Integrated Circuit Design for Time-of-Flight Applications

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1. Time-of-Flight in Medical Imaging
   - Technology transfer
   - Positron Emission Tomography
   - EndoTOFPET-US

2. TOFPET ASIC
   - Chip and channel Architecture
   - Front-End
   - Time-to-Digital Converter
   - Chip integration

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From HEP to Medical Imaging

Looking into the origin of the Universe in **high-energy physics experiments**

Tracking tumour cells by scanning the body metabolism in **positron emission tomography**

Where do these two disciplines meet?

↪**Methods and Instrumentation**

From CMS ECAL (LHC) to PET: scintillators (Crystal Clear Collaboration), photodetectors (APDs), readout electronics and DAQ, trigger software,...

From CALICE HCAL (ILC) to PET: photodetectors (SiPM) and associated front-end readout electronics

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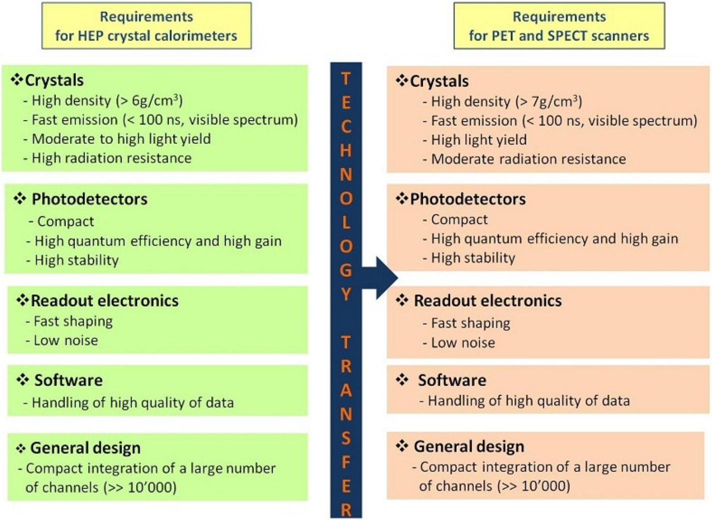

Requirements for HEP crystal calorimeters

Crystals
- High density (> 6g/cm^3)
- Fast emission (< 100 ns, visible spectrum)
- Moderate to high light yield
- High radiation resistance

Photodetectors
- Compact
- High quantum efficiency and high gain
- High stability

Readout electronics
- Fast shaping
- Low noise

Software
- Handling of high quality of data

General design
- Compact integration of a large number of channels (>> 10'000)

TECHNOLOGY TRANSFER

Requirements for PET and SPECT scanners

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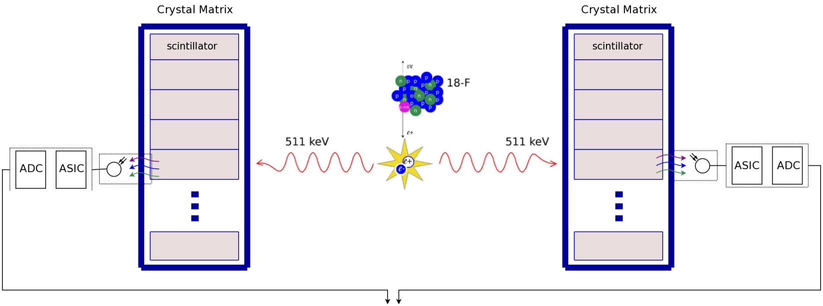
Figure: source http://crystalclear.web.cern.ch/

Basics of PET - the planar detector heads case study



Acquisition & Trigger system

- An injected radiopharmaceutical undergoes a β^+ decay, from which a positron is created.
- Its annihilation in the vicinity of the tumourous tissue produces a pair of high-energy photons flying back-to-back.
- The quasi-simultaneous detection of the two γ rays describes a LOR.
- With multiple LORs, a slice of the image is built. Reconstruction of different angle projections is used to retrieve a 3D image.

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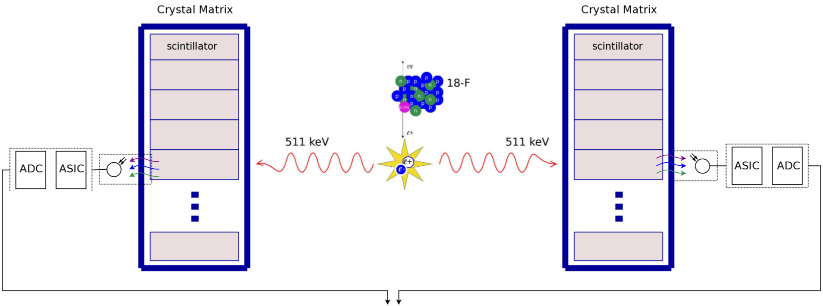

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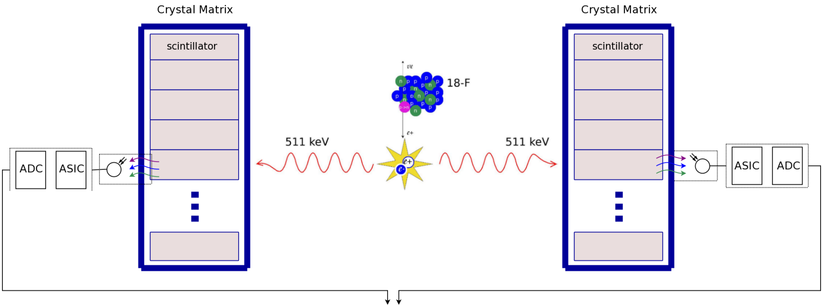

