Experimental Techiques in Particle Physics

Electronics for Radiation Detection

Lecture 9, 2020-12-22

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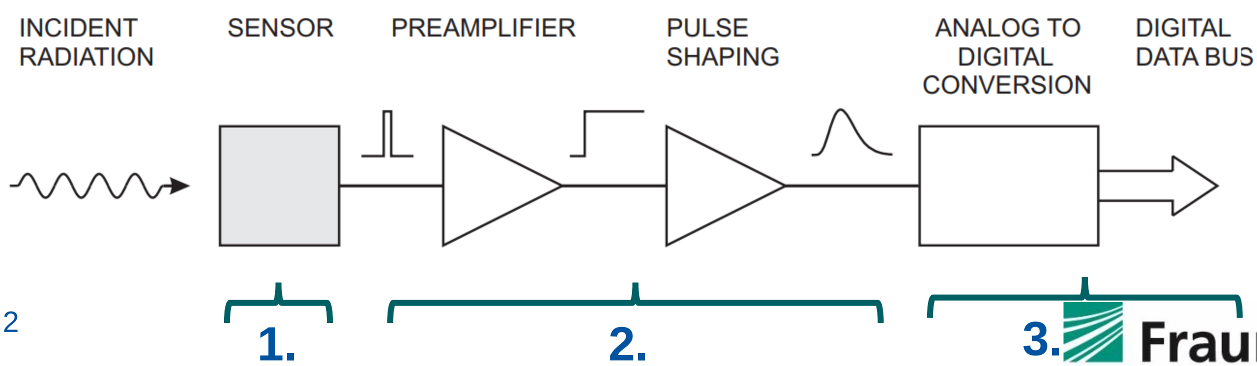
Fraunhofer INT

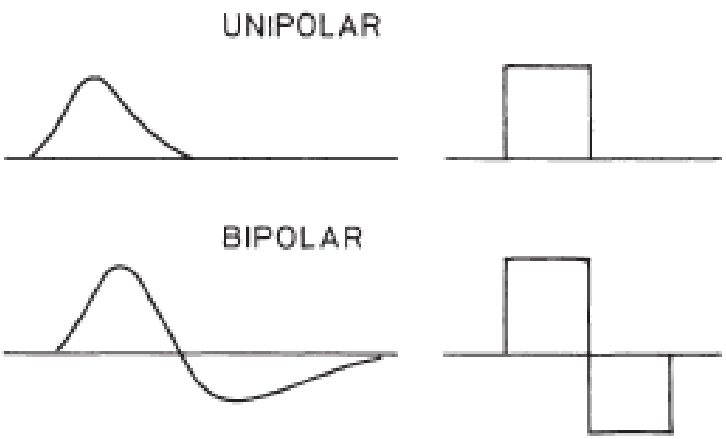
Electronics for Detector systems

The purpose of front-end electronics and signal processing is to

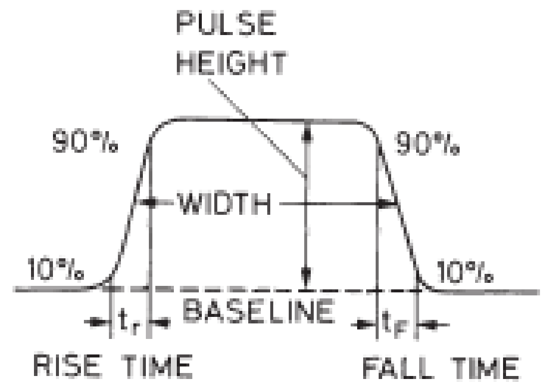
1. Acquire an electrical signal from the detector (this typically a short current pulse)
2. Tailor the response of the system to optimize
    1. The minimum detectable signal (detect „hit“ vs. „no hit“)
    2. Energy measurement
    3. Event rate
    4. Time of arrival
    5. Insensitivity to detector pulse shape
    6. Or combinations of the above
3. Digitize the signal and store for subsequent analysis



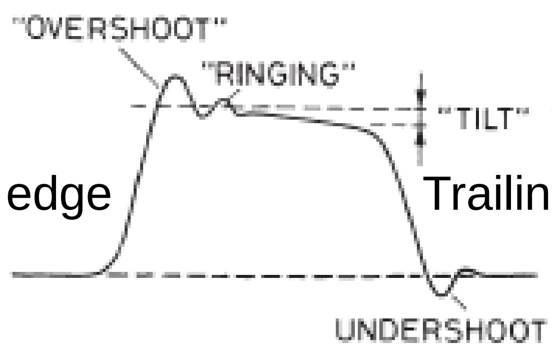
Pulse-Forms and Terminology



<u>Caution:</u>
Some define the timespan from 20 to 80 % for rise and fall time!



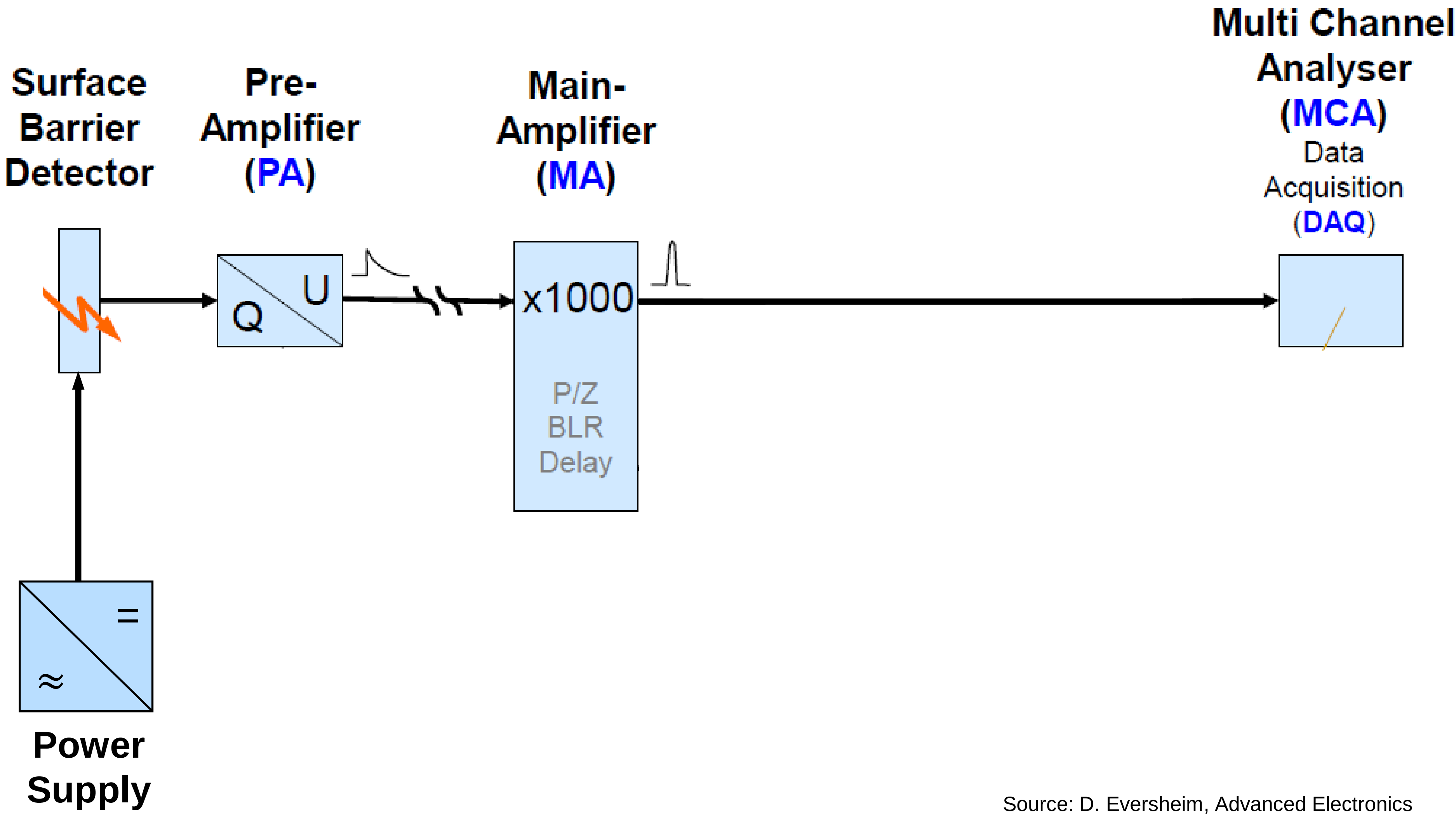
Rising edge



Trailing edge

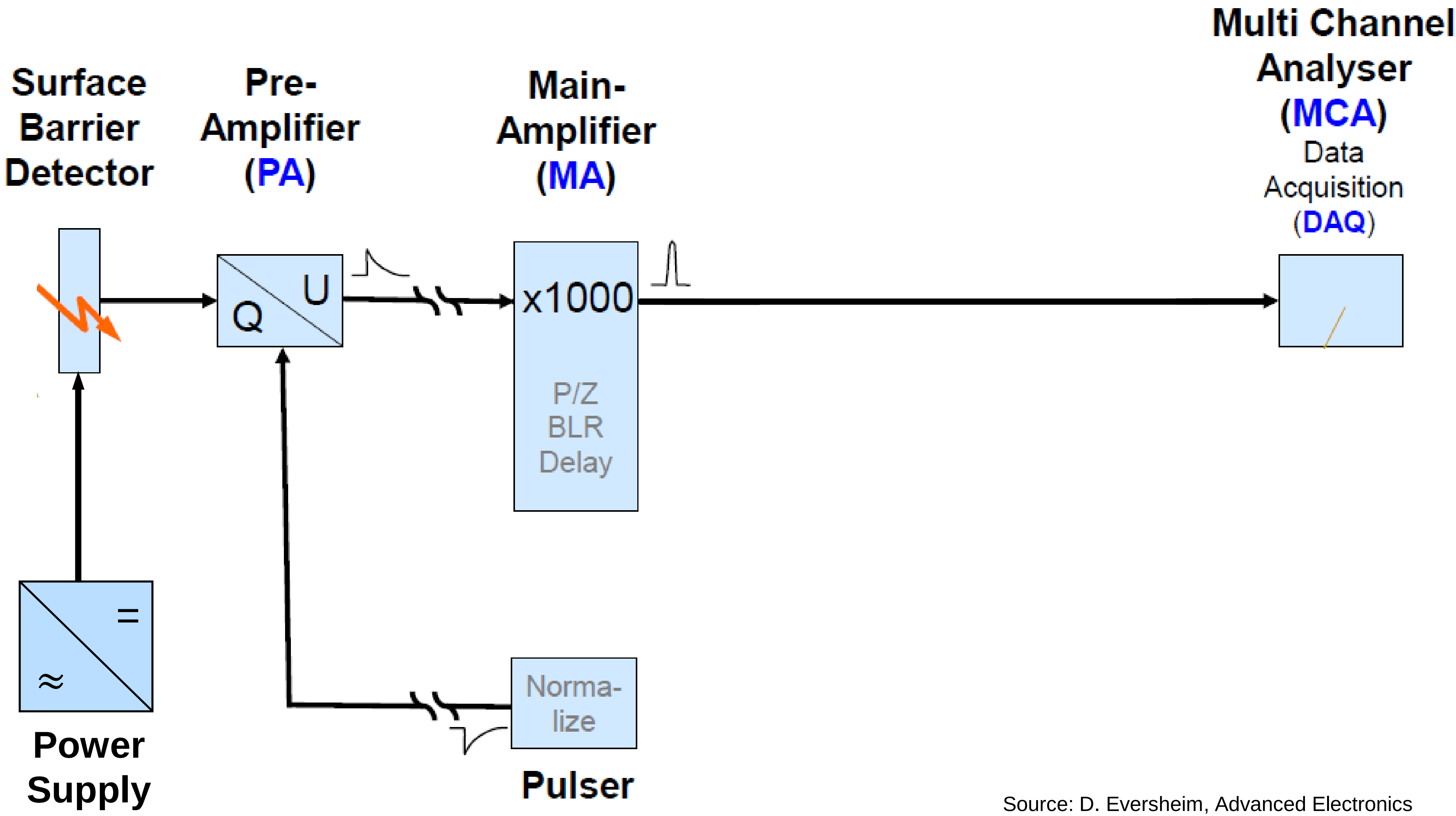
Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Chain of Electronics



