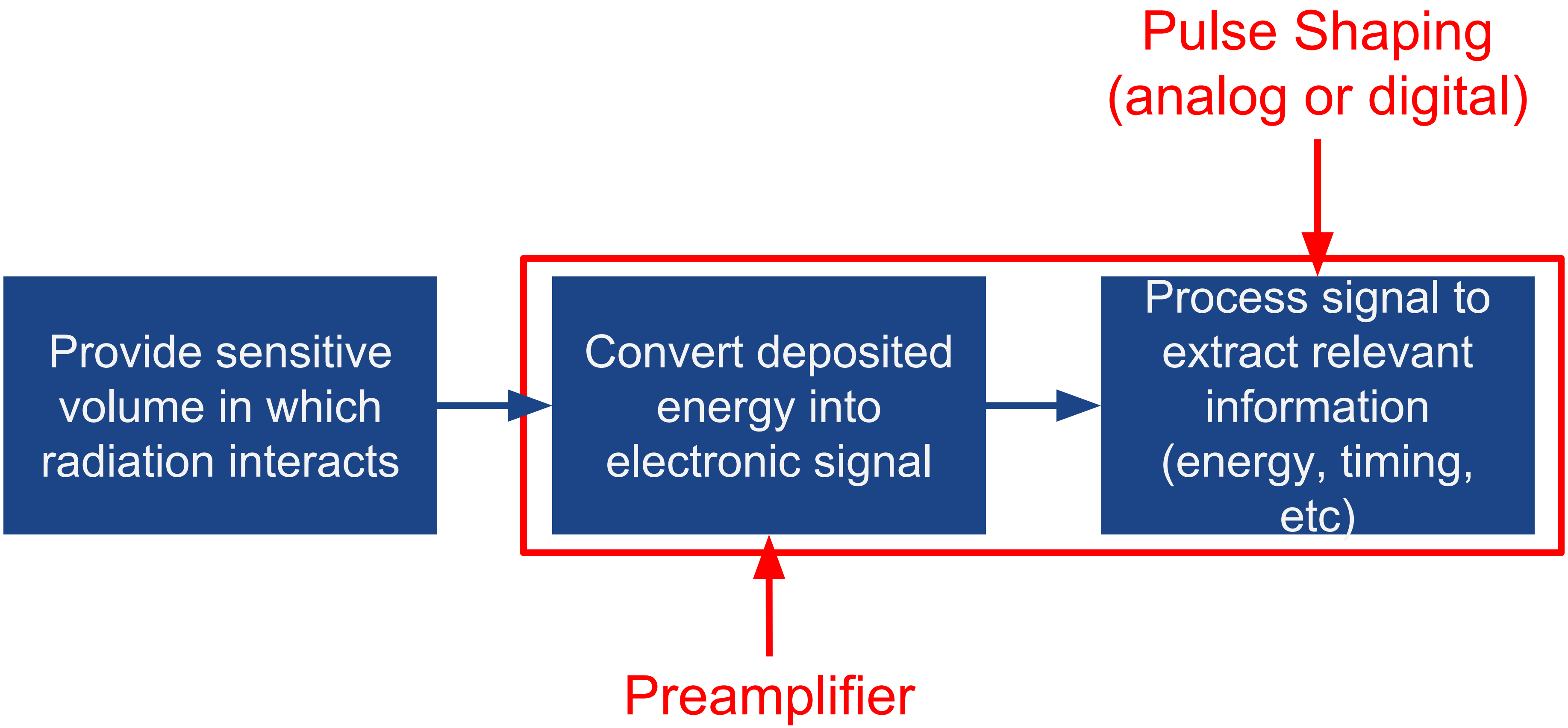
Pulse Formation and Shaping

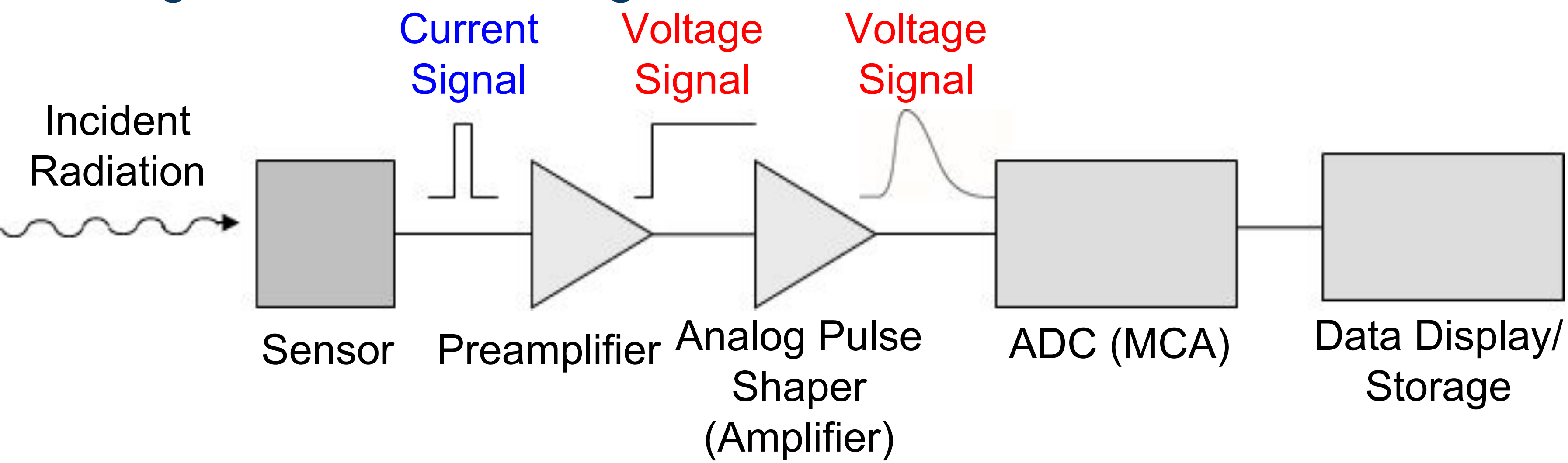


Detector Signal from Single Event

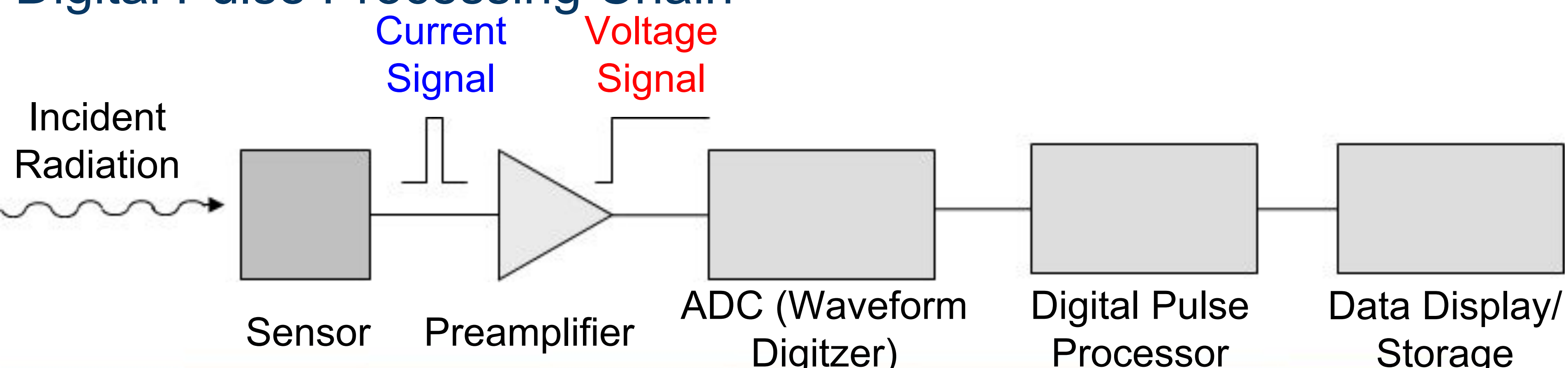
- Short current pulse (ns, μs) induced on electrode by each charge-generating event in detector
- Pulse shape depends on detector material properties, charge carrier mobility, electric field, geometry (weighting field), etc.
  - May contain information about interaction position in the detector
- Total charge delivered in the current pulse contains information about energy deposition or creating interaction
- The main goal in radiation **spectroscopy** is to measure the total charge generated by each deposition event
  - There are other applications where the goals may be different, e.g. particle tracking detectors
  - Design of signal-sensing circuits dictated by application

