AMETEK
MATERIALS ANALYSIS DIVISION

AMPTEK

IEEE NPSS Short Course 2017

Front End Electronics for Radiation Detection & Measurement

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Outline

1. **Overview**
   1. *Purpose of front end electronics in radiation measurement*
   2. *Example system*
   3. *Major challenges*
2. **Signal Acquisition**
   1. *Current pulses*
   2. *Charge sensitive amplifiers*
   3. *Pulse shaping*
   4. *Gain*
3. **Electronic Noise**
   1. *Example: Shot noise*
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   3. *Pulse shaping and noise*
4. **Timing**
   1. *Dead time*
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   3. *Measuring timing*
5. **Pulse Shaping Revisited**
6. **Digitizing the Output**
7. **Why Things Don't Work**
   1. *Practical matters*
   2. *Interference*

- This presentation was presented at the “Short Course on Radiation Detection and Measurement”, which was part of the 2017 IEEE Nuclear Science Symposium, in Atlanta, GA.
- This version, available online, has some additional tutorial information which has been added. A set of notes with additional info is also available.
- Amptek recommends these notes as an introduction to electronics for radiation detection and measurement and as a useful guide to many of Amptek’s customers.

- **Acknowledgement**
    - *Dr. Helmuth Spieler, of the Lawrence Berkeley National Laboratory, taught this short course at the IEEE/NPSS many years*
    - *This presentation draws very heavily on the notes from this class and from his textbook. His textbook (listed in the references) has derivations for many points made in this presentation.*

1. Overview

Overview: Sample system

- **Ionization chamber**
  - *Particle deposits energy, creates mobile electron-ion pairs*

$$N_{sig} = E_{dep} / \varepsilon_i \qquad Q_{sig} = N_{sig} q_e$$

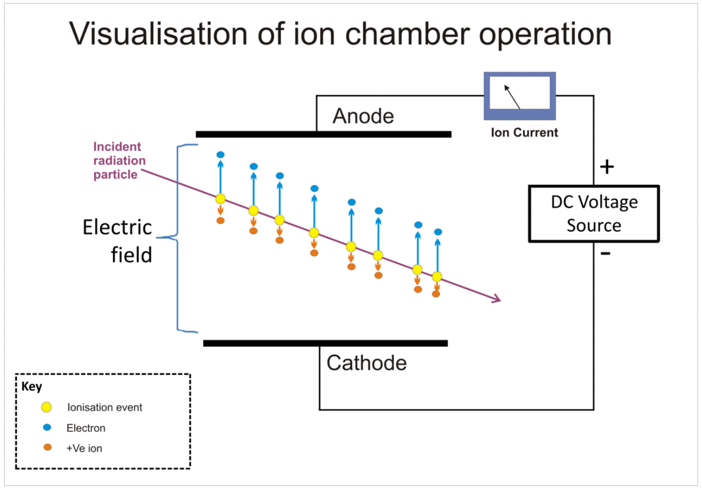
ε_i is ionization energy, ~30 eV in gas→ hundreds or thousands of electrons

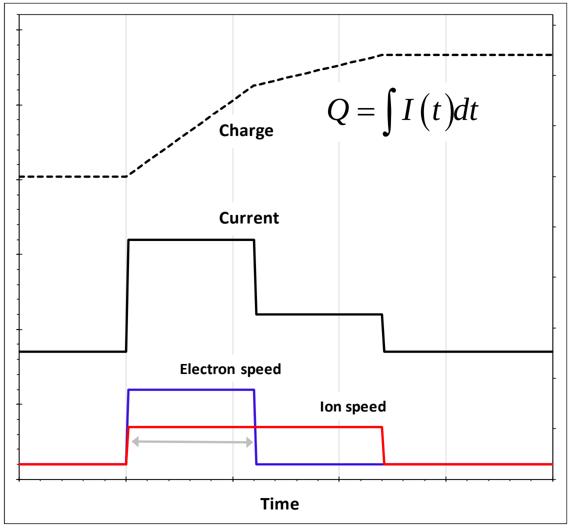
  - *Electric field moves carriers towards electrodes, inducing a current*

$$I_{sig} = Q_{sig} / T_{drift} = q_e N_{sig} / \left(L_{drift} / v_{drift} \right)$$