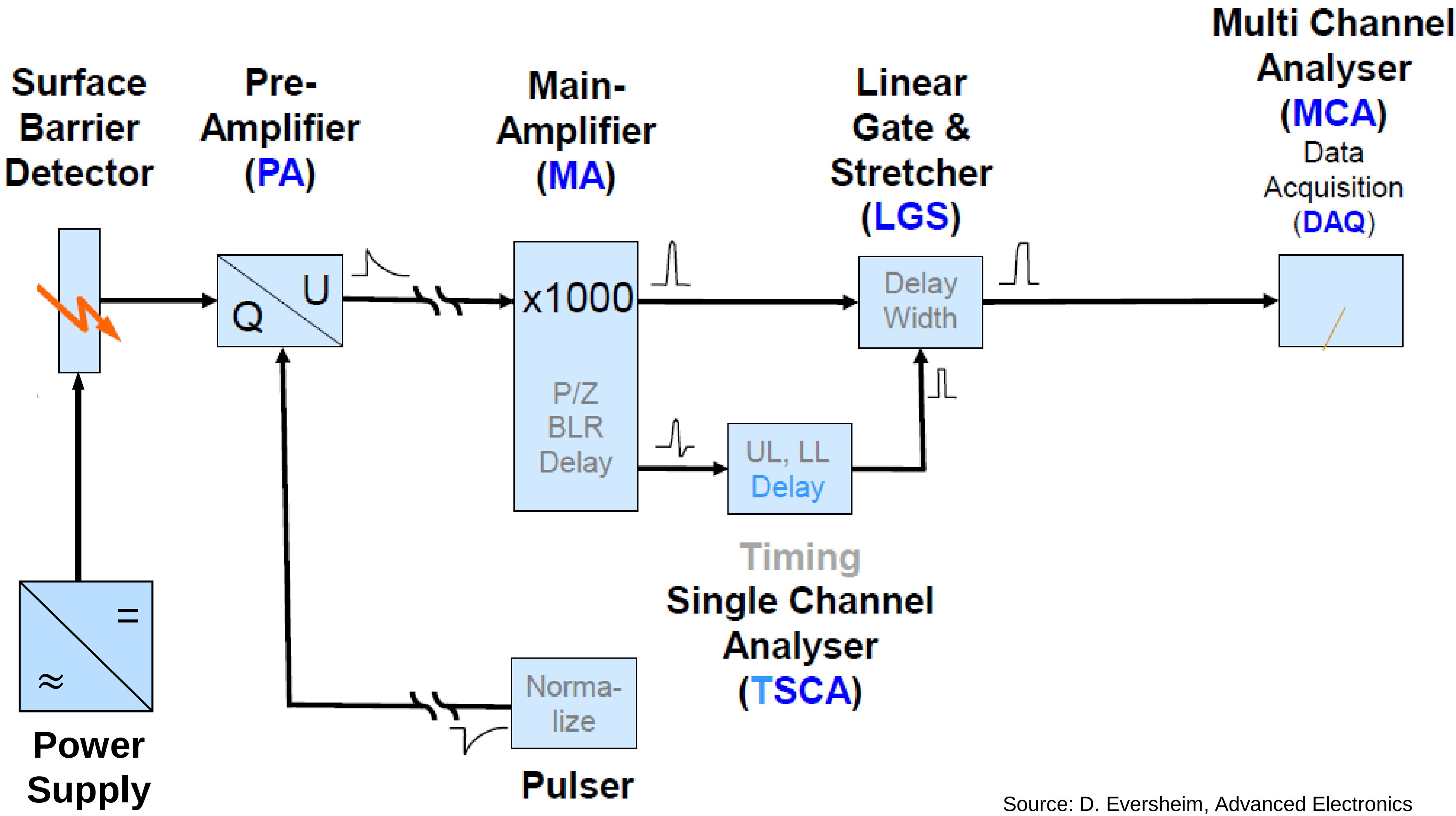
Source: D. Eversheim, Advanced Electronics

Chain of Electronics



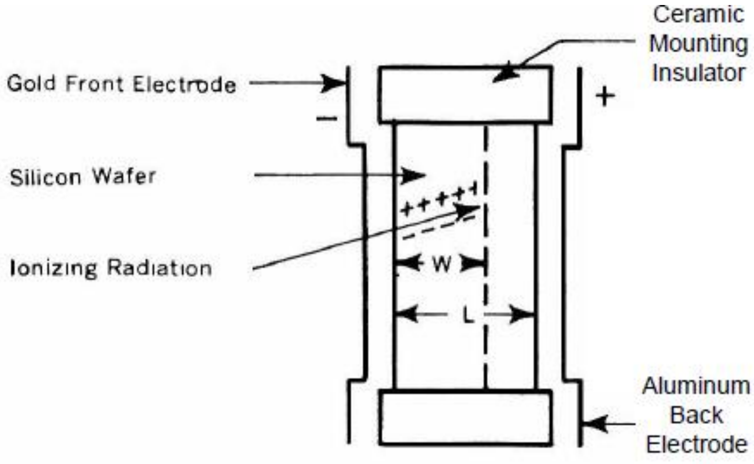
Source: D. Eversheim, Advanced Electronics

Chain of Electronics

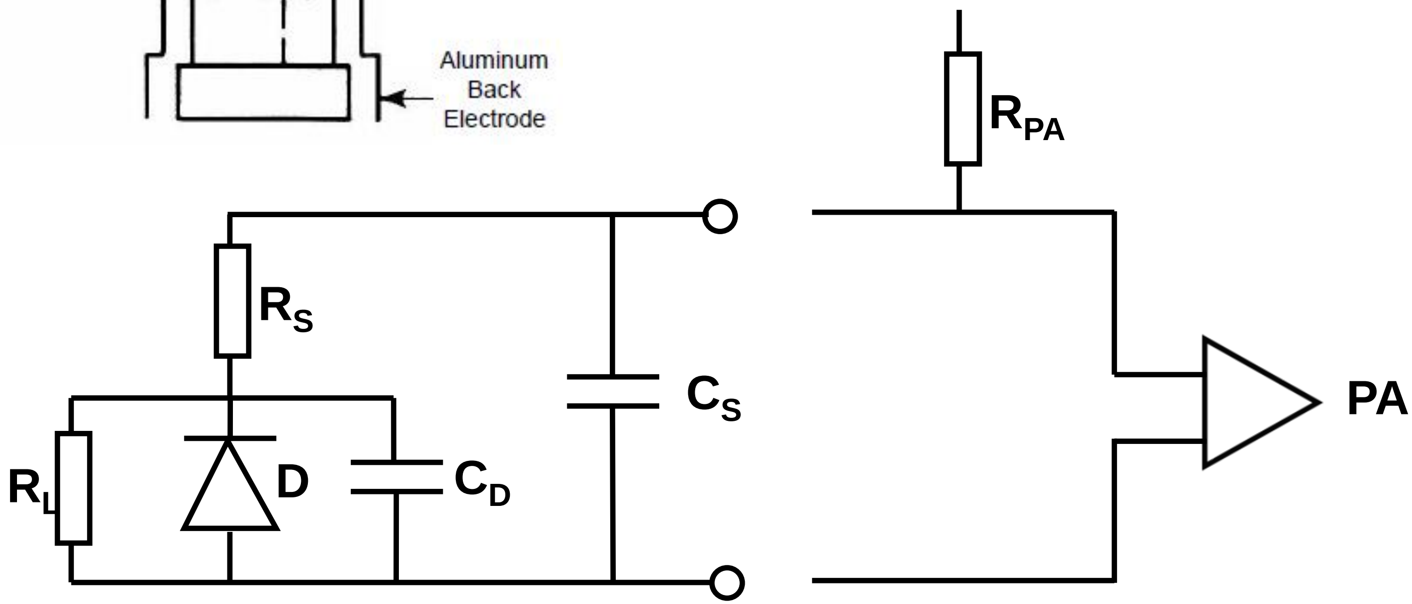


Source: D. Eversheim, Advanced Electronics

Detector Replacement Circuit Diagram



$$W \propto \sqrt{\rho\, U_D} \text{ with } \rho = specific\ resisance$$



$$C_D \propto A_D \frac{1}{\sqrt{\rho\, U_D}} \text{ with } A_D = detector\ area$$

Source: H.U. Schmidt, Meßelektronik in der Kernphysik

Preamplifier (PA)

$$U_{Det} = \frac{Q}{C_D} = \frac{4.45 \cdot 10^{-20}}{(20+25) \cdot 10^{-12}} \left[\frac{{}^{C}/_{eV}}{F}\right] = 0.99 \cdot 10^{-9} \left[{}^{V}/_{eV}\right] \cong 1.0 \left[{}^{mV}/_{MeV}\right]$$

$$\Rightarrow \boldsymbol{signal\ amplification\ is\ essential}$$

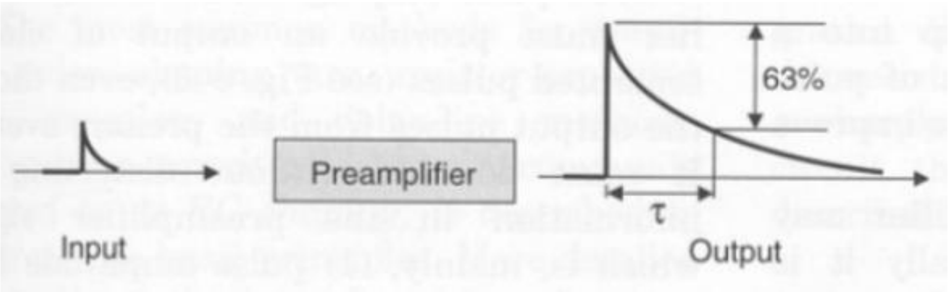
- Radiation detectors generate a signal whose amplitude is proportional to the energy of the impinging radiation.
- The time-to-peak of the signal is the charge collection time.
- Due to the fact that the charge collection time depends on the distance of charge generation from electrodes, the total collection time and hence the time-to-peak of the signal depends on the actual position inside the detector.
- Typical values can be a few ns up to hundreds of ns for Si detectors (for gas detectors up to several µs).
- So the voltage amplitude $U_{Det}(t)$ also changes due to Q(t).
- Preamplifier should produce a signal whose amplitude is proportional to the deposited energy.

Preamplifier (PA) – cont'd

- To amplify the relatively small signal from the detector.
- To match the impedance levels between the detector and the subsequent components.
- To shape the signal pulse for optimal subsequent signal processing.

Detector	Typical Signal Height	Typical Pulse Length
NaI(Tl)	0.5 – 2 V	250 ns
Liquid scintillator	0.05 – 0.2 V	10 ns
Plastic scintillator	0.05 – 0.2 V	1 ns
Semi-conductor	mV	0.1 – 1 µs
Gas propotional	1 to 10 mV	0.1 – 1 µs
Geiger-Müller	1 to 10 V	10 – 100 µs

A few Remarks concerning PA

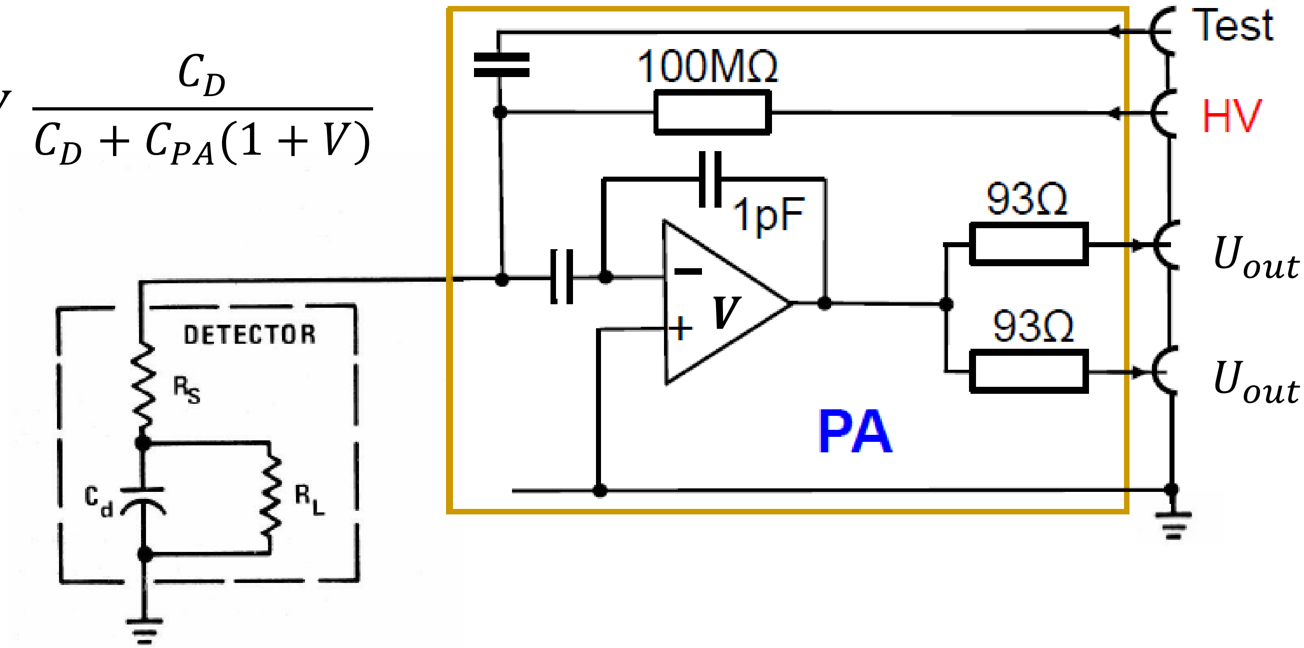


Source: G.F. Knoll, Radiation Detection and Measurement

- The output from the preamplifier is $V(t) = V_0 e^{-t/_{R \cdot C}}$ where $V_0 = {}^{Q}/_{C}$ and $\tau = R \cdot C$ is the time constant, typically between 10 and 100 µs.
- The amplification needed for scintillation detectors is typically small because the original signal is already amplified by photomultipliers (several orders of magnitude).
- Higher amplification is required for semiconductor detectors due to small detector signals.
- Preamplifier should be located as close as possible to the detector to minimize noise or to maximize the signal-to-noise ratio.

Preamplifier (PA) - cont‘d

$$U_{out} = -\frac{1}{C_D}\int i(t)dt\, V \,\frac{C_D}{C_D + C_{PA}(1+V)}$$



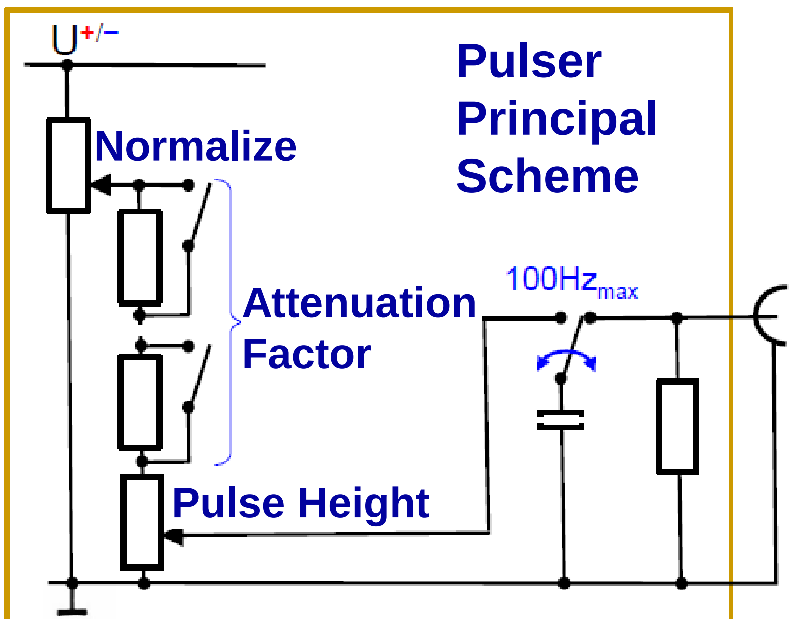
$$V \to -\infty \quad \Rightarrow \quad C_{PA}\cdot V \gg C_D$$

$$U_{out} = -\frac{1}{C_{PA}}\int i(t)dt = -\frac{Q}{C_{PA}}$$

So the nominal ***charge sensitivity*** is about ***45 mV/MeV*** for a ***C_{PA} of 1 pF*** (compared to 1 mV/MeV without PA).