Spectroscopy Signal Processing Chain

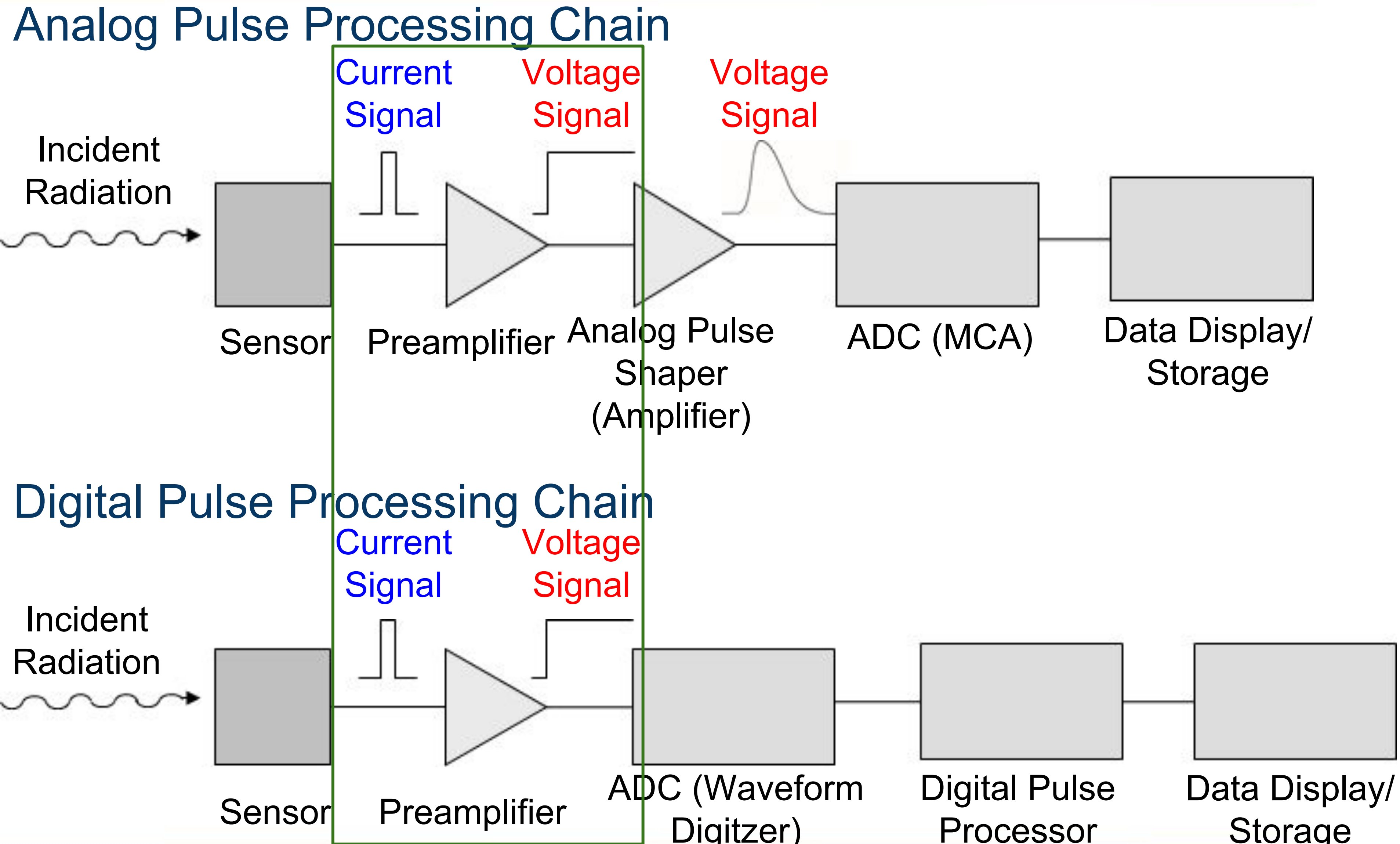
Analog Pulse Processing Chain



Digital Pulse Processing Chain



Spectroscopy Signal Processing Chain



Preamplifier Electronics

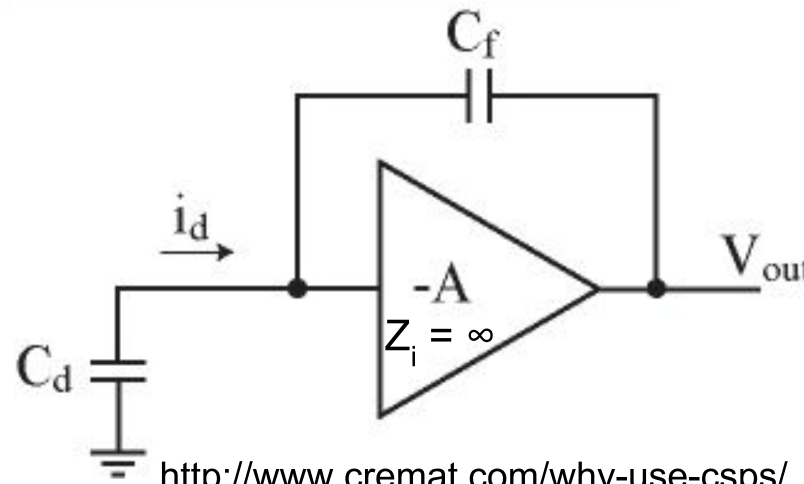
- Total charge in detector current pulse is proportional to energy deposited by interaction in detector.

$$E \propto Q_s = \int i_s(t)\, dt$$

  - Need to integrate current signal: Preamplifier!
- Desired properties for spectroscopic preamplifiers:
  - Integrate all of the signal from detector
  - High gain (CSA: V/pC)
  - Response independent of detector
  - Low noise, stable
- Further considerations based on system/application
  - Event rate, multichannel detectors, etc.
- N.B. “Preamplifier” has more to do with position in the signal chain than its role in “amplification”

Charge Sensitive Preamplifier I

- Active integrator w/ negative feedback
  - Input impedance $Z_i \rightarrow \infty$
    - No signal current through amplifier input
  - High open-loop gain (A is large)



http://www.cremat.com/why-use-csps/

Voltage difference across C_f: $v_f = (A+1)\, v_i$

$\Rightarrow$ Charge deposited on C_f: $Q_f = C_f v_f = C_f (A+1)\, v_i$

$Q_i = Q_f$ (since $Z_i = \infty$)

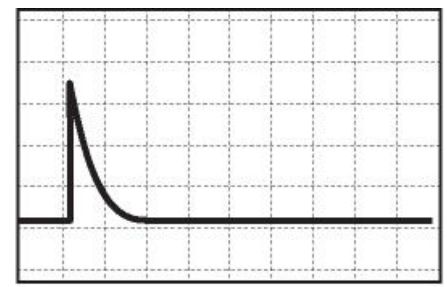
$\Rightarrow$ Effective input capacitance

$$C_i = \frac{Q_i}{v_i} = C_f (A+1)$$

Gain

$$A_Q = \frac{dV_o}{dQ_i} = \frac{A \cdot v_i}{C_i \cdot v_i} = \frac{A}{C_i} = \frac{A}{A+1} \cdot \frac{1}{C_f} \approx \frac{1}{C_f} \quad (A >> 1)$$

From [Spieler]