V_{drift} is drift velocity, L_{drift} is drift length, T_{drift} is drift time

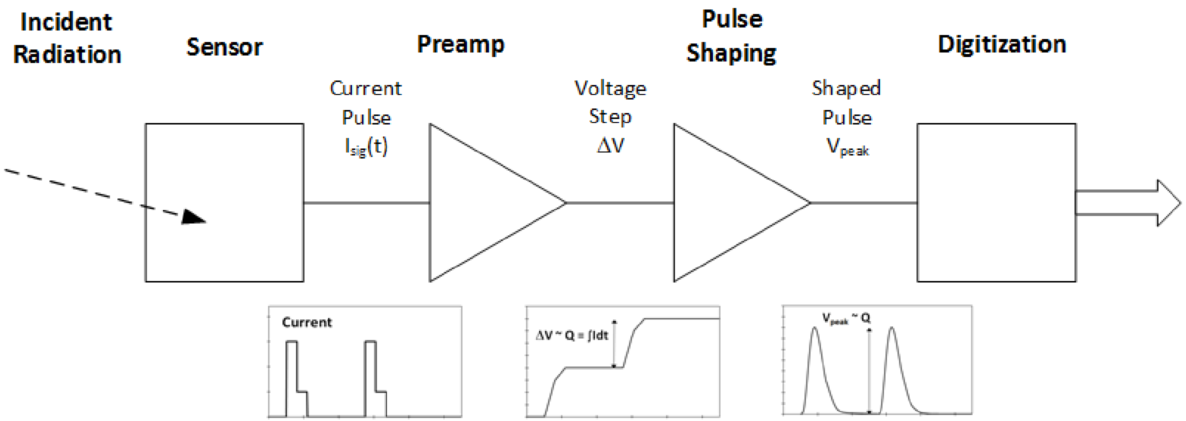
  - *Each interaction produces a discrete current pulse I(i) of some duration*
  - *To determine energy, one measures charge*





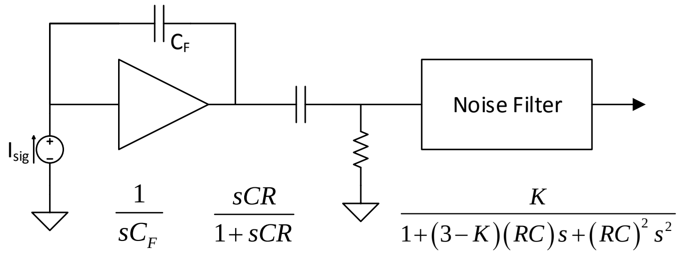
Overview: Purpose of front end electronics

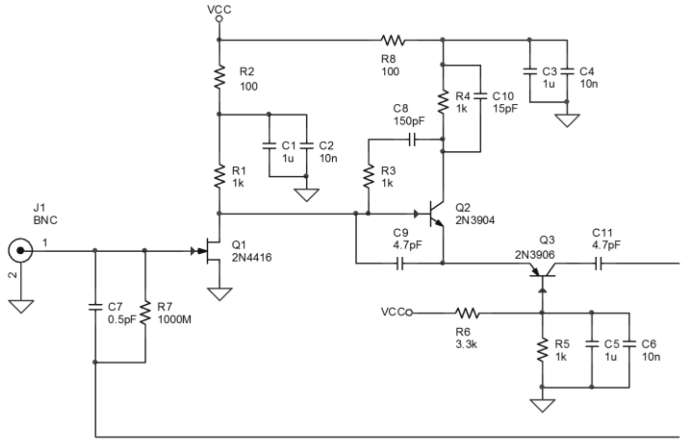
- *Radiation deposits energy in a detection medium*
- *Energy is converted into an electrical signal*
  - Primary signal is charge proportional to energy absorbed
  - Results in a short and small current pulse
- *Tailor the time and frequency response ("shape" the pulse)*
  - Not always necessary but always present in some form
  - Must optimize for something: rate, noise, timing, etc
- *Digitize the output and store for subsequent analysis*
  - Count rate over threshold, count timing, digitized pulse heights
- *Although detection systems look different and use radically differing technologies, all share common purpose and key functions*



