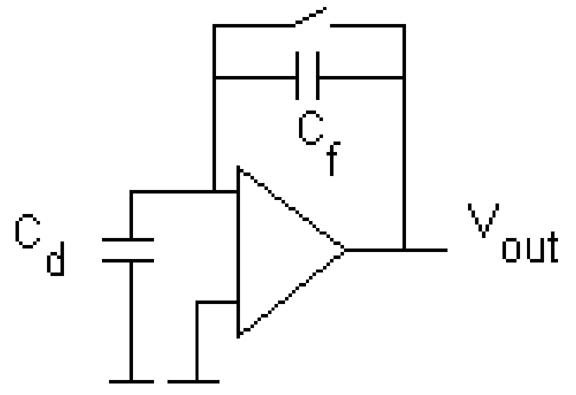
- **Transfer from cell to cell is noiseless, 99.999%… efficiency**
- **Charge is transfered from the last pixel to a voltage follower (floating gate) after reseting the node. The node is sensed before and after transfer**

Correlated Double Sampling (CDS, eliminates reset noise)

CCDs readout



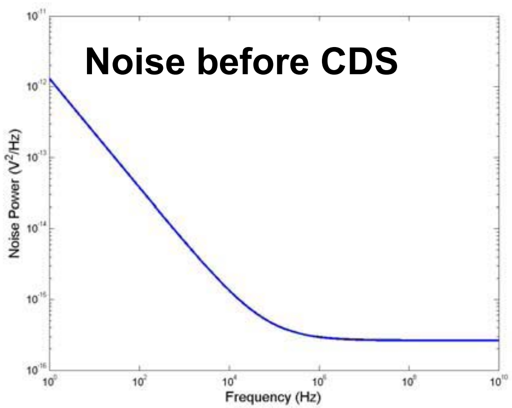
Off-chip amplification, noiseless transfer CCD to readout chip

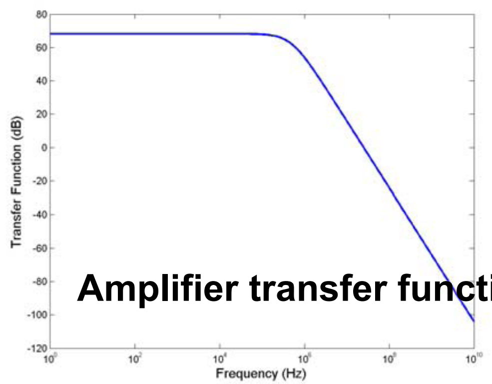


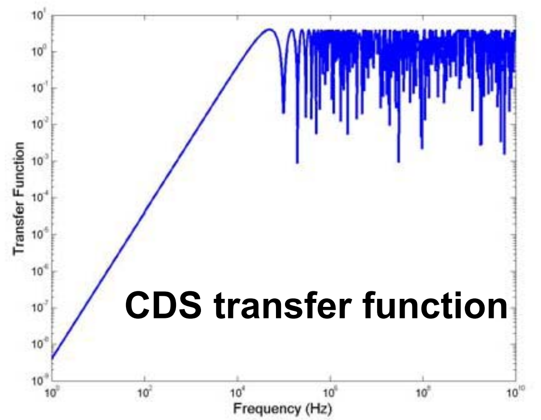
Fairchild

On readout chip capacitive transimpedance amplifier after on-CCD CDS

http://www.fairchildimaging.com/main/documents/CCD_CMOS_Hybrid_FPA_for_Low_Light_Level_Imaging.pdf







CCD readout

- Most CCD noise is system noise after CDS
- Cooled at -100˚C (173K), dark current is negligible
- Charge transfer efficiency almost perfect (i.e. 1 ppm charge diffusion)
- Companion (bi)CMOS ASIC needed for amplification, ADC, clock generation

CCD readout ASICs:

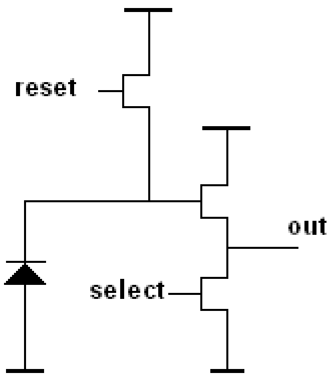
- ASPIC (LPNHE Paris) for the Large Synoptic Survey Telescope (LSST) focal plane at 173K. 350 CMOS.
  - > 16-bit dynamic range, noise < 7 μV rms
  - Correlated Double Sampling
- CRIC (LBNL) for SuperNovae Acceleration Probe / Joint Dark Energy Mission (SNAP/JDEM). Space boarded telescope at 140K, 10 kRad tolerance. 250nm CMOS.
  - Correlated Double Sampling
  - > On-chip pipe-line ADC (13-bit),
  - noise < 6.8 μV rms
- Sidecar (Teledyne)
  - Up to 16 Mpixel support
  - 36 analog channels, Correlated Double Sampling
  - 16-bit ADC 100 kHz
  - 12-bit AC 10 MHz
  - CCD clock signals generation: kHz-MHz, 10-20V clocks

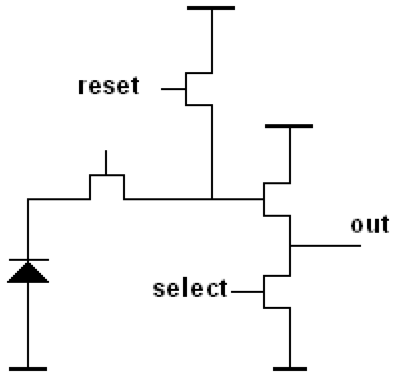
http://www.teledyne-si.com/imaging/sidecar.html

Monolithic Active Pixel Sensors (MAPS)

Pixels instrumented with amplifier and switches

Sensitive volume is a silicon epitaxial layer surrounded by a reverse biased collecting PN junction

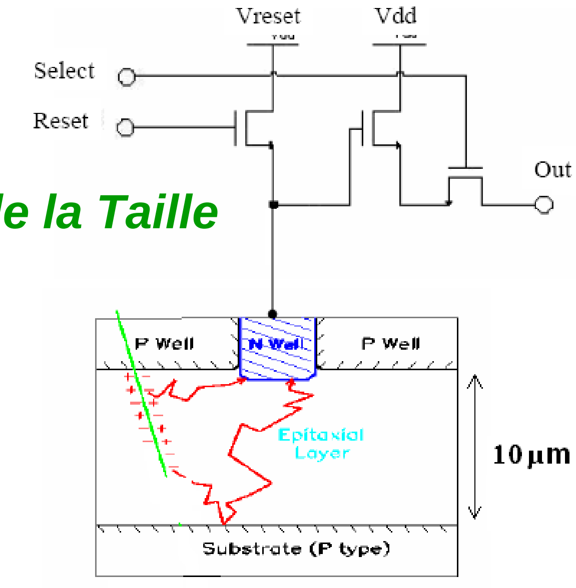




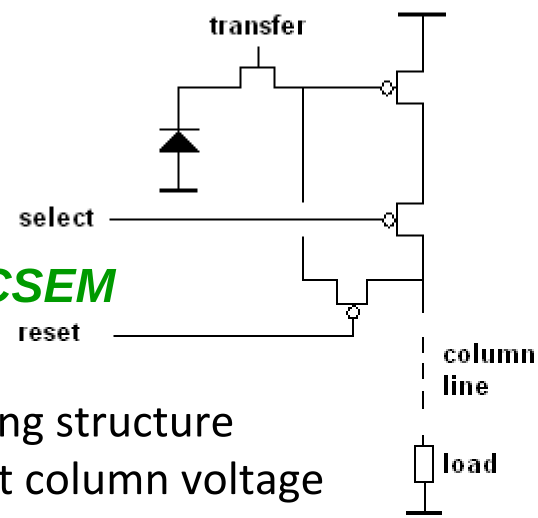
3-transistor structure

4-transistor structure

4-T isolates pixel and multiplexer structures allowing using CDS



C. de la Taille



R. Kaufmann, CSEM

Amplifying structure
Resets at column voltage

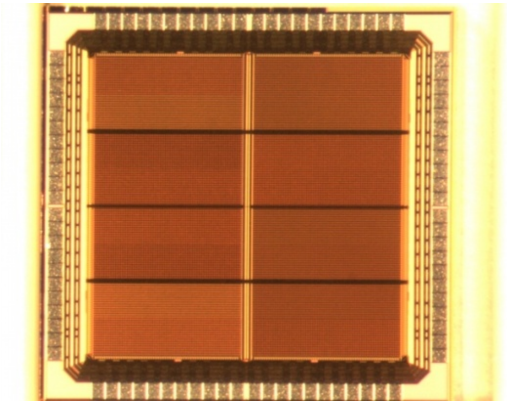
IEEE Trans Nucl Sci Vol 57 n5 Oct 2010, p2490-2496

M. Tyndel, R. Turchetta et al.

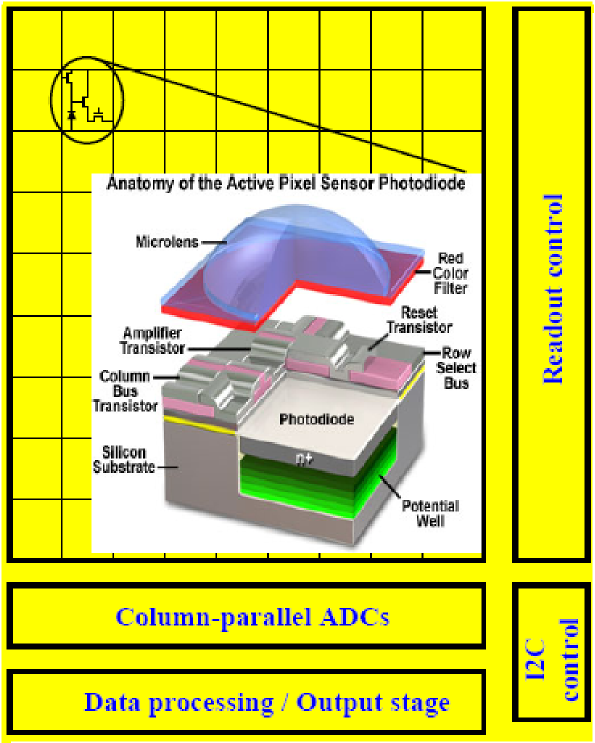
Monolithic Active Pixel Sensors (MAPS)

Pixel ADC: limited area

Time over threshold see FEI4
One comparator / pixel needed



C Hu, IPHC Strasbourg



R. Turchetta, RAL

IEEE Trans Nucl Sci Vol 57 n5 Oct 2010, p2490-2496

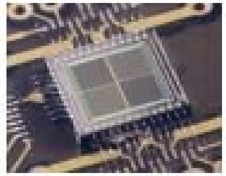
M. Tyndel, R. Turchetta et al

Monolithic Active Pixel Sensors (MAPS)

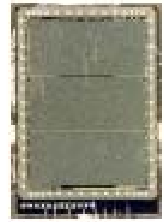
Mimosa line

IPHC Strasbourg

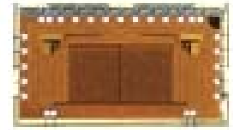
many chips



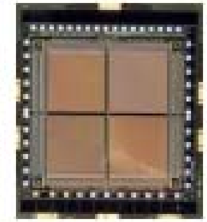
mimosa 01



mimosa 02

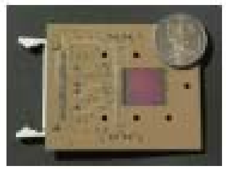


mimosa 03



mimosa 04

mimosa 05

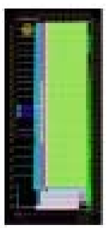


mimosa 05 + PCB

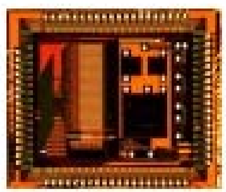
mimosa 05 wafer

mimosa 05 wafer

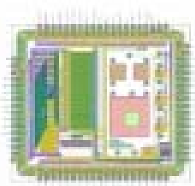
mimosa 05 wafer (detail)



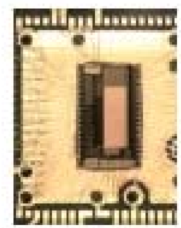
mimosa 06 layout



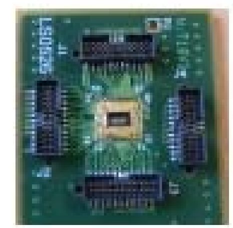
mimosa 07



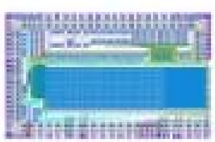
mimosa 07 layout



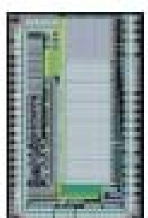
mimosa 08

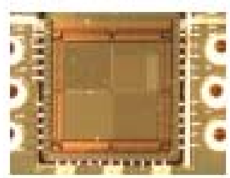


mimosa 08 + PCB

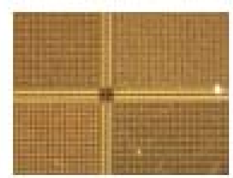


mimosa 08

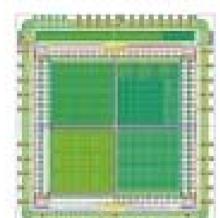




mimosa 09

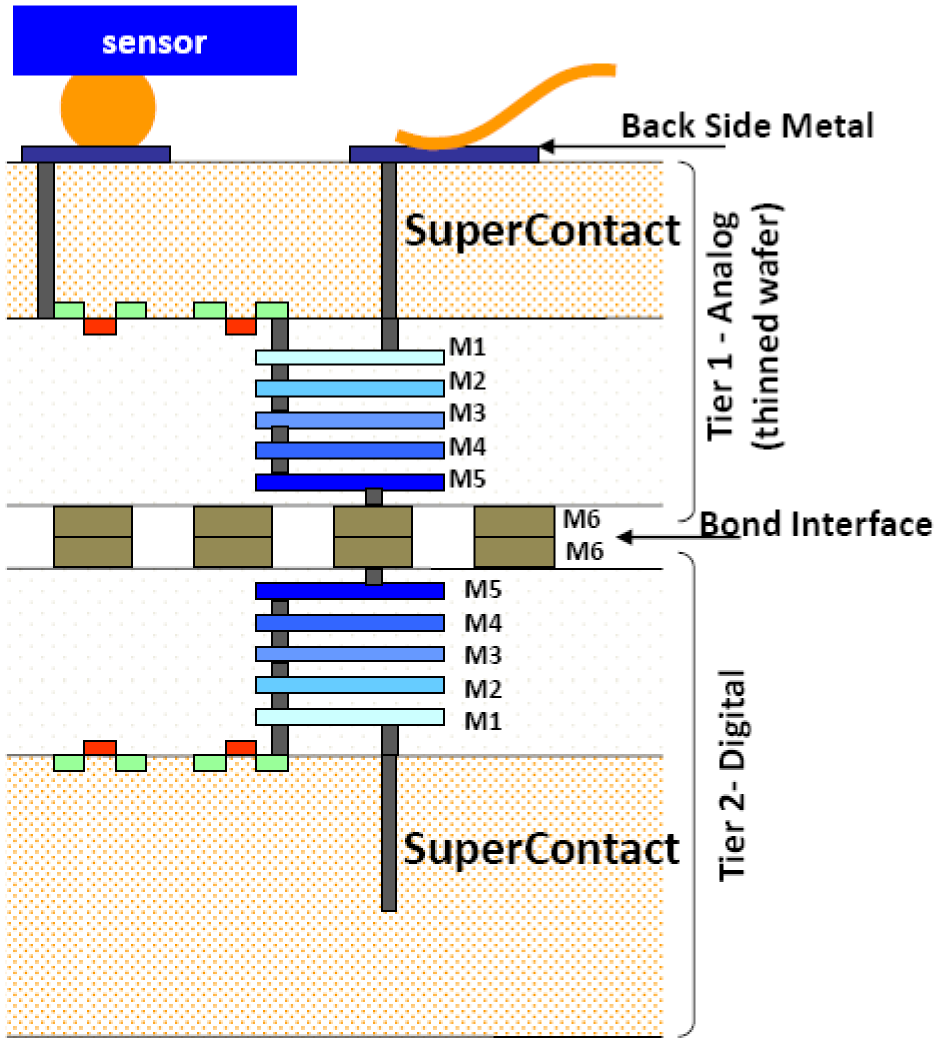


mimosa 09



Hybrid Pixel Sensors (see 3D section)

-



Detector of any material and type bump-bonded to readout electronics

2-tier (analog + digital)

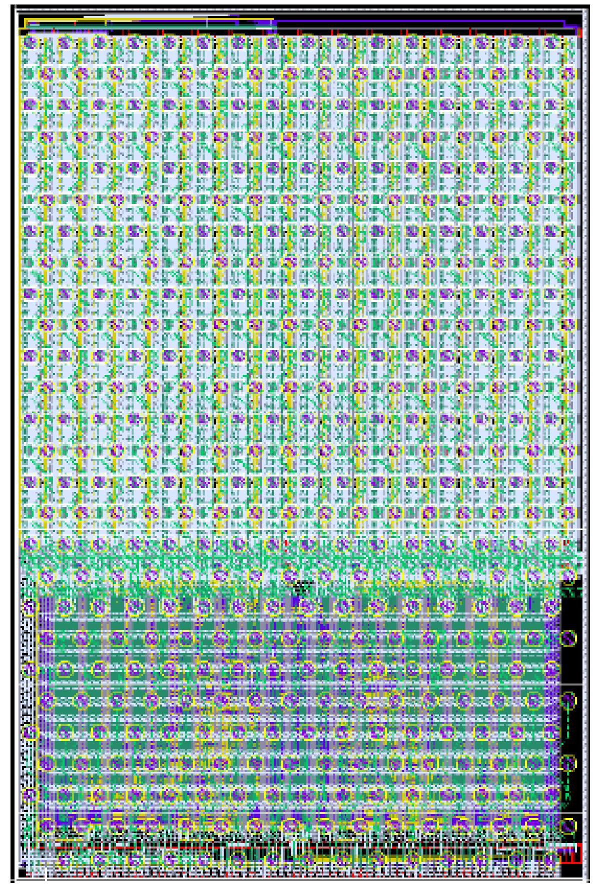
Silicon Vias (TSV)

DEPFET readout   CMOS 180nm

DEPFET: modulate the drain current of a MOSFET with ionisation created on the gate (MPI, Gemany)

DCDB Production Details

- Implemented in UMC 180nm CMOS technology
- Area: 3240x4969 μm²
- ~ 2x3 Mini@sic Blocks on a EuroPractice MPW run
- Additional 7th metal layer (redistribution layer) with bump-bond pads including bumps
- Production + bumping costs: ~ 20800 EUR (for 60 pcs.)
- Production time: 5 months total
  - 3 months: MPW run
  - 2 months: 7th metal layer + bumping



J. Knopf

Jochen Knopf - ziti - Heidelberg University - TWEPP 2010   15

90

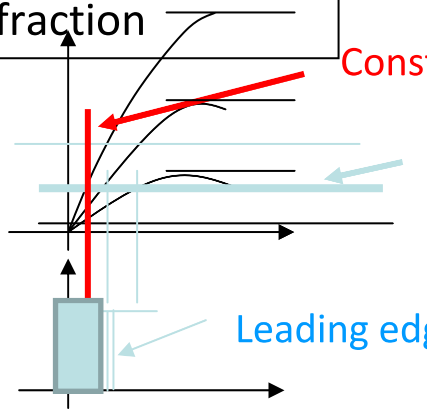
- Introduction
- Contexts
  - High Energy Physics
  - Space, Medical
- Photodetectors
  - Vacuum
  - Solid state
- Photodetectors Electronics
  - Components
  - Technologies,
  - Photon counting
  - Amplitude, charge
  - Imaging
  - Timing
  - 3D integration
- Conclusion