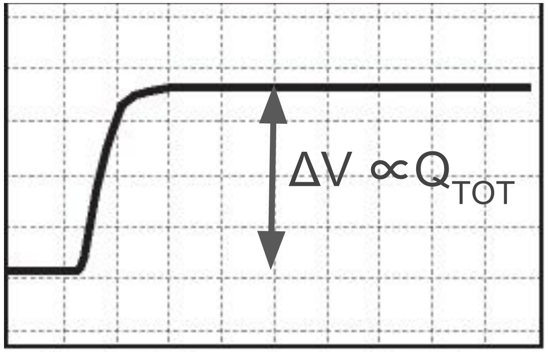


$i_d(t)$: detector current pulse: 10ns/div

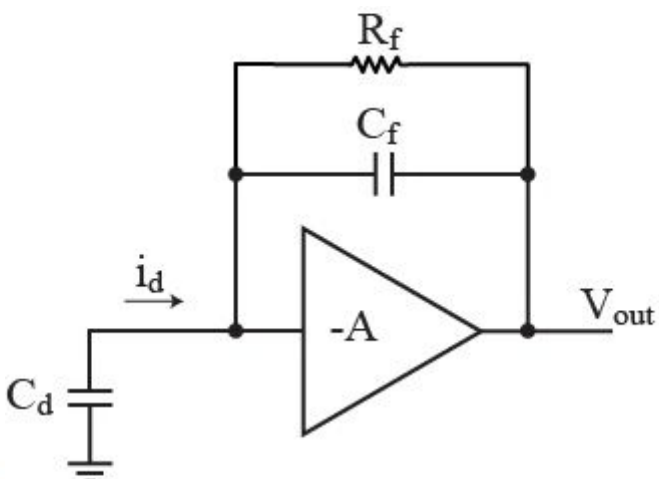
$V_{out}(t)$: CSP output pulse: 10ns/div

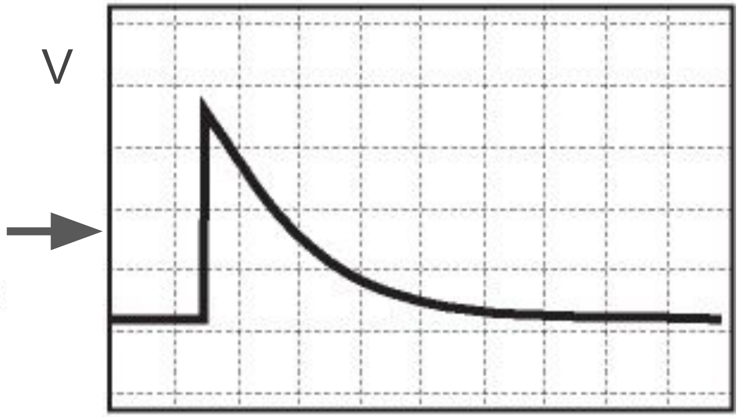
Charge Sensitive Preamplifier II

- Magnitude of voltage impulse ∝ total charge
- Rising edge contains additional information
  - Timing
  - Position sensitivity
- Resistive feedback
  - Discharge back to baseline
  - $\tau = R_f C_f >> t_{collection}$



$V_{out}(t)$: CSP output pulse: 10ns/div



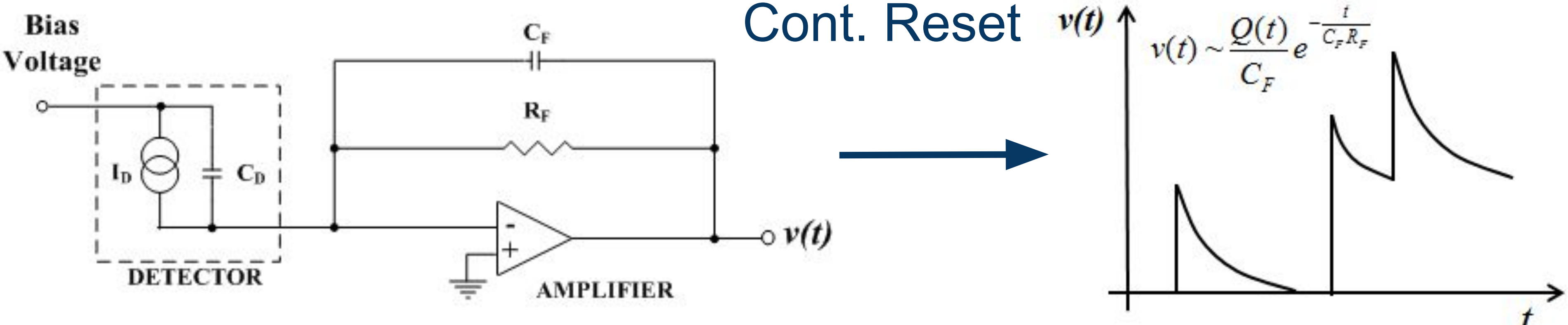


CSP output pulse: 100µs/div

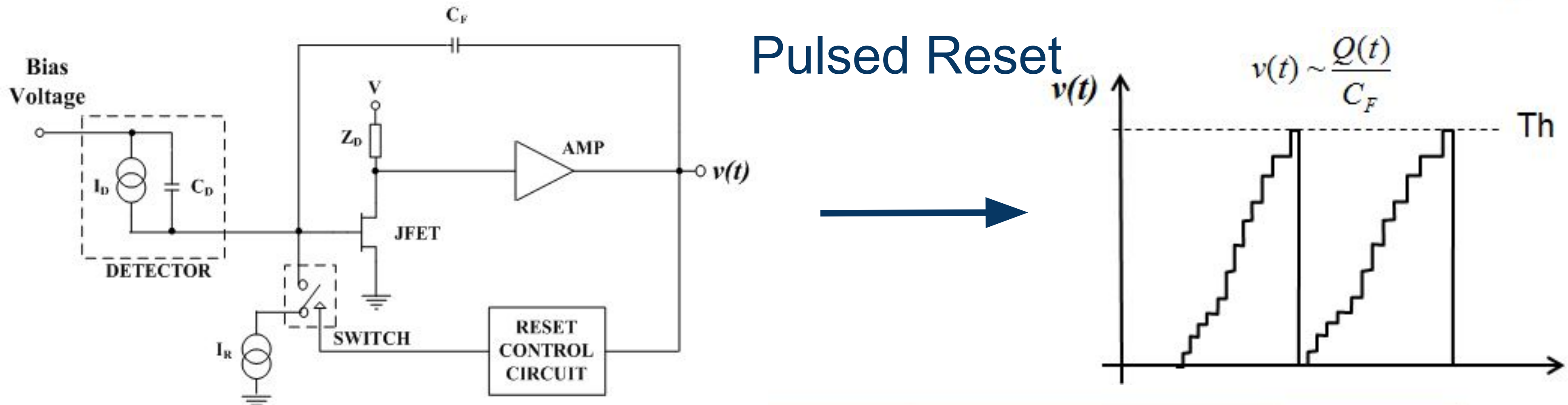
Charge Reset

- Continuous (passive) reset may not be ideal
  - High rates can cause DC voltage to exceed supply: "lock-up"
  - Thermal noise in R_f bad for ultra-low noise applications

Cont. Reset

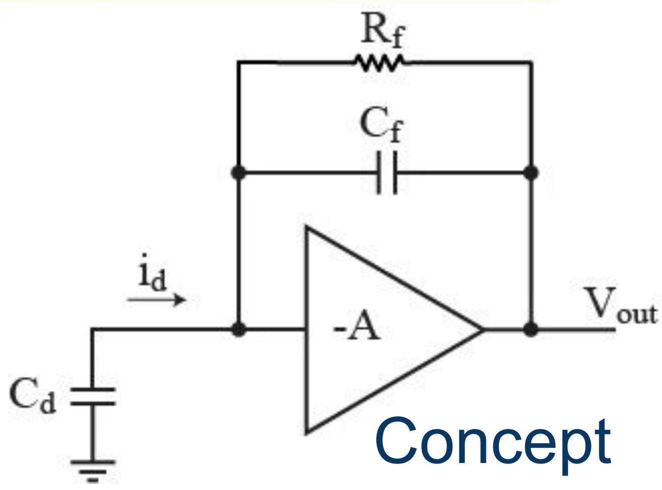


Pulsed Reset



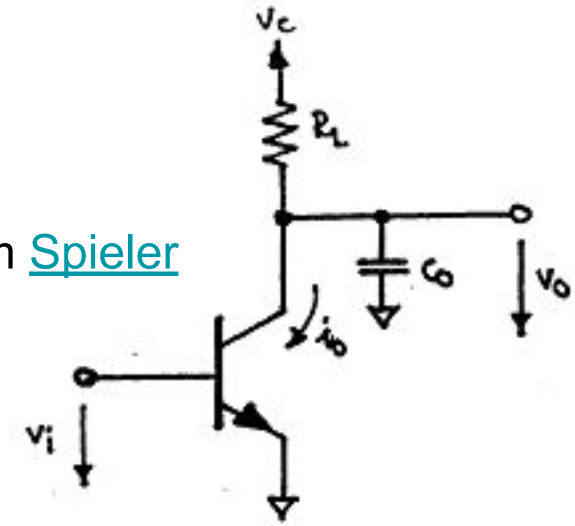
Realistic Charge Sensitive Preamplifiers