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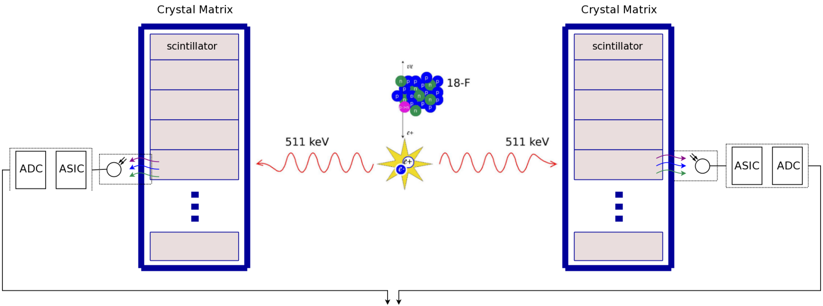

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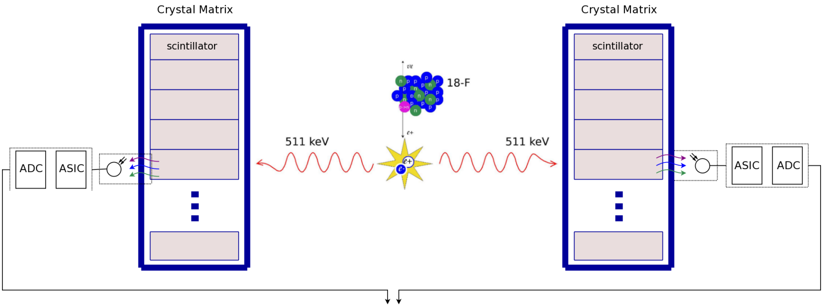

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Did I loose something? Calorimeters, PET Scanners...?

↪ A PET Scanner is fundamentally an electromagnetic calorimeter with a good timing measurement resolution.

- **Energy resolution is needed:**
  - Incident radiation is not mono-energetic: photons can have undergone scattering (body, inter-crystal, ...) prior to detection - sufficient energy resolution (better than 20%) is needed **to separate the 511 keV photo-peak from the Compton events.** These can be rejected or reconstructed.
- **Timing resolution is needed:**
  - A good time resolution (< 10 ns) is needed **to unambiguously determine to which LOR the detected event belongs**, other than allowing the rejection of random hits (background noise). If exceptional ($<$200 ps), it could constrain the annihilation coordinate to a segment of the LOR... here comes the TOF-PET

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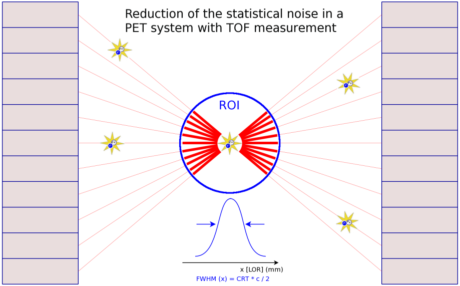
Motivation for Time-of-Flight measurements in PET



↪ A 200 ps coincidence resolving time (CRT) confines the annihilation coordinate to a 3 cm segment along the LOR.

- This measurement can identify, with an error Δx, the position of the annihilation along the chord that defines the travel path of the back-to-back photons
  - spatial resolution is the same
  - **background rejection is significantly improved**
- Consequently achieving:
  - **Higher SNR of the reconstructed image,**
  - **Shorter exam time, or**
  - **Reduced injected dose of radiopharmaceutical**

Motivation for Time-of-Flight measurements in PET

Now... When is TOF information necessary? Do all PET systems benefit from it?

↪ Not necessarily.

- **Full-body PET**
  - Yes, TOF can dramatically reduce the background rejection and improve the image quality, in particular for large patients or low-uptakes.
- **Dedicated PET (e.g. PEM, Small Animal, Brain Imaging)**
  - Probably not. The distance between plates (case of ClearPEM) or diameter (PET rings) is already small; unless a CRT much better than 100 ps could be achieved...
- **Endoscopic PET**
  - Absolutely yes. An endoscopic PET probe is useless if the random events from due to the proximity of the internal organs cannot be supressed.

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Building up the world's smallest calorimeter

Combined TOF-PET (200 ps time resolution), ultrasound imaging and endoscopic biopsy

PET components:
- dSiPM/crystal endoscopic probe
- aSiPM/crystal external plate

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ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

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Context

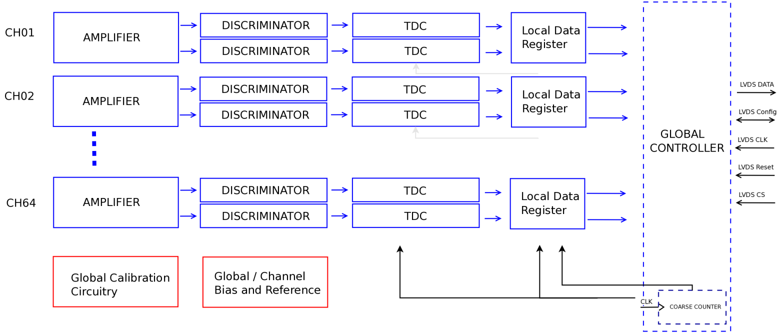
- **Design of a low power SiPM readout ASIC for Time of Flight applications**
- integrates signal conditioning and discrimination circuitry and high-performance TDCs for each of 64 independent channels
- targets 25 ps r.m.s. intrinsic resolution and features fully digital output
- TOFPET ASIC developed in the framework of the **FP7 project EndoTOFPET-US**
  - PET time-of-flight detector plate (4000 channels)
  - MPPC (16-channel arrays, 3x3 mm2) and LYSO crystals
  - Coincidence time resolution (CTR) 200 ps (FWHM)

Features of an ASIC for SiPM readout in PET applications

Parameter	Value
Number of channels	64
Clock frequency	80 – 160 MHz
Dynamic range of input charge	**300 pC**
SNR ($Q_{in} = 100$ fC)	$>$ 20-25 dB
Amplifier noise (in total jitter)	$<$ 25 ps (FWHM)
TDC time binning	**50 ps**
Coarse gain	G_0, $G_0/2$, $G_0/4$
Max. channel hit rate	100 kHz
Max. output data rate	320 Mb/s (640 w/ DDR)
Channel masking	programmable
SiPM fine gain adjustment	**500 mV (5 bits)**
SiPM	up to 320pF term. cap., 2MHz DCR
Calibration BIST	internal gen. pulse, 6-bit prog. amplitude
Power	**$<$ 10 mW per channel**