Overview: Goals

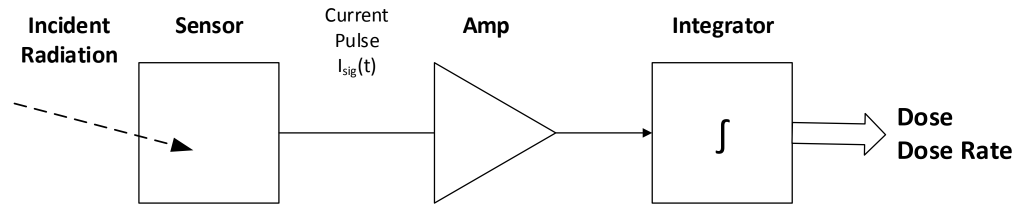
- **Course Goals**
  - *Understand the major challenges, trade-offs and compromises*
  - *There are no "one-size fits all" solutions!!*
- **Signals and Systems vs Hardware Components**
  - *Signals and system are the focus of this course*
    - Block diagrams, transfer functions → Defines functionality and performance
  - *Hardware components are the workhorse*
    - Schematics, components → Really do the job – outside the scope of this course



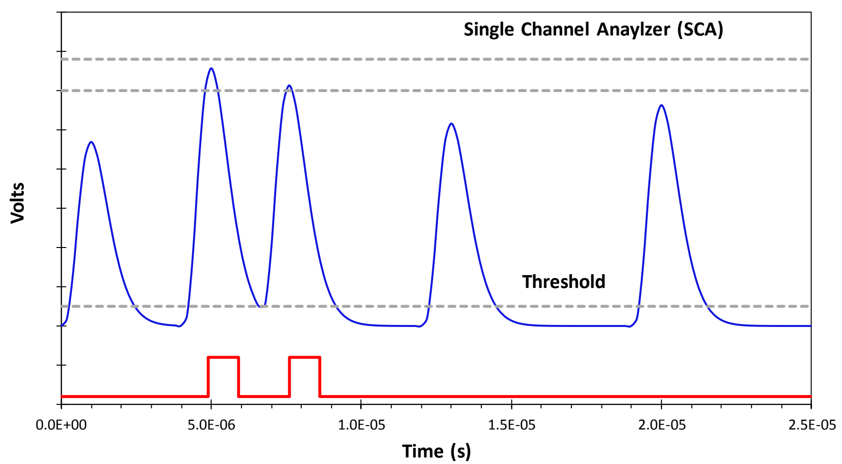


Overview: Operating Modes

- *Measure continuous current → Dose rate or dose*

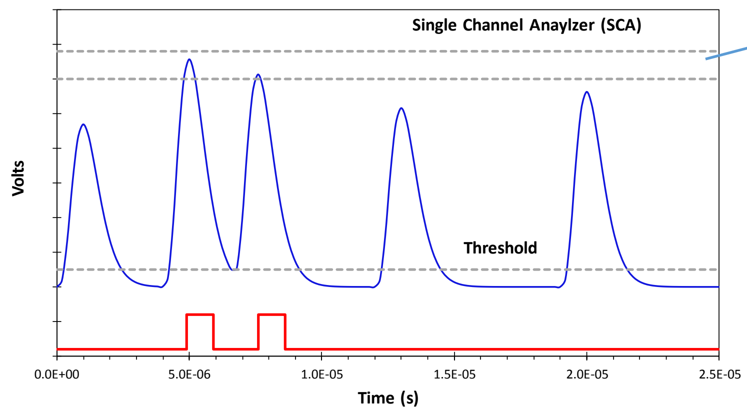


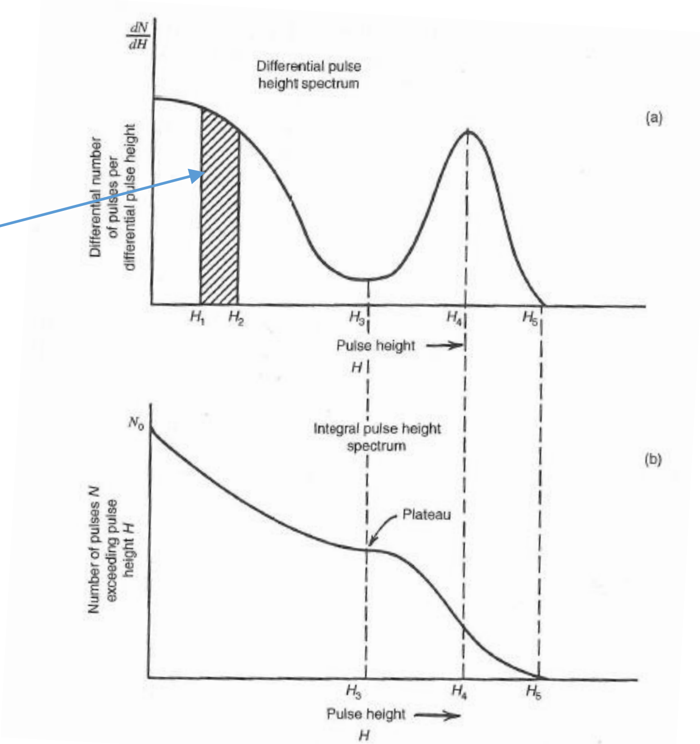
- *Measure each pulse → Counts, spectroscopy, timing, etc*
    - Focus of this course
    - System response is in <u>counts</u> or counts per unit time