- Cartoon illustrates operating principles, but assumes idealized components
  - Infinite input impedance, infinite speed
- Real CSA designs requires consideration of many more factors
  - Frequency response (impedance)
  - Timing characteristics (slew rate)
  - Matched input impedance for multichannel systems
  - Etc.
- Spieler is an excellent resource addressing these considerations



Concept

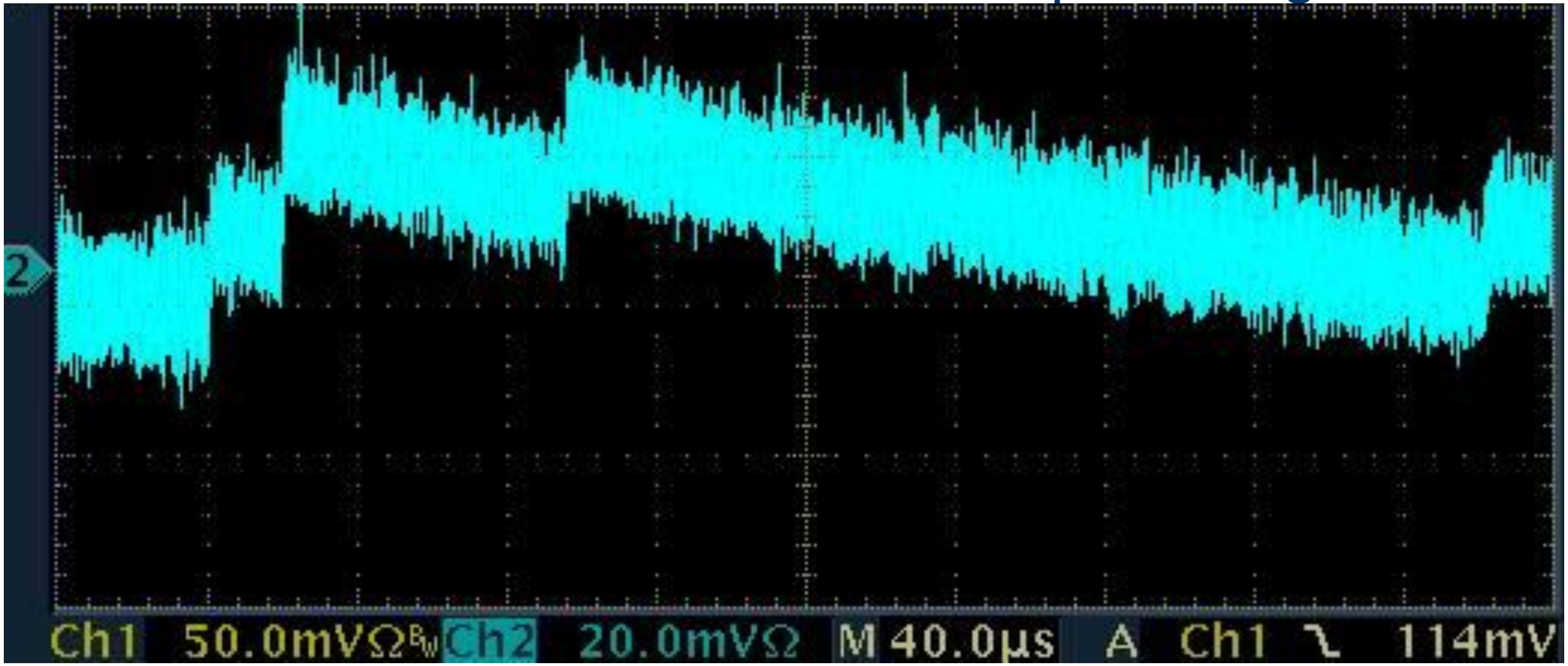
From Spieler



Implementation

Output of Preamplification Stage

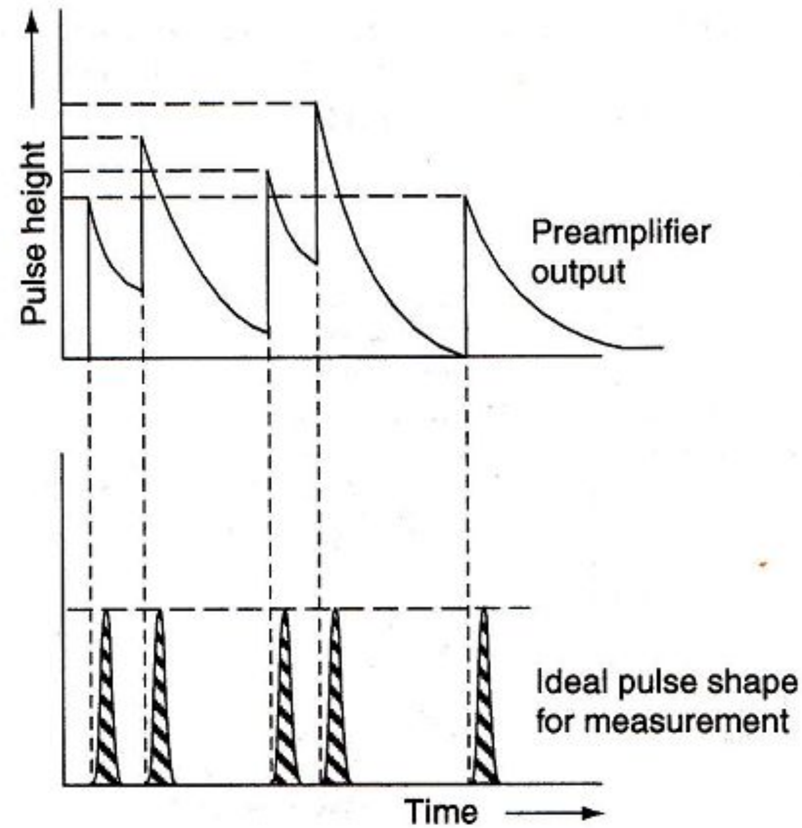
- Successfully converted detector signal to a step voltage, but…
  - Poor signal-to-noise ratio
  - Continuous reset preamps have long tails → pulse pileup
  - Tail pulse shape
- Not suitable for direct measurement of peak-height



http://www.cremat.com/why-use-csps/

Pulse Shaping I

- Spectroscopic information in magnitude of voltage step from preamplifier
  - Pulse height ∝ energy absorbed
- Maximize SNR
  - minimize noise contributions to energy resolution
- Optimum shaping depends on:
  - Noise spectrum for system
  - Requirements for pile-up free counting
- N.B. the original shape of the signal is lost!
  - Pulse shape analysis



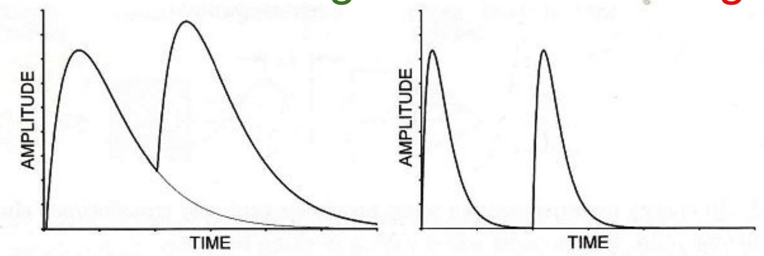
Gilmore 4.12

Pulse Shaping II

- Pulse shaping is full of trade-offs
- Example 1: SNR vs. Rate capability
  - SNR is often improved by limiting high-frequency response (LP filter)
  - This broadens the pulse, reducing rate capabilities
- Example 2: SNR vs. Peak Detect
  - Optimal pulse shape for maximizing SNR = cusp
  - Sharp peak not optimal for MCA
- “Optimum” shaping driven by application