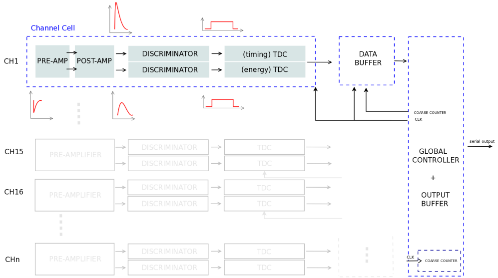
Overview of the chip architecture

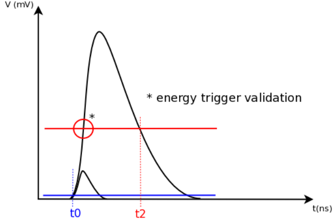
The TOFPET ASIC consists of a 64-channel analogue block, calibration circuitry, Golden-references and Bias generators and a global controller.



- LVDS 10 MHz SPI configuration link and dark count measure
- LVDS up to 640 Mbps data output interface; 8B/10B encoding
- On-chip DACs and reference generators

Overview of the channel architecture



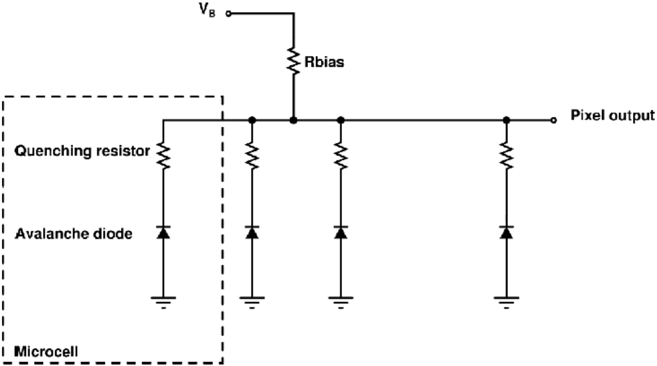


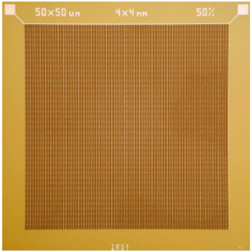
ToT (energy meas) = t2 - t0

- Time and charge measurements with independent TDCs
- Trigger level **0.5 p.e.** with SNR = 25 dB
- Target intrinsic resolution 25 ps r.m.s.
- Charge measured with Time-over-threshold
- Low-power 8-11 mW p/channel
- **Single-Ended Input**

SiPM basic principle

- The aim of Silicon Photon Multiplier (SiPM) is to reproduce in a silicon device the light detecting performance of traditional vacuum based Photo Multiplier Tubes (PMT)
  - Silicon devices are very cheap if produced in large quantities.
  - Good quantum efficiency
  - Compatible with magnetic field.



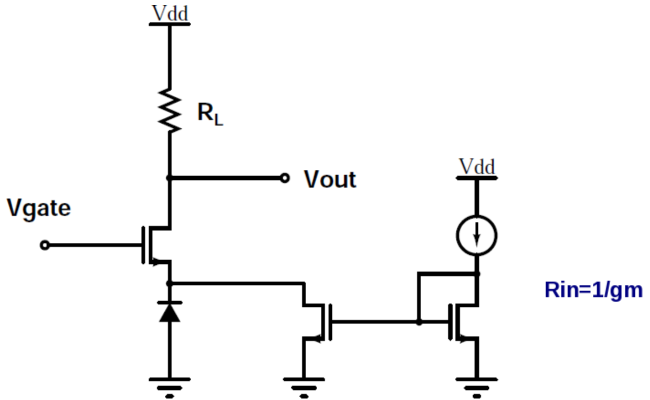


SiPM basic properties

- Typical pixel size from 1mm x 1mm to 3mm x 3 mm
- Each pixels is formed by many independent elements (micro-cells) in parallel
- Each cell is a reverse biased diode biased at the onset of breakdown
- A photon create an electron hole-pair. The electron triggers the break-down
- A very large current starts flowing generating big signals
- The voltage drop across the series resistor brings the voltage across the diode below the break-down point, quenching the avalanche.

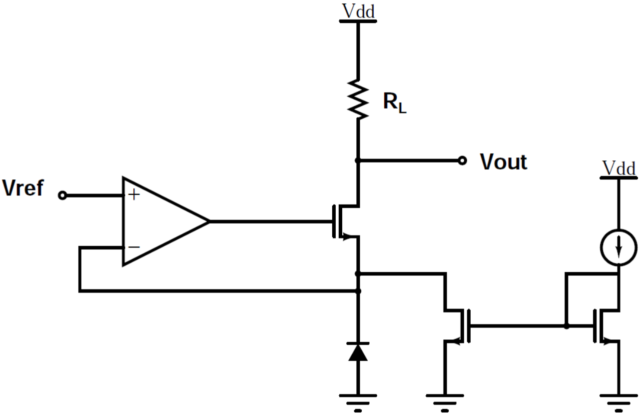
Front-end design for SiPM readout

- aSiPM have very large capacitance, but provide very high signal
- No much amplification is needed, but very good insensitivity to the input capacitance
- Low impedance current buffer is a good choice
- Option 1: standard common gate without feed-back



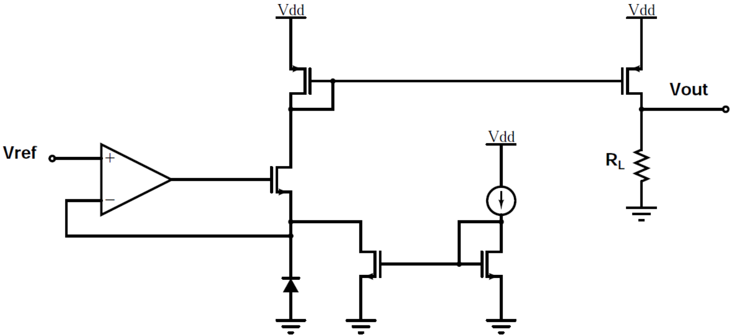
Regulated Common-Gate

- DC input impedance decreased by gain A
- differential loop for adjustment of input DC node voltage
- noise performance independent of Zin trimming
- poor dynamic range