Timing techniques

$$\sigma_t = \frac{\sqrt{t_r t_s}}{SN}$$

Threshold based + TDCs

Constant-fraction



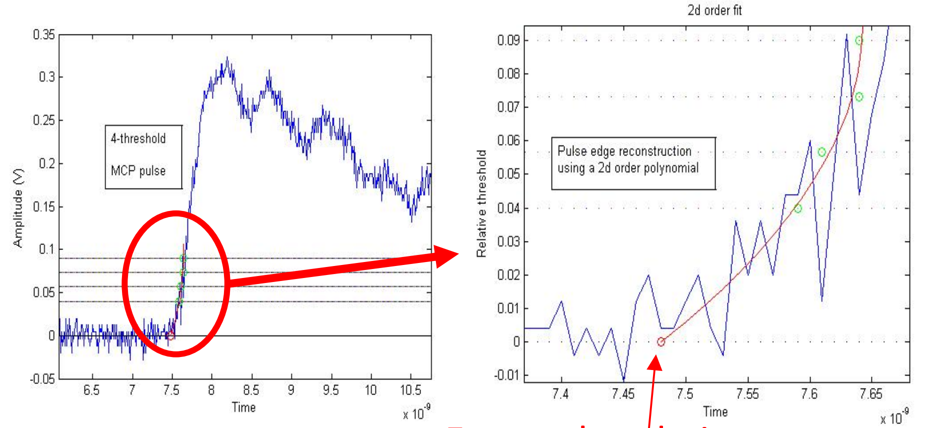
Constant fraction

Leading edge

Leading edge errors

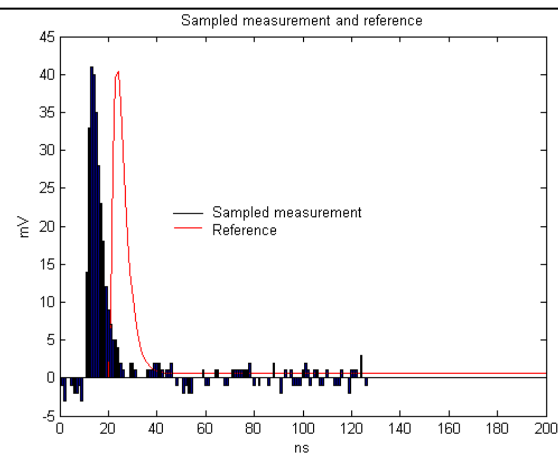
Constant Fraction: Amplitude independent

Multi-threshold



Extrapolated time

Pulse sampling and Waveform analysis



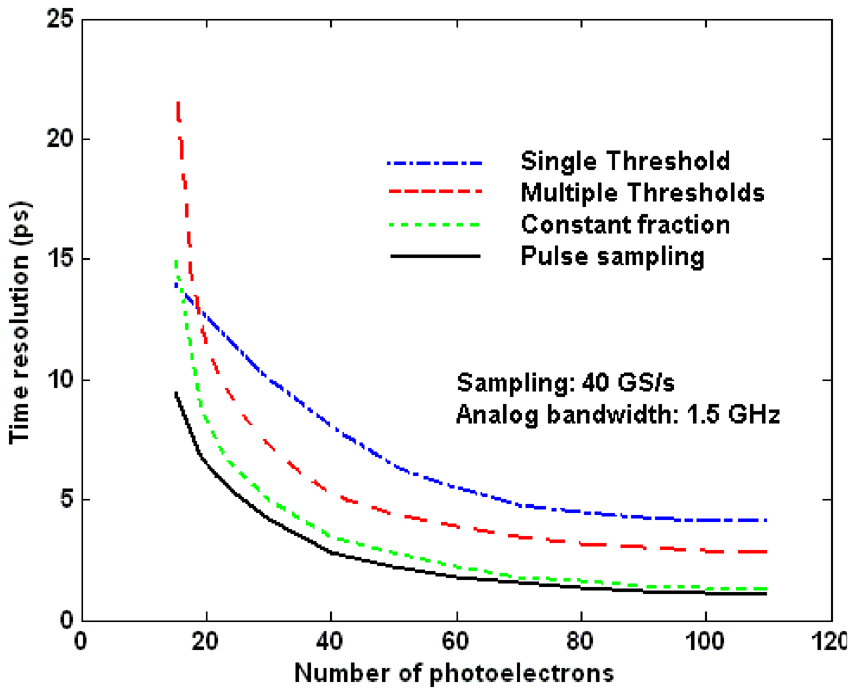
Waveform sampling + Digital Signal Processing

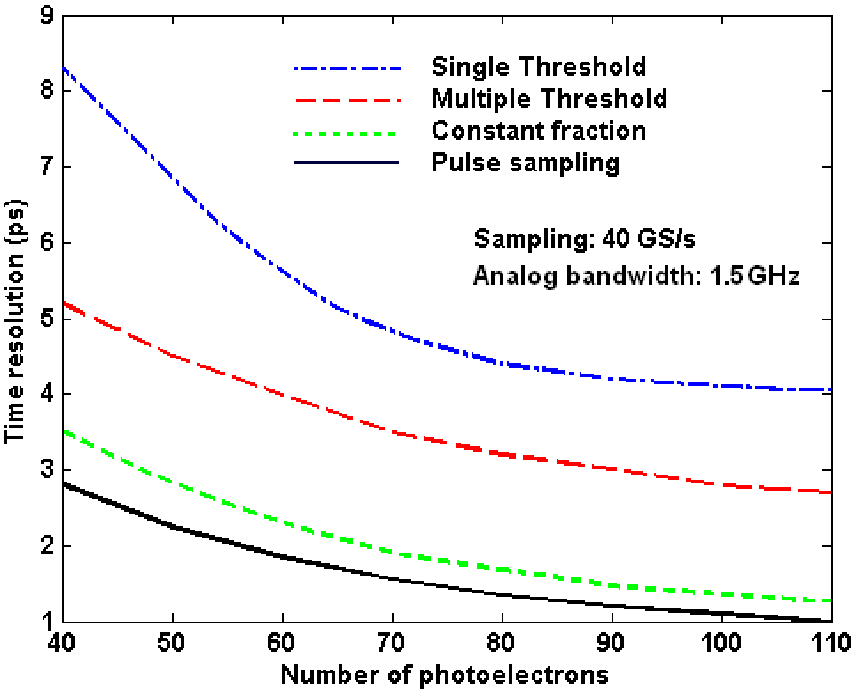
Sample, digitize,

Fit to the known waveform

92

Methods compared (simulation)





zoom

Time resolution vs Number of photo-electrons

Time to Digital Conversion

Many custom ASICs based on analog or digital techniques

Analog

- **Ramp between Tstart and Tstop**
- **Digitize level with an ADC, or ramp down slow and count**

10ps resolution possible

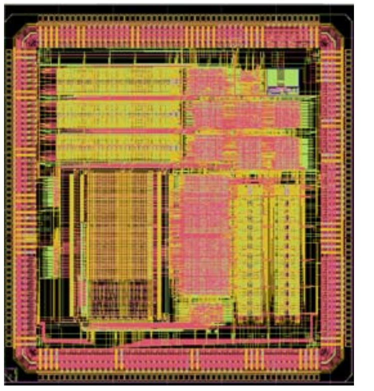
Digital

- **Count clock for coarse time (<100MHz)**
- **Interpolate with vernier digital delay lines locked on clock**

10ps resolution possible

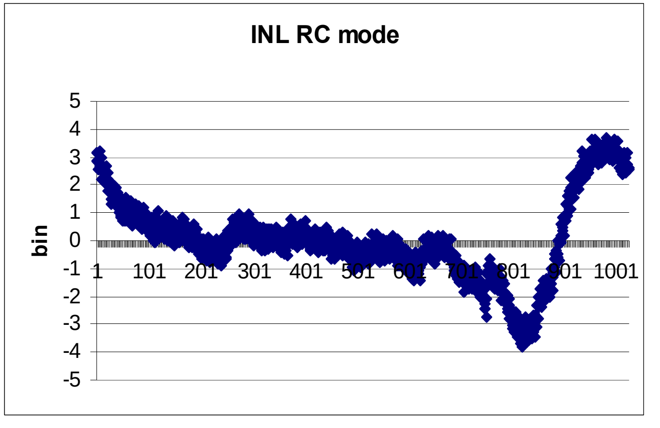
Hybrids !

HPTDC (CERN)

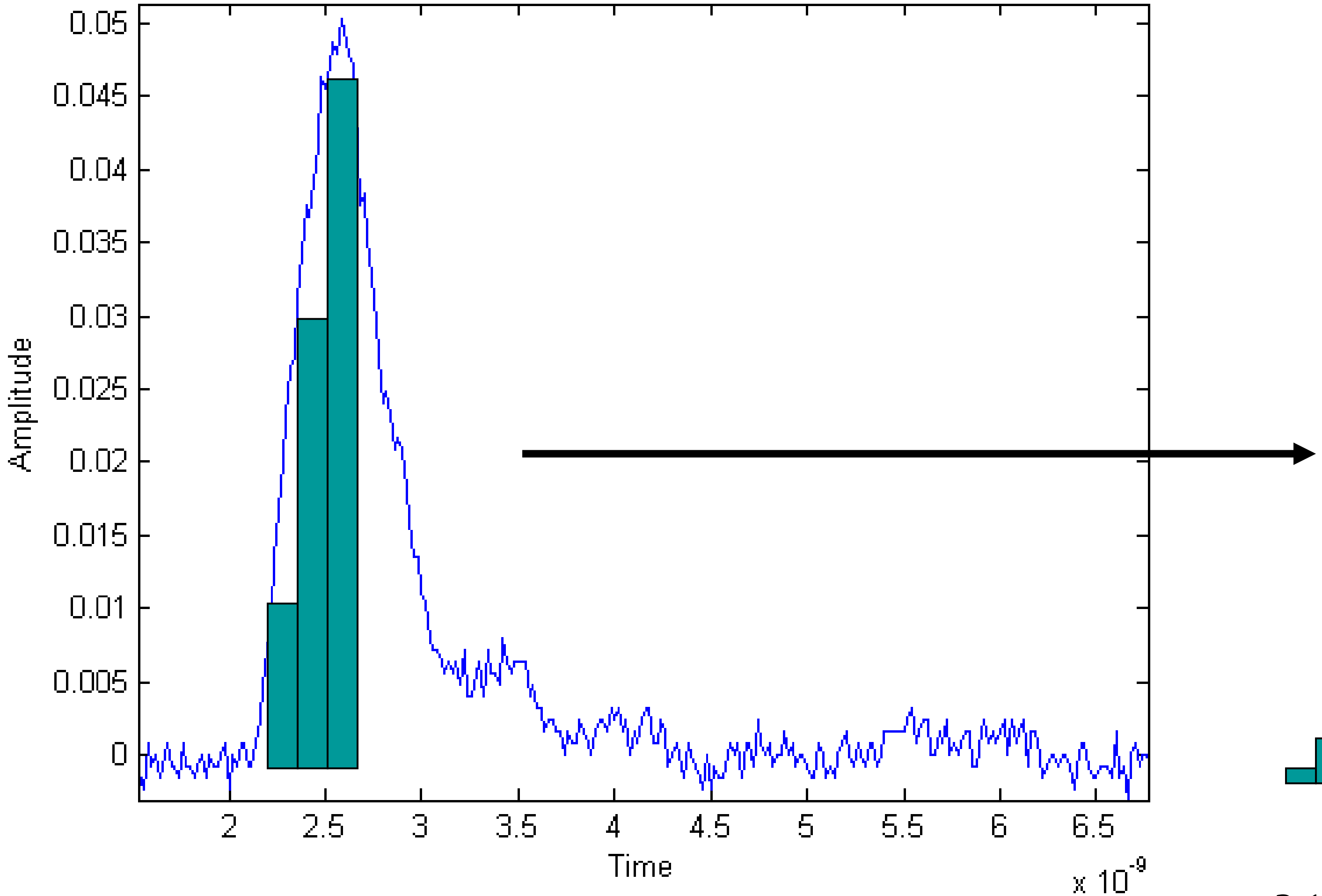


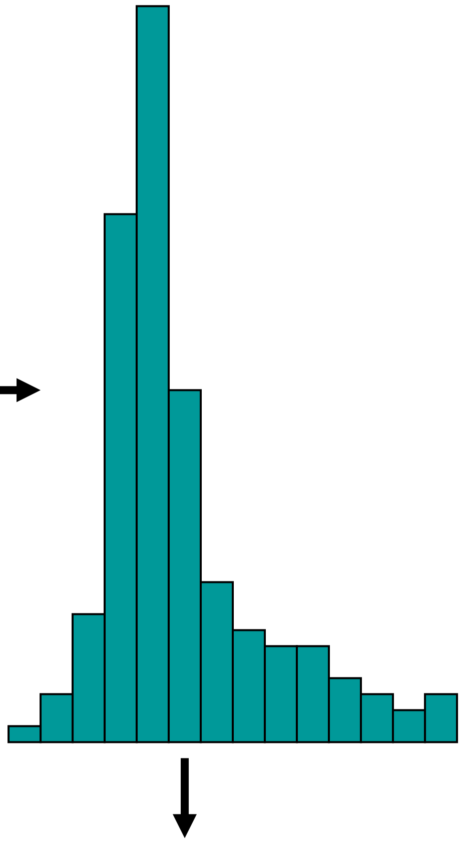
- 32 channels(100ps binning) or 8 channels (25ps binning)
- LVDS (differential) or LVTTL (single ended) inputs
- 40MHz time reference (LHC clock)
- Leading, trailing edge and time over threshold (for leading edge time corrections)
- Non triggered
- Triggered with programmable latency, window and overlapping triggers
- Buffering: 4 per channel, 256 per group of 8 channels, 256 readout fifo
- Token based readout with parallel, byte-wise or serial interface
- JTAG control, monitoring and test interface
- SEU error detection.
- Power consumption: 0.5W – 1.5W depending on operating mode.

J. Christiansen CERN



Pulse Sampling





2 12 25 80 128 50 32 …

↓

Waveform analysis

Sampling period, digitization (number of bits)

Pulse Sampling

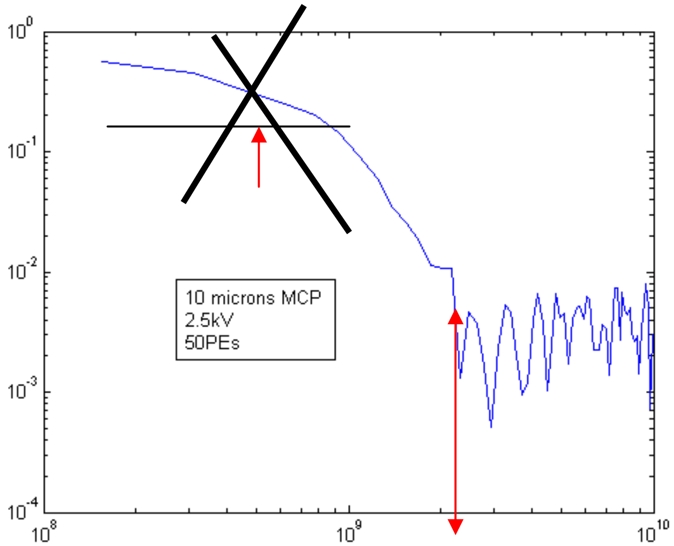
ADC: Number of bits

Quantization noise is LSB/ $\sqrt{12}$
Signal noise should be significantly more than Q noise
X_{max} Largest signal of interest :

$$Nbit = Log_2 (X_{max} / LSB)$$

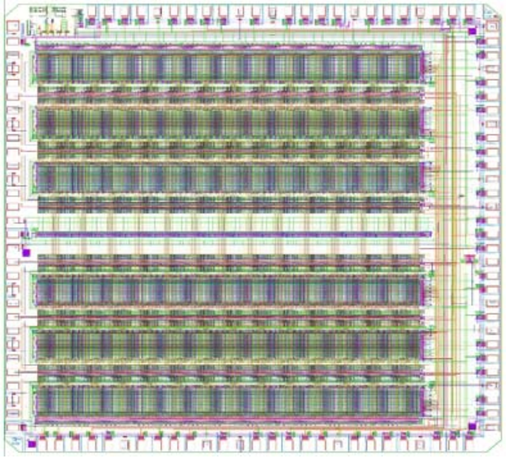
Sample rate 1/τ

1/τ above twice the Shannon-Nyquist frequency: the highest frequency above noise NOT the 3dB cut-off:



Example: PSEC3 6-channel Sampling ASIC specifications

10 GS/s sampling ASIC for Micro-Channel Plates Readout



Maximum sampling rate	**15GS/s**
Analog Bandwidth	**2 GHz**
Dynamic range	**0.8V**
Number of channels	**6**
Number of cells	**256**
Sampling window	**adjustable 500ps-2ns**
ADC Resolution	**8-bit (12-bit implemented)**
Crosstalk	**1%**
DC Input impedance	**50Ω internal (channels 0 and 1)**
	50Ω internal (channels 2 and 3)
Clock	**40 MHz**
Conversion clock	**1-2 GHz internal ring oscillator**
Readout time	**4 x 256 x 25ns=25.6 ms**
Power	**40mW/channel @ 1.2V**
Process	**IBM 8RF-DM (130nm CMOS)**

Input analog bus laid out as a 50 Ω transmission line

RF design above 1 GHz

Devices behaviour are more and more geometry dependent

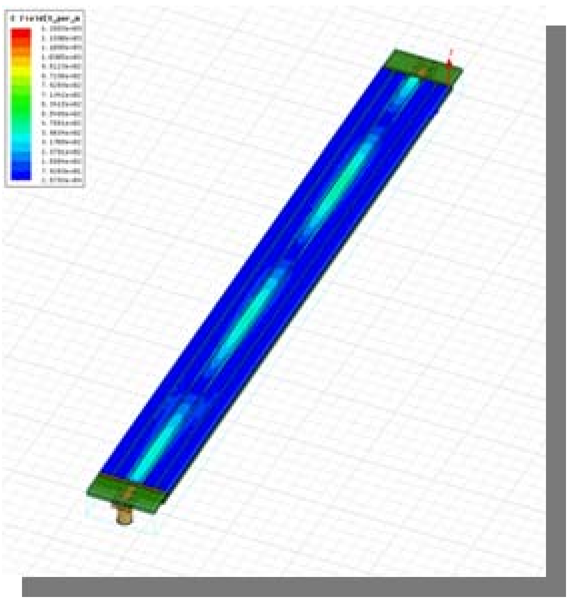
- **Controlled impedance 50 Ω paths**
- **Devices characterized by linear S (scatter) parameters**
- **Electromagnetic waves softwares**

Tools for Silicon, GaAs, RF transmission lines,

- **Network analysers**
- **Time Domain Reflectometry**
- **50 Ω Calibrated components**
- **RF software layout and simulation tools**
  Agilent ADS
  Ansoft HFSS

RF design

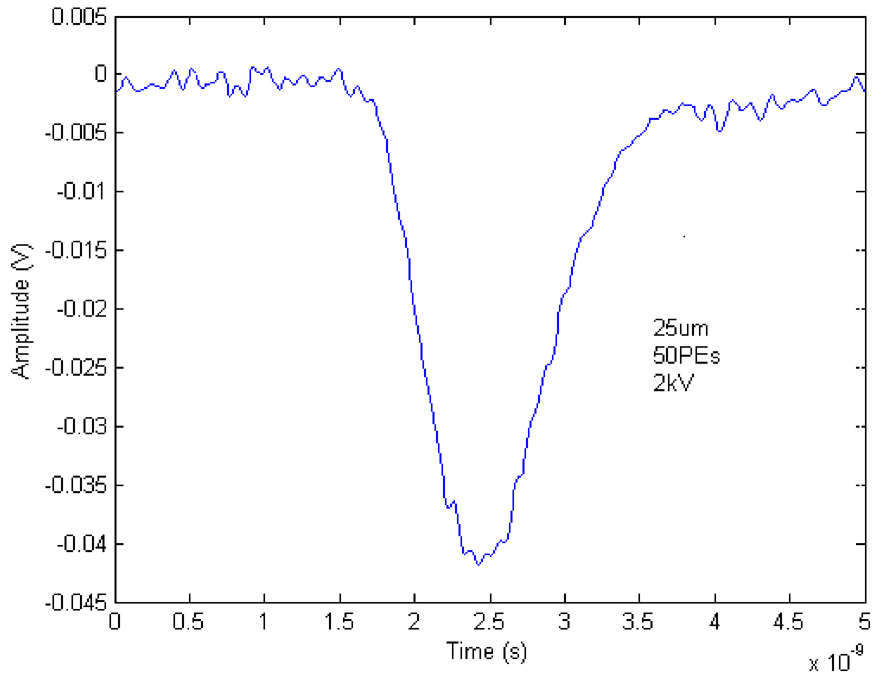
DC-10 GHz simulations of a large area (20 x 20 cm) Micro-Channel Plate based detector using Ansoft HFSS electromagnetic simulator



Transmission line implemented on glass for 2D Micro-Channel plate readout

Simulation shows that device is functional up to 2.3 GHz at 15dB

Processing of digital sampled data

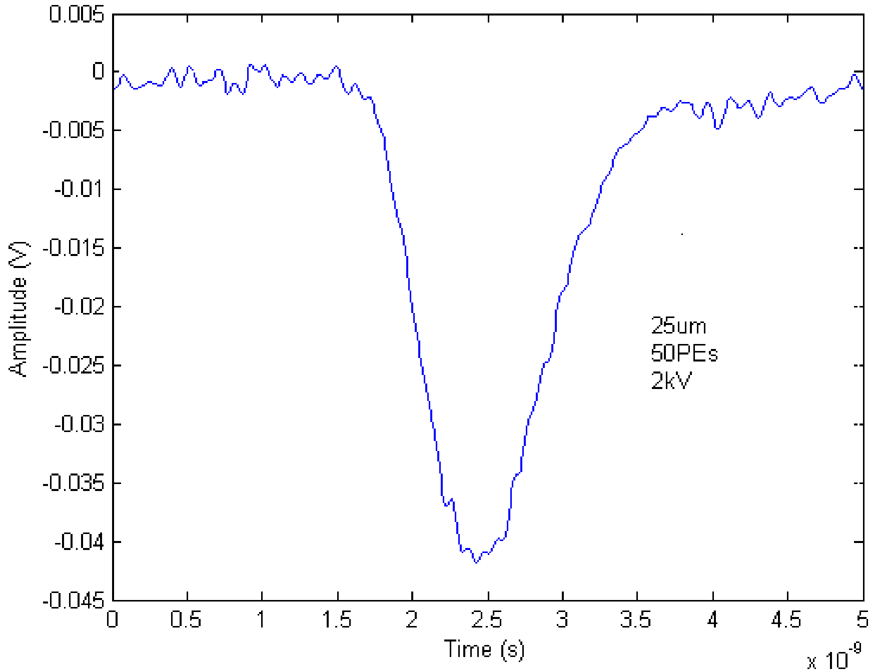


Determine which information is useful in the waveform:
Rising edge, integral, maximum amplitude.