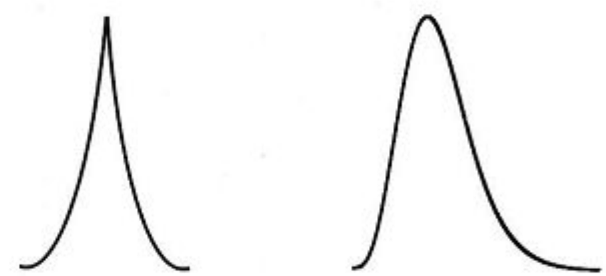
Better HF Noise Filtering

Worse HF Noise Filtering



Increased Pileup

Reduced Pulse Pileup

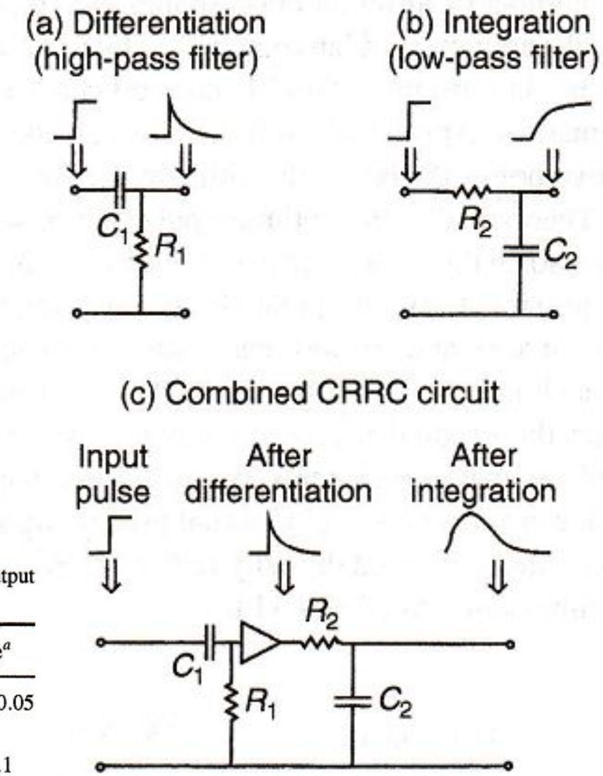


Theoretical Optimum for SNR

Finite peak width better for MCA

Review: Analog Signal Shaping

- Analog pulse shaper often implemented as CR-(RC)^n network
  - Unipolar, Gaussian-like (high n increases symmetry)
  - CR = differentiator (HP filt.)
  - RC = integrator (LP filt.)



Gilmore 4.13

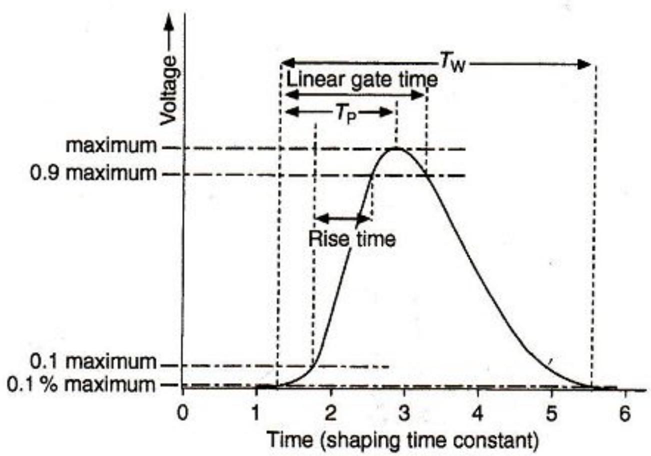


Table 4.1 Measured timing factors for semi-Gaussian output pulses

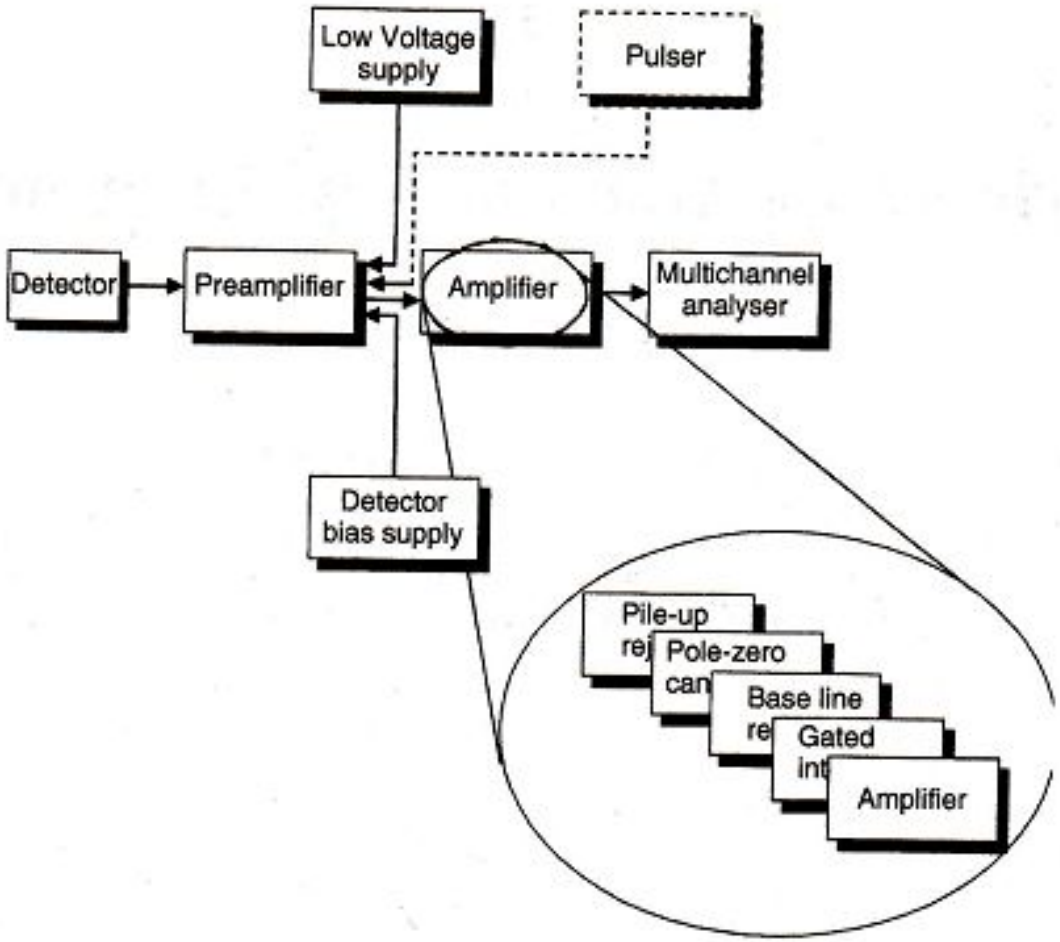
Factor	Time interval	Symbol	Time[a]
Rise time	0.1 to 0.9 of pulse maximum	—	1.26+0.05
Peaking time	threshold[b] to maximum	T_P	2.1+0.1
Linear gate time	threshold to 0.9 of max. beyond max.	T_{LG}	2.6+0.2
Width	threshold to threshold	T_W	5.6+0.5

[a] Time is specified in units of time constant.
[b] The threshold used was, as near as possible, 0.1 % of peak maximum.