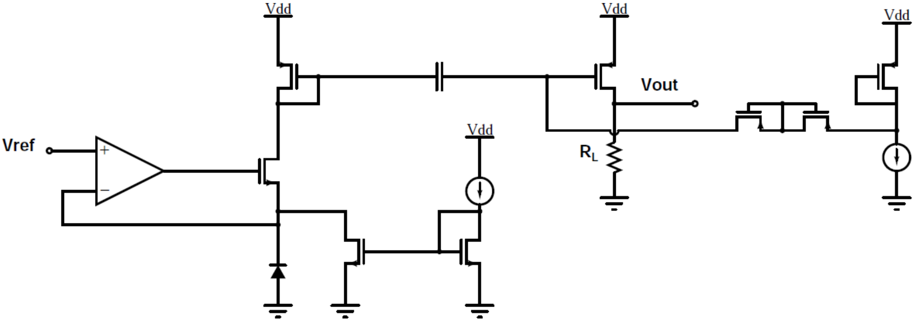


Regulated Common-Gate with CM Load

- no saturation of the input stage
- baseline (input of discriminator) floats with Zin adjustment

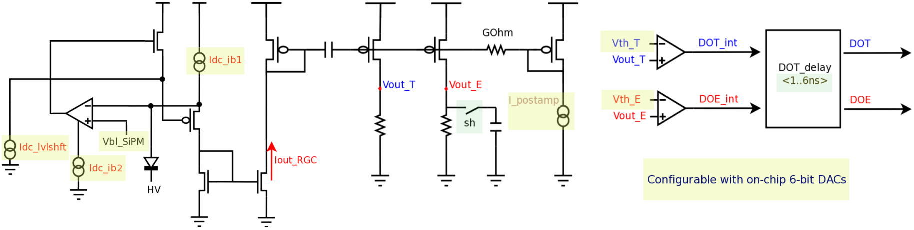


Regulated Common-Gate with CM Load and AC coupling



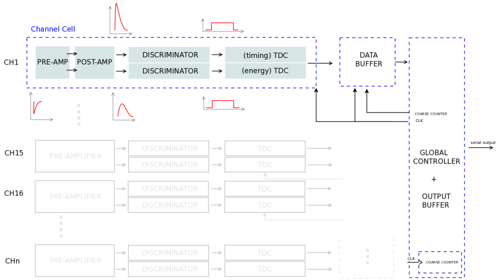
Front-End of the TOFPET ASIC

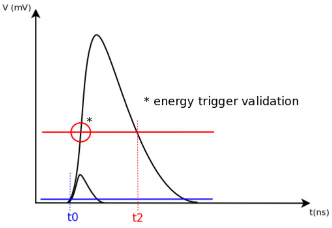
- Low-Zin pre-amplifier, 2 independent TIA branches for Timing and Energy triggers
- Fine adjustment of the HV bias (6-bit over 500mV range) of the SiPM
- Selectable shaping function for Vout_E
- Selectable delay line for dark count filtering
- Usable for p-type or n-type (hole, electron collection) devices



Configurable with on-chip 6-bit DACs

Inputs for TDC





ToT (energy meas) = t2 - t0

- t0: 50 ps time stamp from rising edge of DOT
- t2 : 50 ps time stamp from falling edge of DOE

Time-to-digital Conversion

Simpler approach: count the cycles of a reference clock of the measurement interval. Need more accuracy? Increase clock frequency. Reasonable? :

- power budget..
- feasibility. Maximum frequency around 5GHz for deep sub-micron CMOS (max 200ps accuracy).

- **Digital-based TDCs**
  The clock is asynchronously subdivided (reference clock interpolation). Multiple phases of CLK are obtained with a chain of delay elements (susceptible to PVT variations) or a DLL.
- **Analogue-based TDCs**
  An analogue integrator perfoms time-to-voltage conversion, which can be then digitized by an ADC. The minimum resolving time Δ_t is dependent on the maximum time to be measured (**DR**) and the number of bits (**N**) of the ADC.
  $DR = 2^N \cdot \Delta_t$

↪ Analogue interpolation seems to be more suitable for low power, compared to the more power-hungry DLL-based TDCs.

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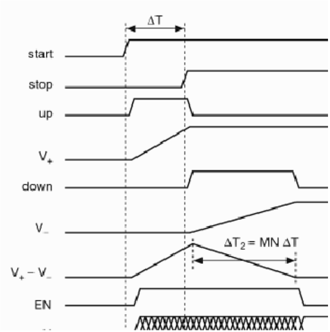
Analogue-based TDC

For short measurement intervals, the analogue integrator can be devised with a current source charging a capacitor during the measurement interval (extensive calibration is needed, non-linearity due to finite Z_{out} of the current source, ..)
Possible way out? A dual-slope analog-to-time interpolation:



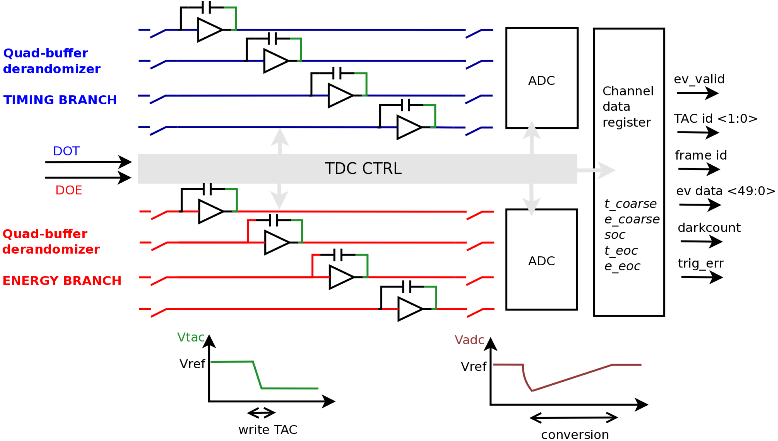
from: Stephan Henzler "Time-to-Digital Converters"
Springer series in advanced microelectronics , 2010