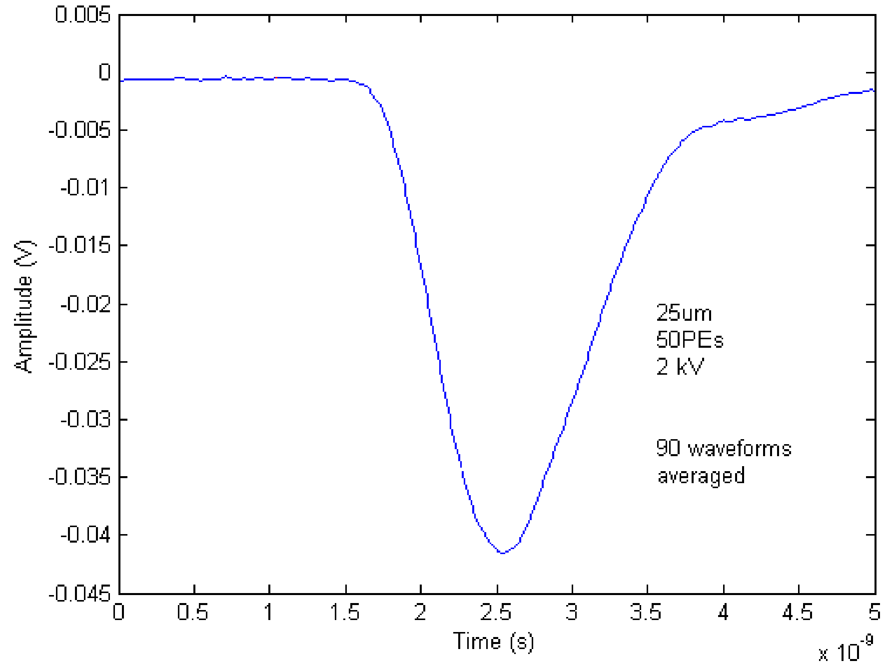
For photo-detectors, usually time and charge (integral of the current pulse)

Pulse shaping can be done in digital if power and speed allow (ADC)

Fast timing: Processing of sampled data



Original MCP measured signal



Signal template (obtained by averaging 100 signals to remove noise)

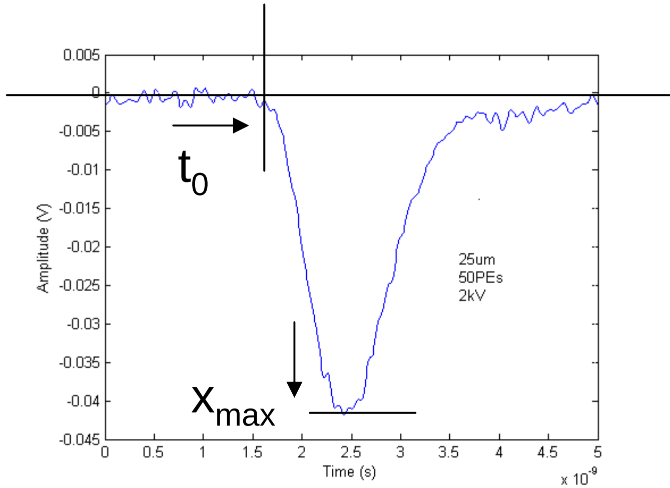
Example: Least squares algorithm:

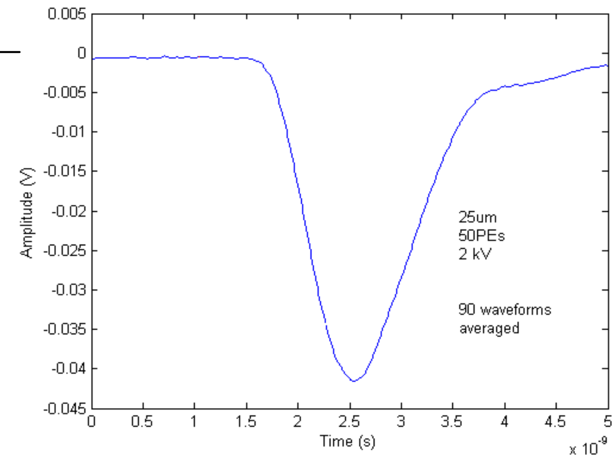
Minimize $$\chi 2 = \sum_{i=1}^{N} (x_{meas_i} - x_{temp_i})^2$$

to get accurate time and maximum amplitude

Processing of digital sampled data

Example: find pulse time and maximum amplitude





Solve: $$\chi 2 = \sum_{i=1}^{N} (x_{meas_i} - x_{temp_i})^2, \quad \partial\chi^2 / \partial t_0 = 0, \quad \partial\chi^2 / \partial x_{max} = 0$$

Obtain t_0 and $x_{max:}$:

$$a = \sum_i x^2_{temp\ i} \qquad bp = \sum_i x'^2_{temp\ i} \qquad b = \sum_i x^2_{temp\ i} \, . \, x'^2_{temp\ i} \qquad d = b^2 - a \, . \, bp$$

$$mp = \sum_i x^2_{meas\ i} \, . \, x^2_{temp\ i} \qquad mp' = \sum_i x^2_{meas\ i} \, . \, x'^2_{temp\ i}$$

$$\boxed{t_0 = 1 / d \ (mp' . b - mp . bp) \qquad x_{max} = -1 / t_0 \ (mp' . a / d + mp . b / d)}$$

Digital filtering

Signal as a sequence of numbers, compute weighted sums with a Digital Signal Processor.

- **Finite Impulse Response: convolution with the sampled impulse response**
- **Infinite Impulse Response: recursive, use of the z-domain frequency response:**

Analog

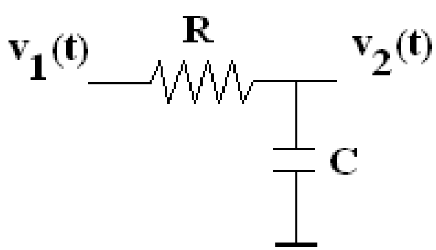
$$P(j\omega) / Q(j\omega) = \frac{\sum_n a_n \, j\omega^n}{\sum_m b_m \, j\omega^m} \qquad j\omega \longrightarrow 2/\tau \, \frac{1 - z^{-1}}{1 + z^{-1}}$$

Digital

$$y_k = y(k\tau), \quad x_k = x(k\tau)$$

$$P(z) / Q(z) = \frac{\Sigma \, a_i \, z^{-i}}{\Sigma \, b_j \, z^{-j}} \qquad y_k = \sum_j a_j \, y_{k-j} - \sum_j b_j \, x_{k-j}$$

Example: 1st order RC filter



Analog

$$H(j\omega) = \frac{1}{1 + RCj\omega} \qquad y(t) = C \exp(-t / RC)$$

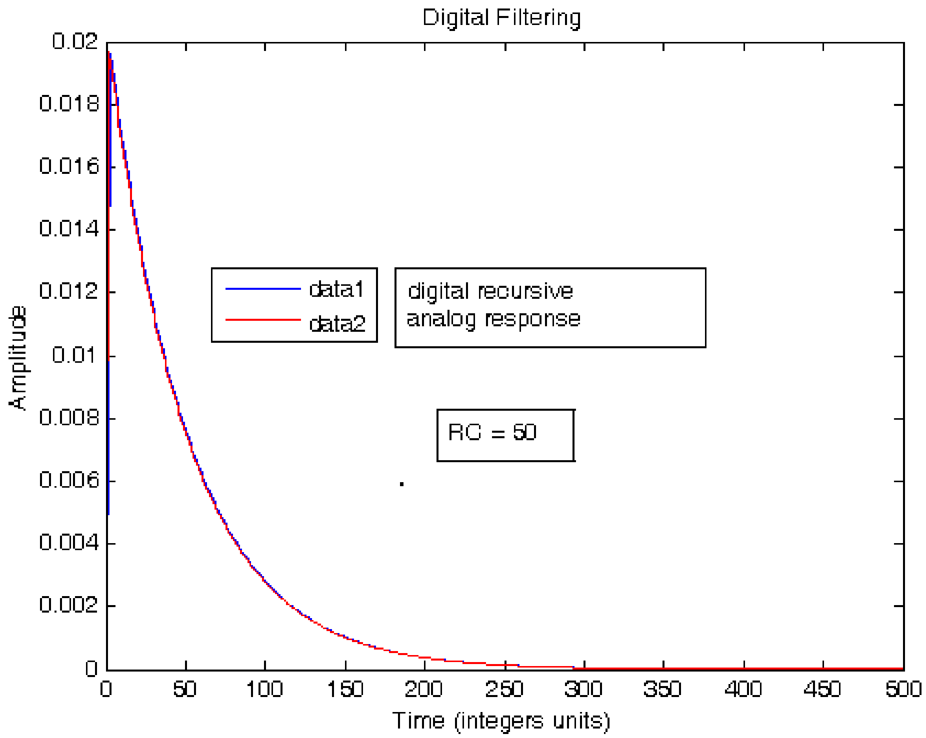
Digital recursive

$$P(z) / Q(z) = \frac{1 + z^{-1}}{(1+a) + (1-a)z^{-1})} \qquad y(k) = -\frac{1}{1+a}\left[(1-a)\, y(k-1) + x(k) + x(k-1)\right]$$

$$a = RC / \tau$$

Digital filtering

Example: 1st order RC filter



Analog

$$H(j\omega) = \frac{1}{1 + RCj\omega}$$

$$y(t) = C\exp(-t / RC)$$

Digital recursive

$$H(z) = \frac{1 + z^{-1}}{(1 + a) + (1 - a)z^{-1})}$$

$$y(k) = -\frac{1}{1 + a}[(1 - a)\,y(k - 1) + x(k) + x(k - 1)]$$

Pico-second timing and 2D position for large area detectors with delay lines

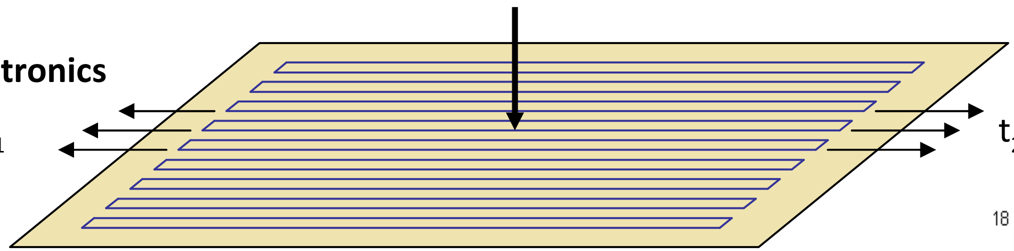
- Delay lines readout and pulse sampling provide

  - **Fast timing (2-10ps)**
  - **One dimension with delay lines readout 100mm- 1mm**
    Transverse dimension can be obtained from centroids

    Less electronics channels for large area sensors

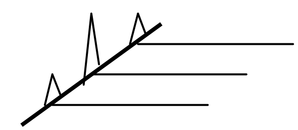
Pico-second electronics

t_1, a_1

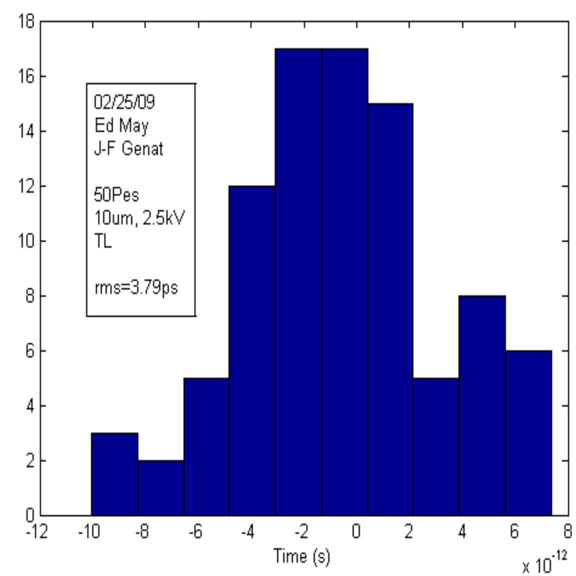


t_2, a_2

Pico-second electronics



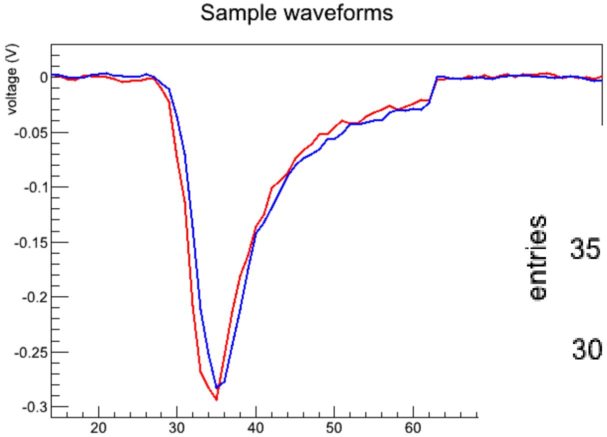
Timing extration with sampling and Digital Signal Processing
3.8 ps translates in 190 μm position resolution wiith 50 photo-electrons
5 x 5 cm² MCP



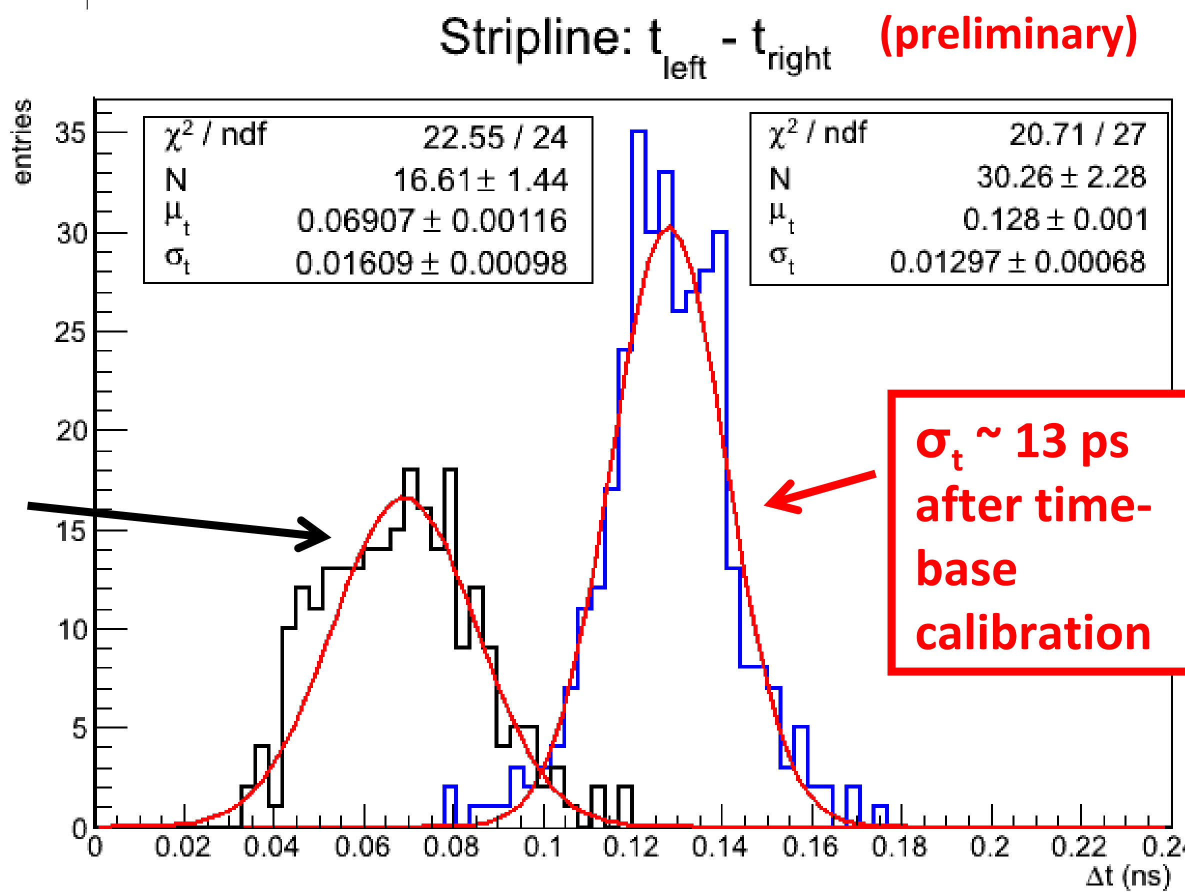
½ $(t_1 + t_2)$ = time
$v(t_1 - t_2)$ = longitudinal position
$\Sigma \alpha_i a_i / \Sigma \alpha_i$ = transverse position

Example: Transmission Line-Micro-Channel Plates readout

LAPPD Collaboration



σ_t ~ 17 ps assuming nominal 100ps per cell



σ_t ~ 13 ps after time-base calibration

E. Oberla

- Introduction
- Contexts
    - High Energy Physics
    - Space, Medical
- Photodetectors
    - Vacuum
    - Solid state
- Photodetectors Electronics
    - Components
    - Technologies,
    - Photon counting
    - Amplitude, charge
    - Imaging
    - Timing
    - 3D integration
- Conclusion

3D Integration

Goal: increase the integration density

Interconnections: Two options: die to die

-1 Stack up several layers of different IC processes Interconnections.
Through Silicon Vias (TSV) if more than 2 layers
Die can be tested

2-tier

2-tier w/TSV

Multi-tier hybrid w/TSV

-2 2D in a thinner process

K. Torki

Limit of CMOS (10nm) is coming soon, option 1 will be mandatory
In addition, thin processes are *always* expensive. But 3D could be as well…

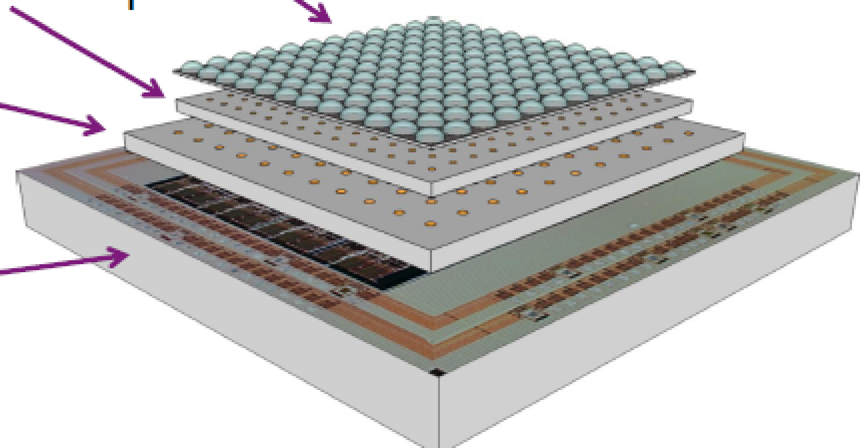
3D tools emerging:
- **Simulation**
- **Layout**
- **Extraction**

http://cmp.imag.fr/Spl-Session_3DIC/02_CMP.pdf

3D Imagers

AREA 3D INTEGRATED IMAGERS

- Status: system architecture study of an **imaging system on a chip-stack**
  - Integration of micro-optics layer:
    - Ultra wide field of view
    - Filters for hyperspectral imaging
  - Shared pixels = multiple pixels per bump
  - Smart analog/digital read-out:
    - Ultra high dynamic range
    - ADC per group of pixels
    - Variable resolution (active binning)
  - Smart digital processing:
    - 2D distributed group of processors
    - Face recognition