    - Counts are <u>discrete</u> and <u>stochastic</u> → Counts-per-sec, not Hz
    - Electronics optimize signal to noise ratio, then increment a counter at output



Overview: Operating Modes

- *Typical pulse information*
  - Total rate → Count pulses above threshold
  - Rate of a peak → Count pulses in pulse height window
  - Energy spectrum → Differential or integral pulse height histogram
  - Pulse timing: Coincidence or measured delay
  - Pulse shape: Risetime or duration or decay
  - Difference in pulse heights





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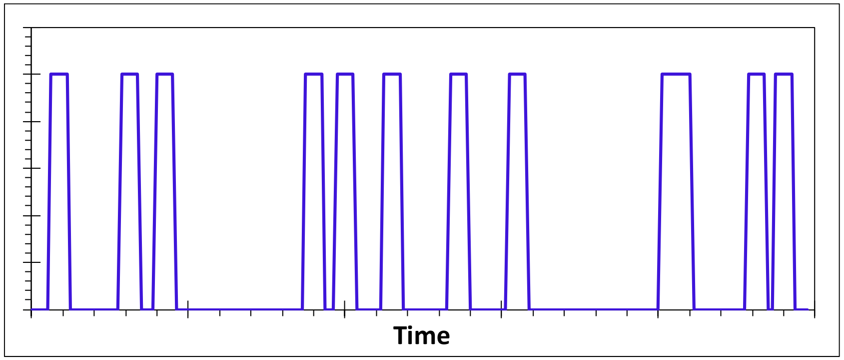
Overview: Challenges

- **Challenge 1: Timing is random**
- **Challenge 2: Precision is limited by fluctuations**
- **Challenge 3: Variations in current profile and in charge collection**
- **Challenge 4: Practical matters**