- A ramp is charged by an integration constant τ_k, and discharged with τ_k/n
- DR is multiplied by $n+1$: "time amplification"
- Hence, time resolution can be enhanced just by increasing n
- Digitally-assisted analogue blocks to finely calibrate the time binning

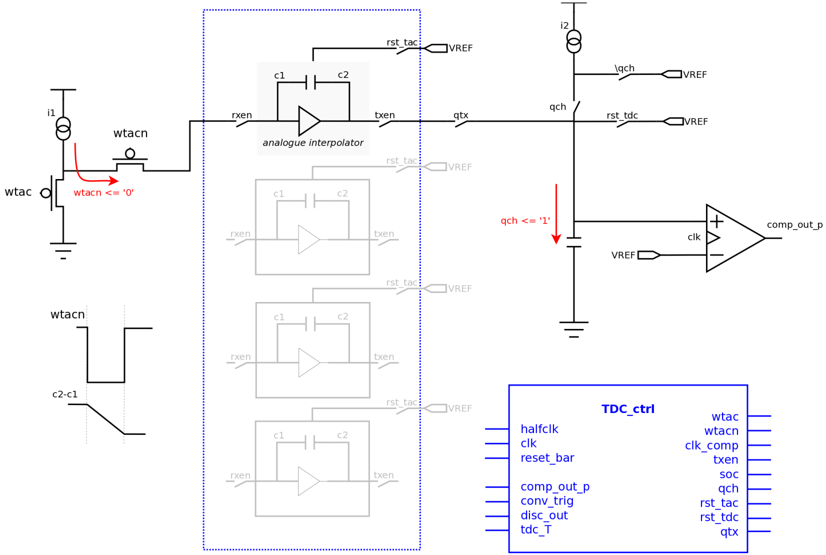
Time-to-Digital Converter

Analogue TDC with 25ps/50ps time binning - based on Analogue Interpolators [Stevens89, Rivetti09]

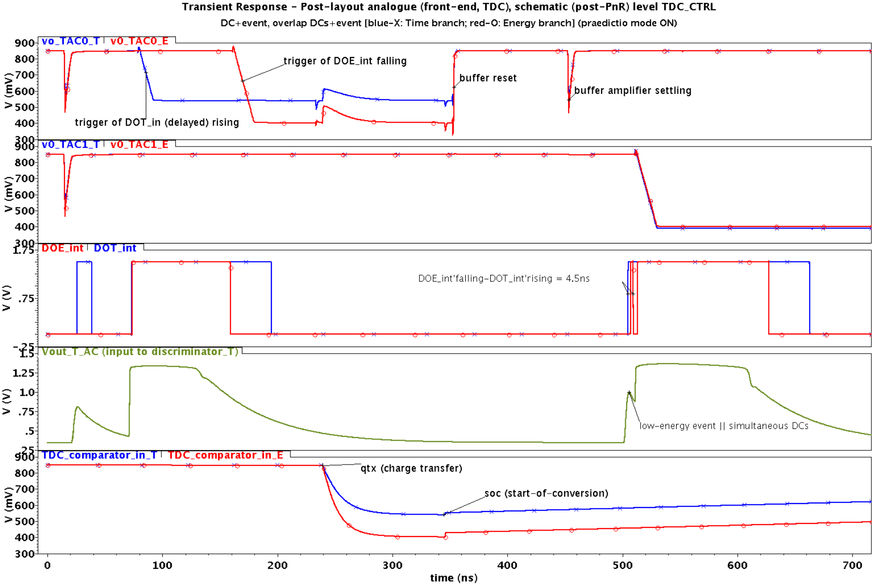
- TDC Control: switching, hit validation, buffer allocation, data reg.
- Time stamp: 10-bit master clock count + Fine time measurement



