Front-end Electronics for Nuclear Physics

Riccardo Introzzi

by Physics Department - INFN PoliTO

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Signals in Nuclear Physics

1. Detector Overview
    - Particle Detectors
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    - Detector Examples

Signal Aquisition

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2. Signal Acquisition
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   - DAQ
   - Basic Front-end
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4. Fast Transient Acquisition
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Fast Circuits for Data Acquisition

5. Fast Signal Acquisition
6. Shaper
   - Pulse integrator
   - PD
   - PHA
7. Discriminator
   - CFD
8. Time Measurement
   - TAC
   - TDC
   - Mean Timer

Fast Circuits for Data Acquisition

5 Fast Signal Acquisition

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Part I

Signals in Particle Physics

Detector Types (1)

Ionizing radiation detectors:

- Gas chambers
  - Ionization chambers
  - Proportional Counters - HV: charge multiplication, (1 keV, 100 keV)
  - Geiger Counters - fixed-size pulses: no energy information
- Scintillators with Photo Multiplier Tubes (PMT)
  - NaI(Tl) - 6% energy resolution, (10 keV, 10 GeV), 1 μs pulses
  - Plastic - poorer resolution, 10 ns pulses
  - Liquid 'cocktails' - mixed with radioisotopes
- Solid State detectors - @ 77 K
  - Si(Li) - (1 keV, 50 keV), 2.5% energy resolution
  - Ge(Li) - (10 keV, 10 MeV), 0.14% energy resolution
  - High Purity Germanium Detectors (HPGe) - Intrinsic semiconductor

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Detector Types (2)

Charged particle detectors:

- Surface-barrier detectors - @ 300 K, (1 Mev, 100 MeV), 0.2% energy resolution
  - Si(Li)
  - Ge(Li)
- Cherenkov detectors - Cherenkov 'light boom', above 1 GeV
- Ionization chambers - Ar, single or multi wire or plate electrodes
- Shower chambers - liquid Ar, 'calorimeters'
- Scintillators with UV PMT - gas or liquid, very fast
  - Ar
  - Xe
- Drift chambers - gas volume criss-crossed by wire arrays with applied voltage to drift out ions and track particle paths
  - Ar-ethane mixture - 0.2 mm spatial resolution

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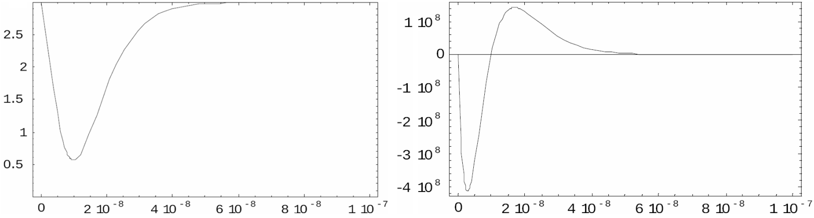
Pulse Shape 1

In general a detection event causes a current burst

- fast voltage ramp (usually negative)
- slower exponential-like decay (∼5 ns)

Anode voltage [V] pulse in a PMT vs time [s]



Pulse Shape 2

Quantity of interest may be related to

- collected charge number (e.g. energy spectroscopy in ionization chambers)
  - the integral of the pulse signal has to be derived
- maximum pulse voltage (e.g. energy spectroscopy in scintillators)
  - the maximum of voltage peak must be found
- pulse timing (e.g. Time of Flight (TOF) in Scintillators)
  - a characteristic time of the pulse shaping is needed
- detection of spatial position/s (e.g. drift chambers, TOF-walls)
  - many different channels are necessary and/or timing post-processing
- trajectory (e.g. particle recognition in drift chambers with magnetic field)
  - trajectory bending: $R = p/(ZeB)$
  - heavy post-processing from multi-channel signals is required

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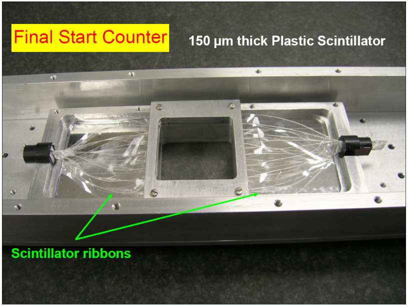
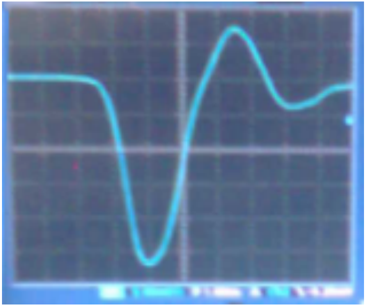
Detector Examples 1

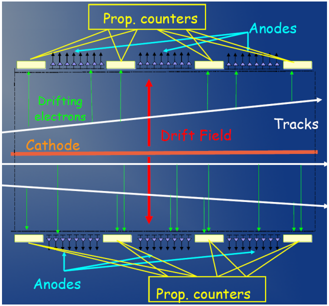
- Trigger detector based on a scintillator
  - The START pulse resolution is O(300 ps), with long tails