Pulser

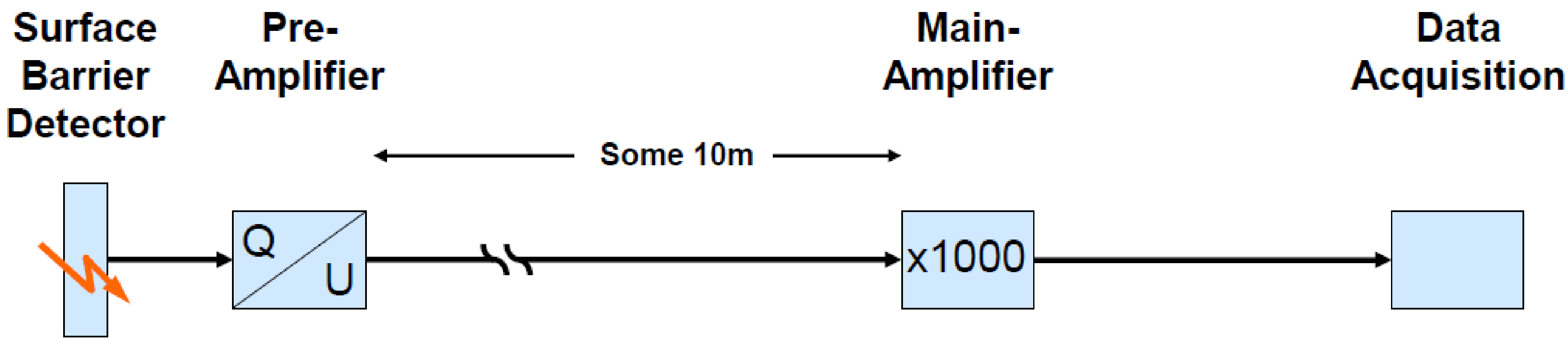
- A pulser simulates detector output pulses.
- The signals have an exponential pulse shape with a few ns to a few hundred ns rise time and s few hundred µs decay time.
- A pulser allows for a relative calibration of different amplifier chains and an absolute calibration of an amplifier chain relative to a known source.
- The NORMALIZE poti allows for calibration relative to known energy.
- The PULSE HEIGHT poti is for the absolute scaling then.



Source: D. Eversheim, Advanced Electronics

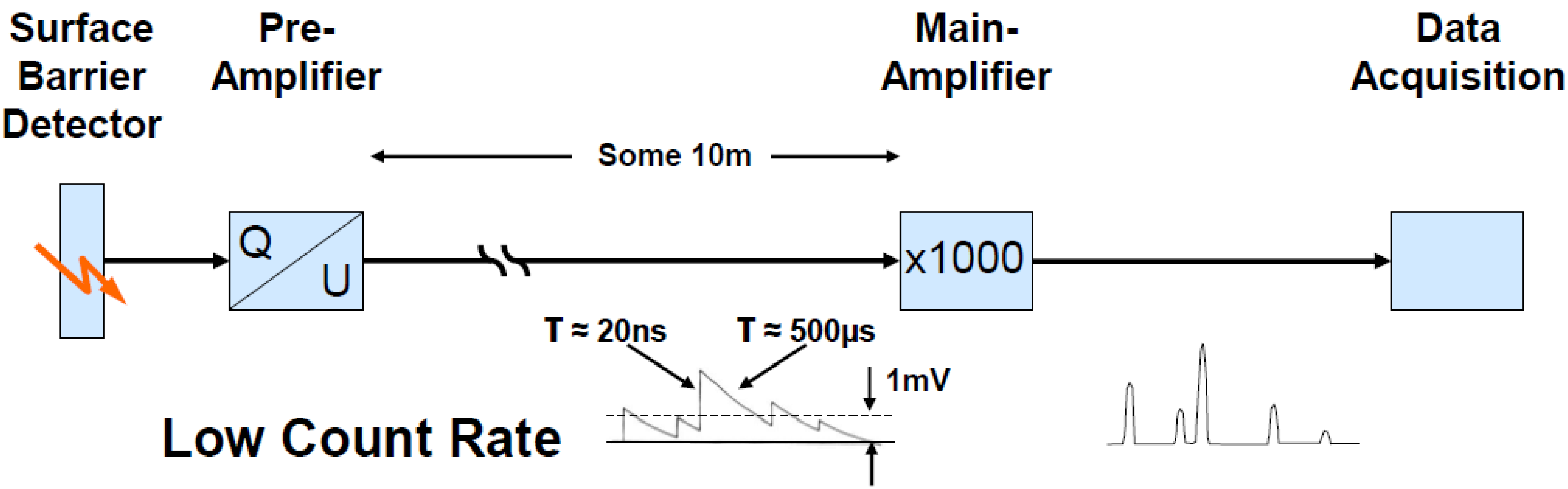
Source: ORTEC

Amplifier Chain



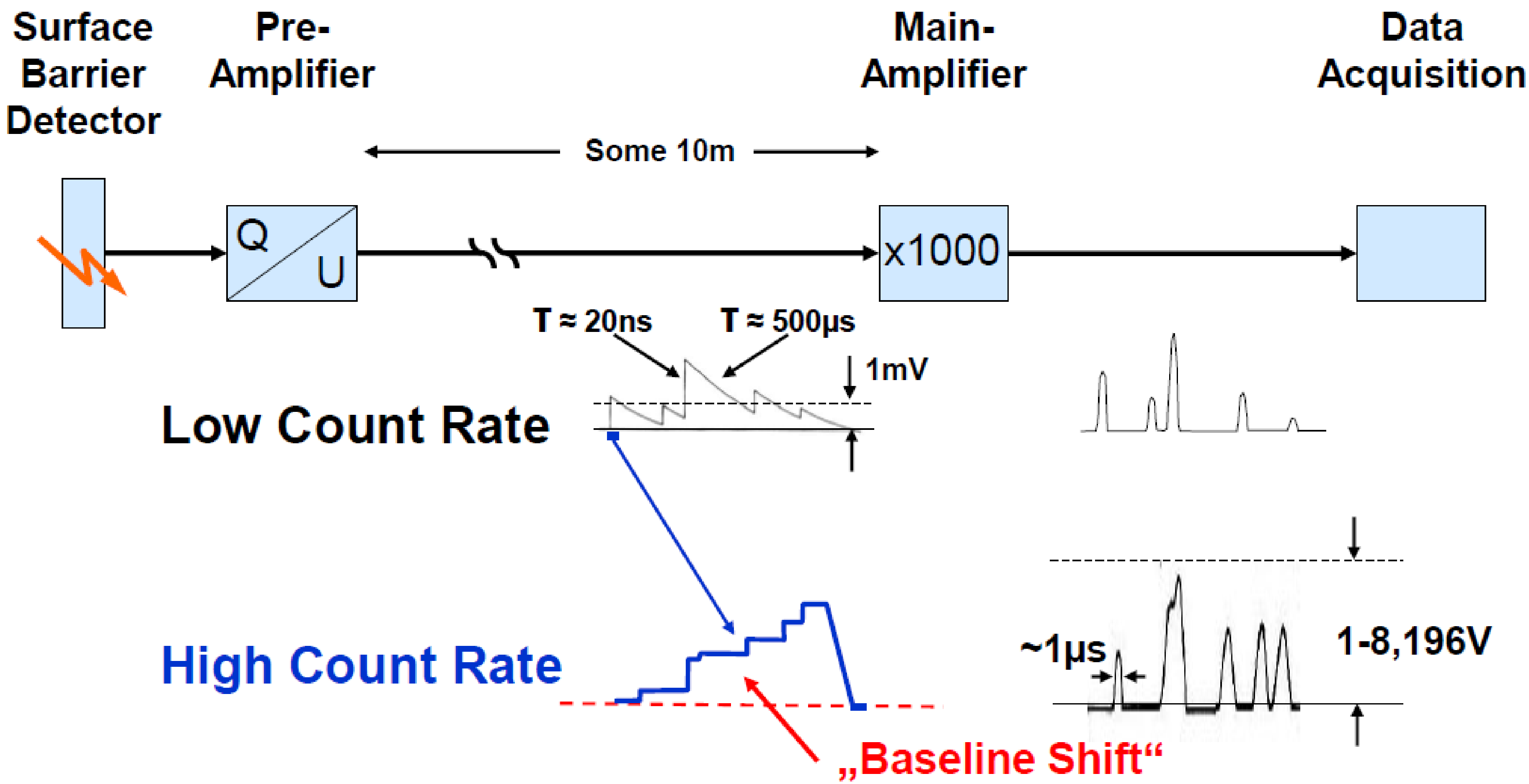
Source: D. Eversheim, Advanced Electronics

PA Output at Low Count Rate



Source: D. Eversheim, Advanced Electronics

PA Output at High Count Rate



Source: D. Eversheim, Advanced Electronics

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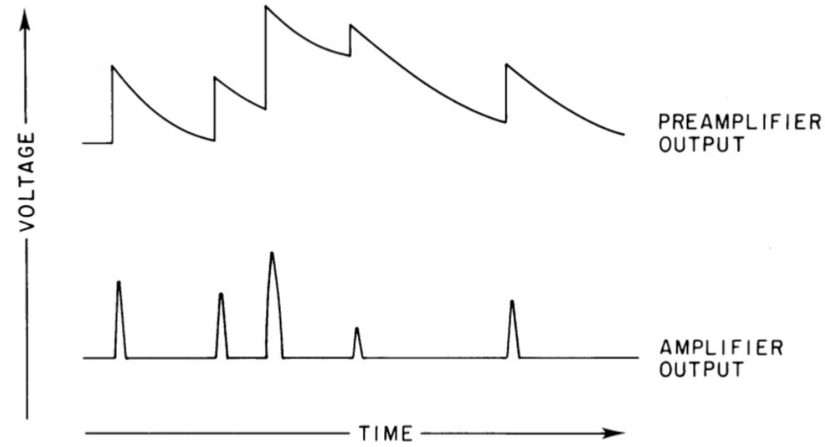
Main Amplifiers (MA)

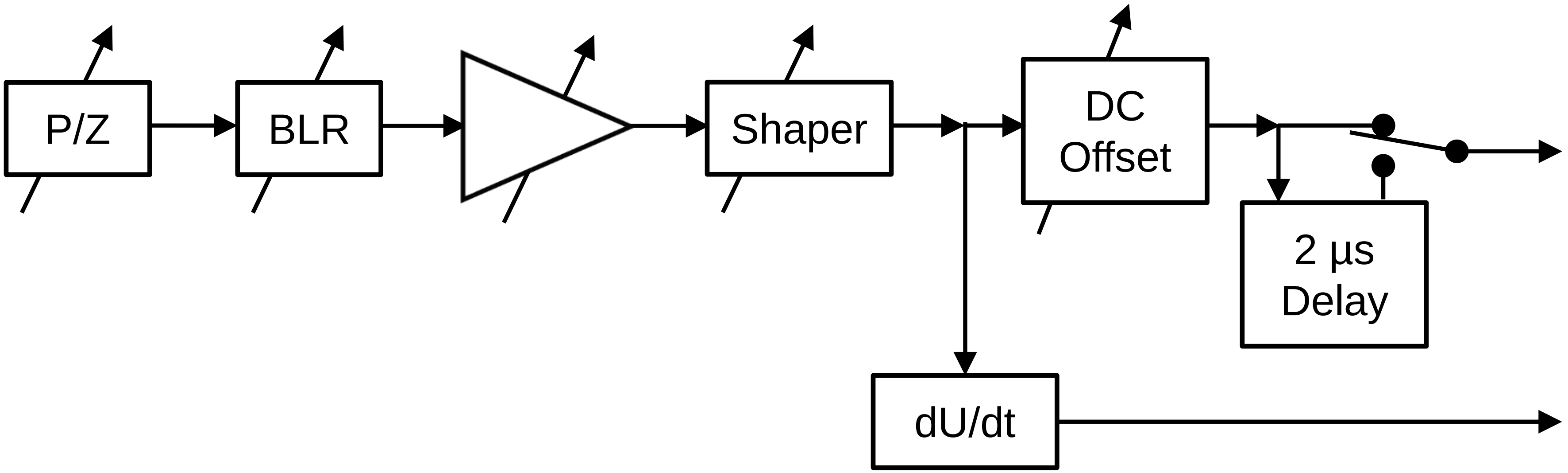
- To amplify the small signals from the preamplifier (1 – 1000x).
- To reshape the slow decaying pulse of the preamplifier into a narrow one (for high count rate and increasing SNR etc.).
- Requirements for shaping: Preserve the input pulse signal information such as pulse height and rise time.