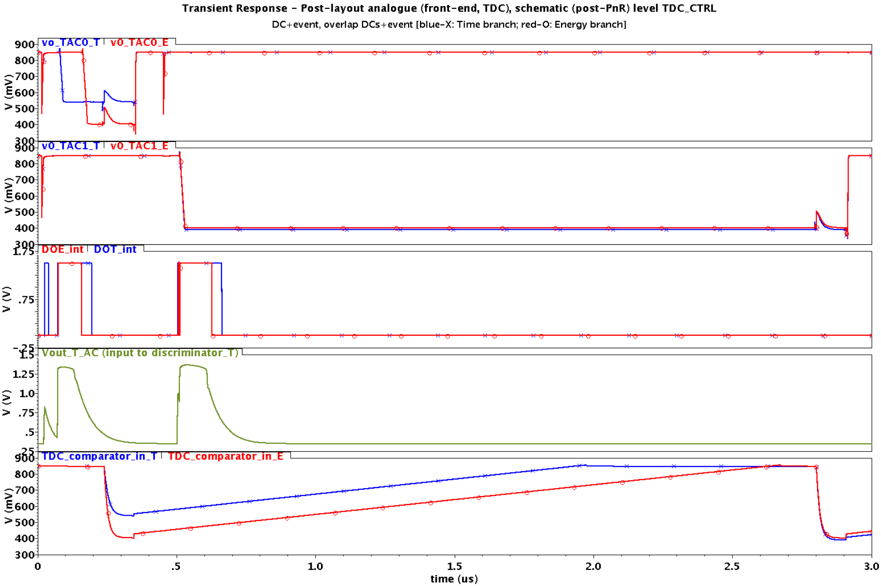
TDC overview



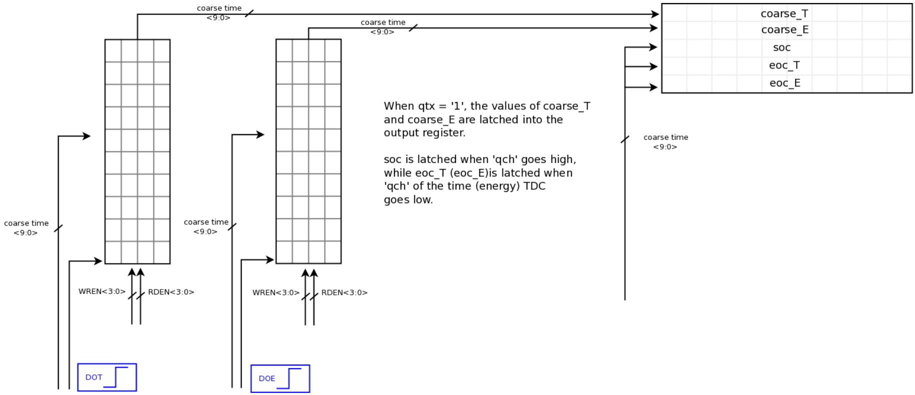
TDC conversion - simulation (Trigger and SoC)



TDC conversion - simulation (2 events)



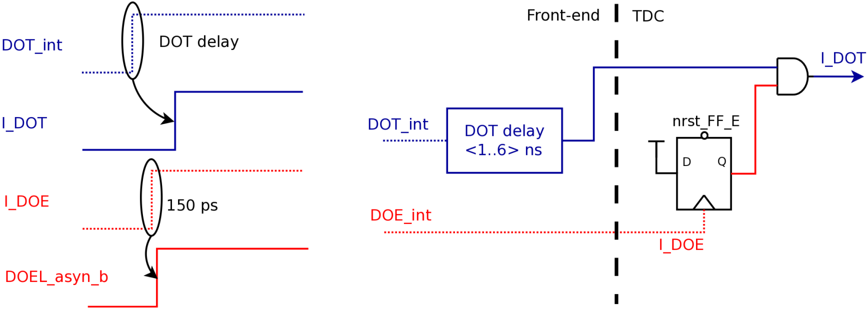
Register Bank



When qtx = '1', the values of coarse_T and coarse_E are latched into the output register.

soc is latched when 'qch' goes high, while eoc_T (eoc_E)is latched when 'qch' of the time (energy) TDC goes low.

Operation with SiPMs - Rejection of dark pulses

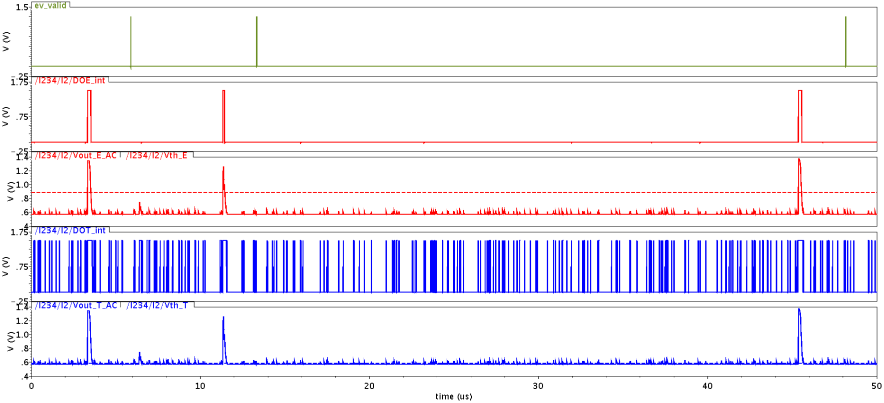


Filtering of spurious pulses: TDC is not triggered

- Quiet operation mode: limited TDC CTRL switching, TAC re-assignment,...
- Critically dependent on the quality of the power supply (main contributor for the delay line jitter)
- Synchronous validation schemes are implemented as backup.

Geant generated SiPM+LYSO data

Simulation of the whole channel (TDC CTRL simulated at transistor level); input is a test vector with data generated from Geant routines[1].



Transient Response (Spectre APS), praedictio mode -- 10 ps input data step

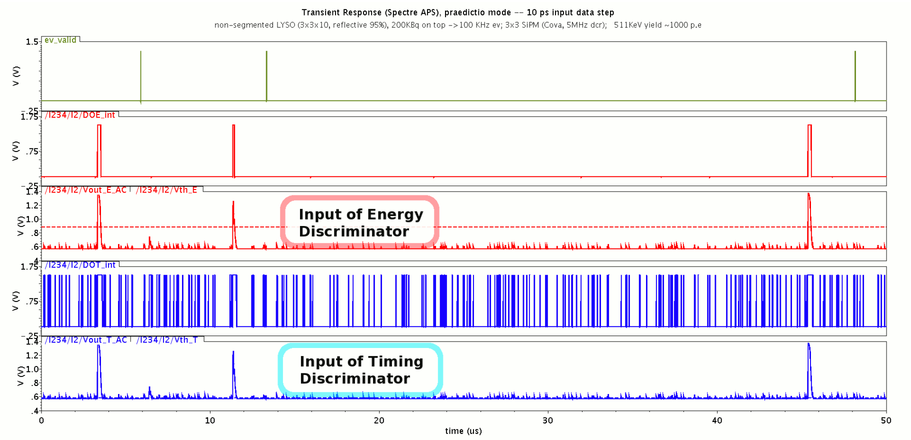
non-segmented LYSO (3x3x10, reflective 95%), 200KBq on top ->100 KHz ev; 3x3 SiPM (Cova, 5MHz dcr); 511KeV yield ~1000 p.e

---

[1] acknowledgment to F. Pennazio, INFN Torino

Geant generated SiPM+LYSO data

Simulation of the whole channel (TDC CTRL simulated at transistor level); input is a test vector with data generated from Geant routines[1].