Overview: Challenges

Challenge 1: Random timing

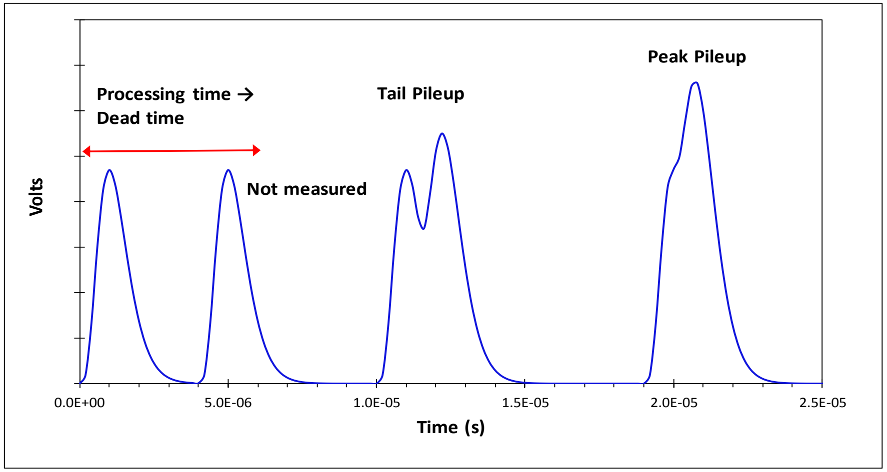
- *Random sequence*
  - Not periodic: cps, not Hz
  - Short intervals always possible



- *Random fluctuation in number of counts*
  - Well known binomial distribution → $\sigma_N = \sqrt{N}$ → $\sigma \sim 1/\sqrt{N}$
  - Want lots of counts and want high count rates

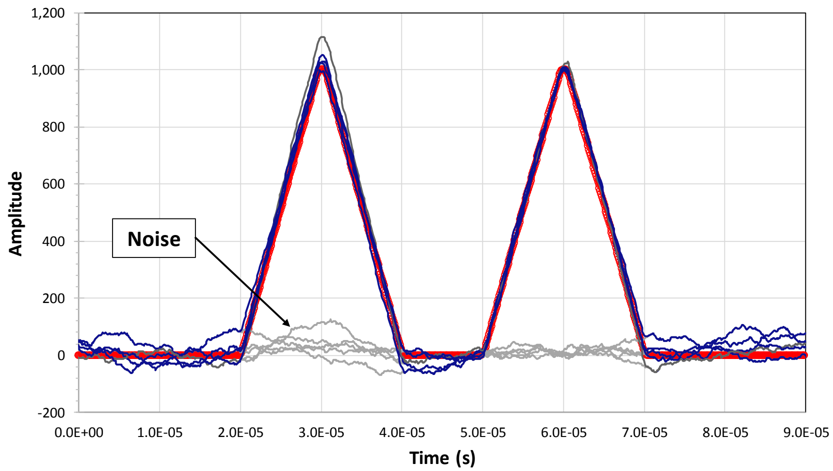
- *Random pulse overlap in time*

  Always some time to process a pulse
  - Dead time → Pulses not detected
  - Tail pile-up → Pulse height error
  - Peak pile-up → "Sum" peaks



Overview: Challenges

- **Challenge 2: Precision limited by fluctuations**
  - *Fluctuations in radiation interaction (scattering)*
  - *Fluctuations in signal charge for same energy absorption*
  - *Fluctuations in baseline from intrinsic noise*
    - Random fluctuations in current : Shot noise, thermal noise, 1/f noise, G-R noise