Source: G.F. Knoll, Radiation Detection and Measurement

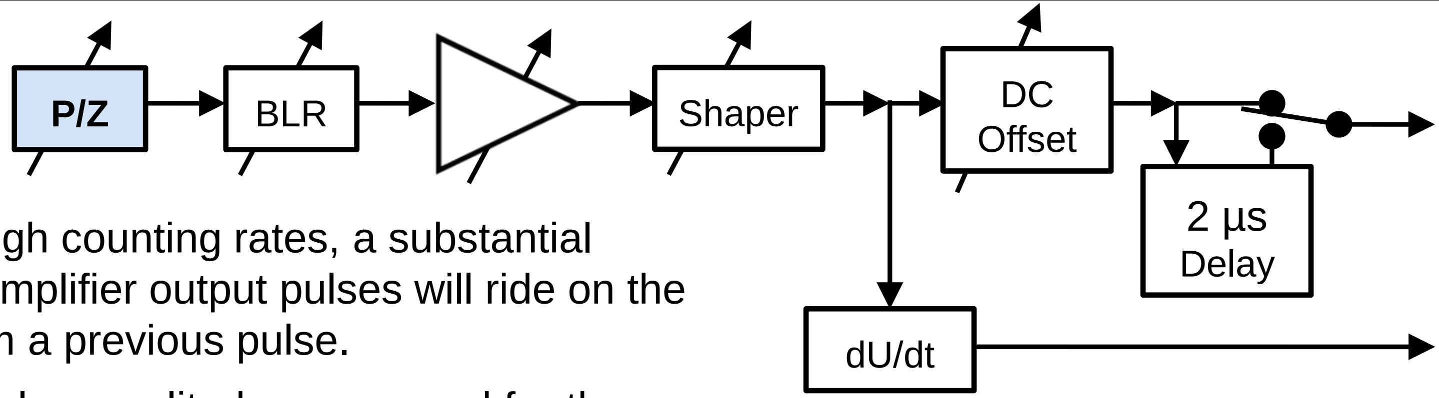
Main Amplifier (MA) or Spectroscopy Amplifier

Main Components

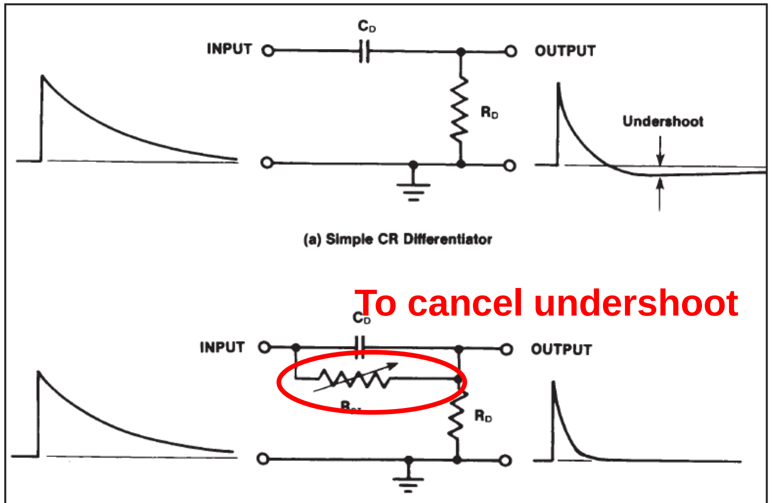


Source: D. Eversheim, Advanced Electronics

Main Amplifier (MA) – Pole-Zero Cancellation (P/Z)



- At medium to high counting rates, a substantial fraction of the amplifier output pulses will ride on the undershoot from a previous pulse.
- The apparent pulse amplitudes measured for these pulses will be too low, which leads to a broadening of the peaks recorded in the energy spectrum.
- Most spectroscopy amplifiers incorporate a pole-zero cancellation circuit to eliminate this undershoot.
- The benefit of pole-zero cancellation is improved peak shapes and resolution in the energy spectrum at high counting rates.
- The result is an output pulse exhibiting a simple exponential decay to baseline with the desired differentiator time constant.
- This circuit is termed a "pole-zero cancellation network" because it uses a zero to cancel a pole in the mathematical representation by complex variables.



(a) Simple CR Differentiator

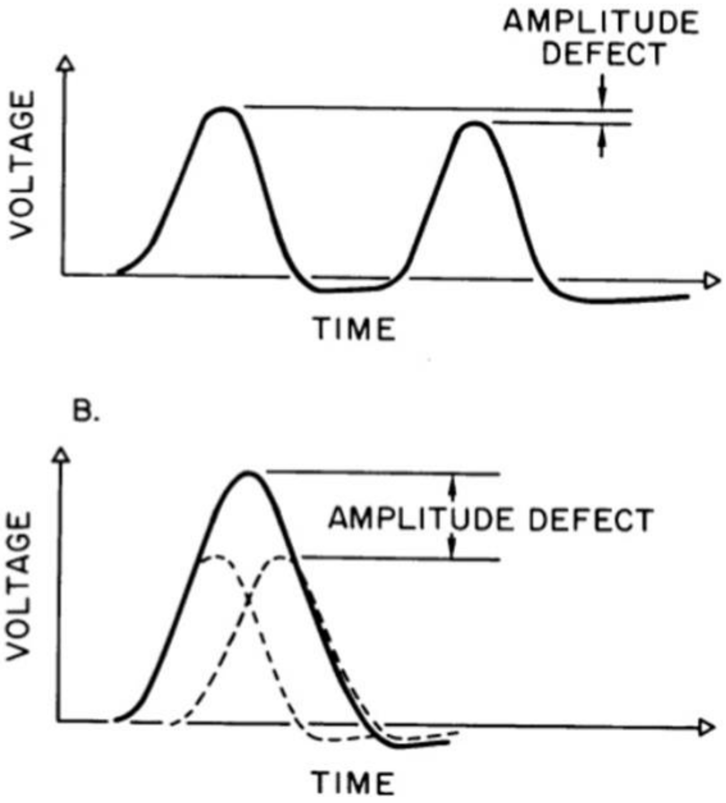
(b) CR Differentiator with Pole-Zero Cancellation

Source: ORTEC

Baseline Shift and Pulse Pile-up

- Baseline Shift is caused by the negative component of the output (at the end of the pulse).

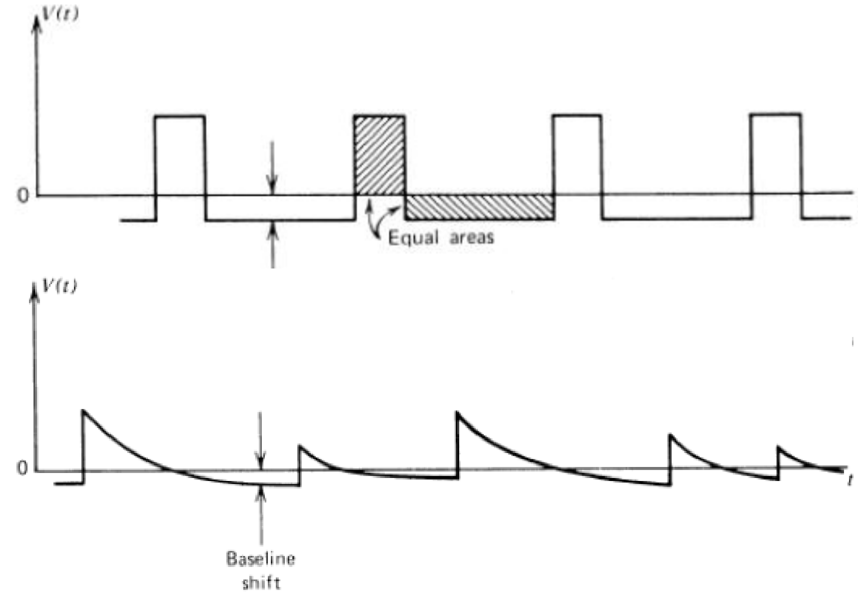
- Pulse Pile-up is caused at high counting rates when pulses fall on top of each other.



Source: G.F. Knoll, Radiation Detection and Measurement

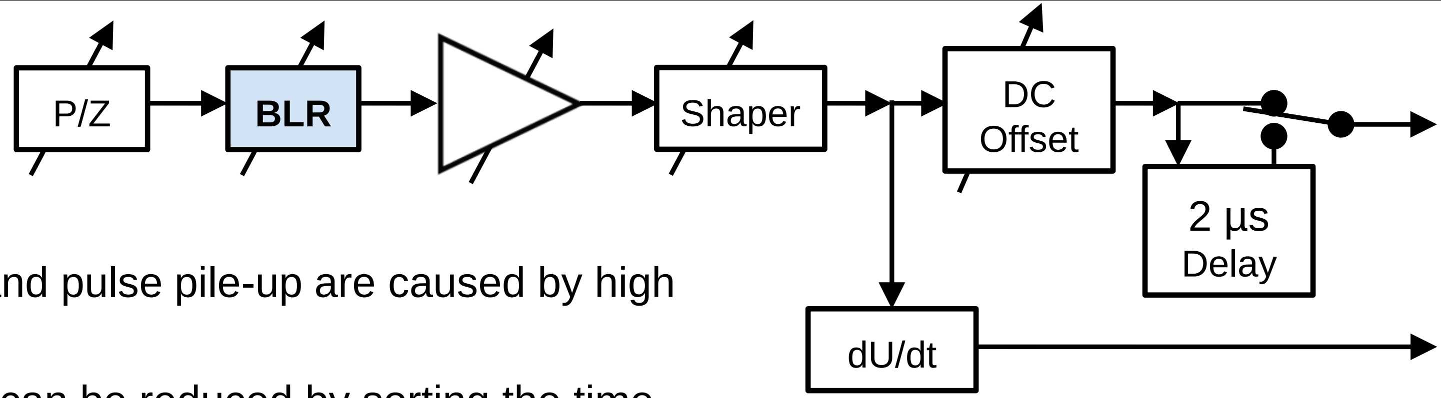
Main Amplifier (MA) – Base Line Restorer (BLR)

- At low counting rates, the spacing between pulses is extremely long compared to the pulse width.
- So the baseline between pulses remains very close to ground potential.
- As the counting rate increases, the baseline must shift down, so that the area of the signal remaining above ground potential is equal to the area between ground potential and the shifted baseline.
  - The baseline shifts to make the total transmitted charge to equals zero.
- The amount of baseline shift increases as the counting rate increases.
- Random count rate lead to fluctuations of the baseline.

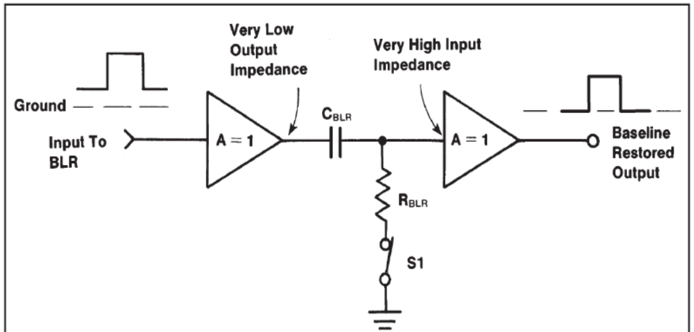


Source: G.F. Knoll, Radiation Detection and Measurement

Main Amplifier (MA) – Base Line Restorer (BLR) cont'd

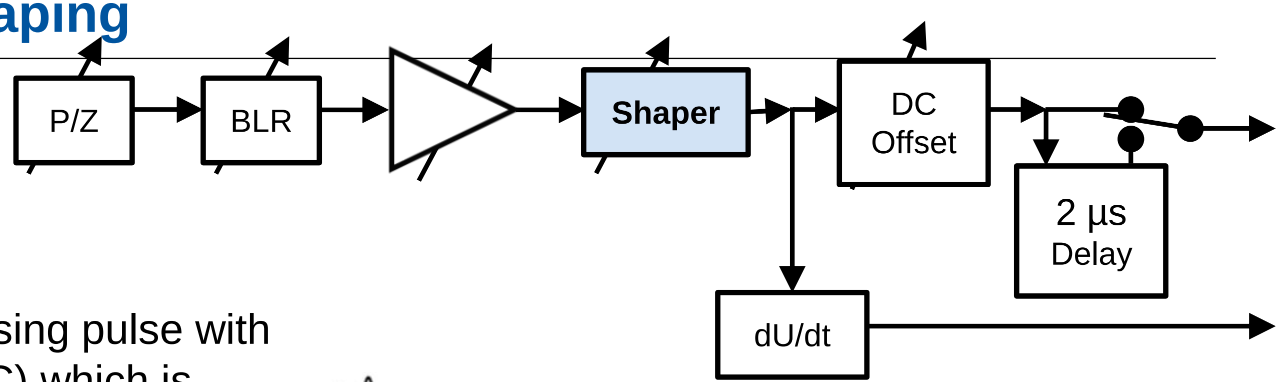


- Baseline shift and pulse pile-up are caused by high counting rates.
- Both problems can be reduced by sorting the time constant but also by reducing the energy resolution and the signal-to-noise ratio (SNR).
- To ensure good energy resolution and peak position stability at high counting rates, spectroscopy amplifiers are entirely dc-coupled (except for the CR differentiator network located close to the amplifier input).
- As a consequence, the dc offsets of the earliest stages of the amplifier are magnified by the amplifier gain to cause a large and unstable dc offset at the output.
- A baseline restorer is required to remove this dc offset, and to ensure that the amplifier output pulse rides on a baseline that is securely tied to ground potential.