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[1] acknowledgment to F. Pennazio, INFN Torino

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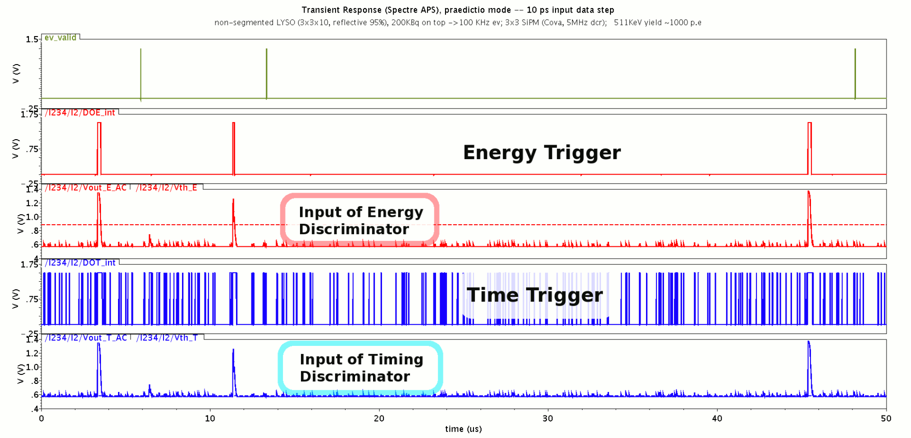
Simulation of the whole channel (TDC CTRL simulated at transistor level); input is a test vector with data generated from Geant routines[1].



Transient Response (Spectre APS), praedictio mode -- 10 ps input data step

non-segmented LYSO (3x3x10, reflective 95%), 200KBq on top ->100 KHz ev; 3x3 SiPM (Cova, 5MHz dcr); 511KeV yield ~1000 p.e

Energy Trigger

Input of Energy Discriminator

Time Trigger

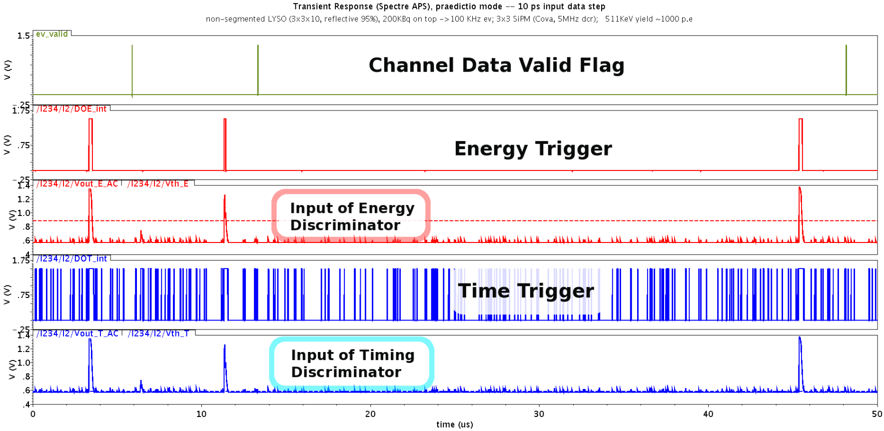
Input of Timing Discriminator

---

[1] acknowledgment to F. Pennazio, INFN Torino

Geant generated SiPM+LYSO data

Simulation of the whole channel (TDC CTRL simulated at transistor level); input is a test vector with data generated from Geant routines[1].



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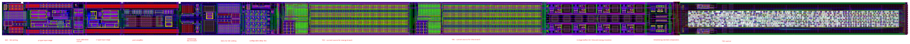
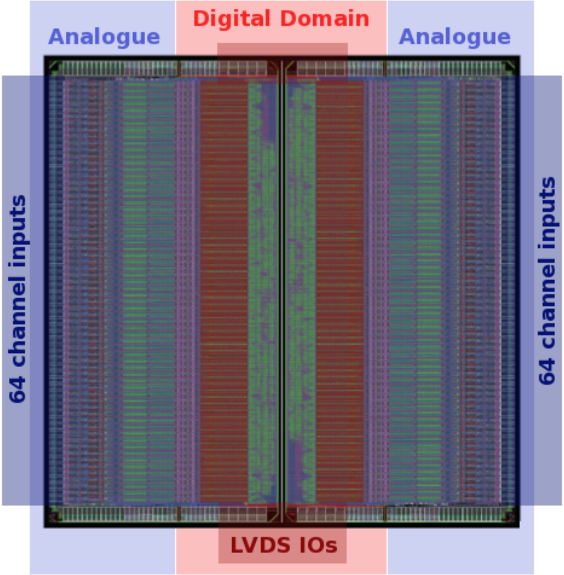
[1] acknowledgment to F. Pennazio, INFN Torino

Channel Layout

- 64 channels, form factor 0.1 x 2.5 mm
- Each channel comprises:
    - front end 2-polarities
    - local calibration circuitry
    - discriminators for timing, energy
    - DACs for input DC setting, thresholds
    - delay line for DCR filtering
    - TDC-analogue: current sources, TACs, wilkinson ADC and latched comparator
    - TDC-digital: sequence control, buffer assignment, 50-bit register, interface with back-end



128-channel System-in-a-Package



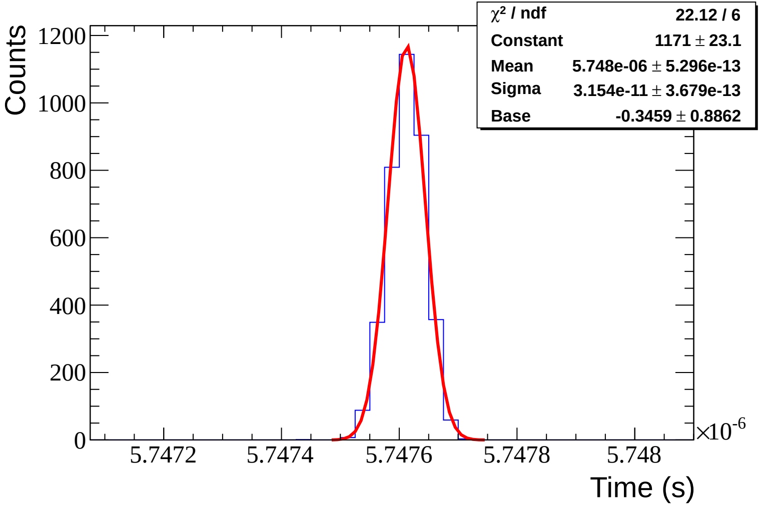
to be continued...