- Next step: demonstrator design and manufacturing

imec PIET DE MOOR 39

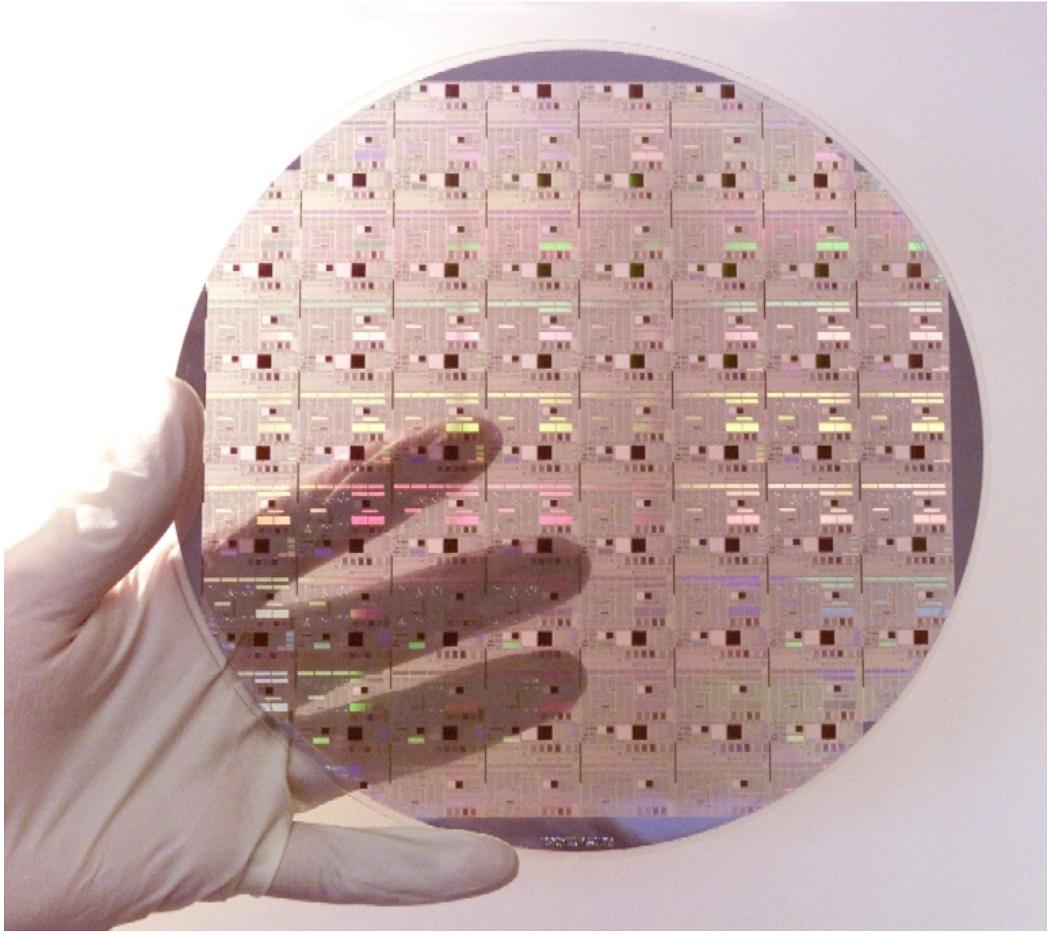
Piet De Moor (IMEC), TWEPP 2010

3D Integration

- Shorter connections
  - Lower impedance
  - Less RC delays
  - Save power

- Higher density
  - Better heat
  - Smaller I/O pitch

Area x Timing x Power =
Factor 15



J.J Lu

Wafer bonding for 3D integration
Cu on SiO_2 interconnect structures

Applications

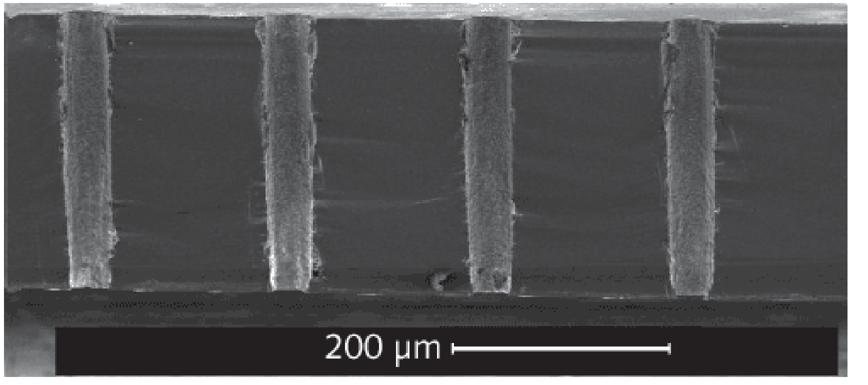
- **Memories, Memory on CPU**

  IBM, Samsung

- **Pixellated photo-detectors:**

  - Optics microlenses, filters,
  - Pixels Photo-Detector,
  - Electronics (analog + digital),
  - Serial opto out

  MIT Lincoln Labs, RTI, Ziptronix



Key feature:

Through Silicon Via (TSV)

2-tier 3D process tools

- **PDK:** **from CMC +**

  TSVs from Tezzaron

- **Libraries:** **Core + I/O from ARM**

- **Memory compiler:**

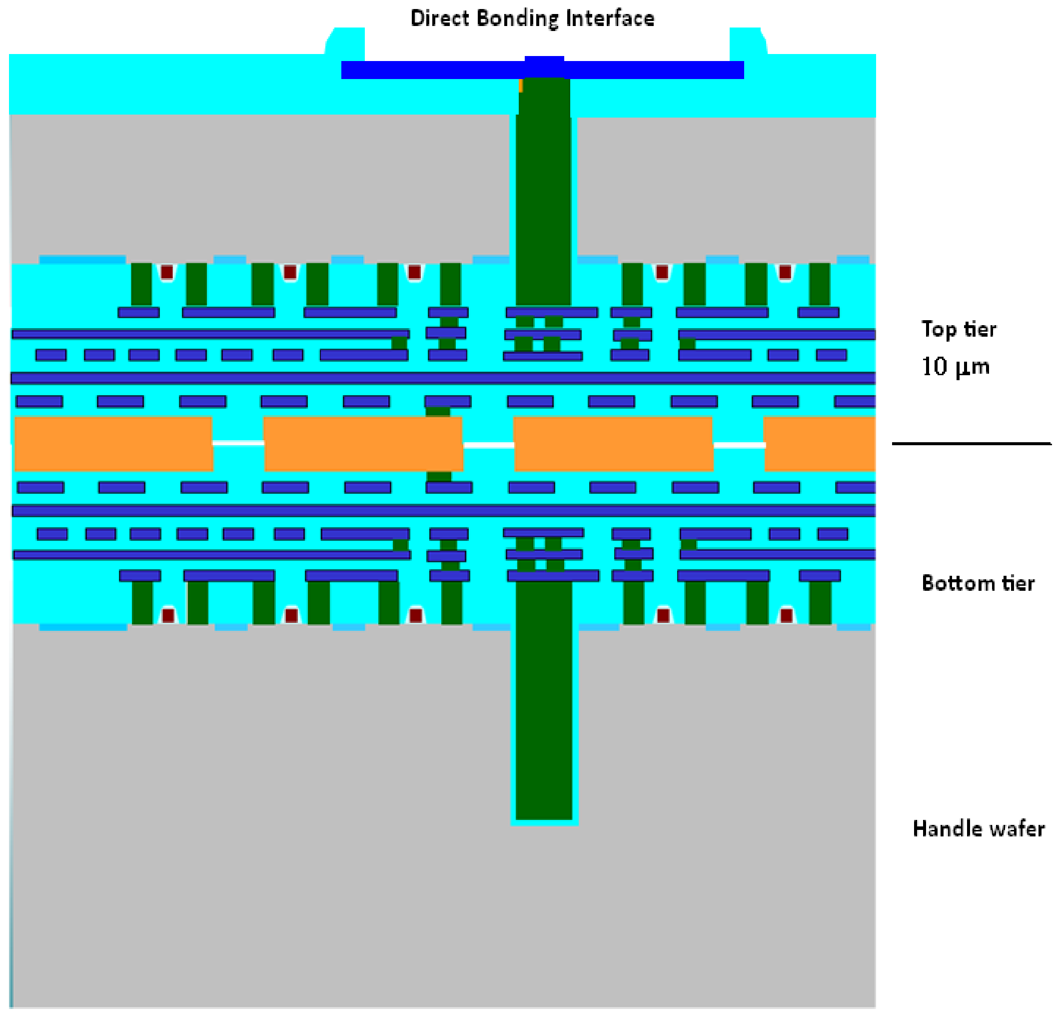
  S/DPRAM and ROM from Al

-**3 D Utilities:**

  Contributions development

-**Tutorial, User's setup**

  Intallation easy



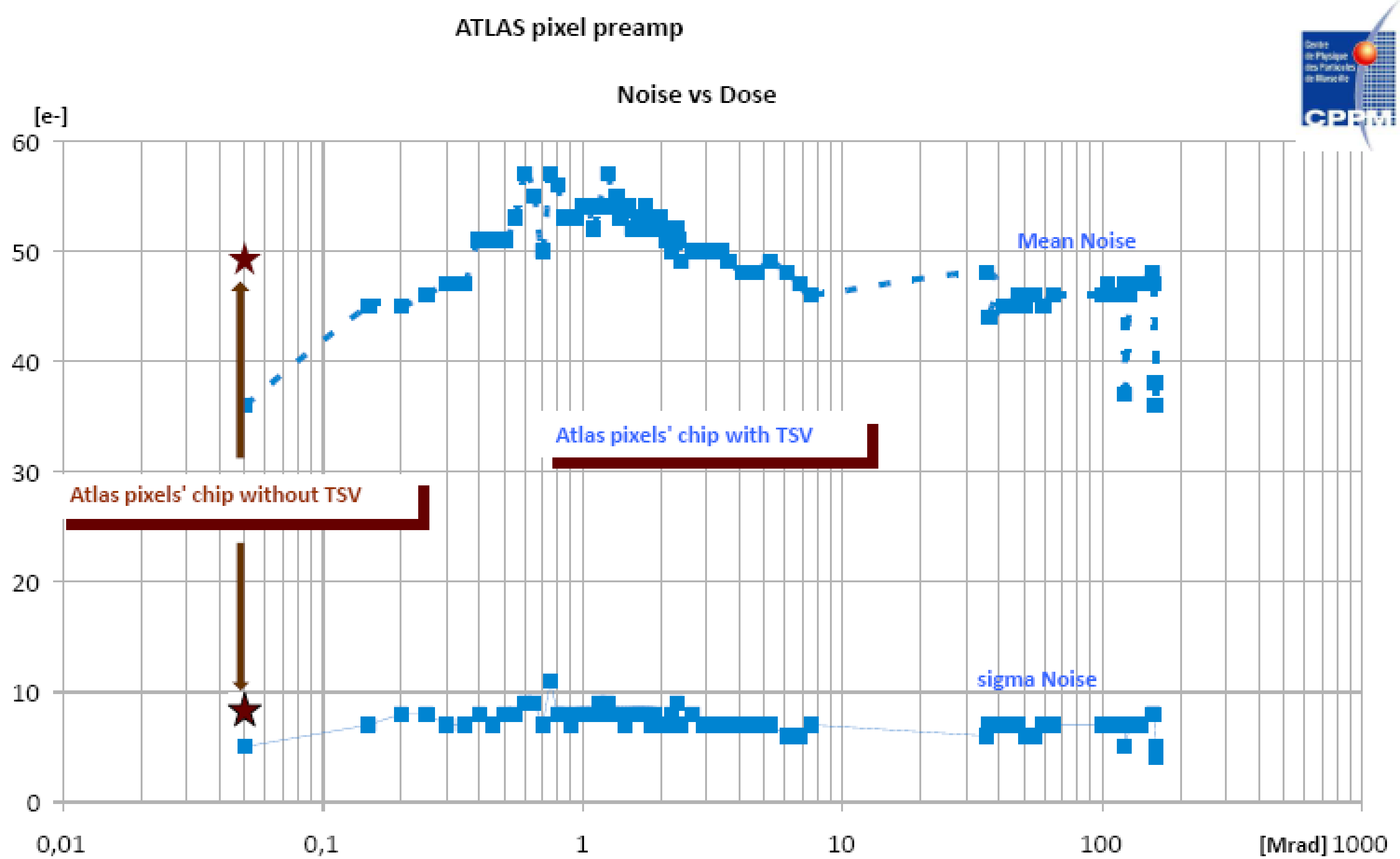
- **Support of Cadence CDB and OpenAccess databases**

K. Torki

3D process radiation hardness

FE-TC4-AE X-ray irradiation

-



A. Rozanov

CMC CMP Mosis FNAL Tezzaron

Canada France US Singapore

Access to 3D technology:

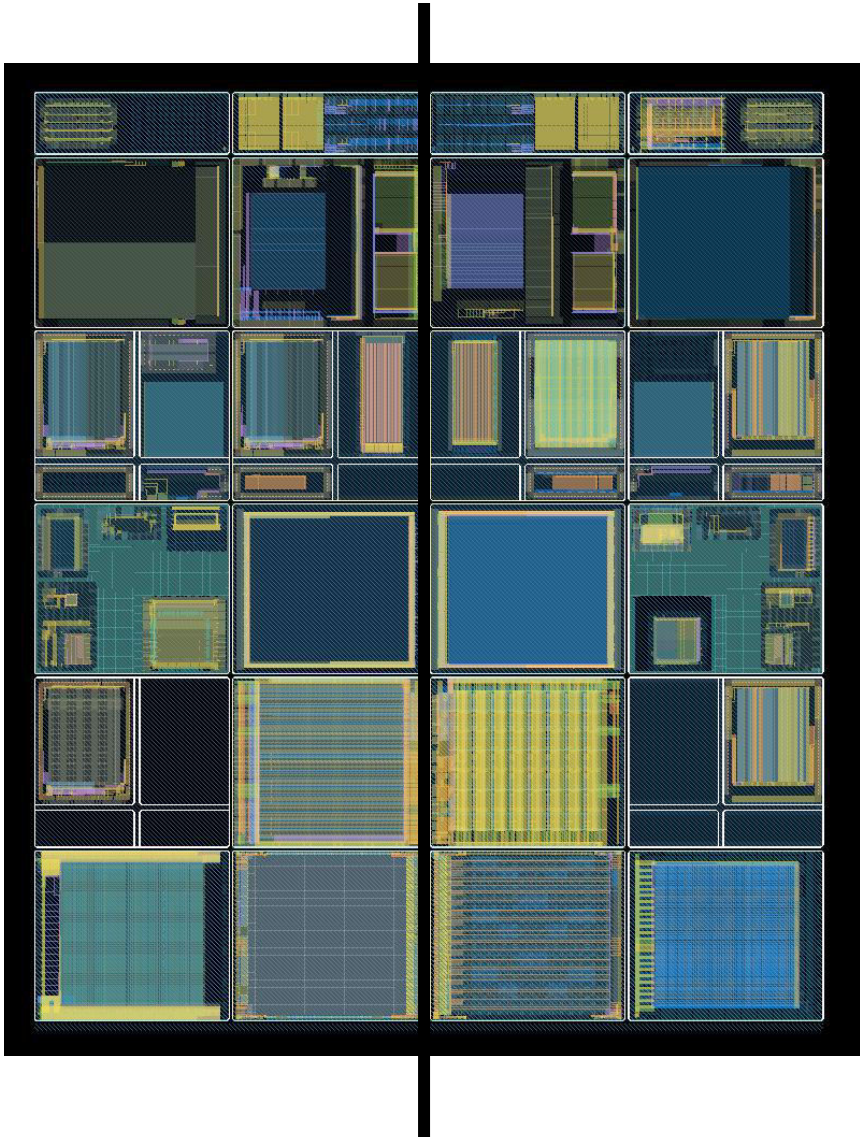
- **2-tier 130m CMOS**
- **Tezzaron, Globalfoundries**
- **Top tier exposing TSV**
- **Backside metal pads for wire bonding**
- **Design kit available**

Discussions with LETI, AMS

Talk to:
Kholdoun TORKI (CMP Grenoble, France)