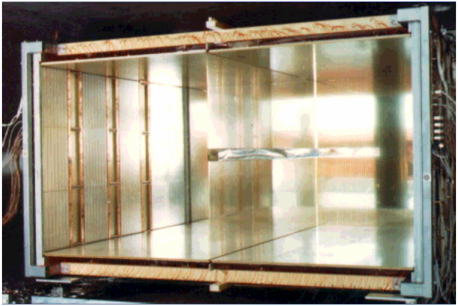




Detector Examples

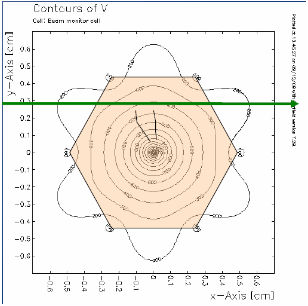
- Ionization Chamber

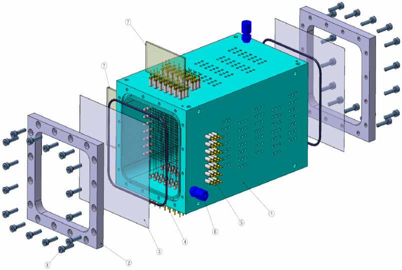




Detector Examples

- Drift Chamber (very small one)
    - Hexagonal cell: 0.5 cm radius
    - Spatial resolution O(100-200) μm





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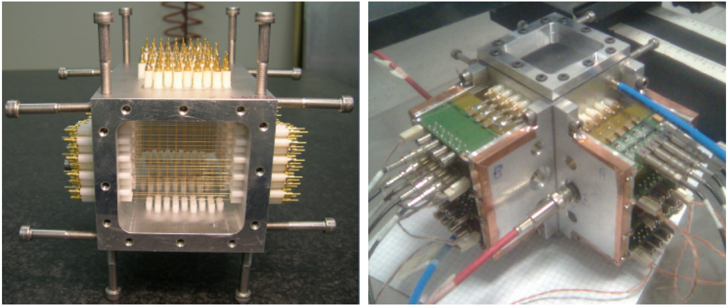
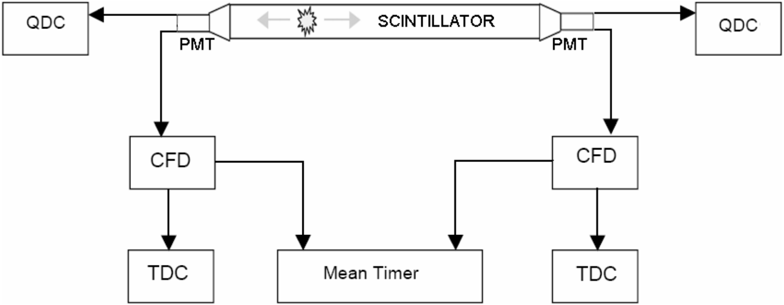


Detector Examples

- TOF-wall
  - based on plastic scintillator
  - slabs are 1.10 m long, 2.5cm wide and 1 cm thick with a PMT at each edge



Detector Examples

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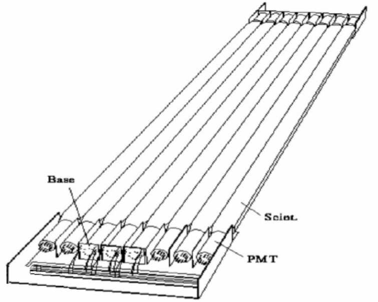
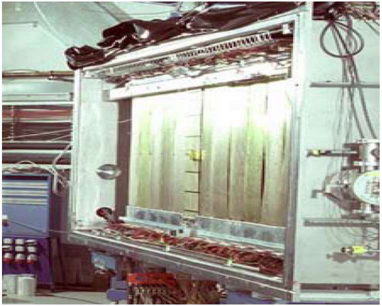


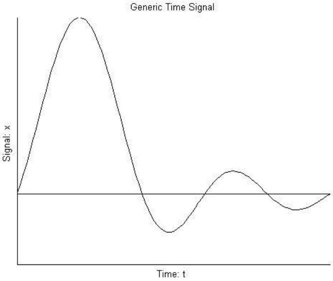


Part II

Signal Acquisition

Nyquist Theorem

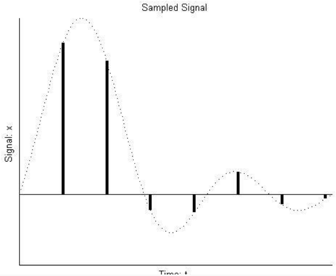
- Consider a generic time signal $x(t)$ which has to be sampled



Nyquist Theorem

- The sampled signal can be built multiplying by a δ comb T spaced in time
  - T is the sampling period

$$\begin{aligned} x_\delta(t) &= \sum_{i=-\infty}^{+\infty} T x(iT)\delta(t-iT) \\ &= x(t)T\sum_{i=-\infty}^{+\infty}\delta(t-iT) \end{aligned}$$



Nyquist Theorem

- Define $\Delta(f)$ as the Fourier transform of the time δ comb
  - the spectrum of a time δ comb is a frequency δ comb
  - $f_s = 1/T$ be the sampling frequency

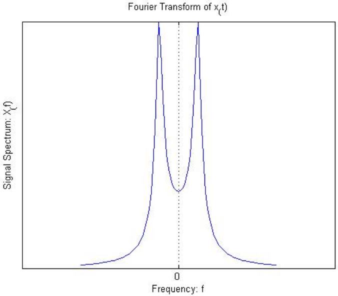
$$\begin{aligned}\Delta(f) &= \mathscr{F}\left[T\sum_{i=-\infty}^{+\infty}\delta(t-iT)\right]\\ &= \sum_{i=-\infty}^{+\infty}\delta(f-if_s)\end{aligned}$$