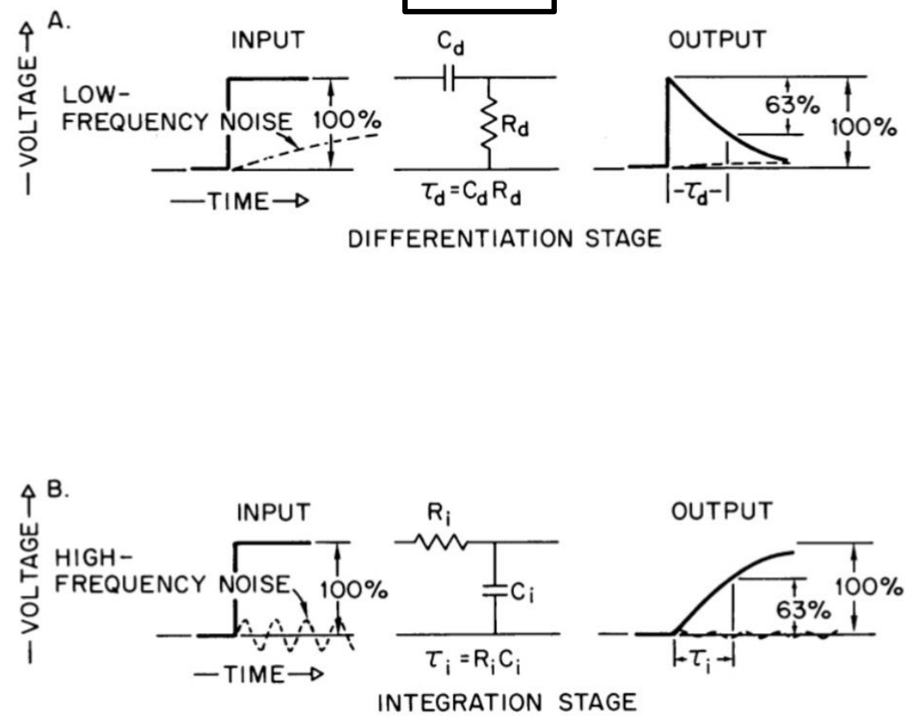


Source: ORTEC

Main Amplifier - RC Shaping



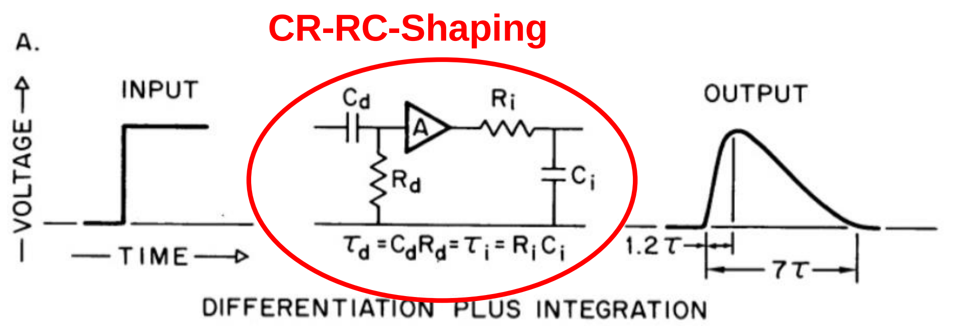
- Differentiation stage:
  - The output is a rapid rising pulse with a decay constant (= RC) which is smaller than that of the preamplifier.
  - The amplitude of the output is proportional of the rising portion of the input and is insensitive to the tail of the pulses.
  - It discriminates against low frequency noise.
- Integration stage:
  - The output pulse rises with the time $V(t) = V_0(1 - e^{-t/R\cdot C})$.
  - It discriminates against high frequency noise.



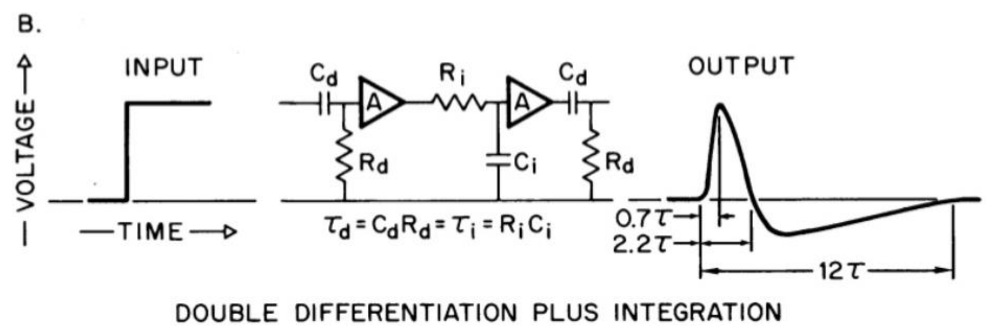
Source: ORTEC

Main Amplifier - RC Shaping cont‘d

- Differentiation plus Integration stage:
  - The output amplitude is determined by the input.
  - The time constant is shortened to a few µs in contrast to several hundred ms of the preamplifier.
  - Only one polarity (except for the small negative overshot at the end.



- Double Differentiation plus Integration stage:
  - The output is bipolar.
  - The rise time is shorter but the total signal duration is longer compared to unipolar output.
  - Preferred for high counting rates.

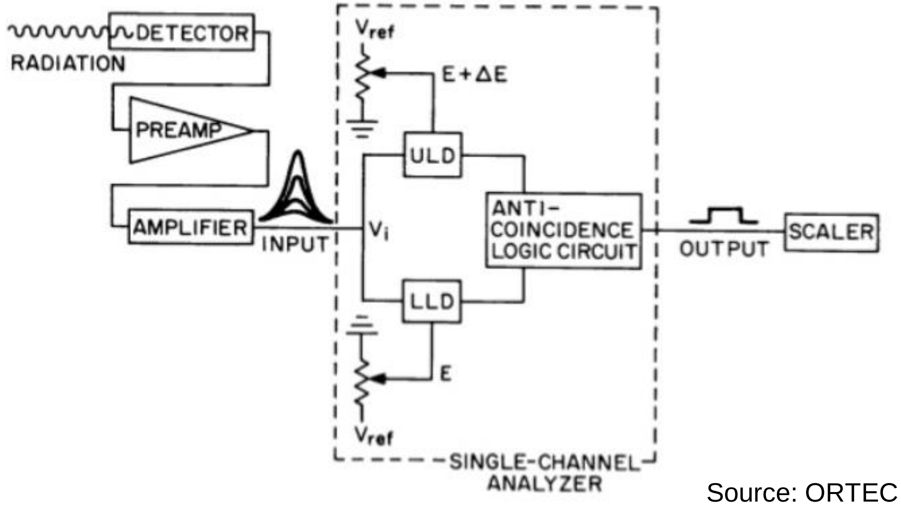


Source: ORTEC

Single Channel Analyzer (SCA)

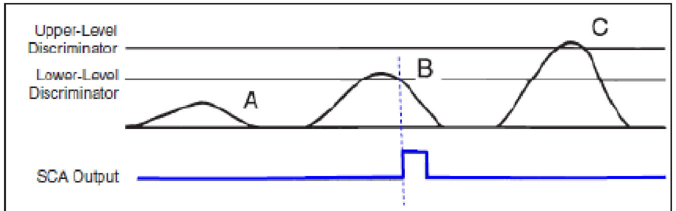
- Purpose: Counting only those events within a single energy range.

- A SCA is composed of three parts:
  - Lower Level Discriminator (LLD),
  - Upper Level Discriminator (ULD)
  - and Anticoincidence.



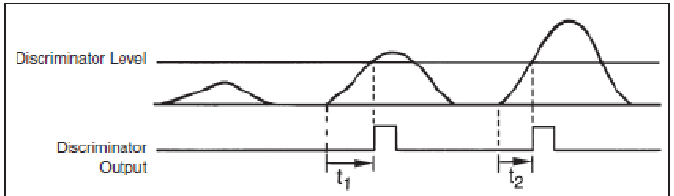
Source: ORTEC

- A logic output pulse is generated when input voltage falls between voltages defined by LLD and ULD.
  - As the conditions are met on the trailing edge, the logic pulse is not generated before it falls below the LL.



Single-Channel Analyzer Function.

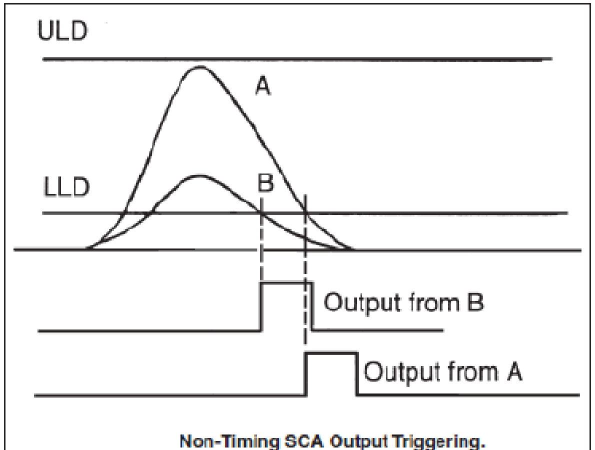
- A SCA without ULD is a circuit called discriminator.



Integral Discriminator Output Triggering.

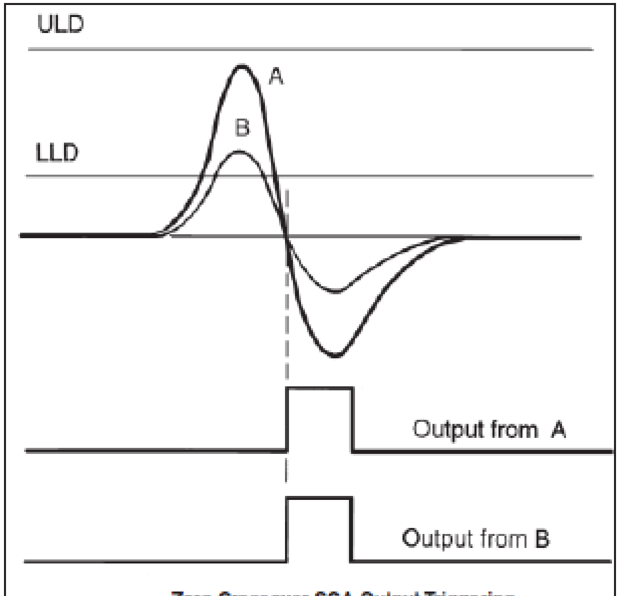
Timing Single Channel Analyzer (TSCA)

- Time Walk can be avoided either by
  - Zero-Crossover SCA Triggering from bipolar signals or
  - by peak sensing SCA output timing.

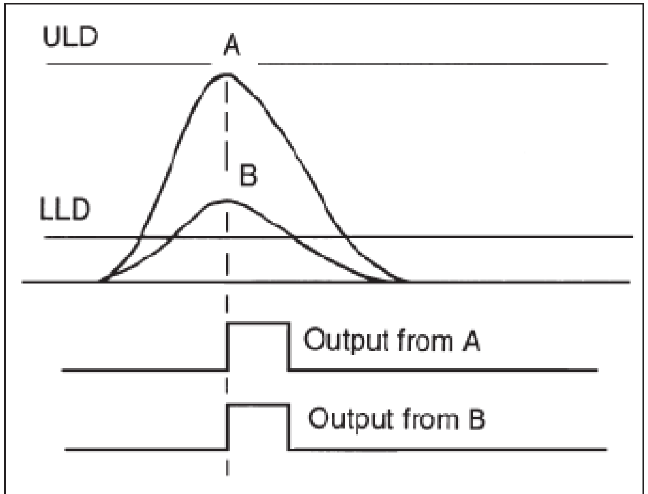


Non-Timing SCA Output Triggering.

Source: ORTEC



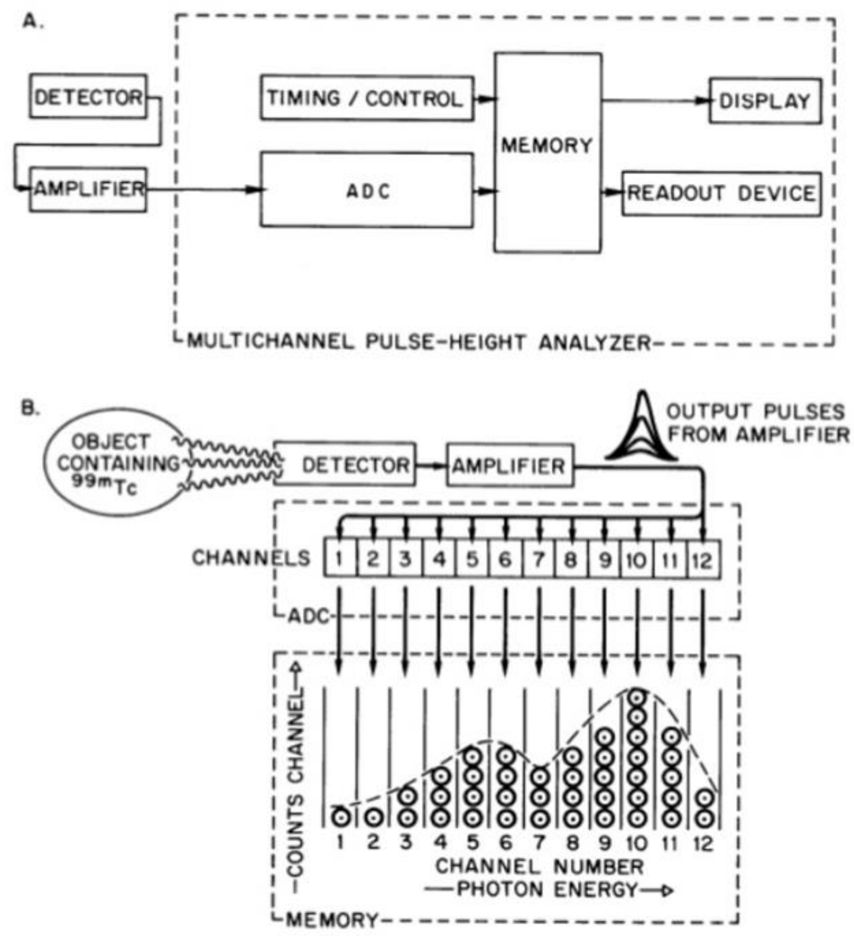
Zero-Crossover SCA Output Triggering.



Peak-Sensing SCA Output Triggering.