http://cmp.imag.fr/products/ic/?p=130nmFaStack

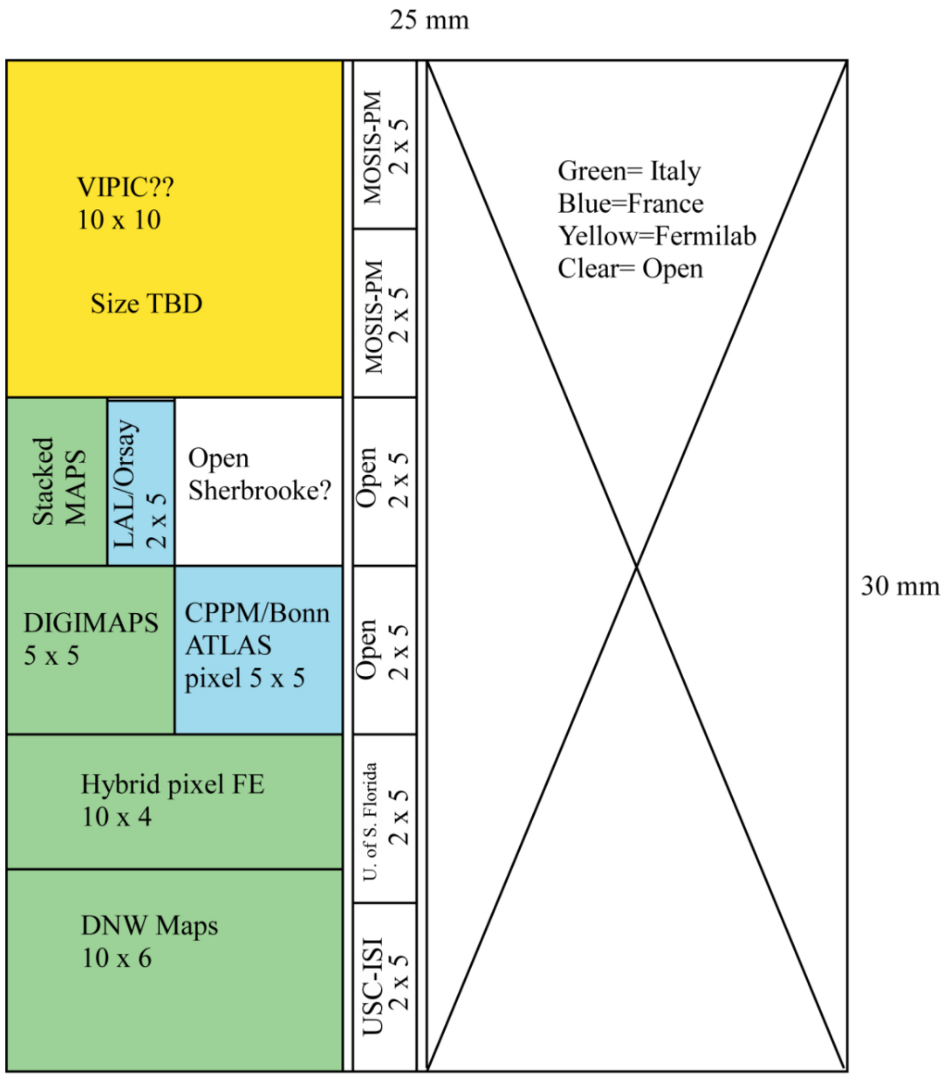
1st MPW run



Fermilab

Top tier **Bottom tier**

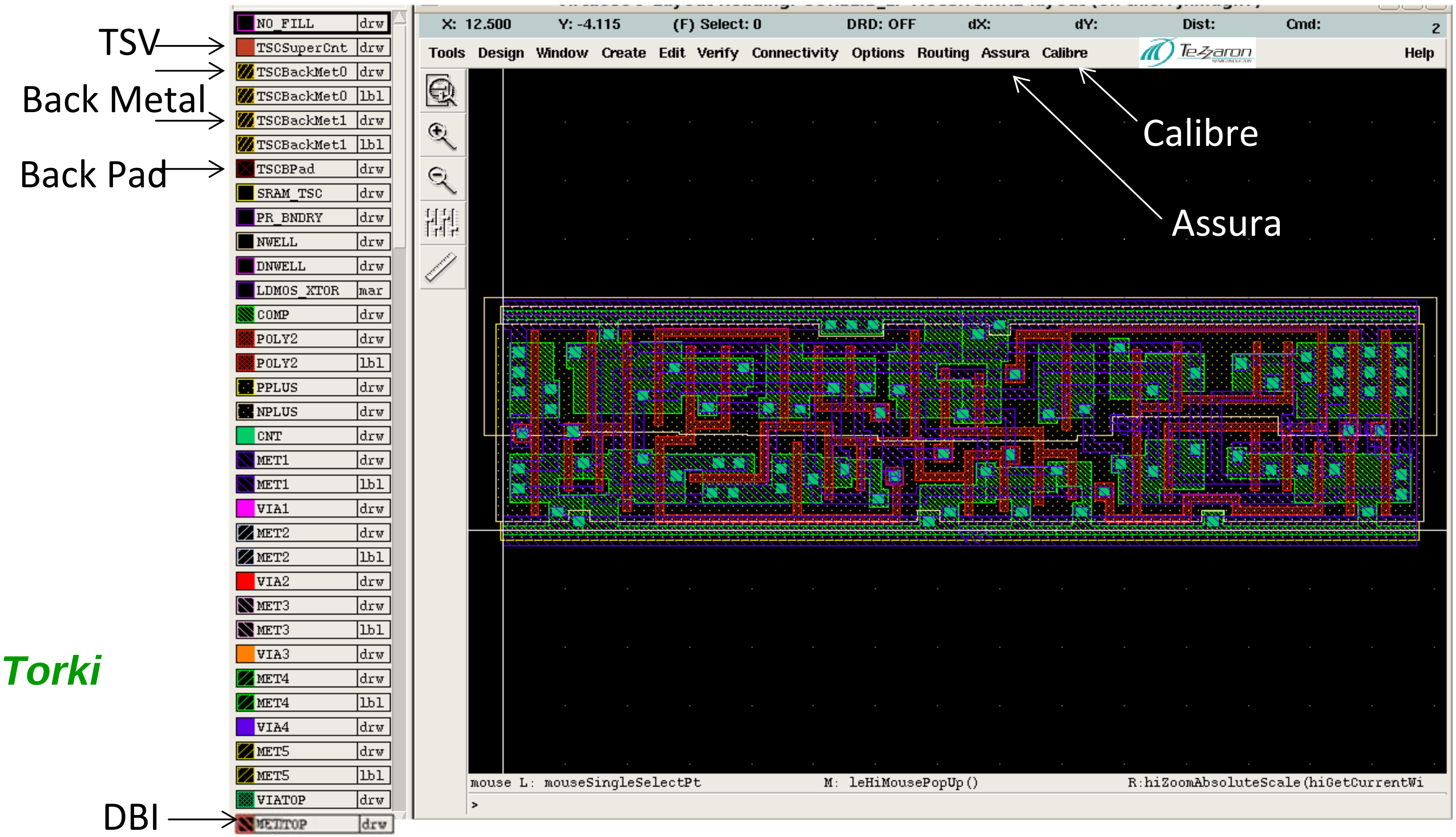
3D Integration CMP/MOSIS/CMC 1st MPW run



K.Torki

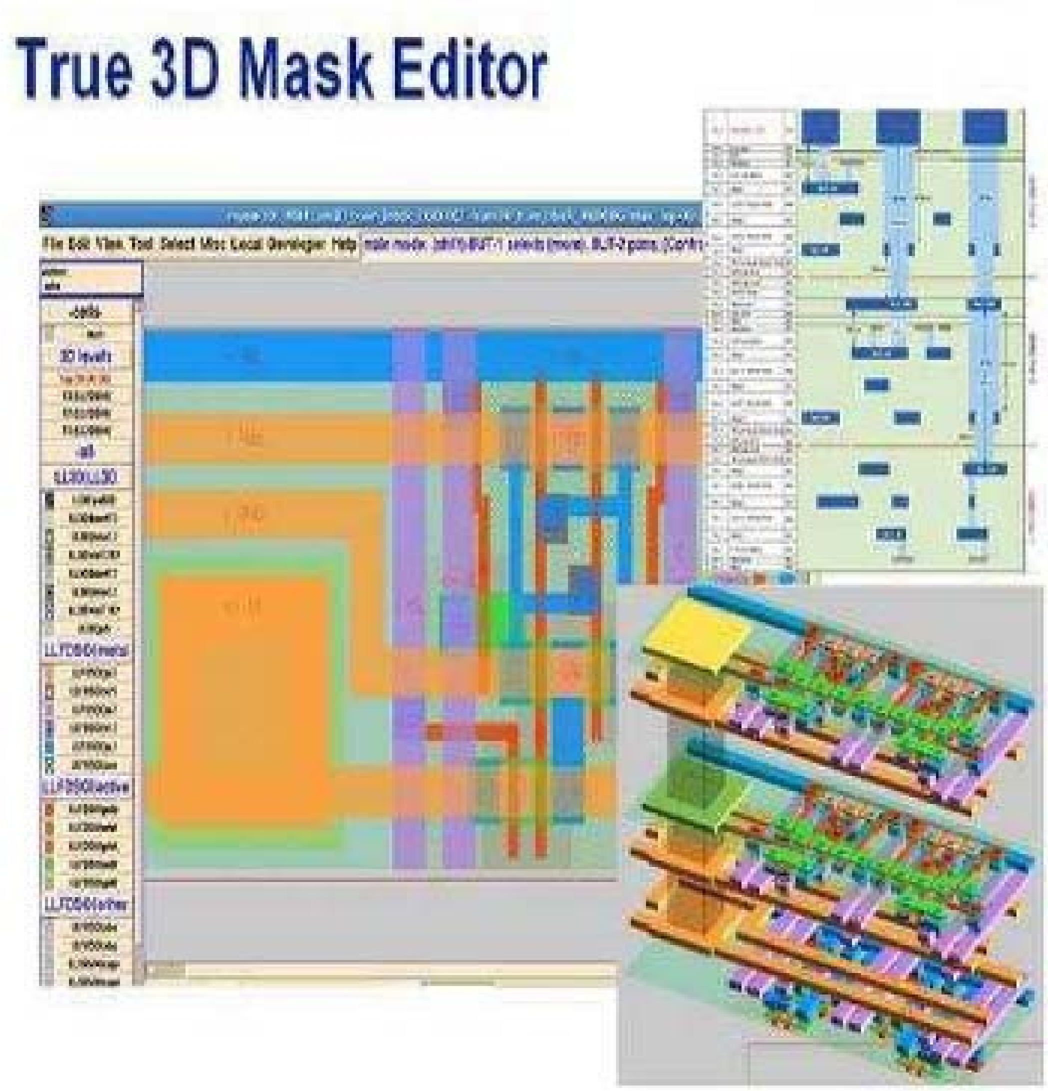
MPW run May 31st, 2011

3D Tools: Virtuoso Layout Editor with 3D layers



K. Torki

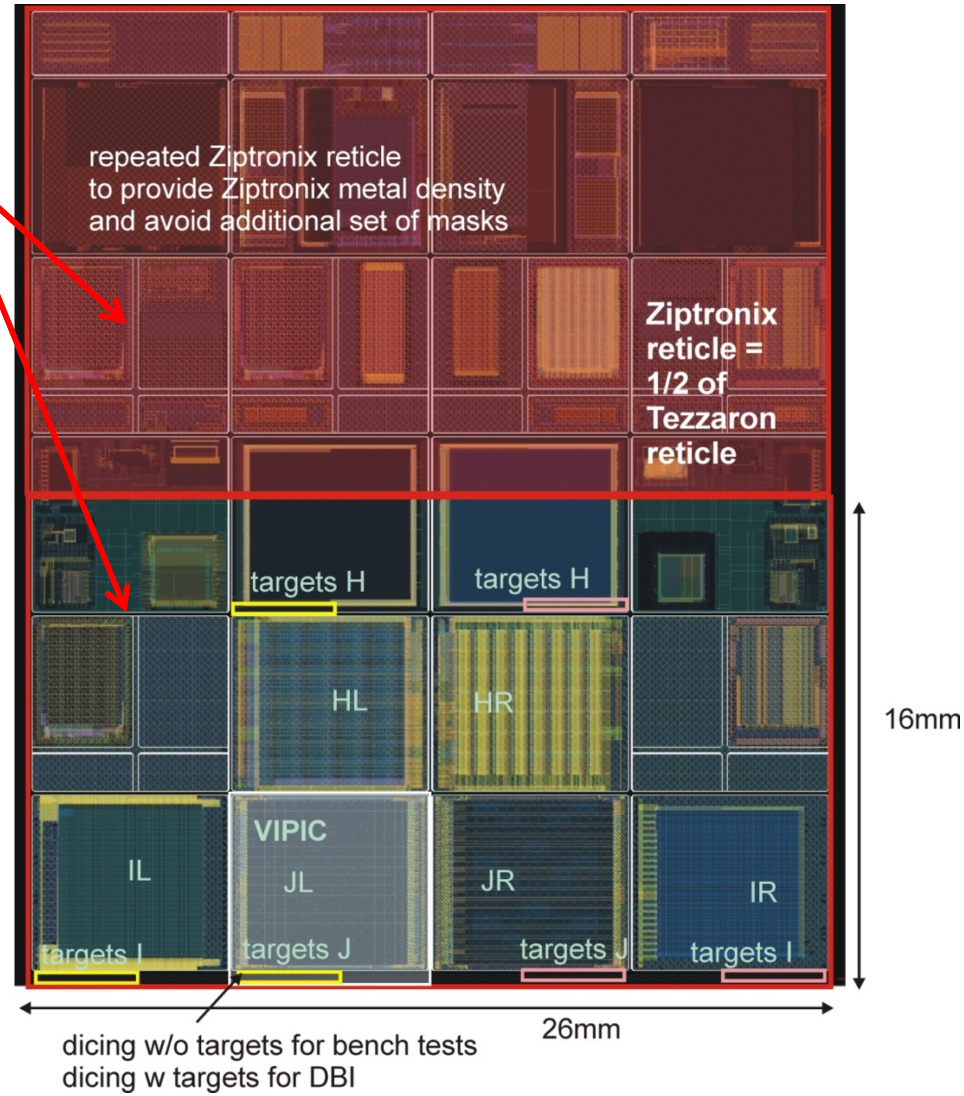
Tools for Tezzaron



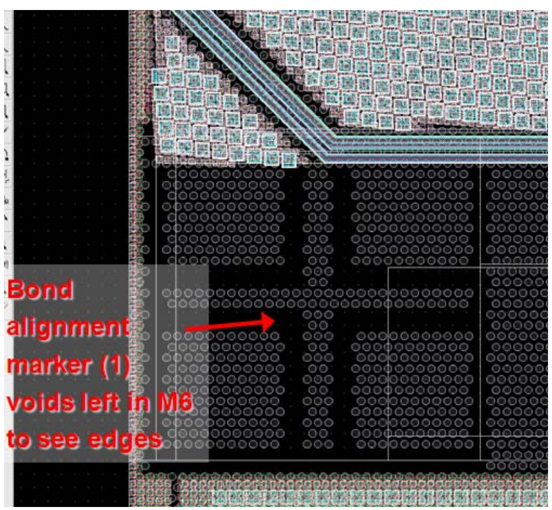
MicroMagix MAX 3D

Example: Some ROIC Wafer Issues

- **Frame size for adding Ziptronix DBI bonding pads was smaller than Chartered frame – repeat bond pad mask twice on 3D frame to avoid extra mask cost.**
- **Space was limited for different alignment targets needed for deposition of seed/DBI post metal and DBI bonding.**
- **IR transparent bond alignment targets are needed on each ROIC and sensor (conflicts with M6 density requirement)**



R. Yarema



Conclusion

Very promising developments open with 3D stacking allowing to use the most suited technologies for each purpose

- **Detection,**
- **Amplification and filtering,**
- **Digital processing**

V
e
r
y

Deep Sub-Micron CMOS combined with Silicon-Germanium facilitate

- **Low noise operation**
- **High level of integration**

to get more and more powefull photo-detectors…

Thanks !

Extra slides

(Some) Photo-detectors

Vacuum

	Principle	Rise time	QE	Gain
• Photo-multipliers	Dynode chain	1-5 ns	25-35%	10^{6-7}
• Hybrid Photo Diodes	Electrons on Si	1-5ns	25-35%	10^{2-4}
• Hybrid APDs	Electrons on APDs			
• Micro-Channel Plates	Micro-pores	100ps	25%	10^{6}

Solid state

	Principle	Rise time	QE	Gain
• PIN diodes	Photo-electric	50ps		
• Monolithic Active Pixel Sensors	Photo-electric	N/A		
• Charge Coupled Devices	Photo-electric	N/A	20% front	N/A
			80% back	N/A
• Avalanche Photo Diodes	Linear multiplication	2-5ns	30-70%	10^{1-3}
• Silicon Photo-Multipliers	Geiger avalanche	200ps	90%	10^{6}
• CdTe/CdZnTe	X-ray			

Large Area Picosecond Photo-Detectors

U-Chicago leaded

- **Large (20 x 20 cm^2) Micro-Channel Plate (MCP) based**
- **Glass window and tray**
- **Photo-cathode**
- **Double Chevron structure**
- **Atomic Layer Deposition (ALD) processed**

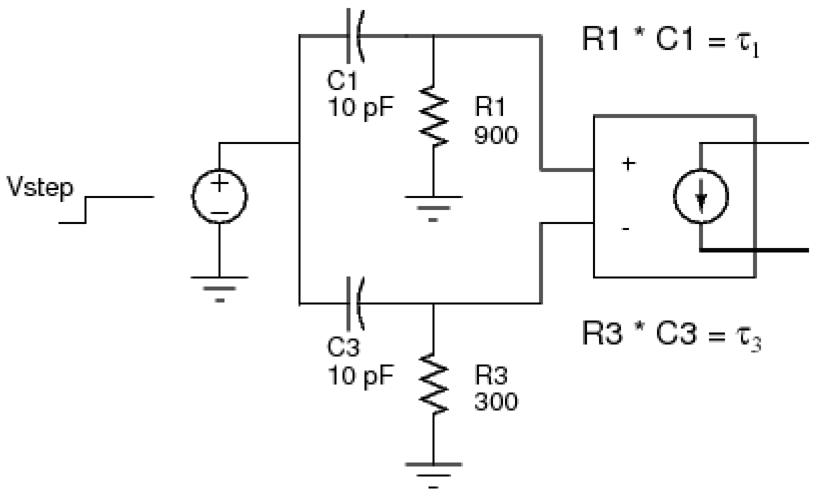
Readout Electronics

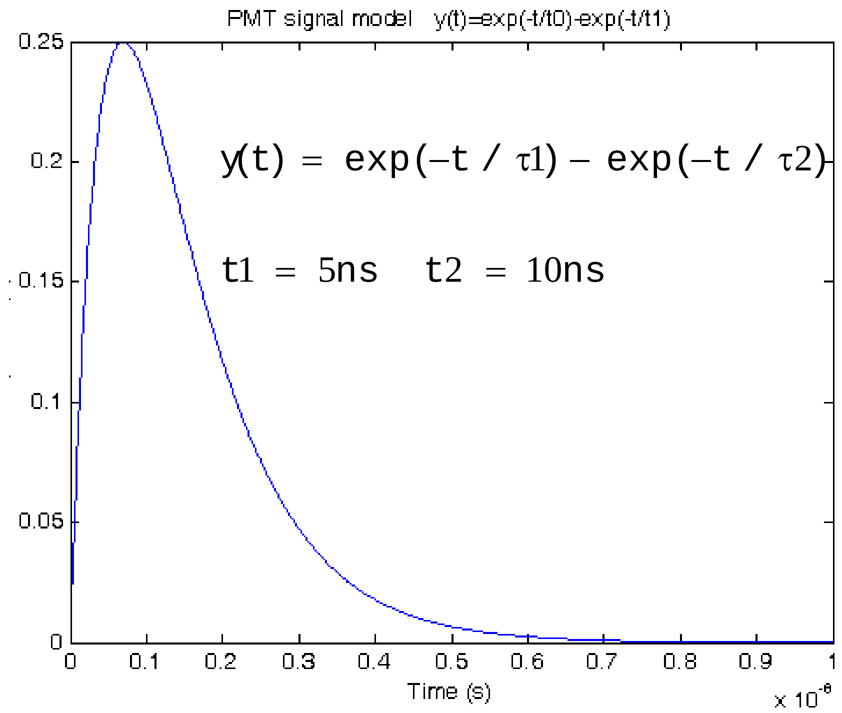
- **Giga-Hertz Waveform sampling**
- **Application Specific Integrated Circuits (ASIC) based**
- **130nm CMOS technology**

Potential applications:

High Energy Physics:	**Detectors, new acceleration techniques**
Medical Imaging:	**Positron Emission Tomography, dosimetry**
Security:	**Airports, trucks**

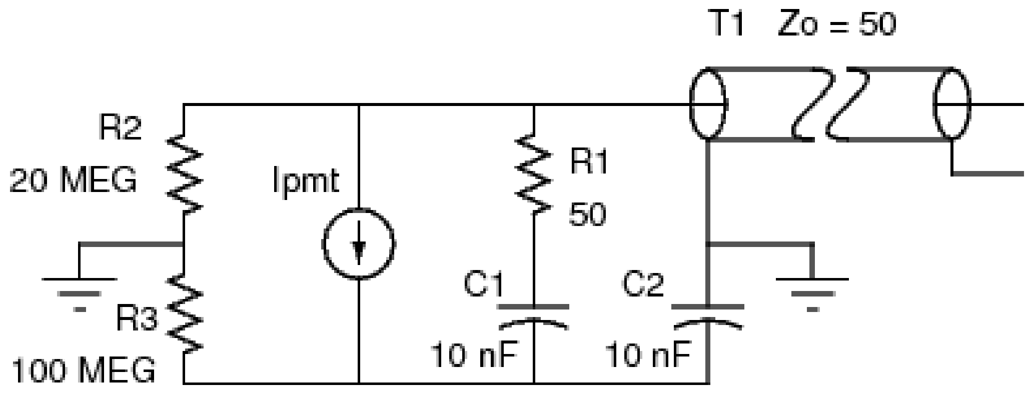
Signal simple Spice model





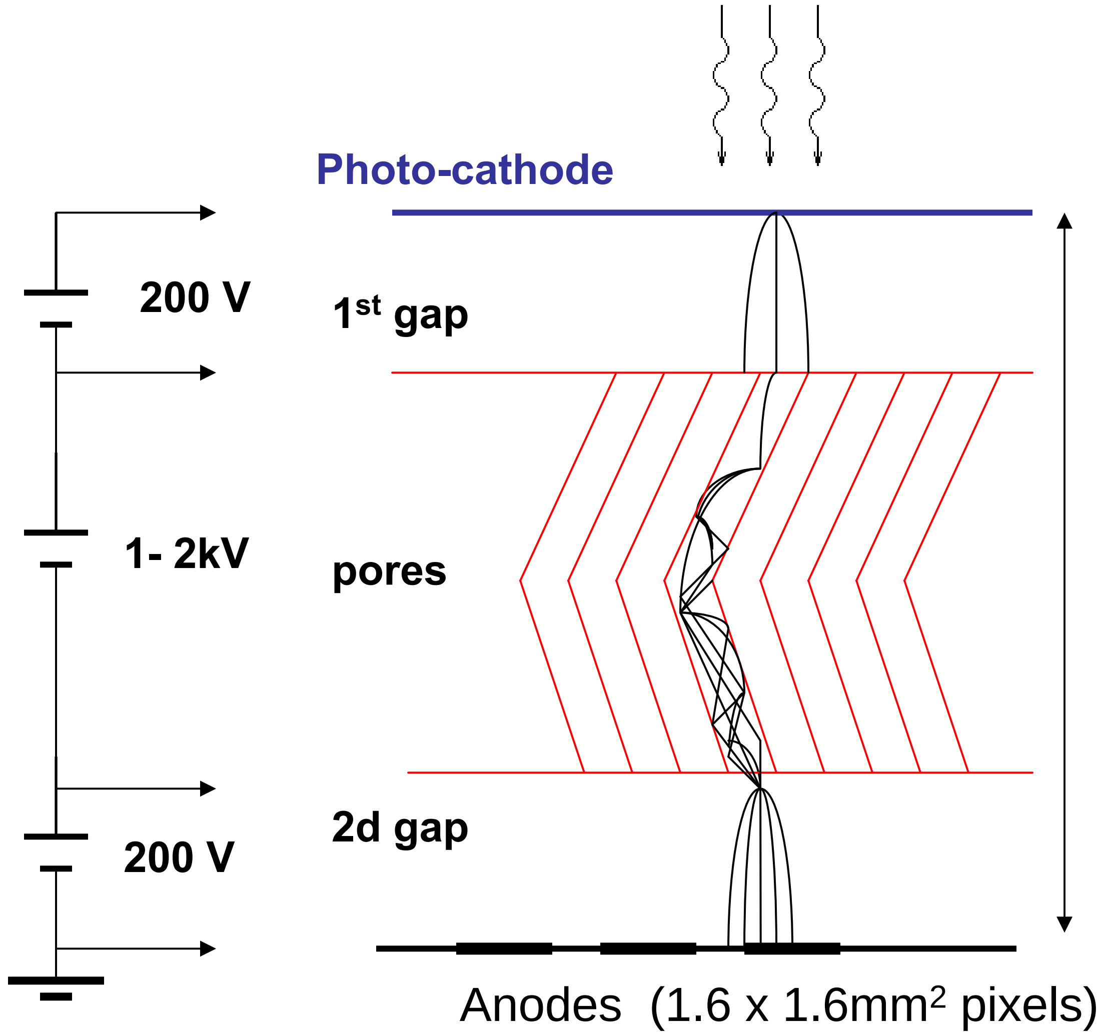
Spice detector model: difference of two exponentials