- Recall the Fourier transform of the product of two functions: convolution product ($\star$) of the respective spectra

$$\begin{aligned}\mathscr{F}[z(t)y(t)] &= \int_{-\infty}^{+\infty}X(a)Y(f-a)\mathrm{d}a\\ &= X(f)\star Y(f)\end{aligned}$$

Nyquist Theorem

- $X(f)$ be the Fourier transform of $x(t)$



Nyquist Theorem

- $X_\delta(f)$ be the Fourier transform of $x_\delta(t)$
- $X_\delta(f)$ is the convolution product of $X(f)$ and $\Delta(f)$

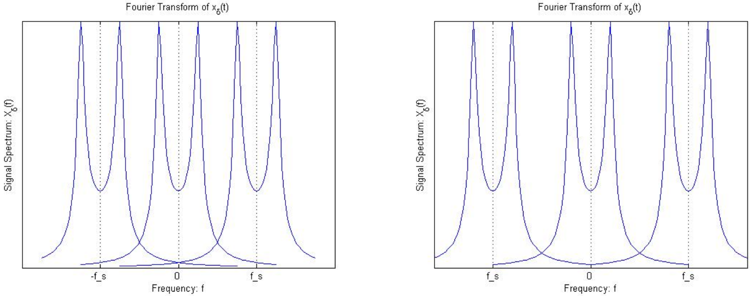
$$\begin{aligned} X_\delta(t) &= X(f) \star \Delta(f) \\ &= \sum_{i=-\infty}^{+\infty} X(f - i f_s) \end{aligned}$$

- The spectrum $X_\delta(f)$ of the sampled signal is the sum of infinite replicas of the spectrum $X(f)$ of the original signal shifted f_s away one from each other

Nyquist Theorem

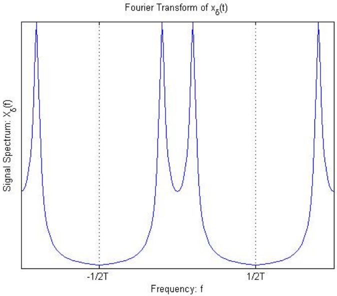
- The Nyquist rule grants the tails of successive replicas do not overlap
  - given the bandwidth extension B of the original spectrum and the sampling frequency f_s

$$f_s \geq 2B$$



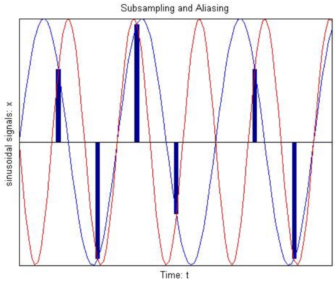
Nyquist Theorem

- Low-pass filtering the base band replica the original signal can be reconstructed
- the task is ideally performed by the Nyquist interpolator: a rectangular low-pass filter
  - the Nyquist pass-band coincides with the bandwidth B of the original signal



Aliasing and Sub-sampling

- Aliasing is give by the spectrum replica tail overlapping: different harmonic lines of the original spectrum are indistinguishable
- It is evident when a given harmonic line is focused
  - in the example a 3 kHz sinusoid, sampled @ 8 kHz, shows ambiguity with a 2 kHz sinusoid



Data Acquisition System

Analog-digital conversion involves two discretization processes:

1. sampling
   - continuous time → discrete time
   - non perfect low-pass filtering for anti-aliasing
   - approximation by real interpolators (real low-pass filter, HW/SW)
2. discretization
   - continuous amplitude → discrete amplitude
   - approximation given by the Least Significant Bit (LSB)

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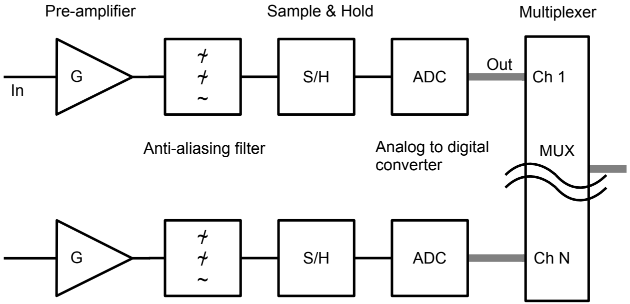
Basic Front-end

- Pre-amplifier
- Anti-aliasing filter
- Sample & Hold (S/H)
- Analog to Digital Converter (ADC)
- Multiplexer (MUX)



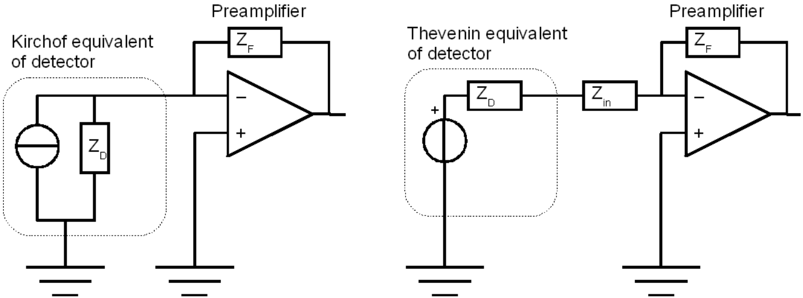
Pre-amplifier

Features:

- first stage amplification:
  - maximizes Signal to Noise Ratio (SNR)
  - adapts voltage levels to the next measurement stage
- low output impedance, considerable current drive
  - buffers the input signal
  - sinks interference current injection: preserve SNR
- OpAmp configuration with SW-tunable feedback are common
  - differential input stage: common mode interference rejection
  - issues on bandwidth, stability and slew-rate require careful design
- pulse current integration is possible with capacitive feedback
  - charge summation is converted to voltage amplitude
  - drift due to input offset currents must be avoided