Typical semi-gaussian pulse resulting from CR-RC^n shaping network. Listed times normalized by shaping time constant

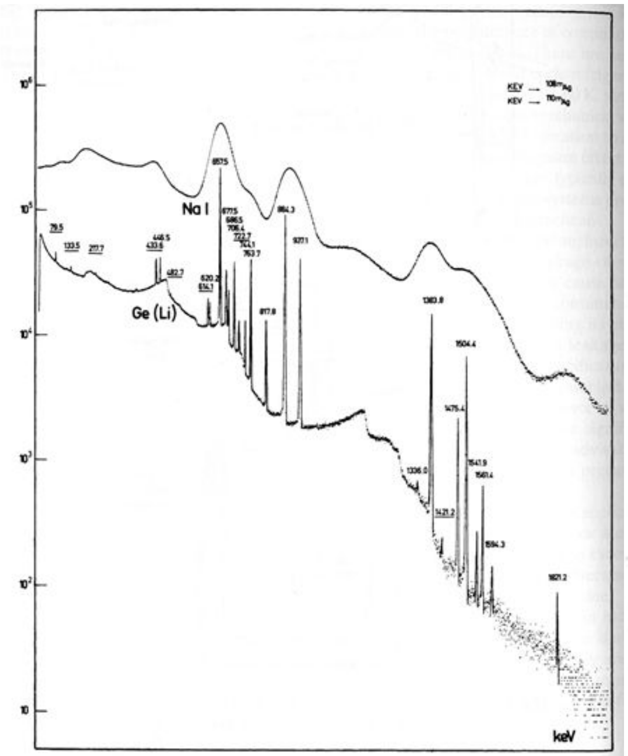
Review: Analog Signal Shaping

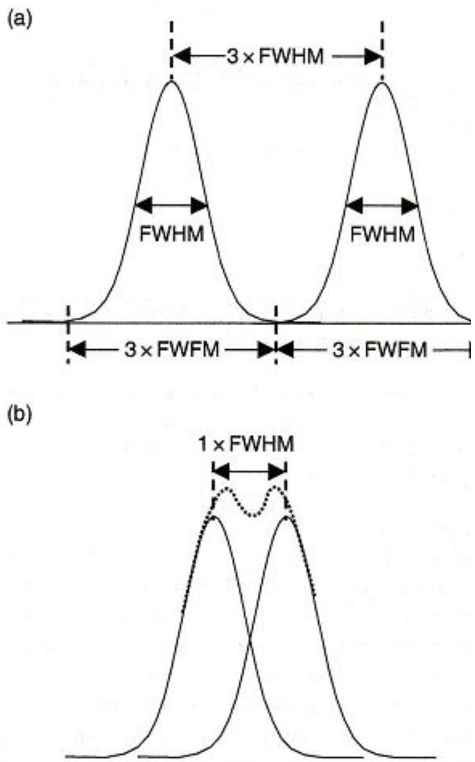
Functions of the "Spectroscopic Amplifier"



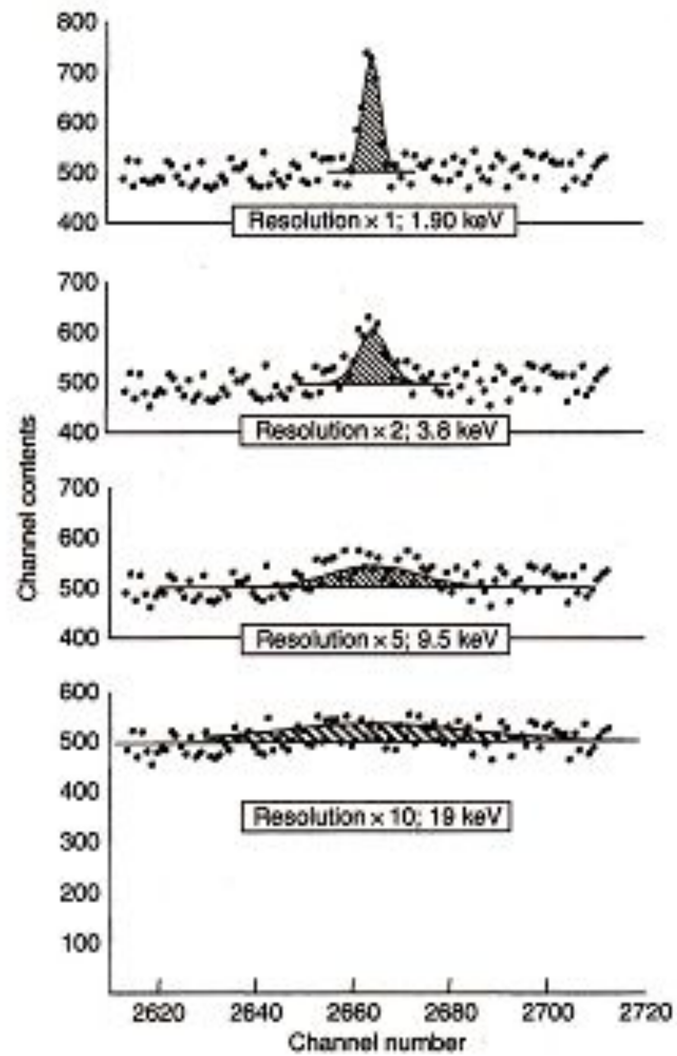
Energy Resolution

- Energy resolution is paramount for spectroscopy
  - Ability to identify features
  - Sensitivity