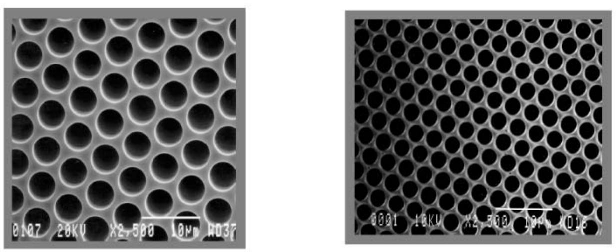
50 Ω Cable driving Spice model



SPICE Model of PMT Cable Driving Circuit

Micro-Channel Plate Detectors





Comparison of 5micron pore and 2 micron pore MCP's (same magnification)

Pore diameter 3-25 μm
Pore aspect ratio: 1:50

Micro-Channel Plates

Optimization for timing

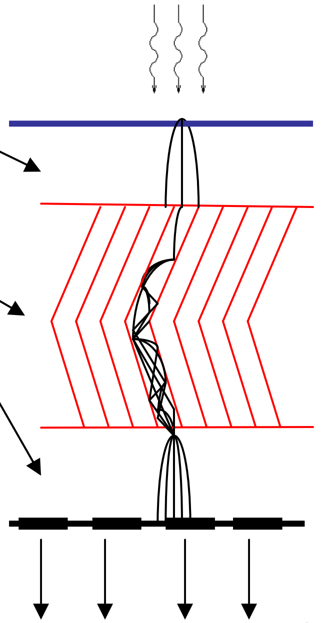
Reduce Transit time

The thinner, the best
Reduce pore size, primary and secondary gaps

Avoid parasitic readout components

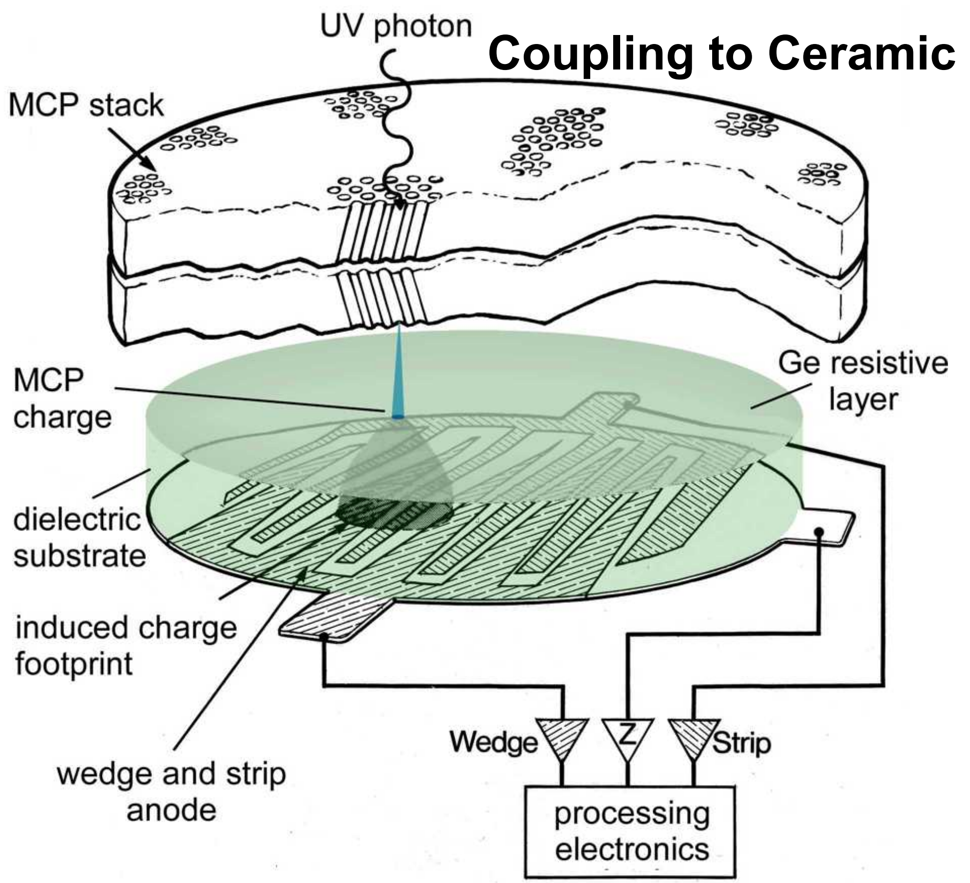
Connectors (!)
Parallel capacitances
Series inductances

Reduce rise-time, consequently improve time resolution



Imaging Micro-Channel Plates Detectors

As imaging device…

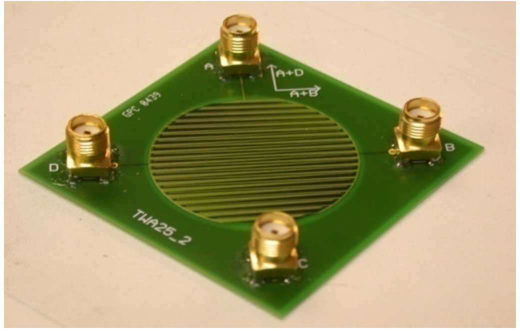


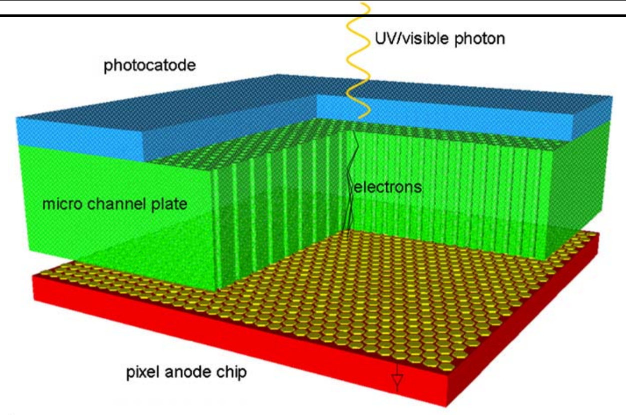
From J. Lapington, for WSO, Uni. Leicester, UK

Coupling to Board

Position: 10μm resolution

Time: 1ns





Coupling to ASIC: 3 μm

From GLAST, Siegmund et al NIM 591 2008

Two-micron space resolution using analog charge division technique

High precision analog measurements.

But integration time= 200ns !

R. Bellazzini et al. / Nuclear Instruments and Methods in Physics Research A 591 (2008) 125–128

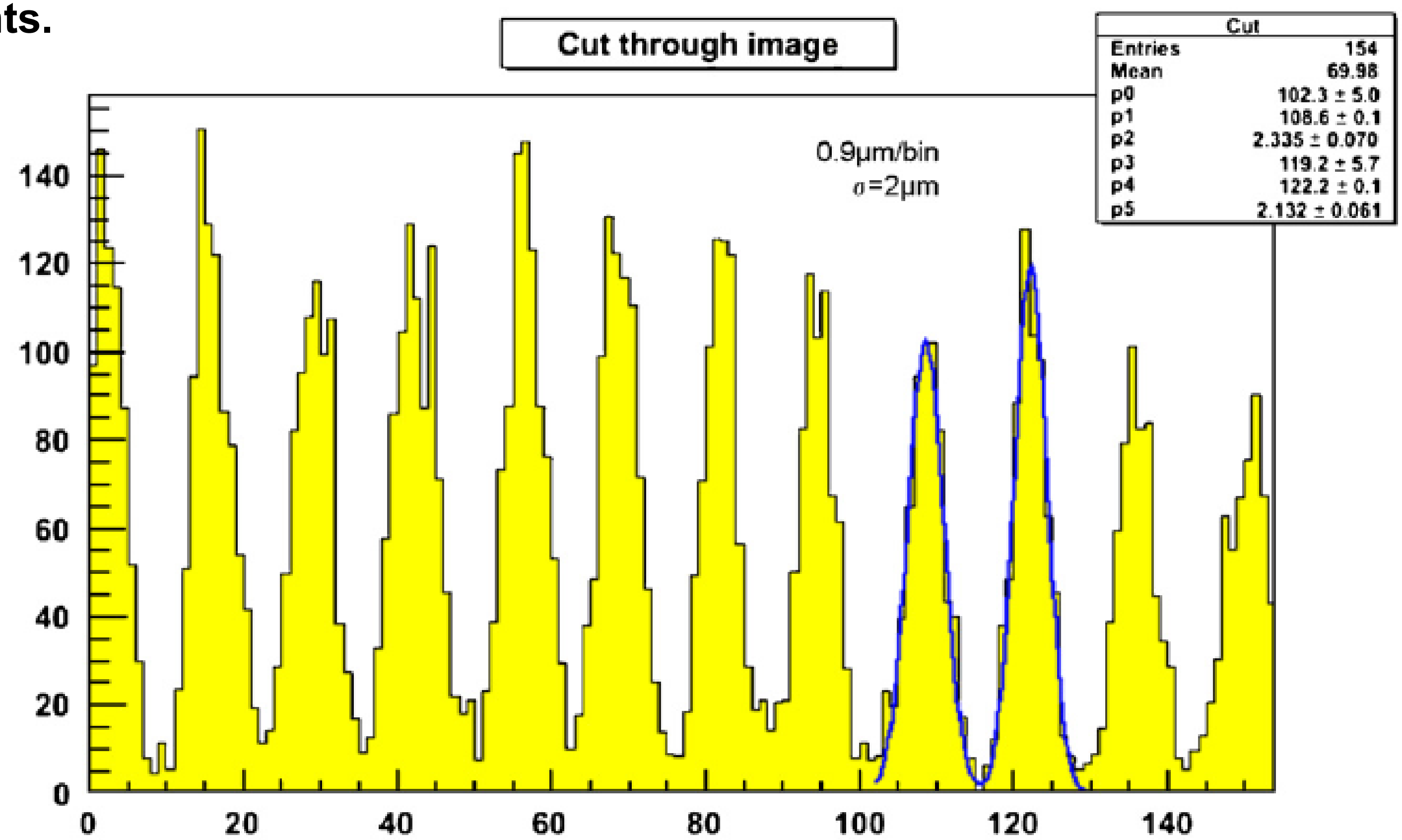


Fig. 4. A profile along a line cut across the MCP pores of Fig. 3. The spatial resolution of the readout is ~2 μm rms, capable of resolving every single MCP pore.

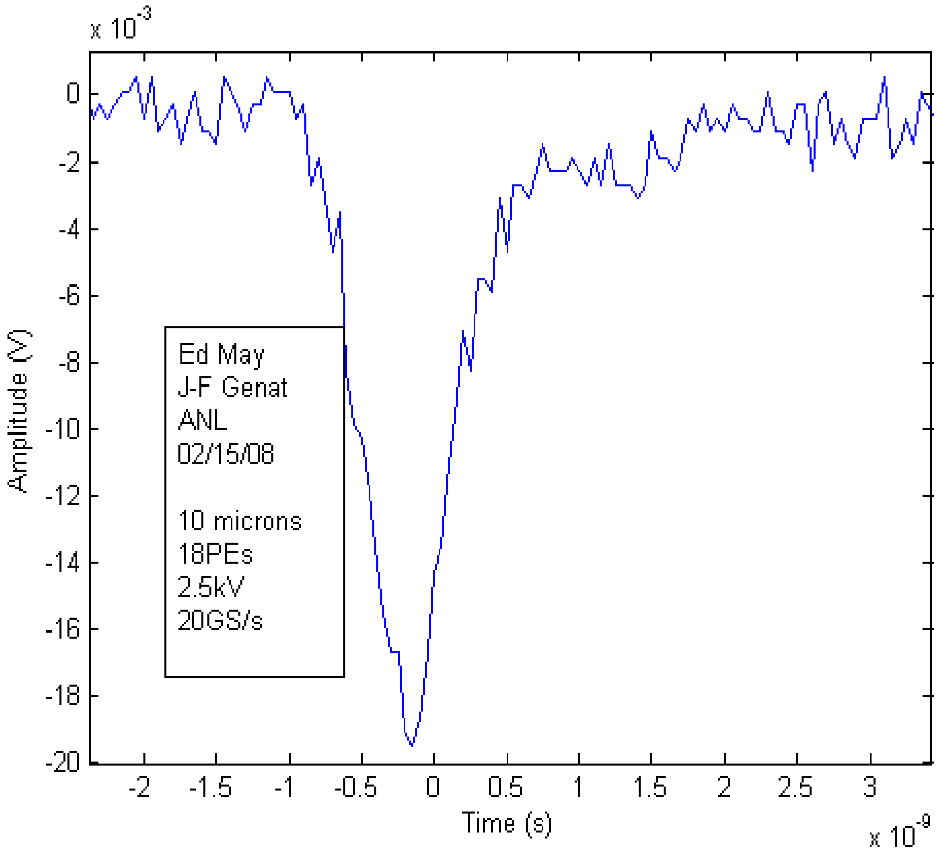
Micro-channel Plates Sampled Waveforms

- **Amplitudes (10µm, 2.5 kV)**

18 Photo-Electrons	**20**	**mV**
50 Photo-Electrons	**35**	**mV**
158 Photo-Electrons	**78**	**mV**

- **Rise times**

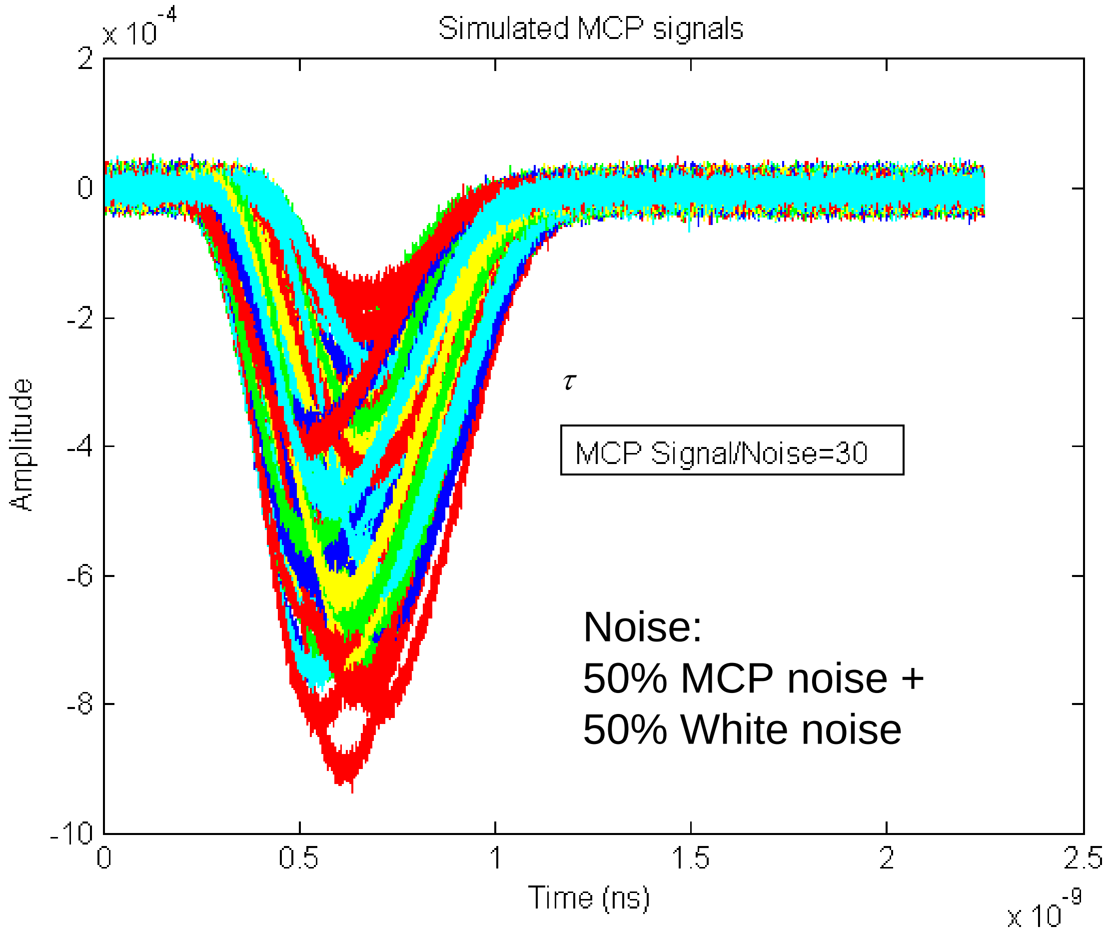
25µm	**600ps**
10µm	**550ps**



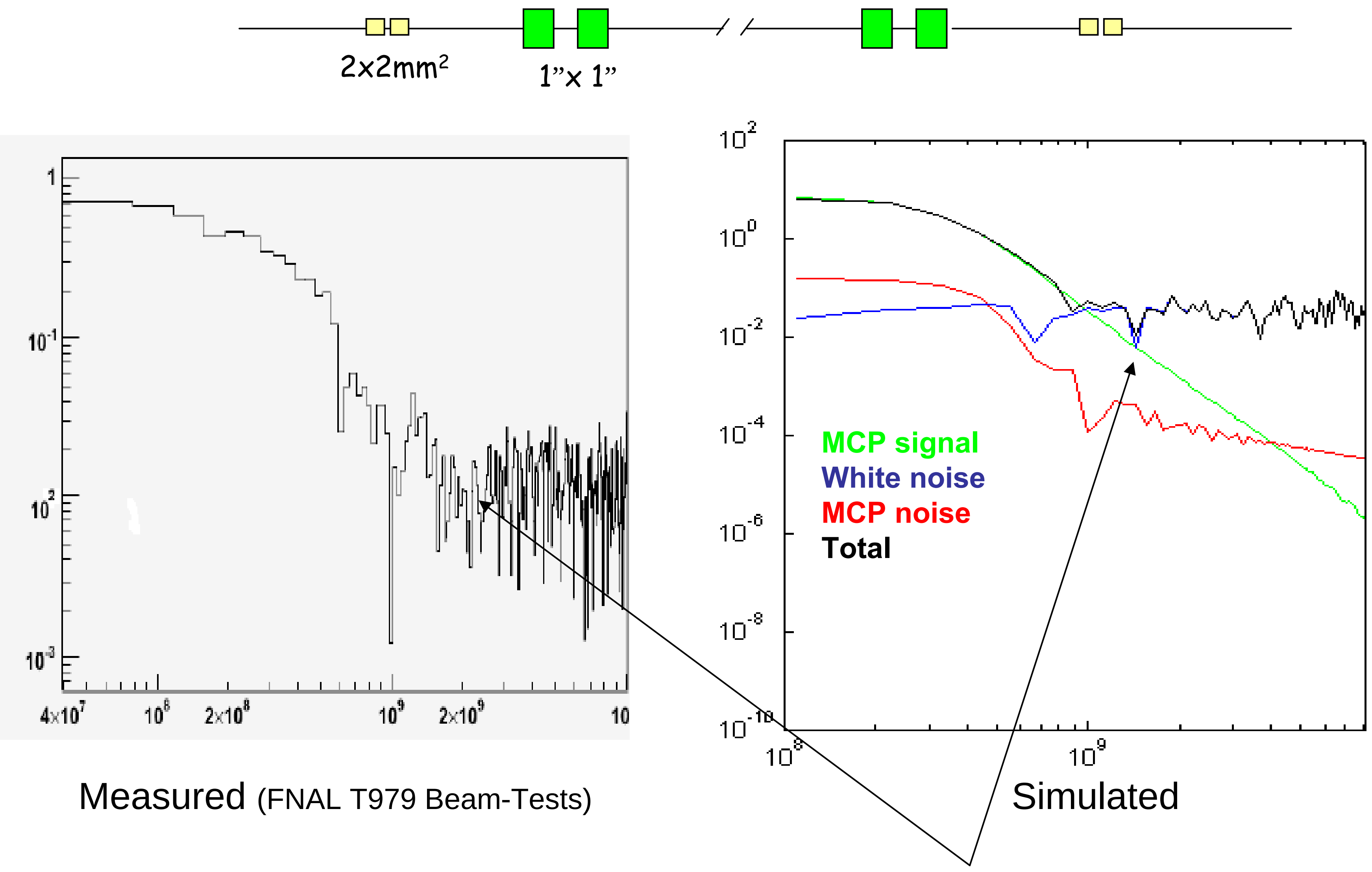
Synthesized signals for simulations

MCP signals: $(t/\tau)\exp(-t/\tau) \otimes (t/\tau)\exp(-t/\tau)$

τ is tuned to a 280ps rise-time



MCP Signals spectra

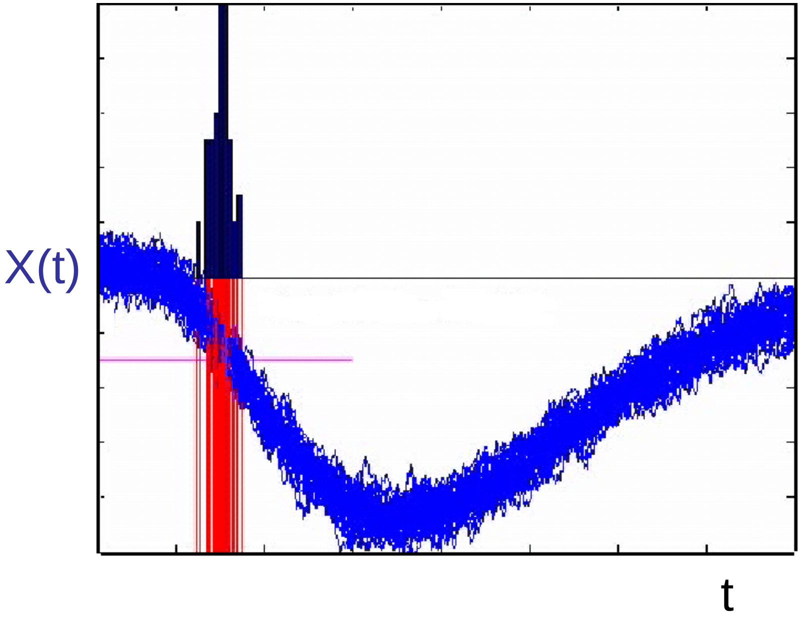


Measured (FNAL T979 Beam-Tests)