Trans-impedance and Voltage amplifiers

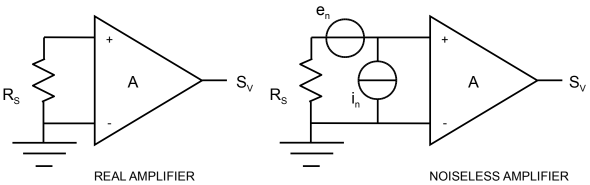
1. trans-impedance amplifier for high source impedance
2. voltage amplifier for low source impedance



Signal and Noise

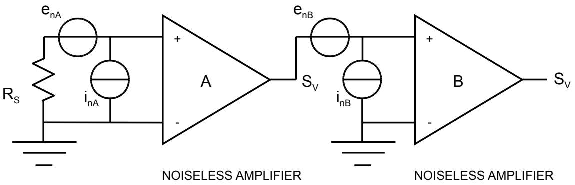
Detectors usually provide very low-level output signals

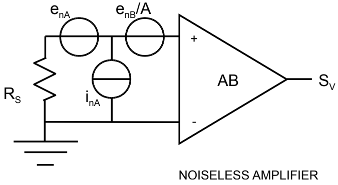
- many source of noise and disturbance can overrun the signal
- careful design is needed especially for the first stage



Signal and Noise

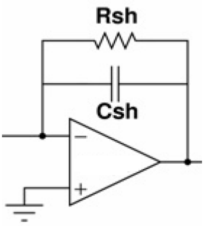
- First stage equivalent noise remains at the input of the chain
- second stage contributes at the input only with its voltage equivalent noise, divided by the first stage gain





Anti-aliasing Filter

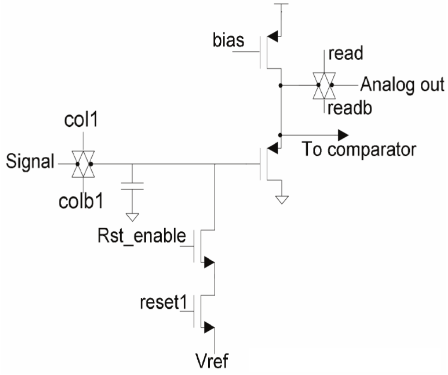
- Low-pass filters are used to avoid aliasing effects
- filters can be implemented in amplifier feedback
- high order filters would be required to take advantage of the full ADC bandwidth
  - trade-off between high slope frequency cutoff and filter size and complexity
  - single pole feedback and OpAmp poles are exploited



Sample & Hold

Fast signals are sampled and then hold during A/D conversion time

- Capacitors as analog memory
  - droop issue: charge/discharge due to read-out I_off
- CMOS Transmission gates as switching elements
  - signal feed-through issue: via C_{DS} of the switch

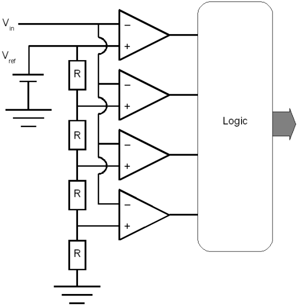


Analog To Digital Converter (ADC)

- A/D Flash
- Successive Approximations Register (SAR)
- Double ramp A/D
- Source Follower Residue Amplification

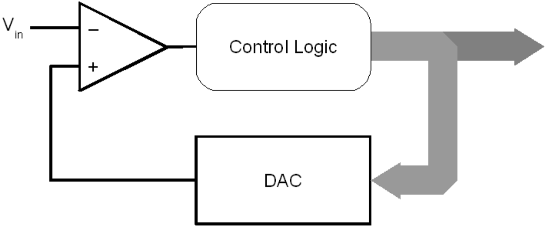
ADFlash

- comparator array (one for each output bit)
- resistive reference scale
    - ratiometric (voltage divider), variable V_{ref}
    - no missing code
    - high precision R needed
    - high power consumption (resistive scale)
- high speed (parallel computation)



SAR ADC

- single comparator
- feedback Digital to Analog Converter (DAC) provide voltage references
- logic controls successive approximations of the input signal
    1. up/down counter strategy
    2. bisection technique



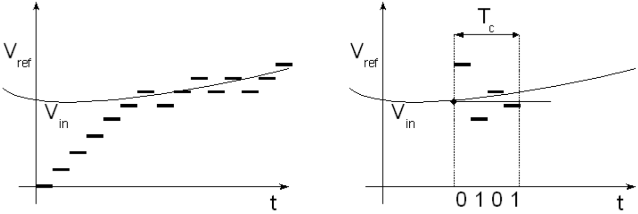
SAR ADC

Up/down counter

- “digital voltage follower”: 1 LSB fluctuation around the input
- long transient at start-up
- single step conversion once the signal is “locked”

Bisection technique

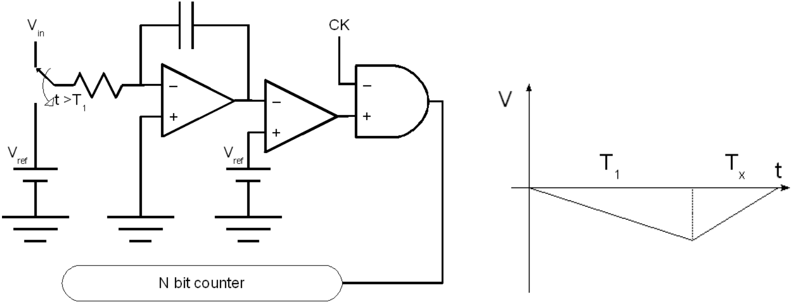
- conversion time: $T_c = N_{bit} T_{ck}$