Multichannel Analyzer (MCA)

- A Multi Channel Analyzer digitizes the amplitude of a pulse and sums the events of the same height in the same memory channel.
- Simultaneous recording of multiple energies.
- The principal of most MCA is different from the single channel analyzer.
- The center of the MCA is the analog-to-digital converter (ADC).
- A memory is required for the sorting of energy channels (i.e. energy spectrum).
- The display of all these channels is called “spectrum”.



Source: ORTEC

Analog-to-Digital Converter (ADC)

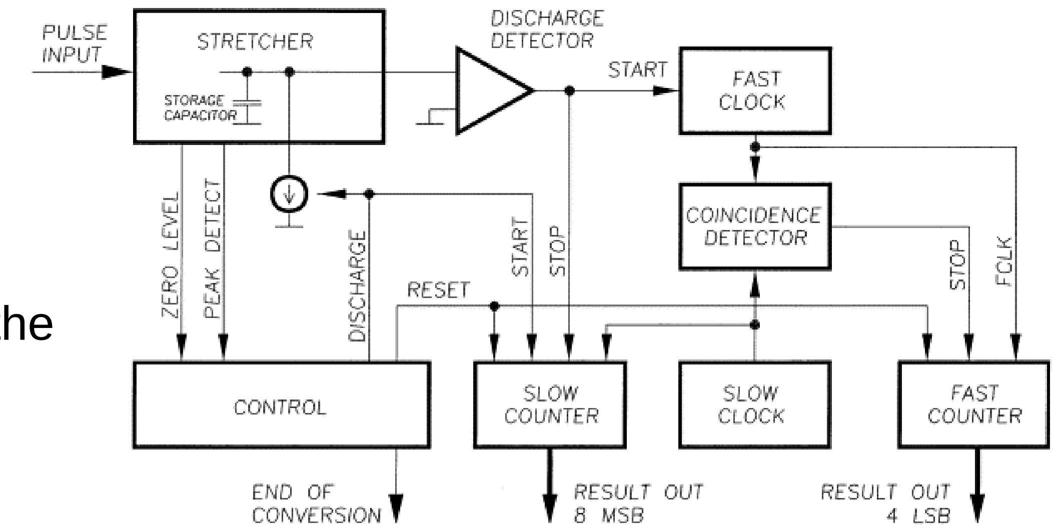
- Two types of ADC are widely used in nuclear electronics for MCA and the interface between detectors and computers:
  - Wilkinson or Ramp Converter
  - Successive Approximation

- Both require time for the conversion which could be a bottle neck for the time resolution.

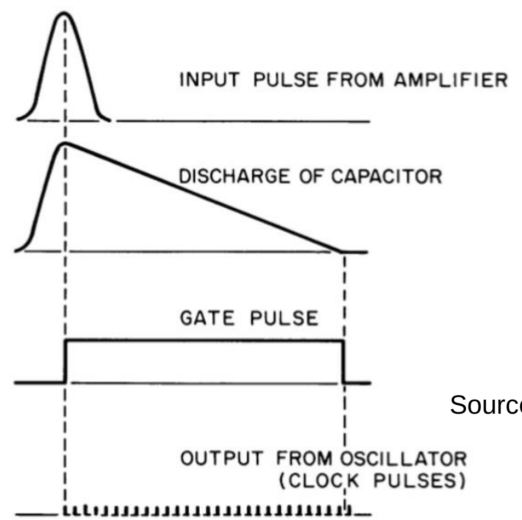
- Both of the converters use binary number representation which means that the more bits are used the more accurate the result will be. But more time and memory is required.

Wilkinson or Ramp ADC

- RC circuitry and clock oscillator.
- Discharging time proportional to the amplitude of the input pulse (radiation energy).
- Clock oscillator produces a pulse train that is counted in a counting circuit during discharging.
- The number of clock pulses counted is proportional to the discharging time which in turn is proportional to the energy.



Source: NIM A, vol. 408, no. 2-3, 1998.



Source: ORTEC

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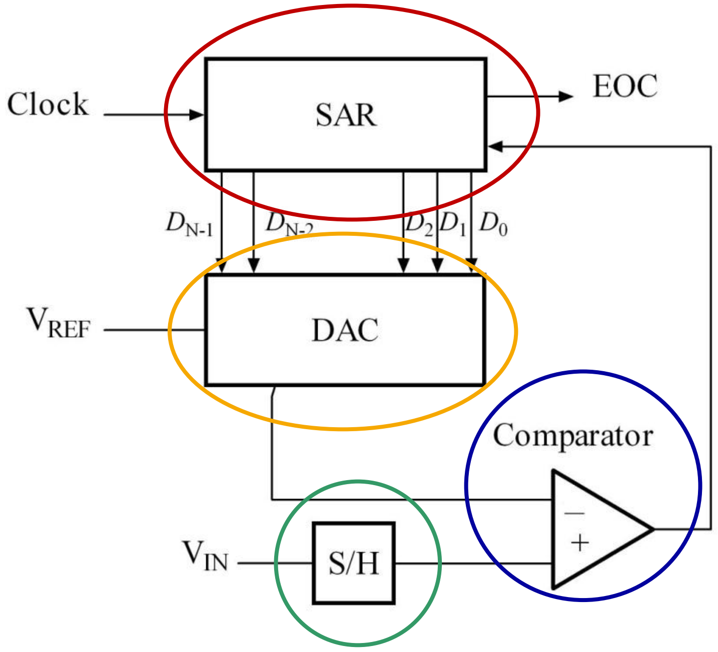
Successive Approximation ADC

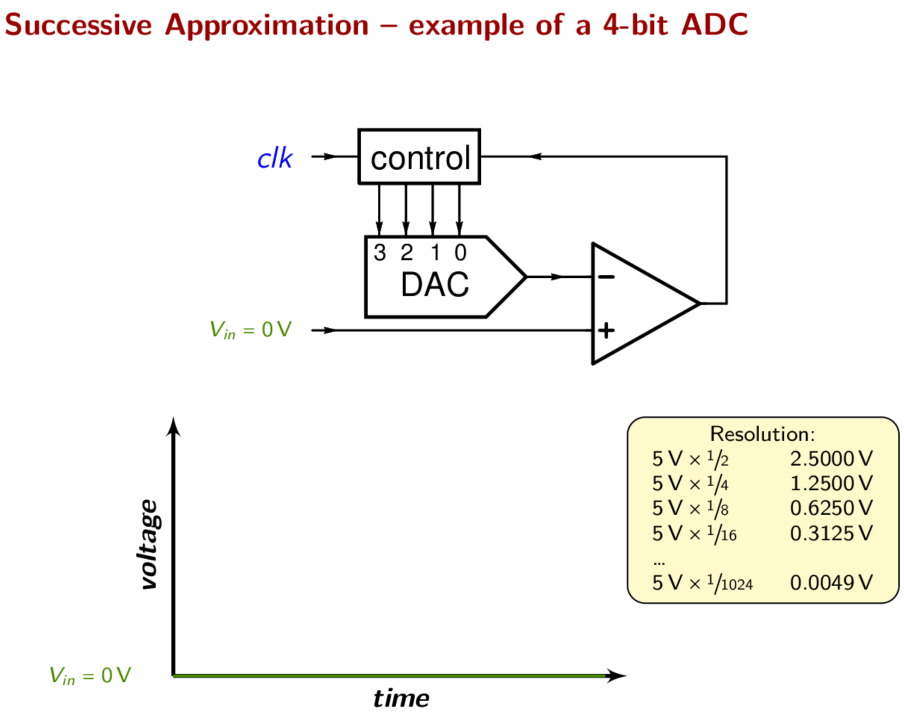
- A successive approximation ADC is a type of analog-to-digital converter that converts a continuous analog waveform into a discrete digital representation via a binary search through all possible quantization levels before finally converging upon a digital output for each conversion.
- The successive approximation ADC circuit typically consists of four main sub-circuits:
  - A sample and hold circuit to acquire the input voltage (Vin).
  - An analog voltage comparator that compares V_{in} to the output of the internal DAC and outputs the result of the comparison to the successive approximation register (SAR).
  - A successive approximation register sub-circuit designed to supply an approximate digital code of V_{in} to the internal DAC.
  - An internal reference DAC that, for comparison with V_{REF}, supplies the comparator with an analog voltage equal to the digital code output of the SAR_{in}.



Source: Wikipedia

Successive Approximation ADC cont'd

- The input pulse is compared with one half of the full scale.
  - MSB
- The comparison voltage is then either increased or decreased by one half of its initial level depending on whether the pulse amplitude did or did not exceed the initial level.
- The process is repeated for several steps (number of bits).

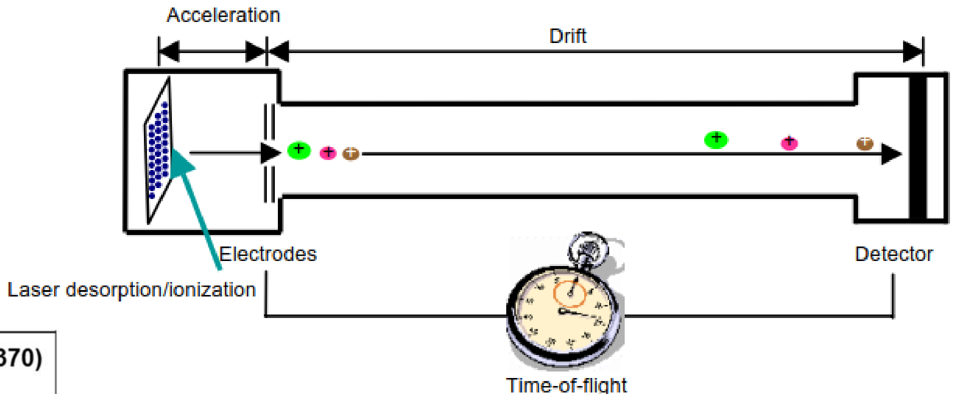


Source: Wikipedia

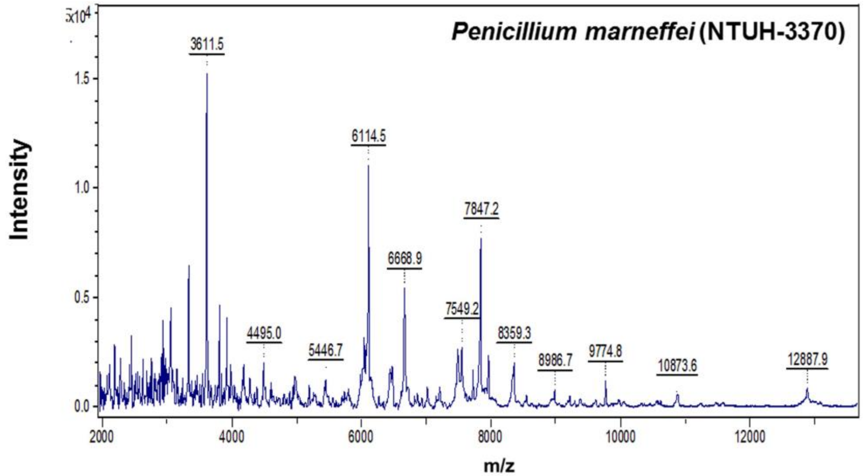
Time Measurements

- Time measurements are necessary when doing coincidence measurements or time-of-flight (TOF) experiments.
- A high timing accuracy between two simultaneous or two successive pulses is essential.

Example: ToF mass spectroscopy:
$ToF \propto \sqrt{m}$



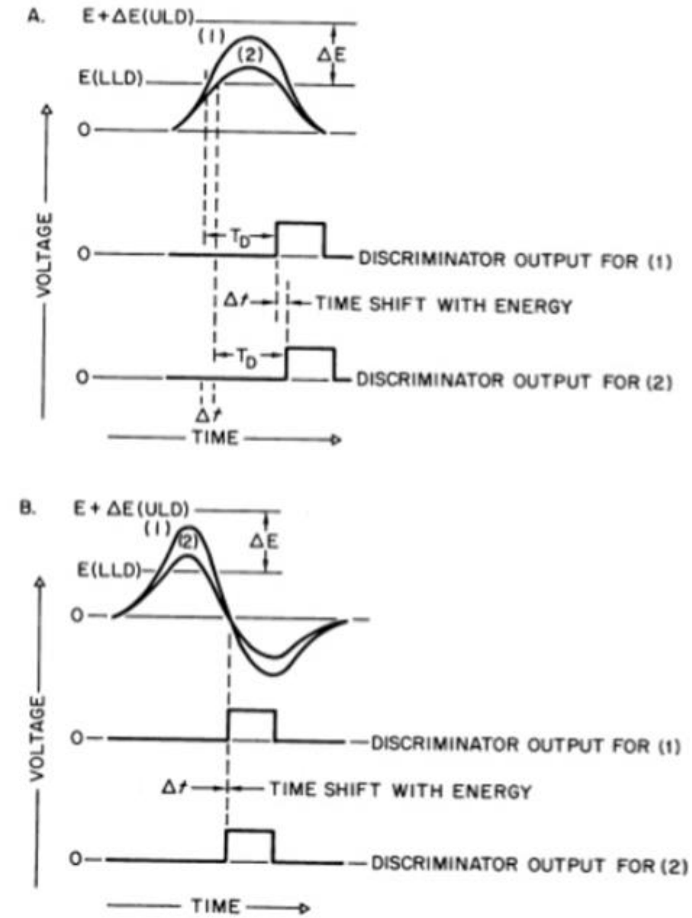
Source: Creative Biolabs.