- one-shot submission (prototype, system chip) with CERN engineering run (June 2012)
- chips received February 2013
- 2 independent test setups (Torino, Lisboa)
- characterization results next Thursday

Multi-Photon Time Resolution

- Laser: no optical attenuator ($N_{ph} > 1000$)

↪ 32 ps r.m.s., includes jitter from the laser and the test pulse



EndoTOFPET-US FP7: Endoscopic PET and Ultrasound

Combined TOF-PET (200 ps time resolution), ultrasound imaging and endoscopic biopsy

PET components:
- dSiPM/crystal endoscopic probe
- aSiPM/crystal external plate

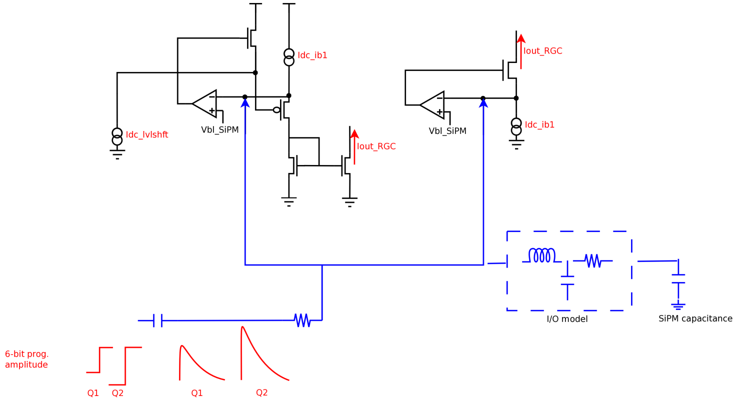
© DESY / Stuhrmann

ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

Thank you!

backup slides

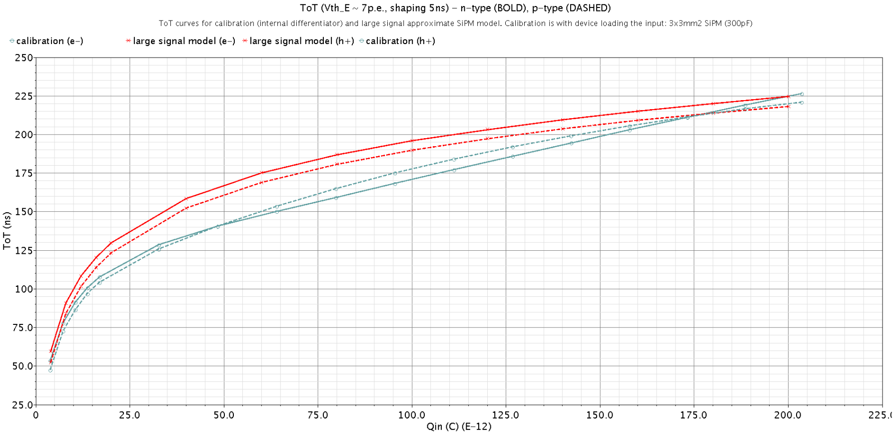
Calibration mechanism



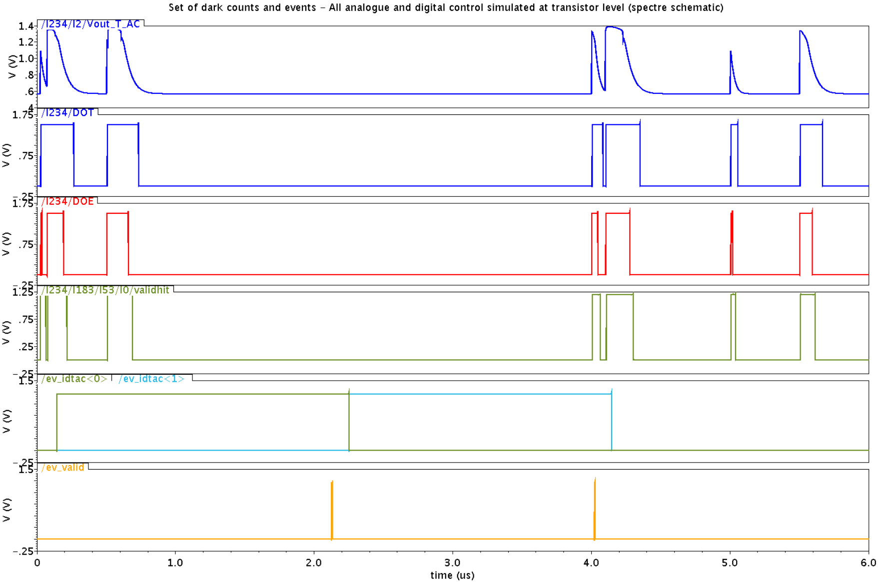
A 6-bit global DAC (current-mode, 20mA conso.) generates a variable amplitude (positive, negative) test pulse, from which an exponential decay is obtained with an RC differentiator.

The calibration is done with the SiPM at the input.

Time-over-Threshold: internal calibration generator vs. spectre ideal current source



TDC data output - simulation: valid event



References

[Stevens89] Andrew E. Stevens, Richard P. Van Berg, Jan Van Der Spiegel and Hugh H. Williams
A Time-to-Voltage Converter and Analog Memory for Colliding Beam Detectors
IEEE JSSC vol 24, no 6, 1989

[Rivetti09] A. Rivetti et al.
Experimental Results from a Pixel Front-End for the NA62 Experiment with on Pixel Constant Fraction Discriminator and 100 ps Time to Digital Converter
NSS MIC Conf. Records 2009