Double Ramp ADC

Two phases method

- fixed-time integration of input
- known-voltage de-integration till the output nulls
- de-integration time is proportional to input
    - a counter is controlled by comparator output



Source Follower Residue Amplification ADC

State of the art ADC

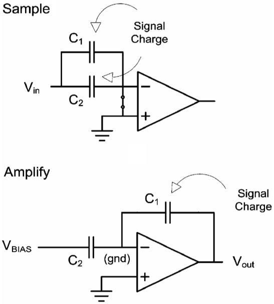
- pipeline of N_{bit} identical stages
- simple working principle:
  - $bit_n = 1 \iff V_{in\ n} - V_{bit_n} > 0$
  - $V_{residue\ n} = V_{in} - V_{bit_n} bit_n$
  - $V_{out\ n} = 2V residue$
- dynamic source follower
- 1 conversion at each pipeline step, just a delay of N_{bit} steps!

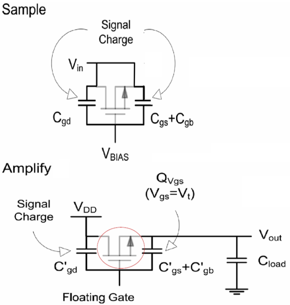
J. Hu, N. Dolev and B. Murmann:
"A 9.4-bit, 50 Ms/s, 1.44 mW Pipelined ADC using Dynamic Source Follower Residue Amplification",
IEEE Journal of Solid State Circuits, **44** 4, 2009

Source Follower Residue Amplification ADC

Residue amplification implementation:

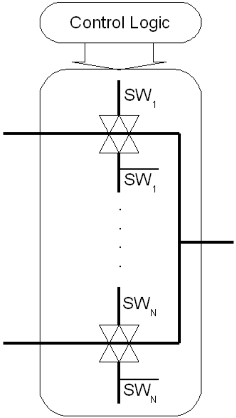
1. OpAmp based
   - cumbersome for power consumption
2. MOS based
   - exploits transistor characteristic capacitances



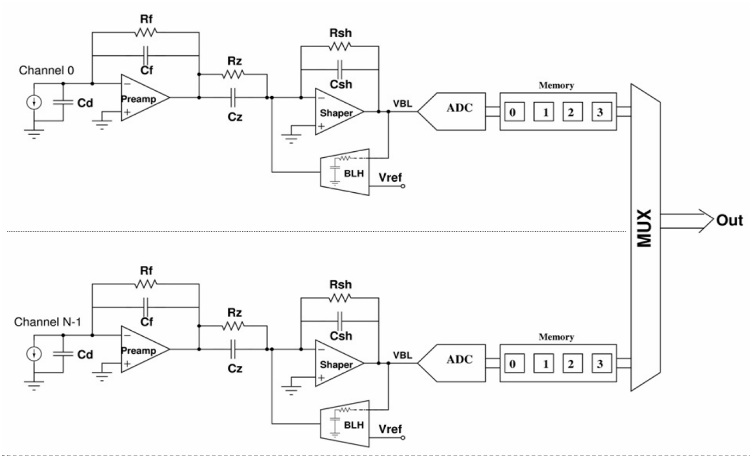


Multiplexer

- Multiplexer (MUX) are switch array controlled by logic
    - transmission gate implementation in analog MUX - bidirectional
    - more switches can be on together (e.g. SAR DAC)

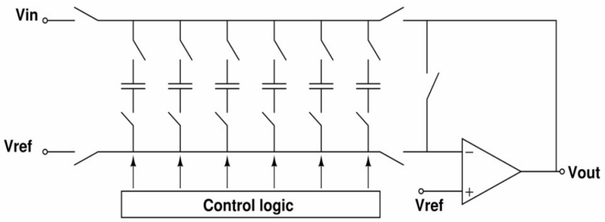


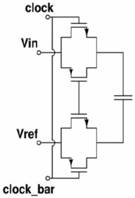
Fast Transient Acquisition



Analog Memory

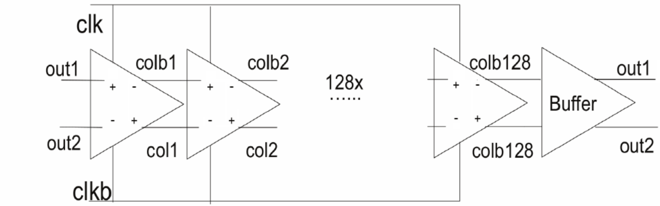
- Analog Memories: array of S/H cells
  - Dead Time → Pipeline





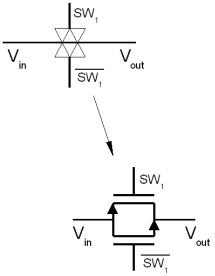
Very Fast Control Logic

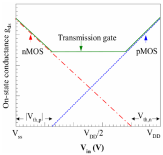
- sampling on both clock edges
- clock multiplication with local Phase Locked Loop (PLL)
- fast shift register with custom Flip/Flop
- delay line: logic gate propagation
    - Clock period variation with temperature