Gilmore 6.1

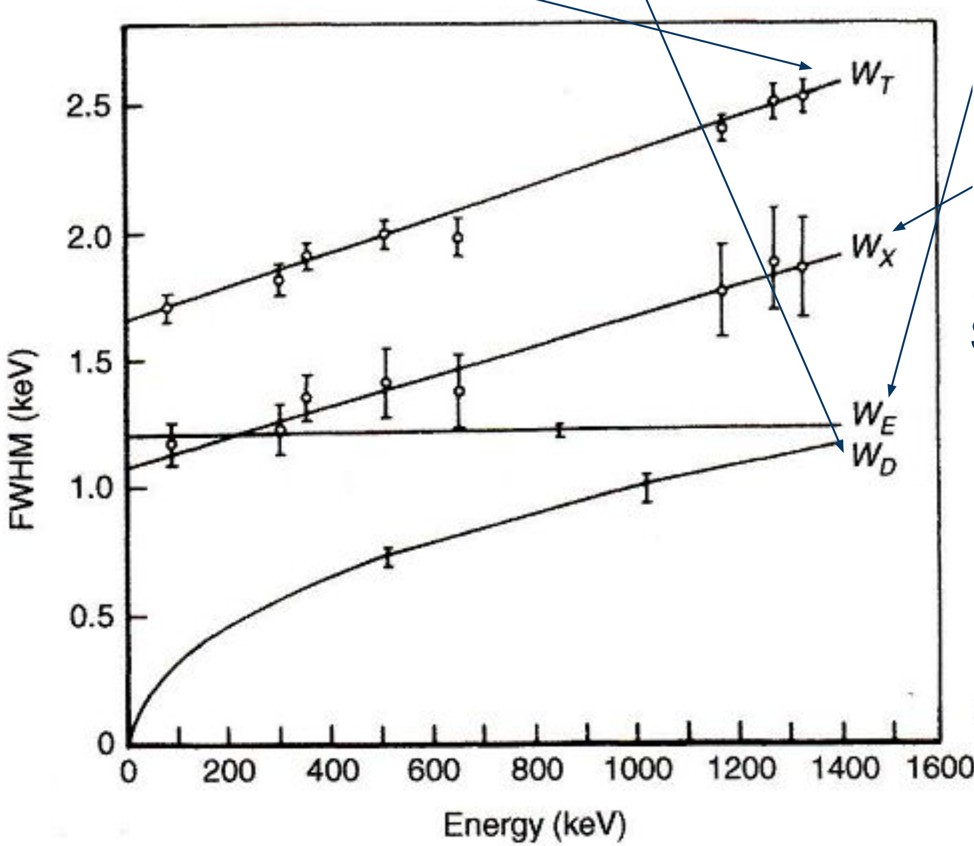


Gilmore 6.2

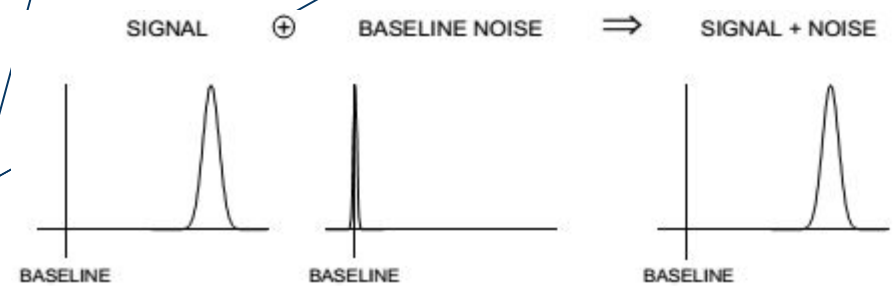
Electronic Noise & Energy Resolution

- Several sources of variability contribute to overall energy resolution

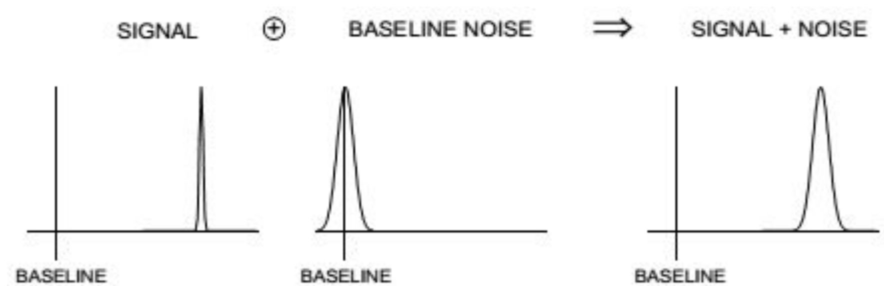
$$(\Delta E_{total})^2 = (\Delta E_{stat})^2 + (\Delta E_{electronics})^2 + (\Delta E_{charge\text{-}loss})^2$$



Knoll 12.11



Signal Variance >> Noise: e.g. Scintillator



Signal Variance << Noise: e.g. HPGe

From Spieler

Sources of Electronic Noise

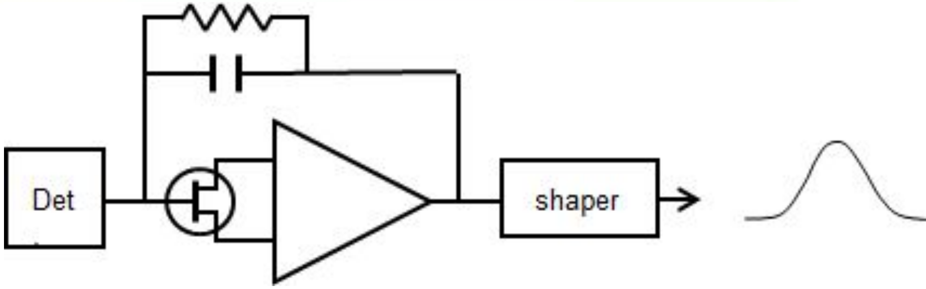
- Detector leakage current - shot noise
- Noise in FET - thermal effects & shot noise
- Continuous-reset preamplifier: thermal noise in feedback resistor
- Transistor-reset preamplifier: leakage current through reset element
- 1/f “flicker” noise

Noise Dependence on Shaping Time

Series (or voltage) noise

$$ENC^2 \sim (4kTR_S + e^2_{na})\, C_d^{\,2}\ 1/\tau$$

(Johnson noise associated with series resistance and the thermal noise of the FET)



Parallel (or current) noise

$$ENC^2 \sim (2qI_L + 4kT/R_f)\,\tau$$

I_L – full shot-noise leakage current

(Fluctuations in the (**surface** or **bulk**) leakage current)

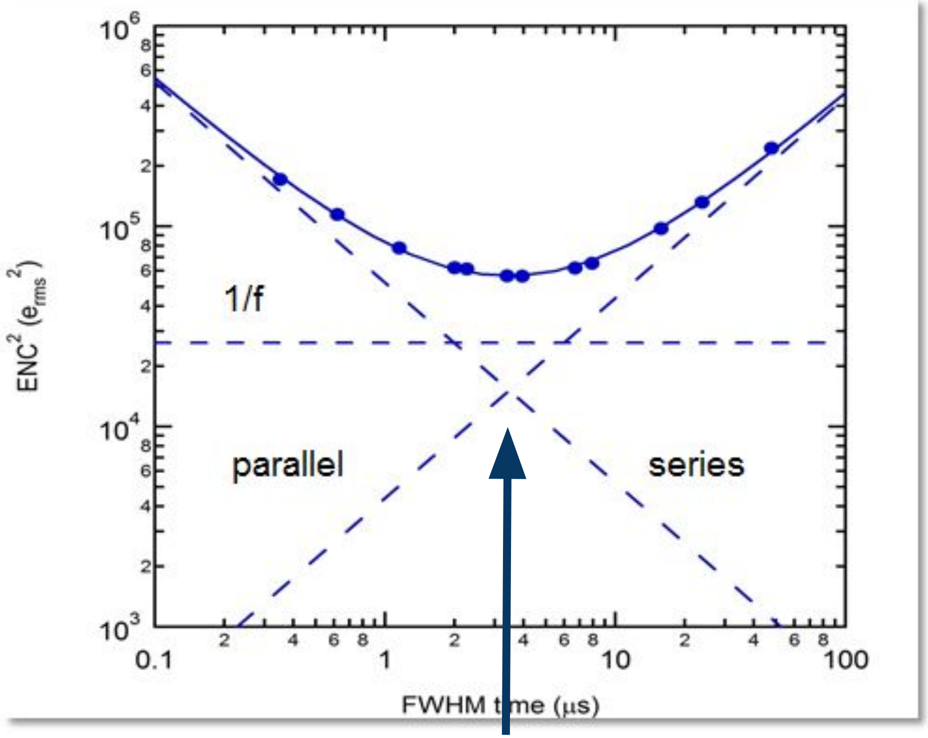
1/f noise

$$ENC^2 \sim A\, C_d^{\,2}$$

Trapping/Detrapping effects in FET, ...

(capture and release of charges in the input FET, **not** dependent on shaping time)

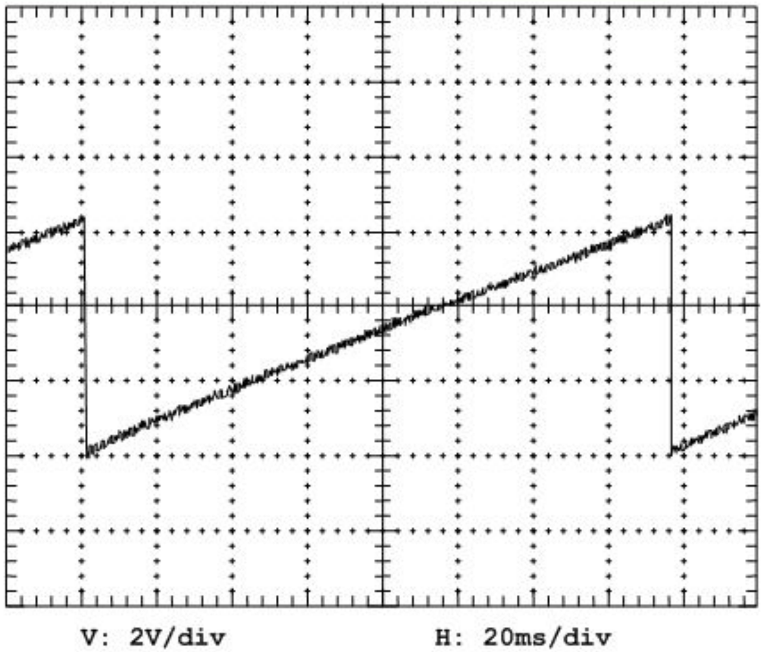
N.B. ENC: Equivalent Noise Charge [e_{RMS}]