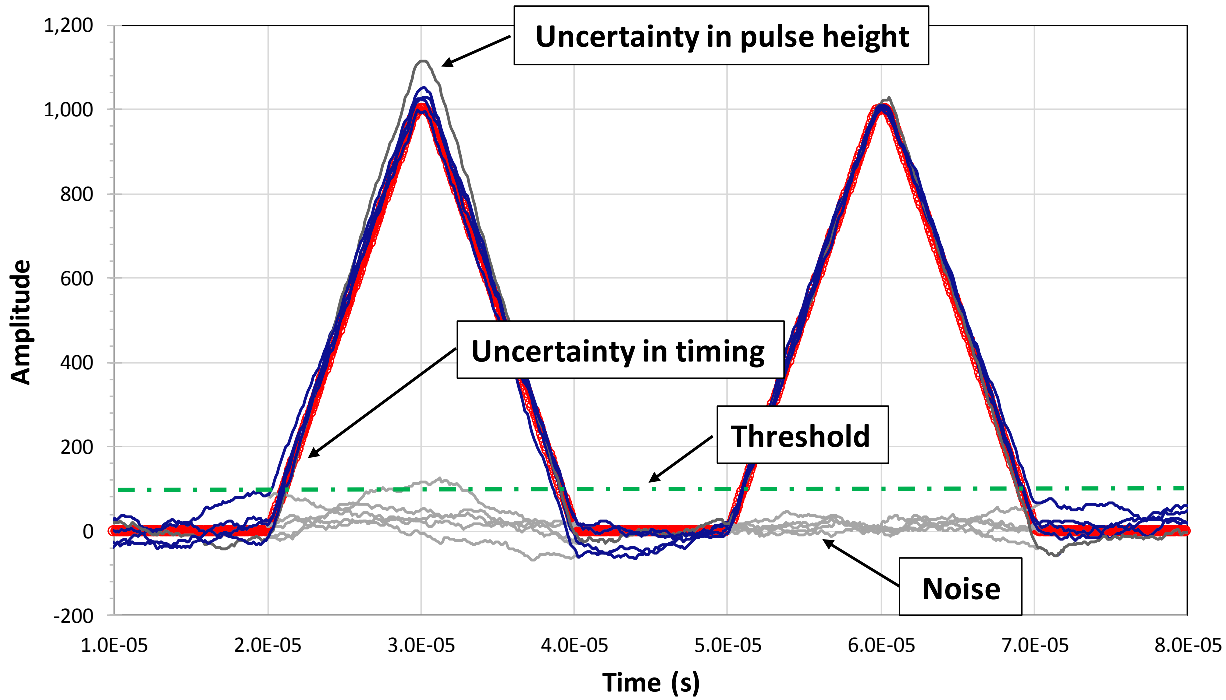


  - *Total fluctuation*
    - Uncorrelated fluctuations add in quadrature

$$\delta E_{Tot} = \sqrt{\delta E_{Fluc}^2 + \delta E_{Noise}^2}$$

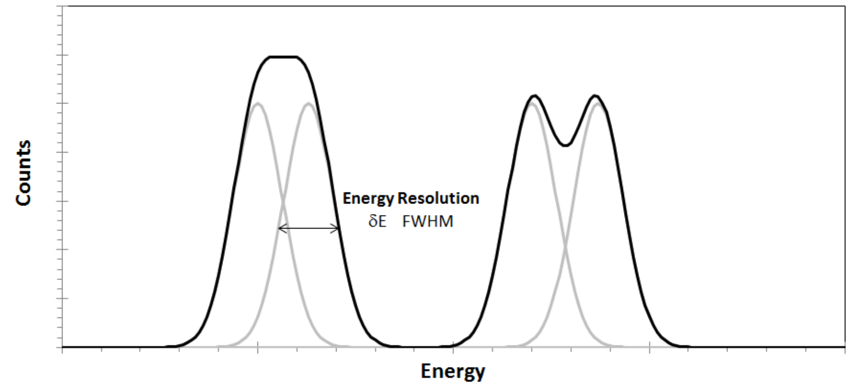
Overview: Noise

- **Noise causes fluctuations in the baseline; pulses ride on top**
- **Consequences of noise**
    1) *Creates a minimum threshold, below which signal cannot reliably be detected*
    2) *If threshold is set too low, you get false counts, an erroneous measurement*
    3) *Noise → fluctuation (uncertainty) in pulse height measurement*
    4) *Noise → fluctuation (uncertainty) in timing measurement (start time, slope, shape)*