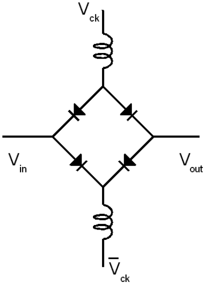


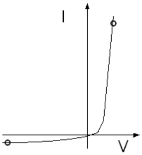
Fast Switches

- CMOS transmission gate - low and constant conductance
- Diode bridge - very fast switching, inductors needed









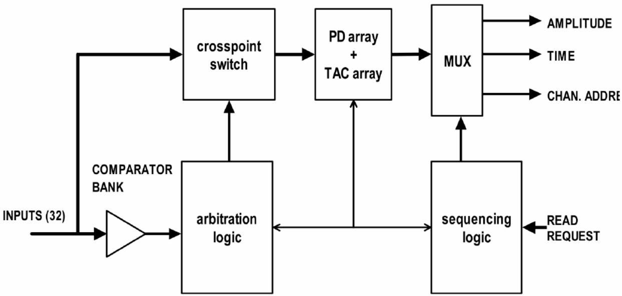
Part III

Fast Data Acquisition

Preliminary Considerations

Full digitization becomes impractical at high data rates (over 100 kHz)
Only quantities of interest are gathered by pre-processing in the analog domain

1. pulse amplitude or area
2. timing detection
3. position detection



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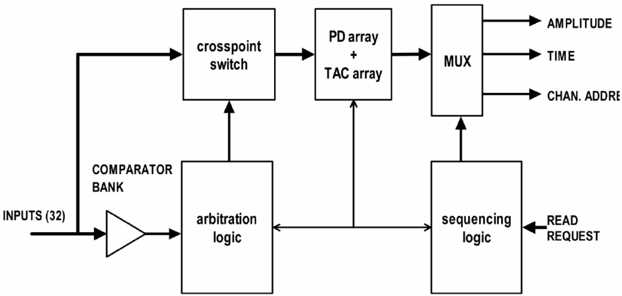

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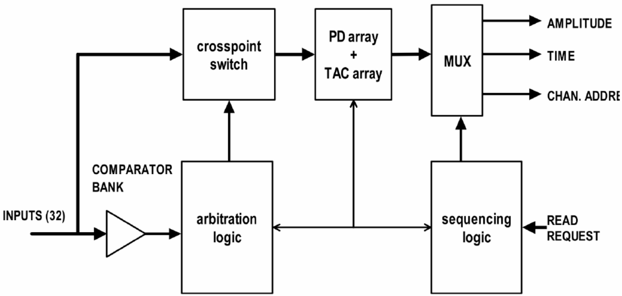

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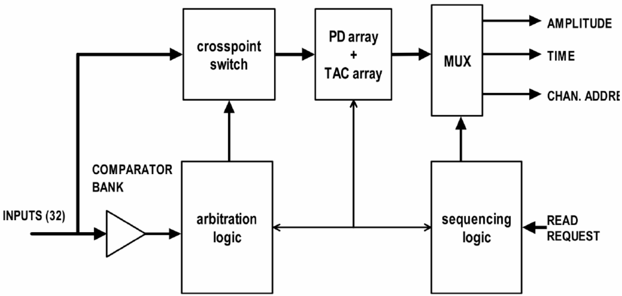
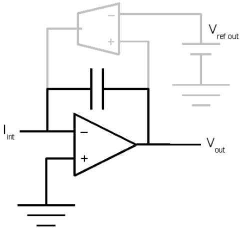


Shaper

- Amplifier: see pre-amplifier in DAQ
- Pulse integrator: provides a signal proportional to the pulse area
    - Proportional Counters are based on integrators as detector read-out
- Pulse detector (PD): outputs the maximum of the peak with a peak detect flag signal
    - Pulse Height Analyzers (PHA) use PDs as detector read-out

Pulse integrator

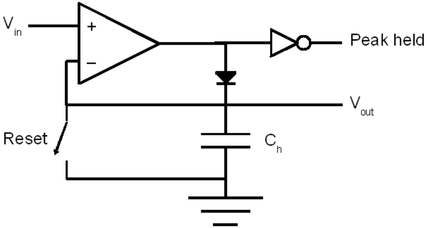
- Exploits a capacitive feedback (i.e. $\mathscr{F}\left[\int .dt\right] = \frac{1}{j\omega C}$)
- OpAmp offset currents can give rise to output drifts
- An Operational Transconductance Amplifier (OTA) controls the DC output - Baseline Holder (BLH)



Peak detector

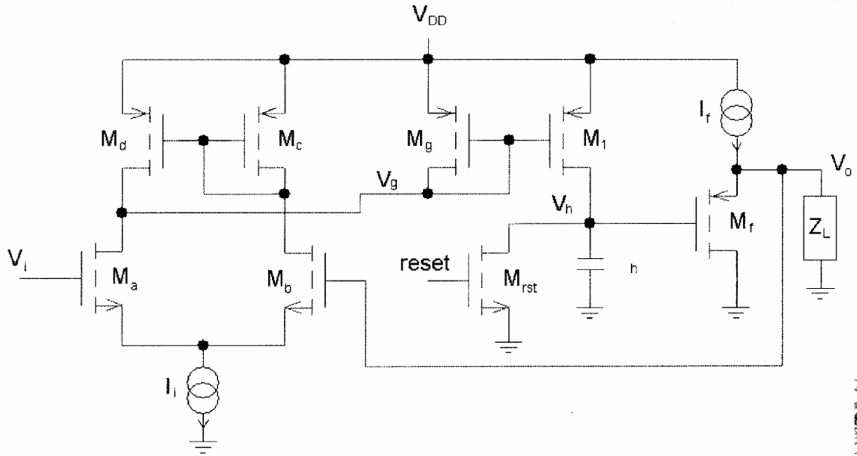
Flags a peak detection and hold the peak maximum