Source: Front. Microbiology, 2015

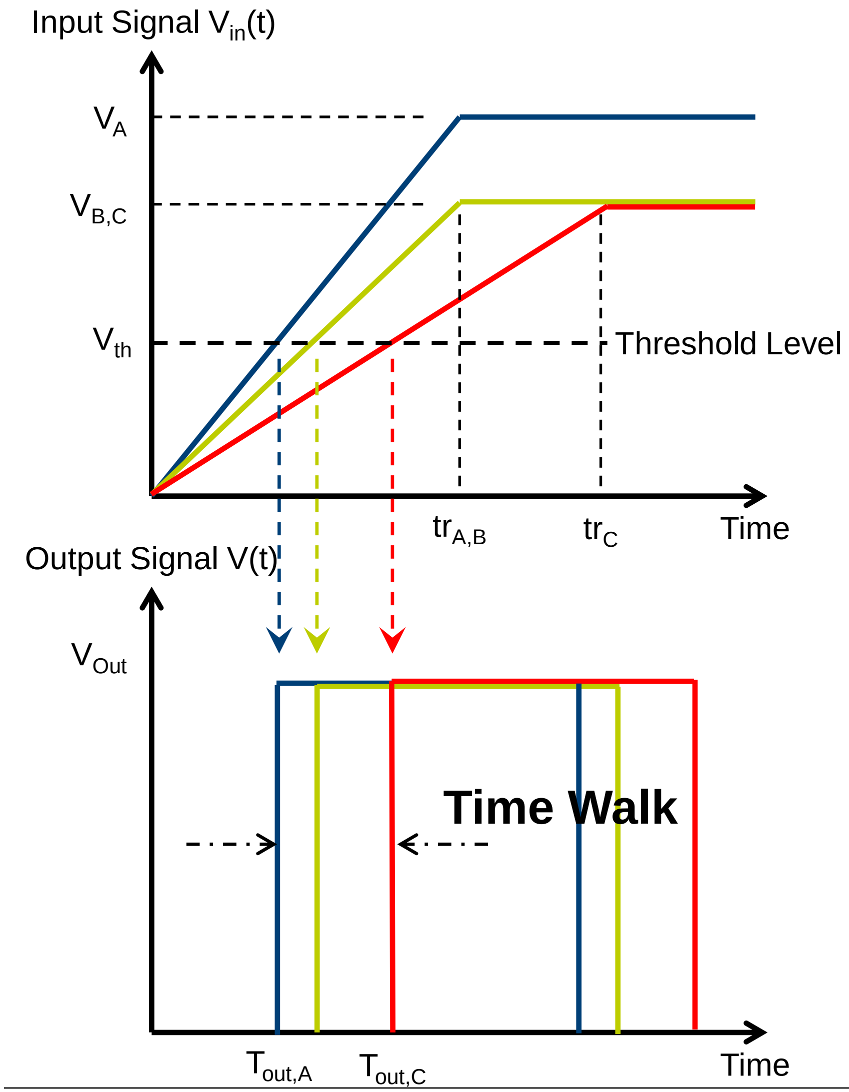
Timing Methods

- There are a number of different timing methods available:
  - Leading Edge,
  - Zero-Crossing,
- Leading-edge uses the rising portion of the input pulse to trigger the lower level discriminator which depends on the pulse amplitude.
- Zero-crossing requires bipolar pulses and is more accurate.

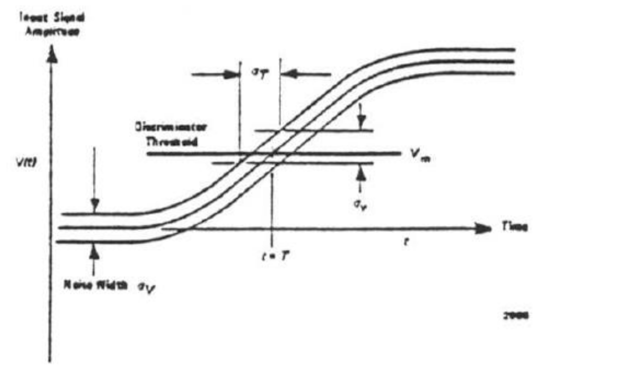


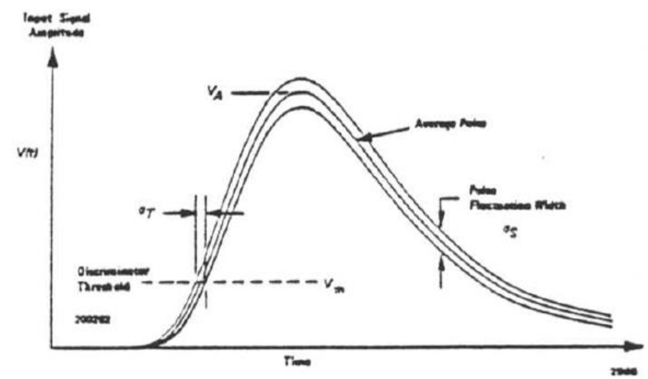
Source: ORTEC

Timing – Leading Edge Discriminator



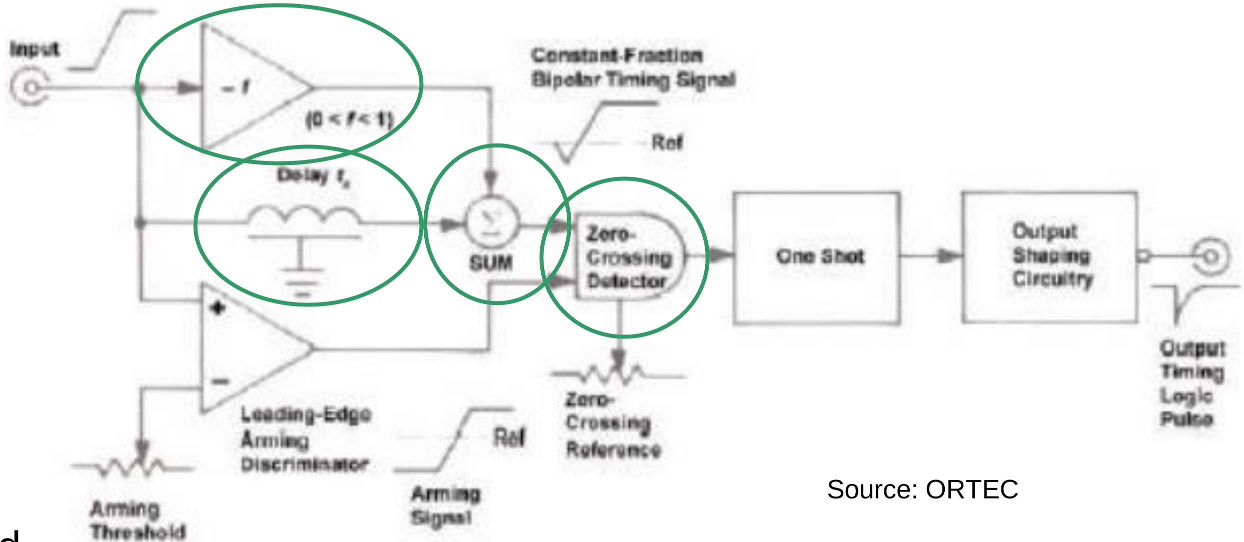
Time Jitter in a leading edge discriminator comes from noise on the input signal or statistical fluctuations of the pulse shape.





Source: IEEE TNS, vol. 32, no. 3, 1985.

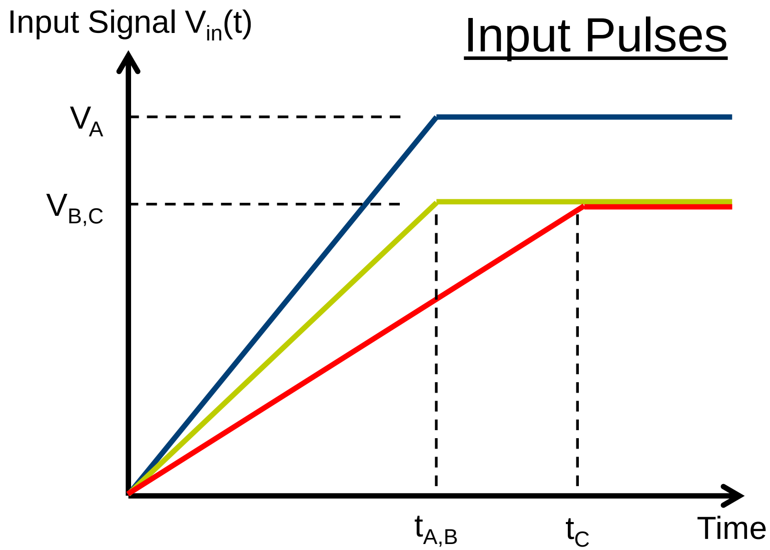
Timing – Constant Fraction Discriminator (CFD)

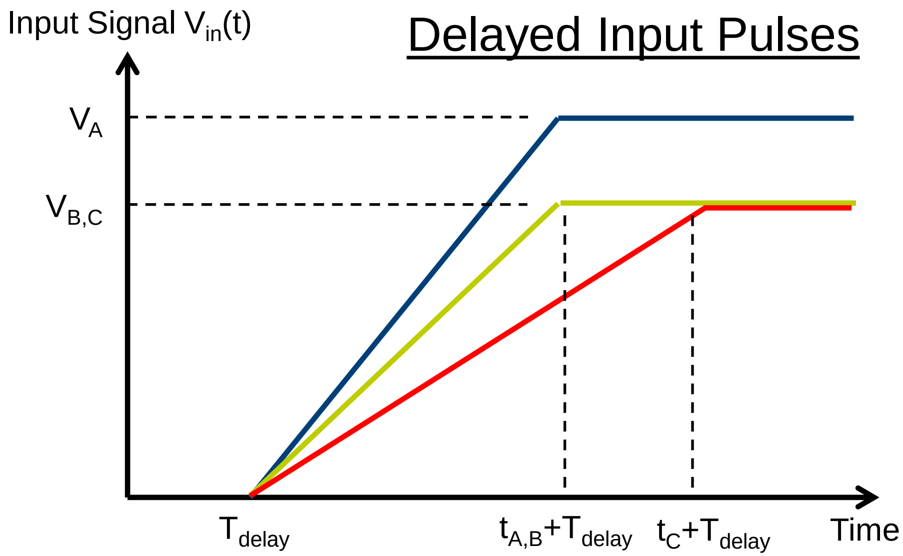


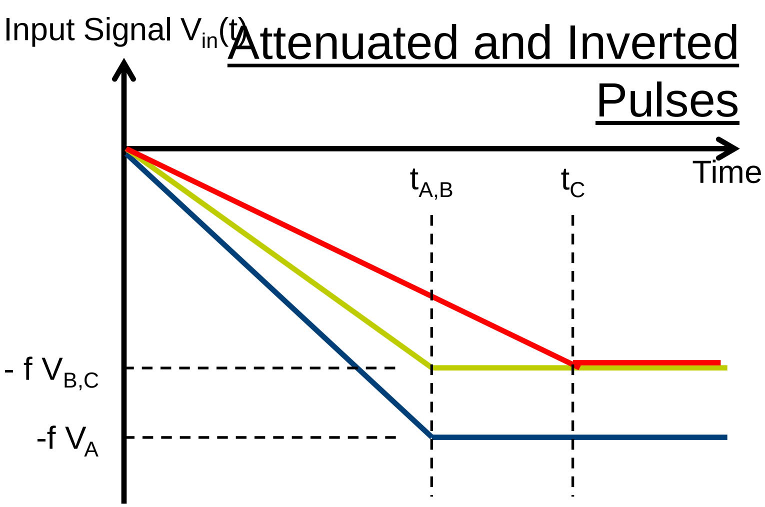
Source: ORTEC

- Principle of operation:
  1. The input pulse is delayed,
  2. A fraction of the undelayed pulse is inverted and
  3. Both signals are added
- $V_{out}(t) = V_{in}(t - T_{delay}) + f \cdot (-V_{in}(t))$ (i.e. a bipolar signal)
- The output signal has a zero crossing time depending only on the parameters T_{delay} and f
- $T_{delay} > (1 - f) \cdot T_{pulse}$ => True Constant Fraction Timing (TCF)
- $T_{delay} < (1 - f) \cdot T_{pulse}$ => Amplitude and Rise Time Compensated Timing (ARC)

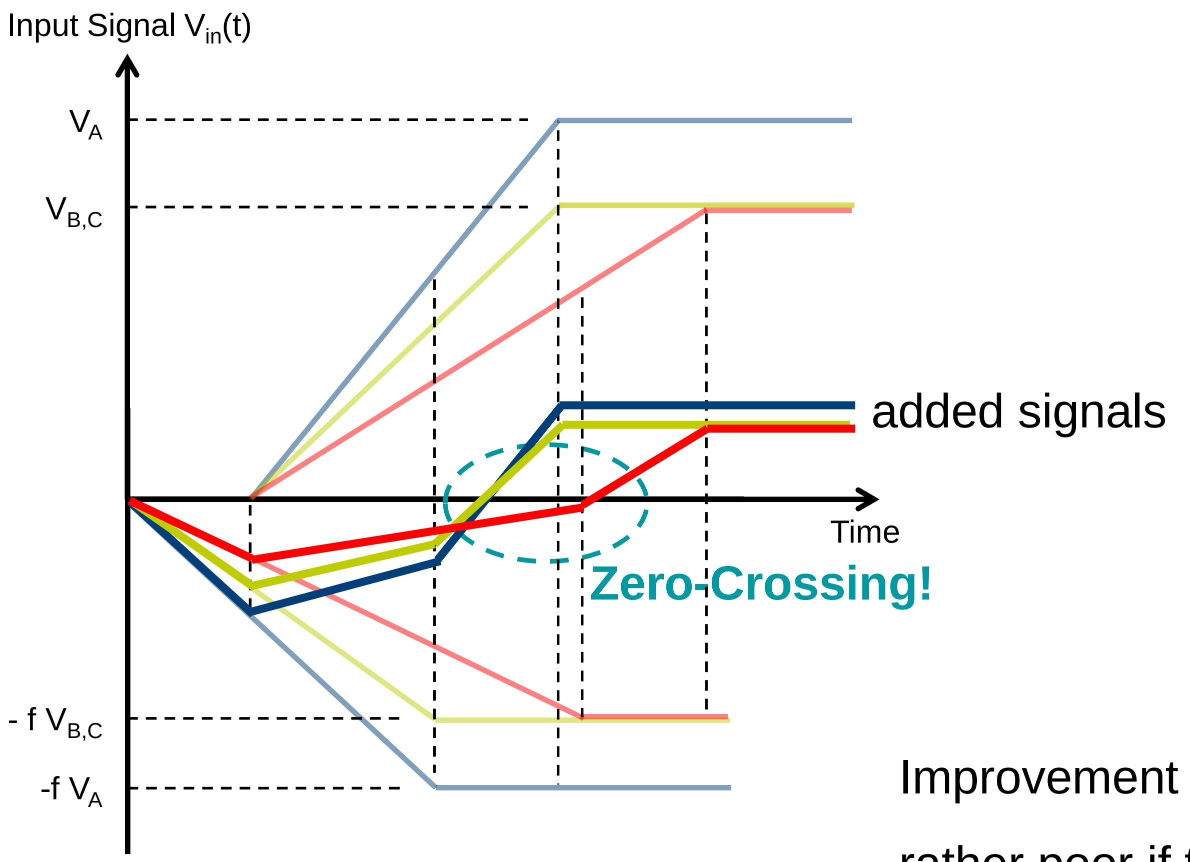
Timing – True Constant Fraction Timing (TCF)