Simulated

Same noise corner at 1.2 GHz

Single Threshold: Noise and Slope

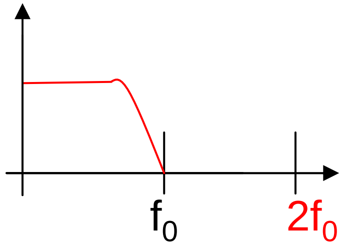


- $rms_{noise} = \sigma_x$
- $\sigma_t = \sigma_x / \frac{dx(t)}{dt}$

Single threshold: Time spread proportional to amplitude noise and inverse to slope

Pulse sampling and Waveform analysis

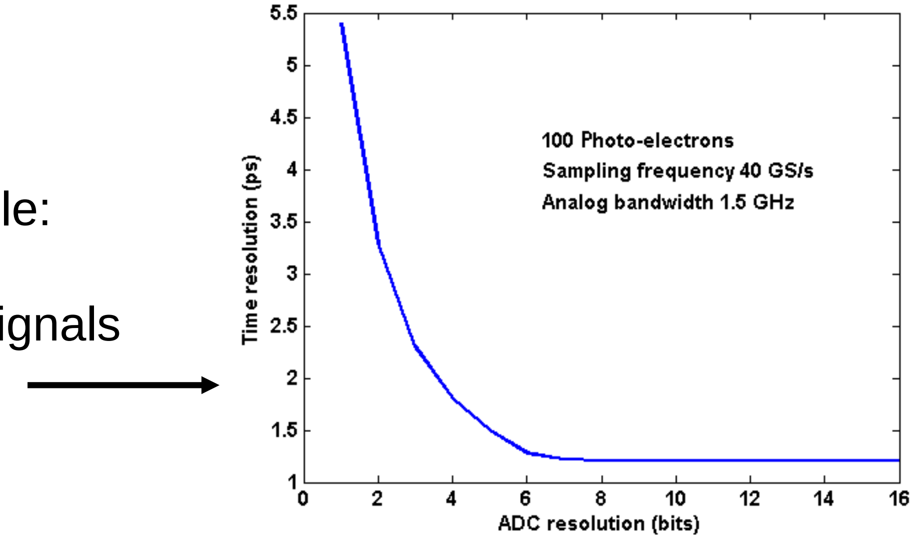
- Sampling frequency: Set at twice the largest frequency in the signal spectrum



- Digitization: Evaluate what is needed from signals properties:

Example:

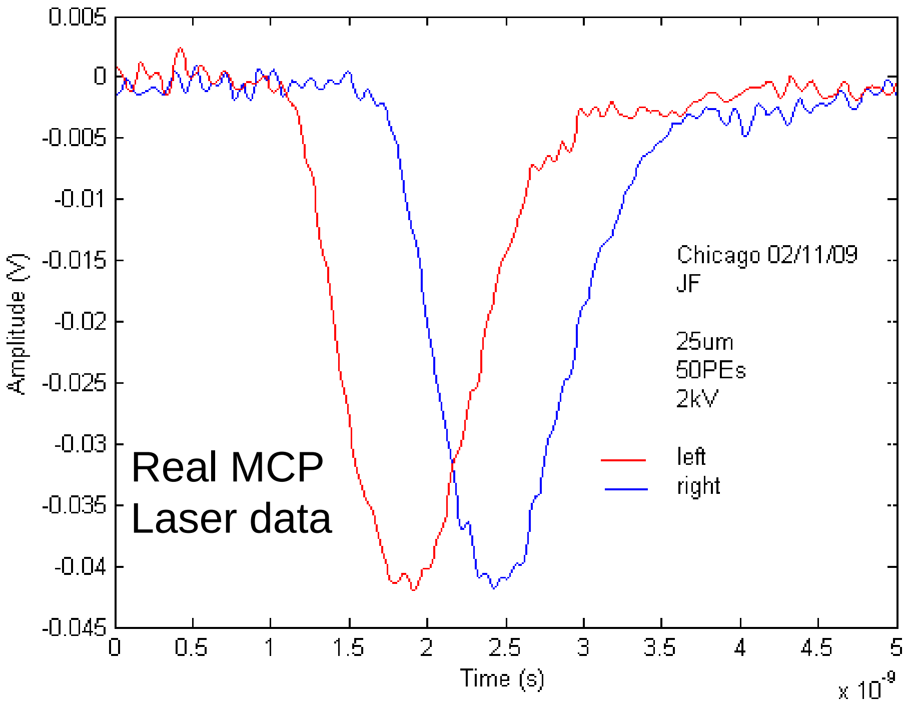
MCP signals



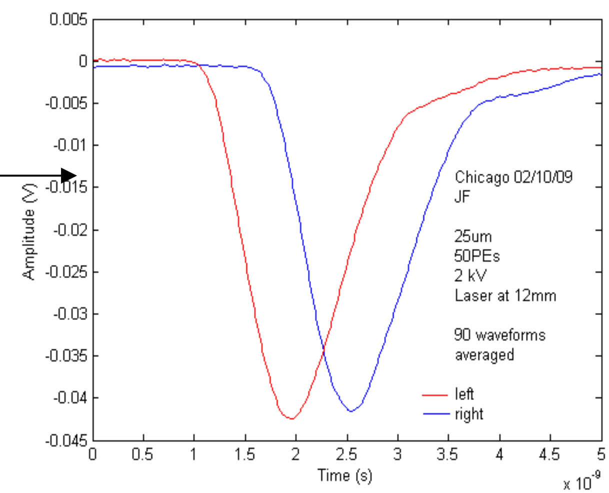
Sampled pulses analysis

Many techniques

B. Cleland and E. Stern, BNL



Signal Template

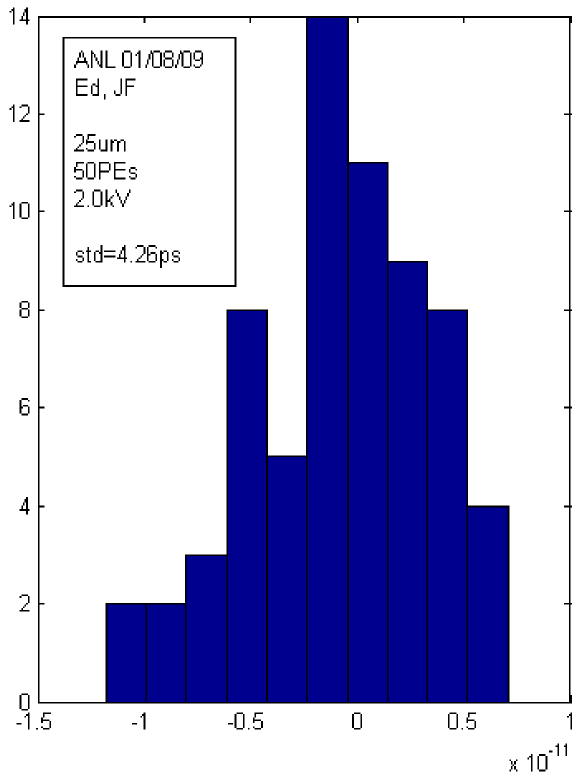


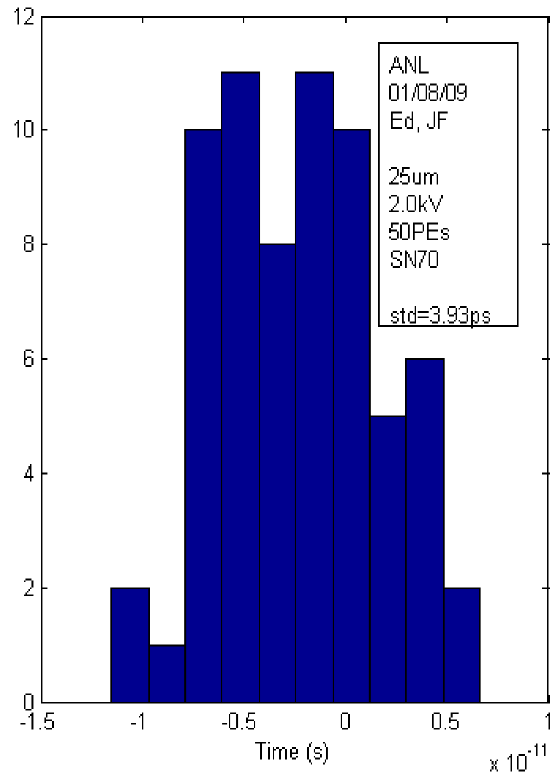
- Extract precise time and amplitude from minimization of χ^2 evaluated wrt a template deduced iteratively from the measurements, at the two ends of the T-line.

- With T-lines, the two ends are highly correlated, so, MCP noise is removed.

Iterative template

At T-lines ends

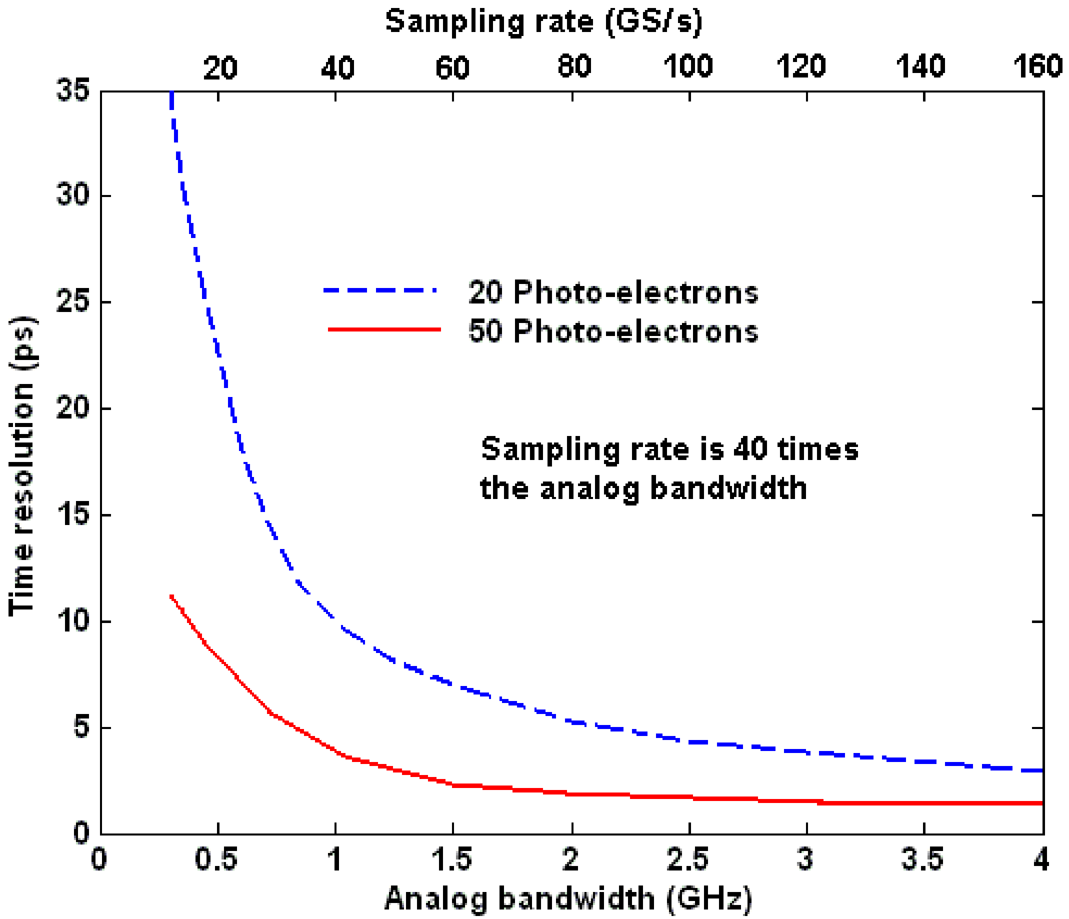




Template from average
std= 4.26ps

Template iterative
std=3.93

Pulse sampling
Timing resolution vs Sampling rate (simulation)

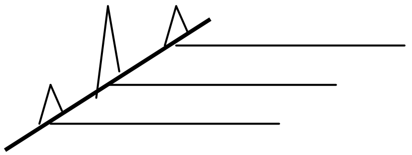


Timing resolution vs Sampling rate / Analog bandwidth

Pulse sampling benefits

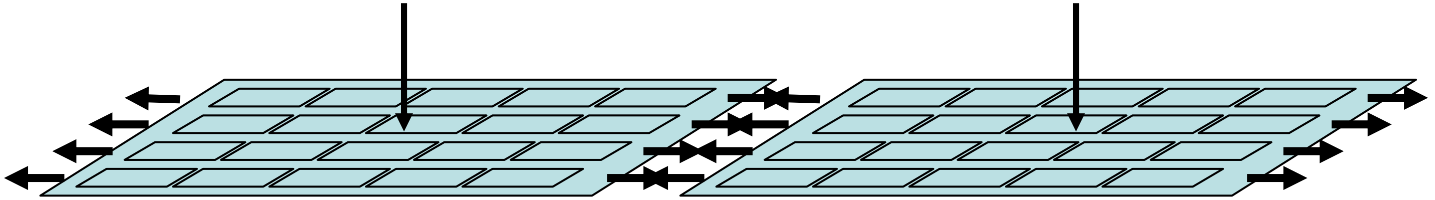
Pulse sampling and waveform analysis:

- Picosecond timing with fast detectors
- Charge: centroids for 2D readout

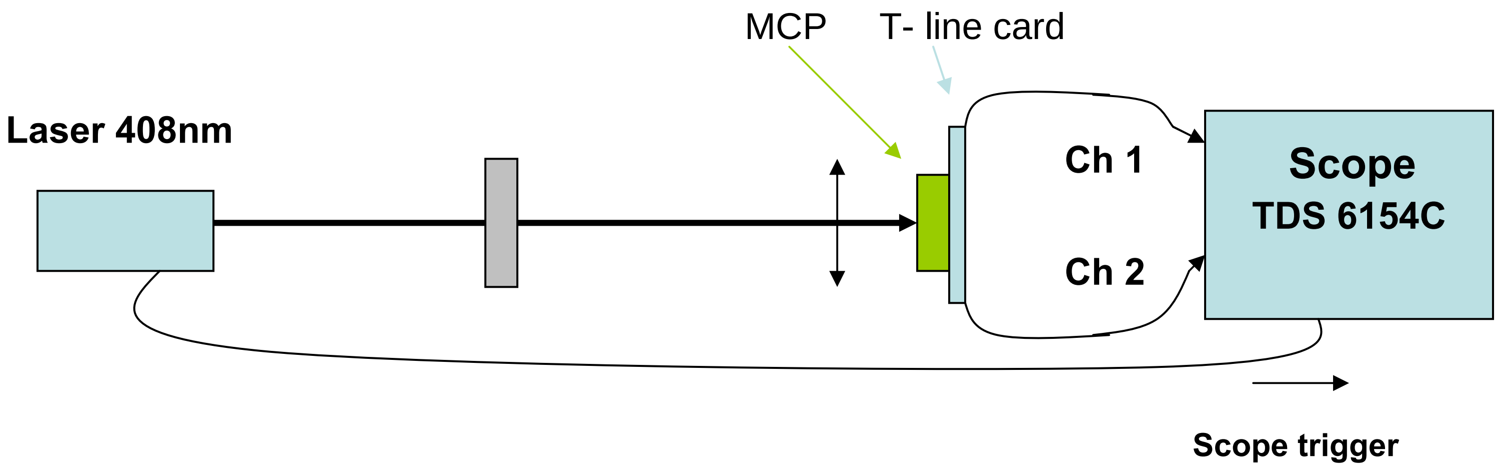


- Resolve double pulse

For large area detectors read with delay lines in series



Position sensing using fast timing

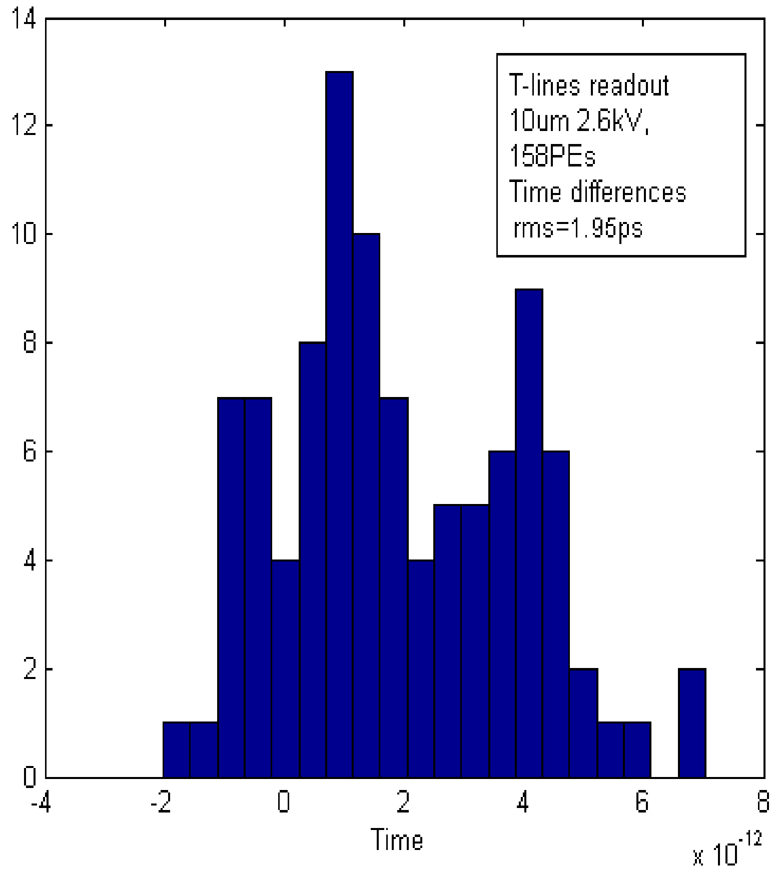


- Edward May, Argonne:

Laser test bench calibrated with the single PE response of a Quantacon (single photon sensitive) PMT.