- exploits unidirectional element
- a capacitor is charged up to the peak maximum and then holds the level



Pulse detector

- PDs are simply implemented in CMOS technology

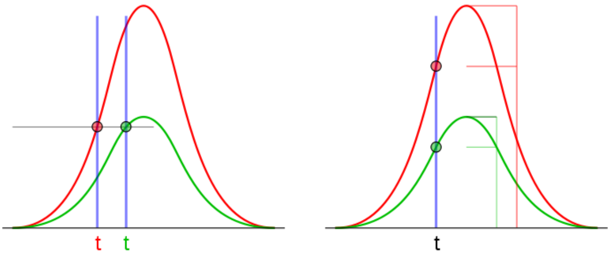


Pulse Height Analyzer

- PDs coupled with ADCs allow to record the pulse height
- Pulse Height Analyzers (PHA) perform energy spettroscopy with a variety of detectors
  (e.g. proportional counters, scintillators, solid state detectors and surface barier detectors)
  - based on a PD-ADC system driving a multichannel scale counter

Discriminator

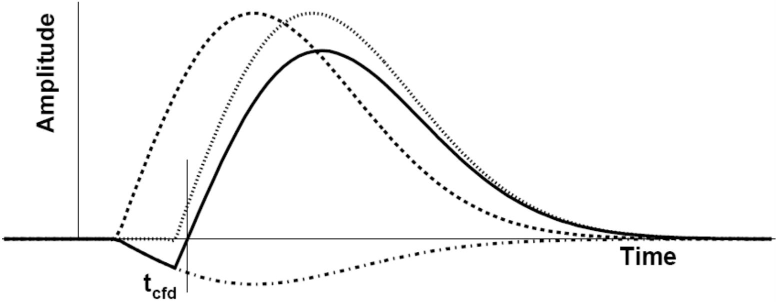
- Often pulses occur with different amplitude and mostly the same shape
- Threshold comparators undergo time-walk errors
- Constant Fraction Discriminator (CFD) allow accurate timing



Constant Fraction Discriminator

Working principle

- split the input in two
- attenuate one
- delay the other
- feed them to a comparator
- the output triggers at a constant fraction of the peak height
  - e.g. 15% for peak rising-edge linearity in scintillator



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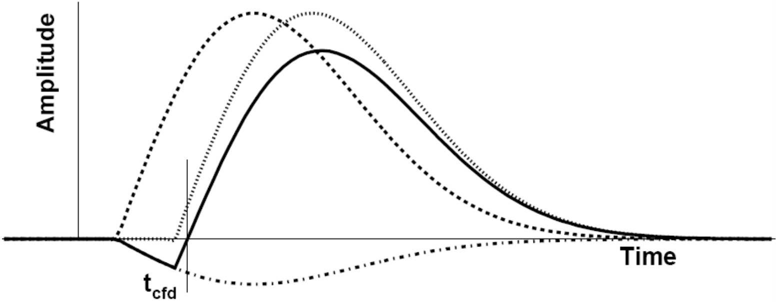

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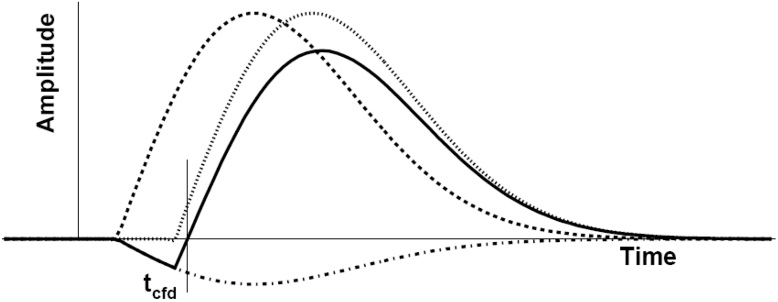

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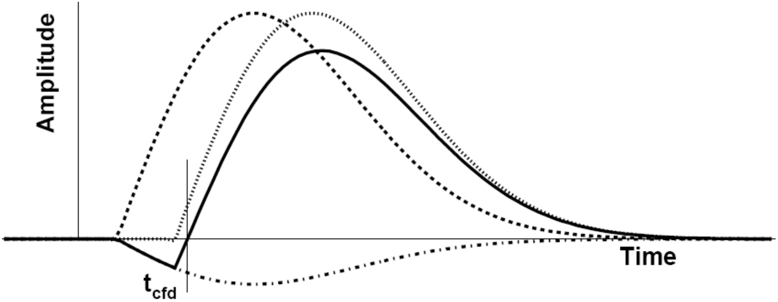

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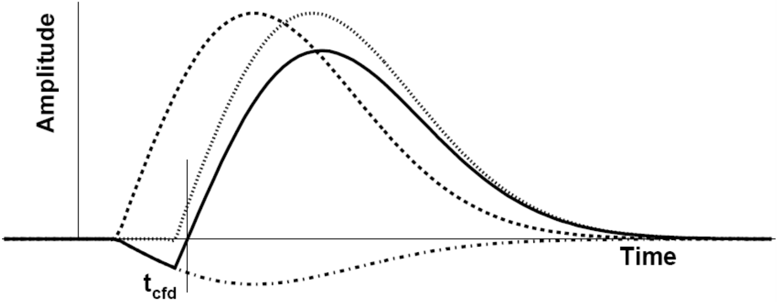
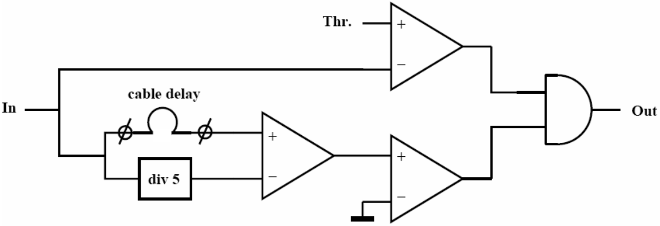