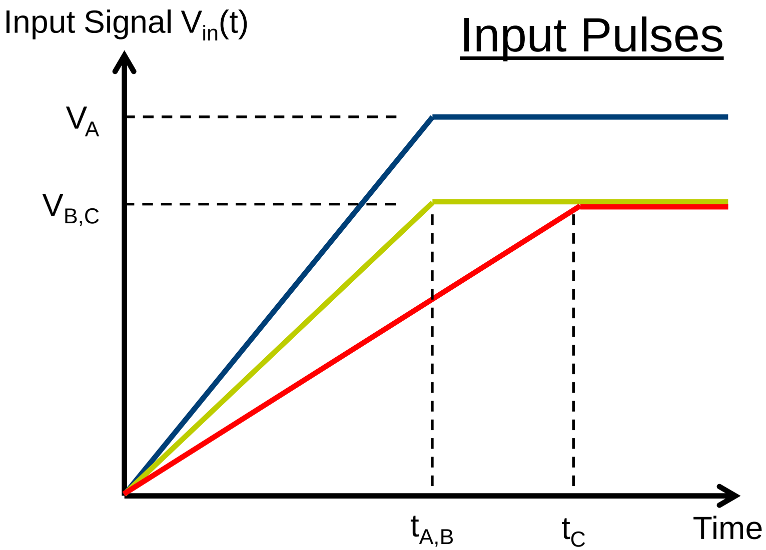


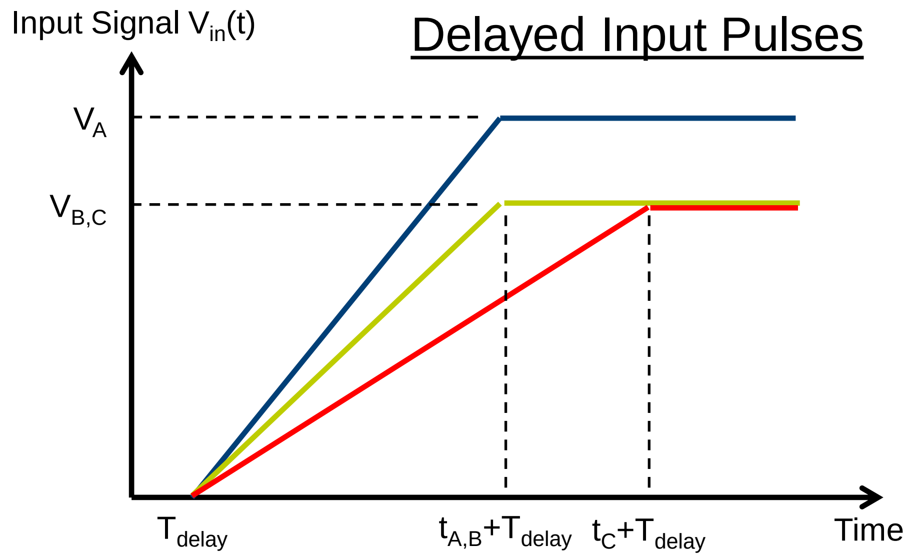
Timing – True Constant Fraction Timing (TCF) – cont'd

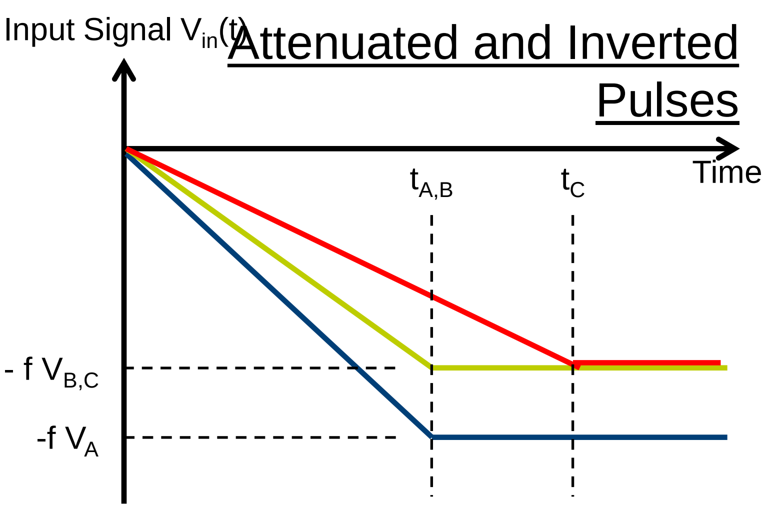


Improvement of timing resolution is rather poor if there is a large variation in rise time.

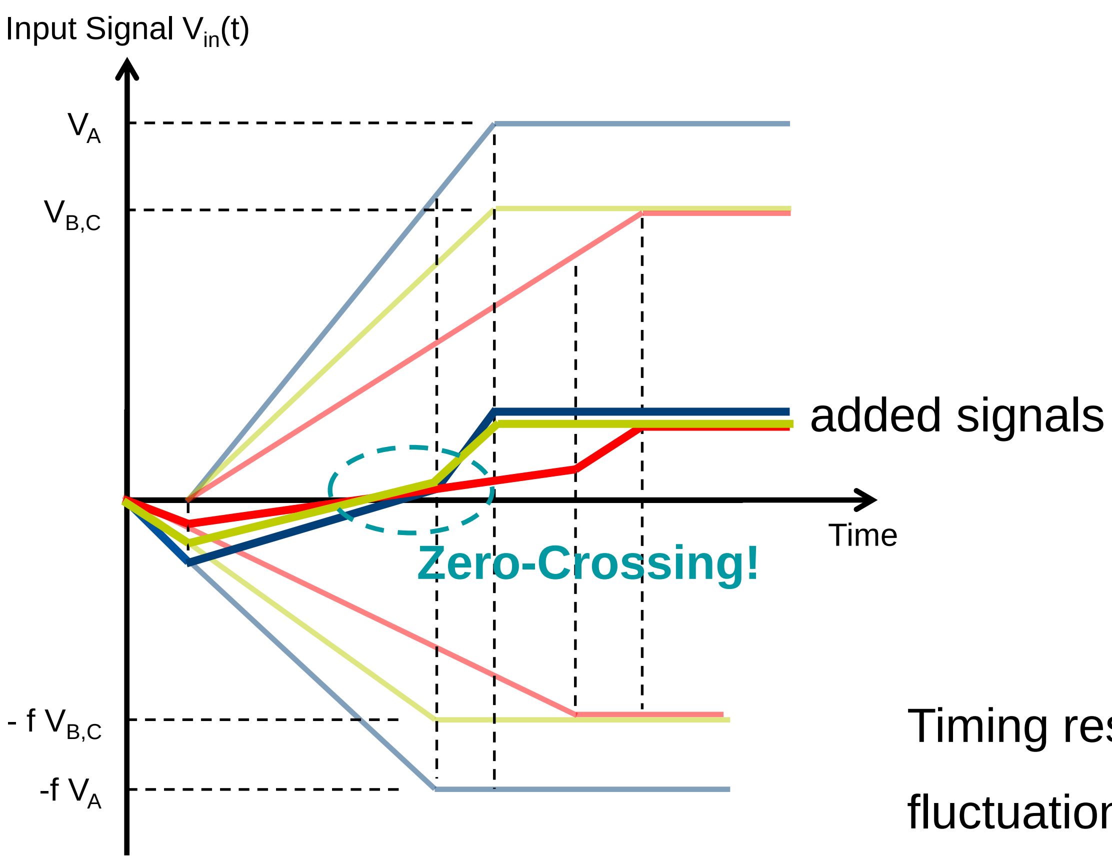
Timing – Amplitude and Rise Time Compensated Timing (ARC)







Timing – Amplitude and Rise Time Compensated Timing (ARC) – cont'd



Timing resolution is much improved for fluctuations of the amplitude as well as for variations of the rise time.

Time to Amplitude Converter (TAC)

- Before a time measurement starts all switches are closed.
- The leading edge of an arriving start signal opens the “start switch”.
  - The converter capacitor is charged.
  - Rate of charging is set by precise constant-current source.
- The leading edge of the stop signal opens the “stop switch”.
  - Charging of the converter capacitor is stopped immediately.
- $\Delta V = \frac{I_{const}}{C_{conv}} \cdot \Delta t$
- The buffered output is passed to an ADC or a MCA.
- By adding a SCA after the output, the TAC can be used to identify coincidence events between the start and stop detector.

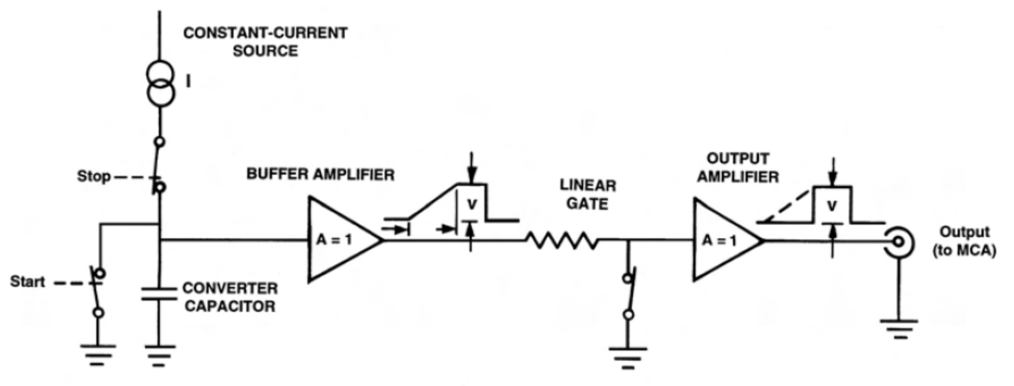
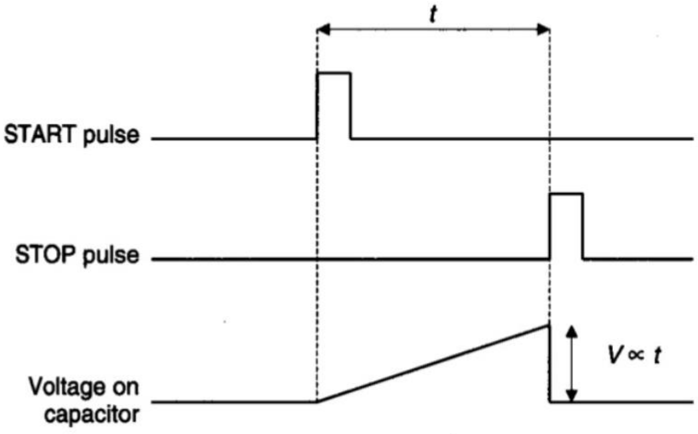


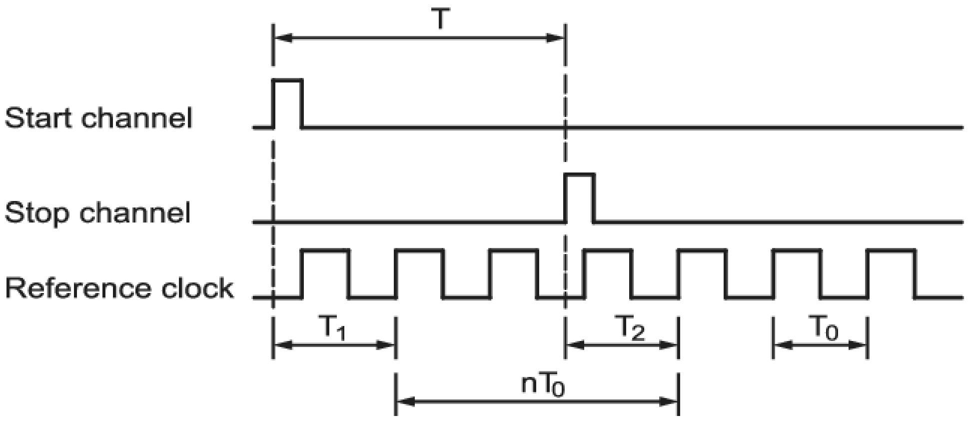
Fig. 1. A Functional Diagram of a Time-to-Amplitude Converter.

Source: ORTEC



Time to Digital Converter TDC

- In its simplest implementation, a TDC is simply a high-frequency counter that increments every clock cycle.
  - The current contents of the counter represents the current time.
  - When an event occurs, the counter's value is captured in an output register.
  - The measurement is an integer number of clock cycles.
  - The faster the clock the finer the timing resolution.
- Problem: start or stop signals are not synchronized with clock.
  - Resolution can be improved, e.g. by triggered oscillators or ramp interpolation with charging capacitors.
- Systems for multiple stops per start signal are available today (MS-TDC).



Source: ORTEC

Thank you for your attention.