- 25/10um pores MCP on transmission lines card
- Scope triggered by the (somewhat jittery) laser signal
- Record two delay lines ends from the same trigger
- Tek 6154C scope at 20 Gs/s

Results



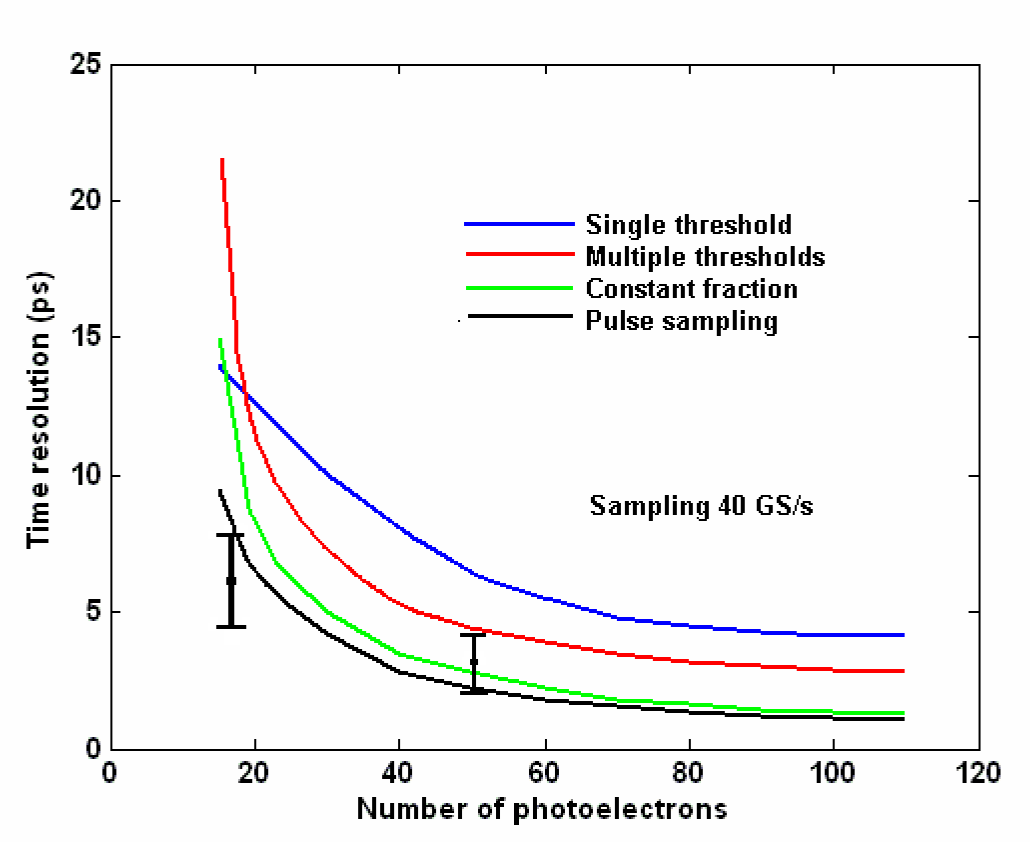
Position resolution (velocity=8.25ps/mm) :	50PEs	4.26ps	213µm
	158PEs	1.95ps	97µm

Measurements vs simulation

50PEs rms=3.82ps vs 2.5ps (simulation)

18PEs rms = 6.05ps vs 7ps (simulation)

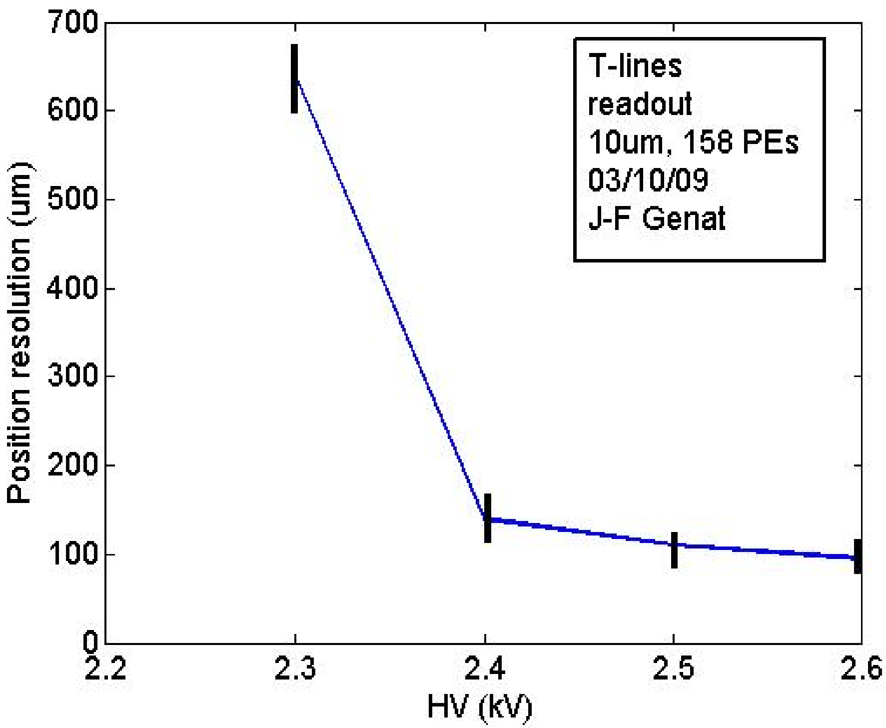
Measurements
do not match exactly
since MCP noise
is partly removed
(T-lines ends correlated)

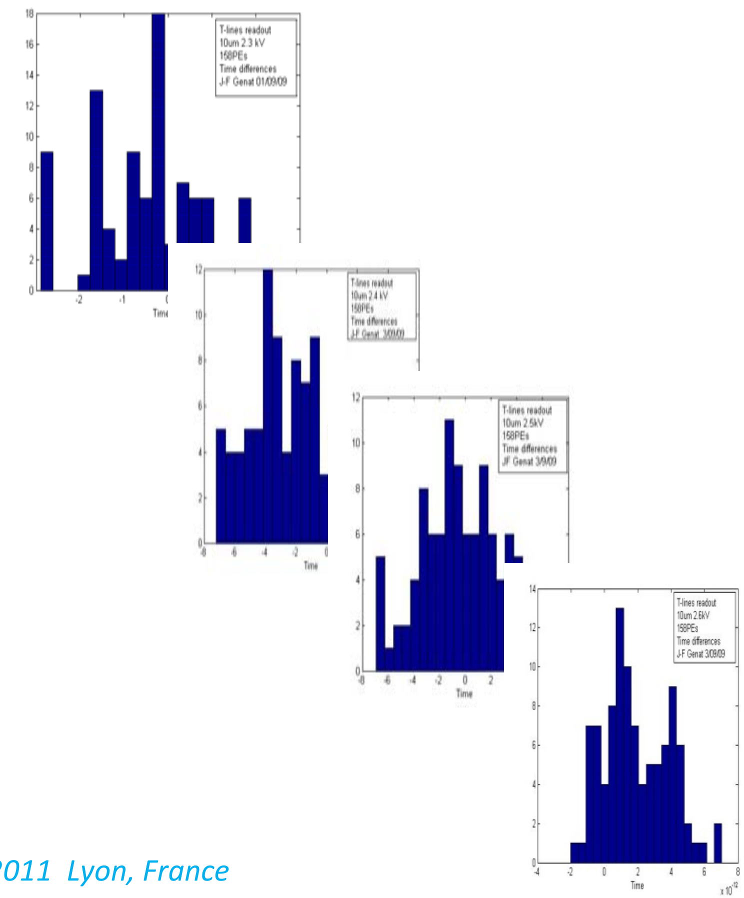


Position Resolution at 158PEs

158 PEs

	HV = 2.3 kV	HV = 2.4 kV	2.5 kV	2.6 kV
Std	12.8ps	2.8ps	2.2 ps	1.95 ps
	640μm	140μm	110μm	97μm





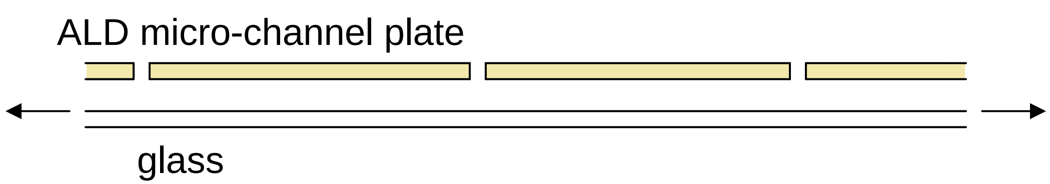
Transmission lines as anodes

- Present Photonis MCPs:
  Pixellated anodes, pitch of 1.6 x 1.6 mm

  - Atomic Layer Deposition (ALD) detectors
  - Waveform sampling with fast sampling chips

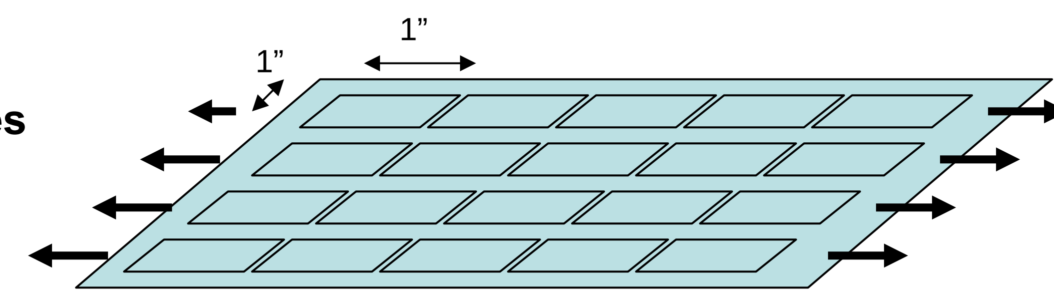
- **Integration of lines as anodes in vacuum for large area sensors**
- **Plates of 1" x 1" in ALD process**
- **Modules of 8 " x 8 " ?**
- **One vacuum vessel (glass)**

Henry Frisch, (U-Chicago)
W. Hau, M. Pellin (ANL)



Check in vacuum
T-lines coupled to Micro-Channel Plates
(impedance, velocity)

B. Adams, K Attenkoffer, ANL



MCPs: Best position resolution

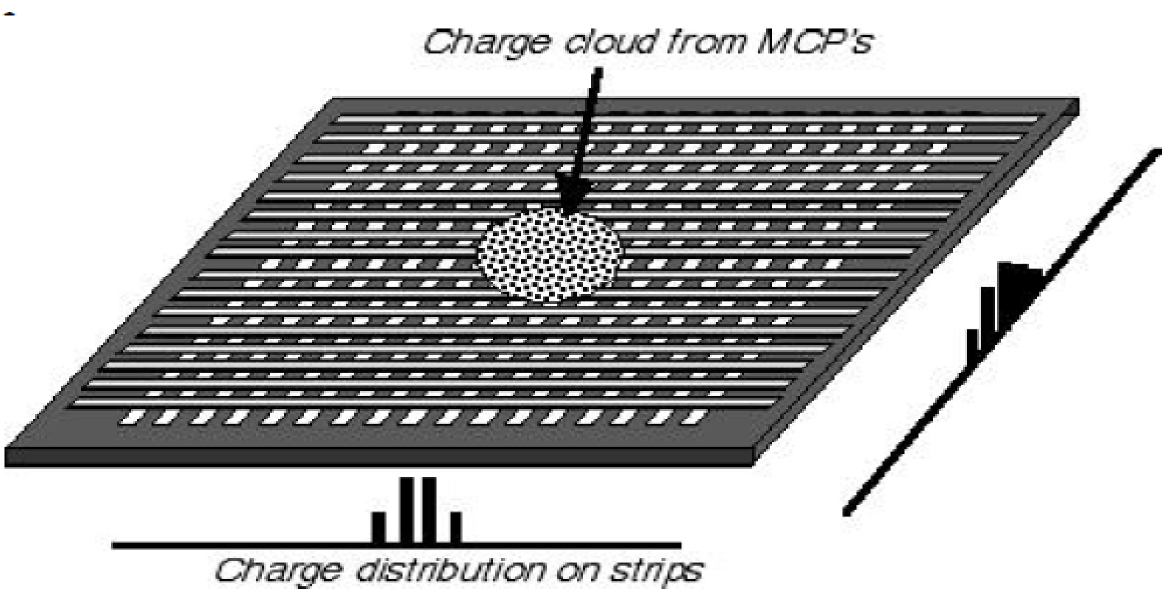


Figure 1. Schematic of the cross strip anode showing the MCP charge cloud, and charge distribution on the cross strips.

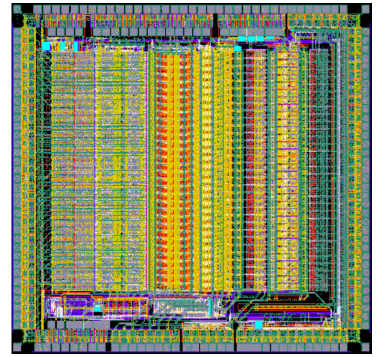
A few microns position resolution using analog weighted sums

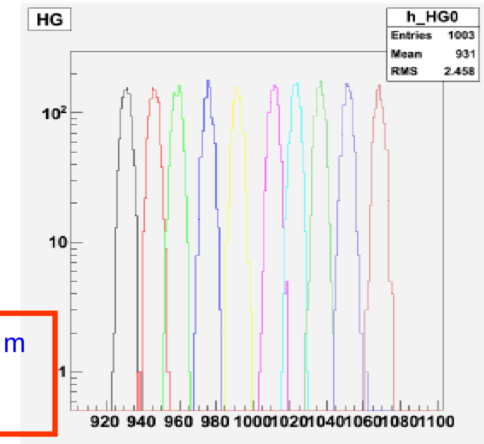
O. Siegmund, A. Tremsin (SSL Berkeley)

350nm Silicon-Germanium

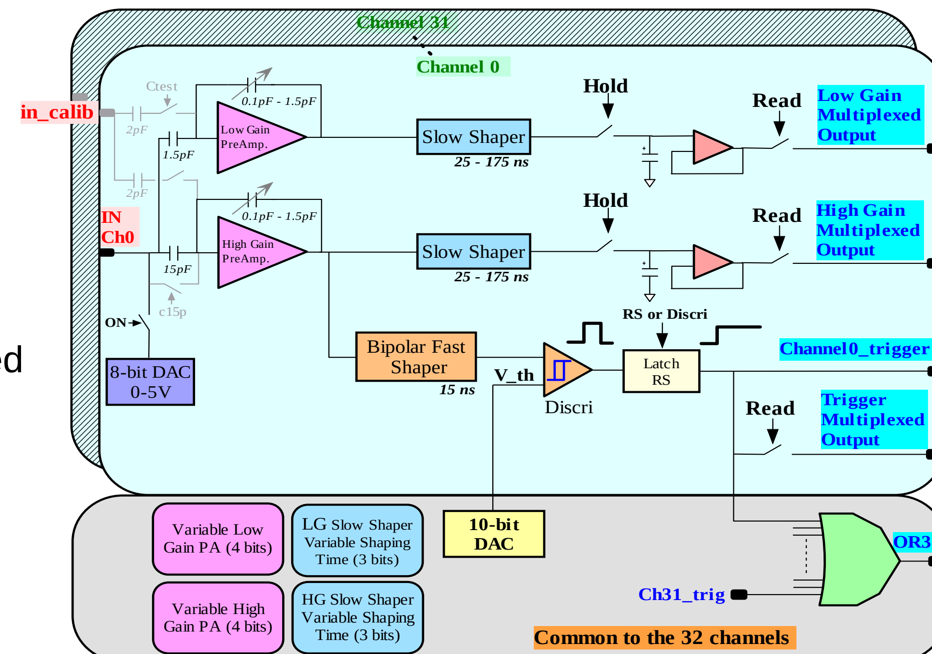
Silicon PMs Readout: SPIROC

- **32-Channel ASIC for Silicon PM readout**
  Includes 32 x 16-deep analog memories and ADCs
- **Internal input 8-bit DAC** (0-5V) for individual SiPM gain adjustment
- **Energy measurement : 14 bits**
  - 2 gains (1-10) 1 pe → 2000 pe
  - Variable shaping time from 25ns to 175ns
  - pe/noise ratio : 11
  - 2 Multiplexed outputs for low gain and high gain
- **Trigger output**
  - pe/noise ratio on trigger channel : 24
  - Fast shaper : ~10ns
  - Trigger on 1/3 pe (50fC)
  - 32 trigger outputs
  - OR 32 output
  - Trigger latch for each channel and multiplexed output
- Individually addressable calibration injection capacitance
- **Embedded features**
  Power pulsing, bandgap, 10-bit DAC





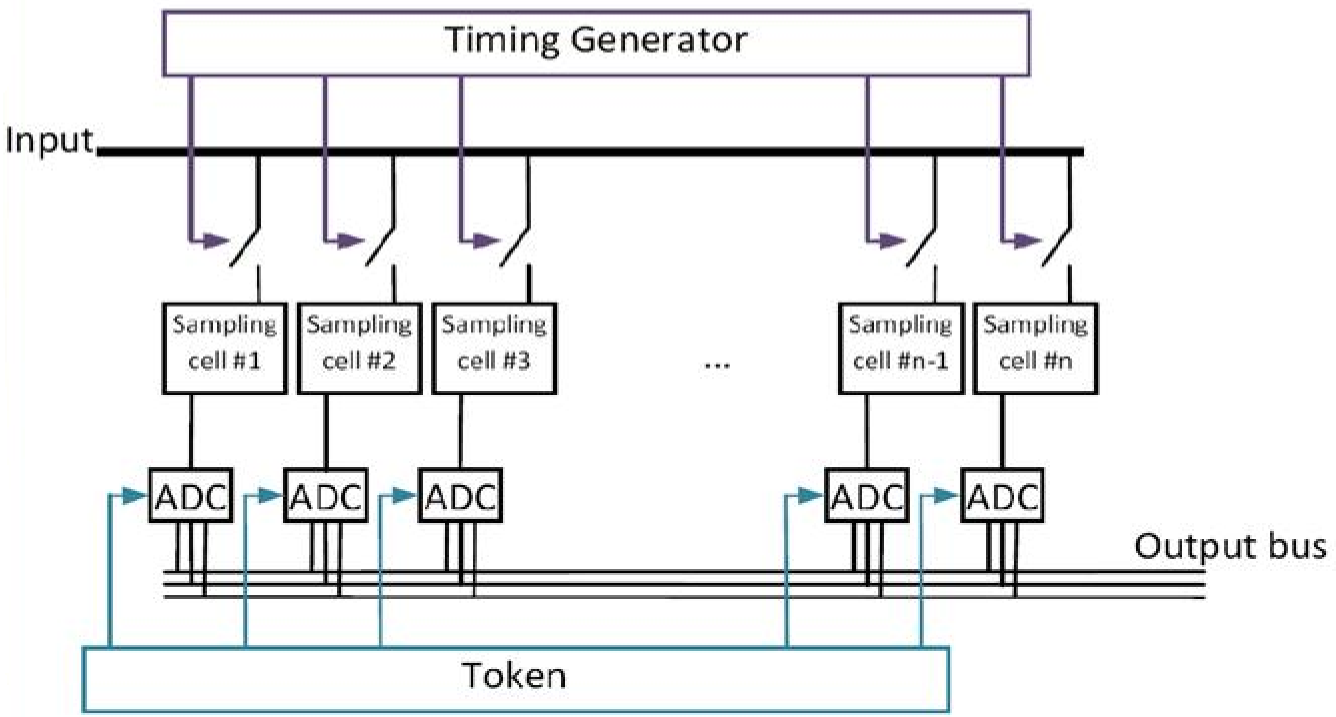
Fabricated in SiGe AMS 0.35 µm
Delivered in December 2009
Chip area: 17 mm²



Switched Capacitor Arrays (SCA)

- **Sampling capacitors: 50-100 fF, input bus 200-1kΩ**
- **Analog bandwidth = 1/2πRC = 1-10GHz**
- **Dynamic range 10-13 bits limited by noise and voltage droop before readout**
- **Timing generator using voltage controlled delay elements of 50-500ps**
- **Depth can be very large (64k) if bandwidth is not constrained**
- **Very low power (readout dominated)**

- **Used in fast oscilloscopes**



15 GS/s 130nm CMOS