Constant Fraction Discriminator

Refined operation

- when the input is steady the two replicas are at the same level
- the comparator output fluctuates between the high and low logic levels
  - on average it should be midway - useful for calibration
- output enabled by a parallel threshold discriminator in proper conditions



Time Measurement

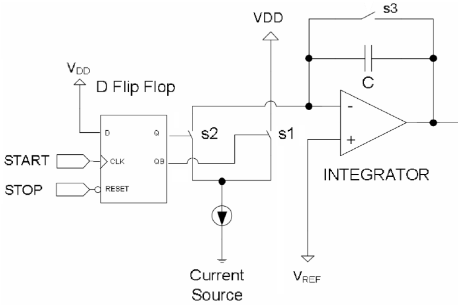
Main functional circuits for time measurement:

- Time to Amplitude Converter (TAC)
- Time to Digital Converter (TDC)
- Mean Timer

Time to Amplitude Converter

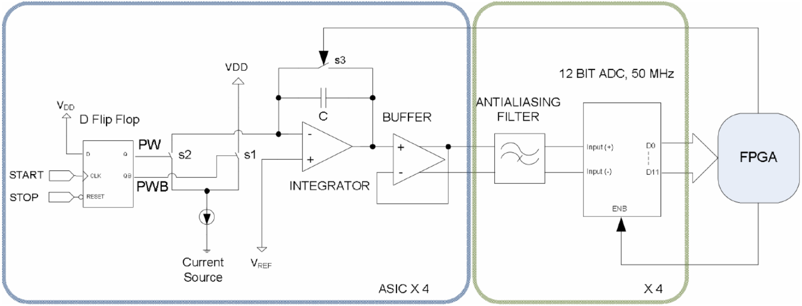
Working principle

- a capacitor is charged at constant current between start and stop edges
- the resulting voltage is proportional to the start-stop interval
- TAC interpolates time between a pulse and a suitable clock edges
- high precision timing with respect to clock edges



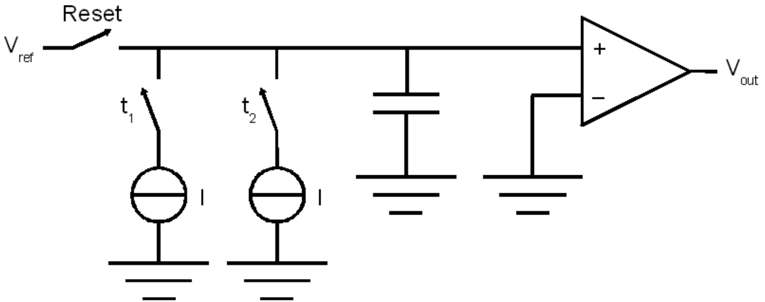
Time to Digital Converter

- A TDC is simply made by coupling a TAC with an ADC



Mean Timer

- Capacitor C is pre-charged at V_{ref}
- each pulse starts a current generator at times t_1 and t_2
- the generators sink a charge $I\Delta t$ from C till the comparator fires



Mean Time

$V_C = 0 \rightarrow \Delta V = V_{ref}$ when the comparator fires

$$\Delta t_1 = t - t_1 \quad \Delta t_2 = t - t_2$$

$$\begin{aligned} -C\Delta V &= I\Delta t_1 + I\Delta t_2 \\ &= I(t - t_1 + t - t_2) \\ &= I\left(2t - (t_1 + t_2)\right) \end{aligned}$$

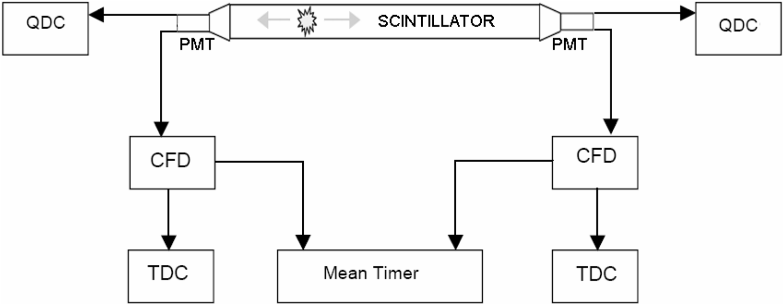
$$-\frac{C\Delta V}{I} = 2t - t_1 - t_2$$

- the output is fired at a time t given by the mean time of t_1 and t_2 plus a constant delay

$$t = \frac{t_1 + t_2}{2} + \frac{C|\Delta V|}{2I}$$

Detector Examples

- TOF-wall element



Conclusions

Radiation Physycs front-end electronics

- highly demanding requirements of fast analog processing
- most solutions are as simple as possible but smart!
- a number of functional blocks available for several detector types
- the ultimate speed performance limits are technology related (e.g. CMOS, parassitic elements, ...)
- what comes next to front-ends: a Huge data trasmission and processing task!

THE END

Thanks for your attention