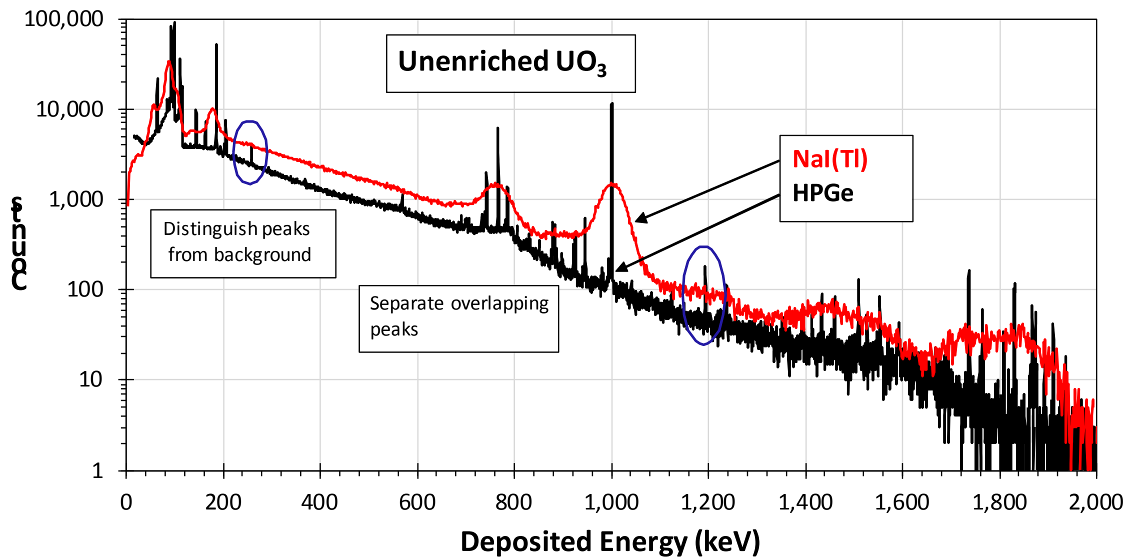


Overview: Resolution

- **Resolution**
  - *If two peaks are separated by > FWHM, there is a valley → they are resolved*
  - *Resolution in energy, timing, position, etc*



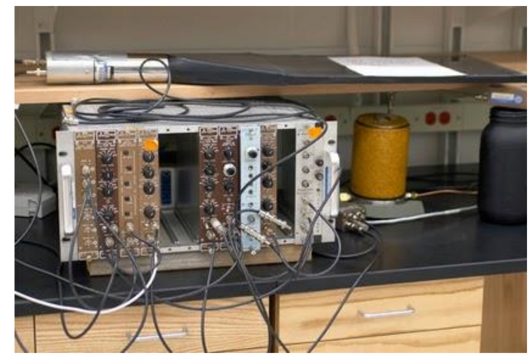
- **Why does it matter?**
  - *Distinguish closely spaced peaks*
  - *Lower minimum detectable activity (narrow ROI → few background counts)*
  - *BUT trade-offs: Higher cost, or lower volume, or lower count rates, or….*

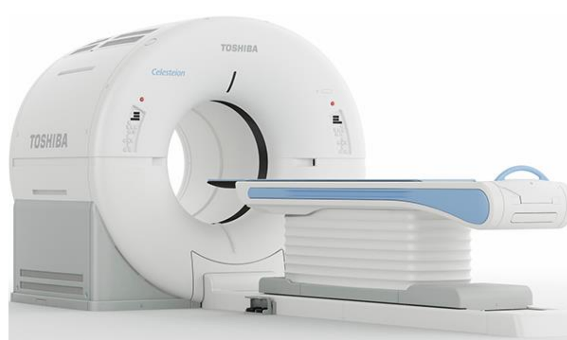


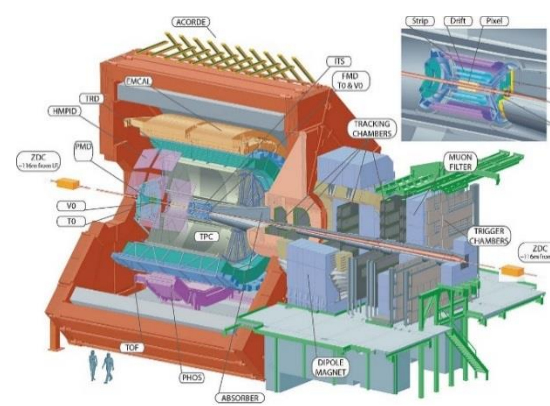
Overview: Challenges

- **Challenge 3: Variations in current and charge**
  - *Variations in signal current profile $I_{sig}(t)$ can cause variations in pulse height, pulse time determination, etc*
  - *Variation in charge collection efficiency can force complicated electronics*

- **Challenge 4: Practical matters**
  - *Cost, power, size, complexity, …*
  - *Ruggedness, radiation hardness, …*
  - *Reliability, configurability, maintainability, …*
  - *Huge range of applications to consider!*







2. Acquiring the Detector Signal

2.1 Input Pulses

What is to be measured?