“Noise Corner” = Optimum SNR

Leakage Current

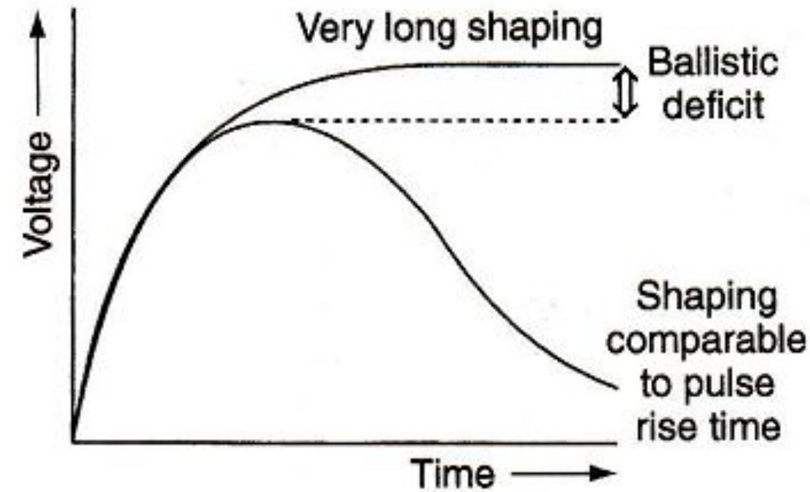
- Source of charge seen at preamplifier output
  - ∴ sometimes referred to as “step” noise
- Bulk leakage current
  - Thermal excitation of charge carriers across bandgap
    - $\propto T^{3/2}\exp(-E_g/(2kT))$
- Surface leakage
  - Channeling/contamination on surf.
  - Mitigate with clean processing, guard rings
- Short shaping times to mitigate effect on energy resolution



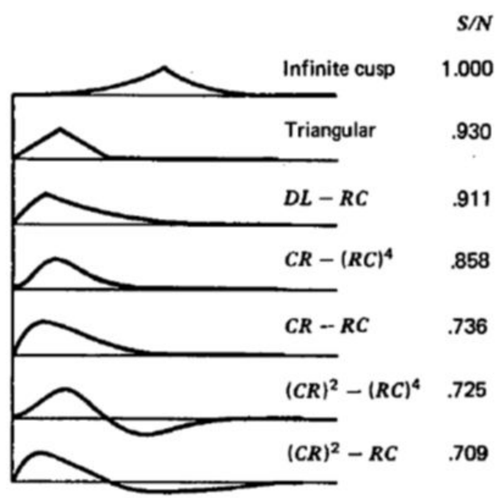
Leakage current seen on output of transistor-reset preamplifier

Ballistic Deficit

- Short shaping time desirable in many circumstances
    - Reduce pileup
    - Minimize parallel noise contributions
- Shaping time on order of pulse rise time → ballistic deficit
    - Charge collection / pulse shape variability
- Can be avoided with trapezoidal shapers
    - Introduce “flat-top” w/ duration>= maximum charge collection time



Gilmore 4.17

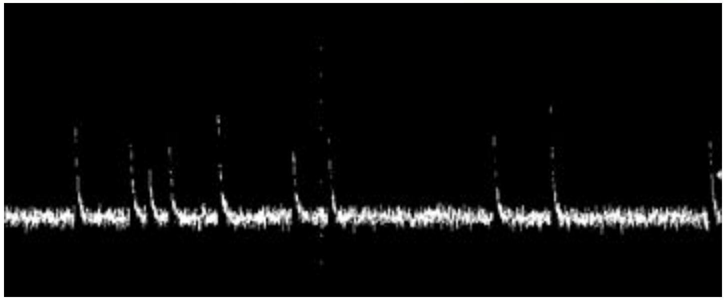


Add flat top for BD

Knoll 17.24

Pulse Pile-up I

- Consequence of random nature of radioactive decay
  - Poisson random process



$$P(x) = \frac{(\bar{x})^x e^{-\bar{x}}}{x!}$$

r – average rate of detector event occurrence

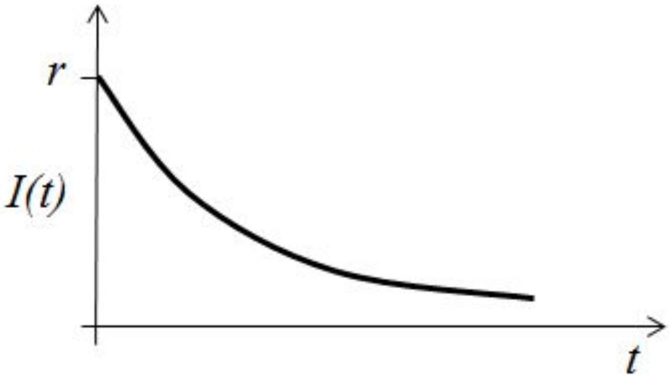
rdt – probability of event occurrence in time interval dt

$$P(0) = \frac{(rt)^0 e^{-rt}}{0!}$$ probability of no event in time interval ***0*** to ***t***

$I(t)dt$ - probability of next event occurrence after delay

of ***t*** relative to previous event:

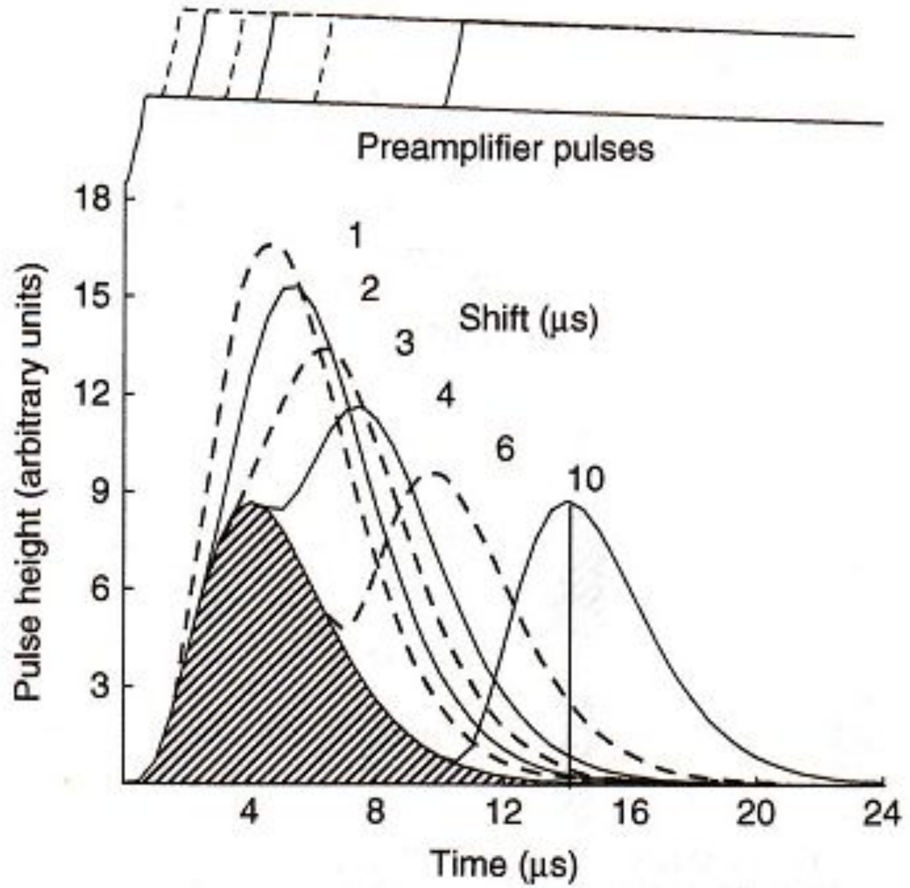
$$\boxed{I(t) = re^{-rt}}$$



$I(t)$ - distribution function of time intervals between adjacent random events

Pulse Pile-up II

- Analog shapers often include "pile-up rejection" circuits
- Information from pile-up pulses is often recoverable
- Digital domain
  - Adaptive filtering
    - Signal shape depends on rate
  - Pile-up flagging
    - Record pile-up events for subsequent processing



Pulse Pileup from CR-RC^4 shaping network with T_{shape} = 1μs (Gilmore 4.22)