What are the characteristics of the input current pulse?

Total charge Q_{dep} and time profile $I(t)$

Acquiring the signal

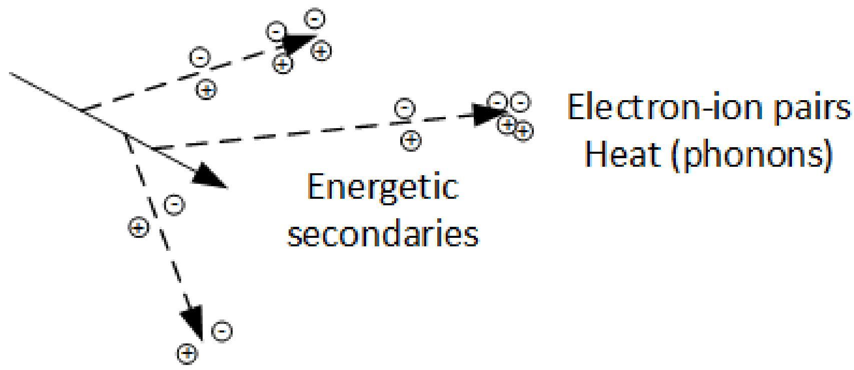
- **Any elementary excitation can be used to detect radiation**
  - *Electrical signal formed directly by ionization*
    - Gases: ~ 30 eV/pair
    - Semiconductors: 1 to 10 eV/pair
  - *Electrical signal formed indirectly*
    - Optical states in scintillator → light intensity (20 to 500 eV/photon) → photodetector produces current
    - Excite lattice vibrations (phonons) → temperature change (meV/phonon) → sensitive temperature sensor
    - Break up Cooper pairs in a superconductor
    - Neutron creates a directly ionizing particle, which is then measured

$$^{0}n + {}^{10}B \rightarrow {}^{7}Li + He$$

- **In all sensors considered here, the output is an electrical signal**

Acquiring the signal

Fano Factor: Fluctuations in charge generation



- In Si, ε_{pair} is 3.6 eV → 6 keV X-ray gives 1,667 e-h pairs and 6×10^{-16} J heat
- If the process were deterministic, exactly 3.6 eV/pair, no variation, $\sigma_N=0$
- If process of creating each e-h pair was random and uncorrelated, expect Poisson variation, $\sigma_N = \sqrt{N} = 41$ *e-h*
- Correlations → Fano factor *F*, reducing variation below Poisson.

$$\sigma_N = \sqrt{N_{sig} F_{Fano}}$$

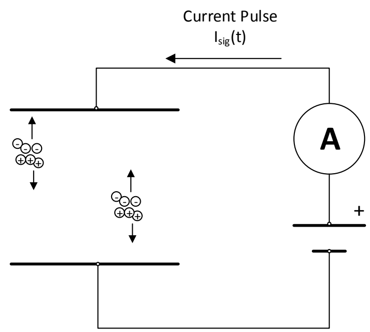
- *F* is a property of the material: Ar ~ 0.20, Ge ~ 0.13, Si ~ 0.12

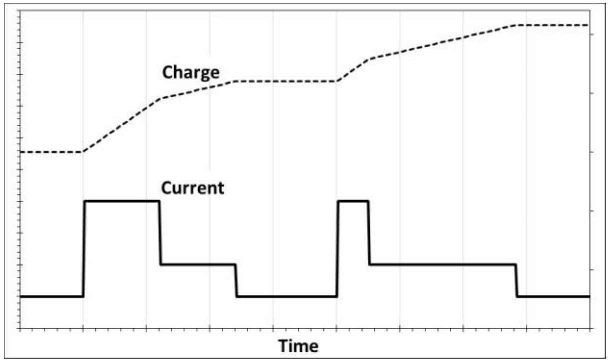
Acquiring the signal

Ion Chamber

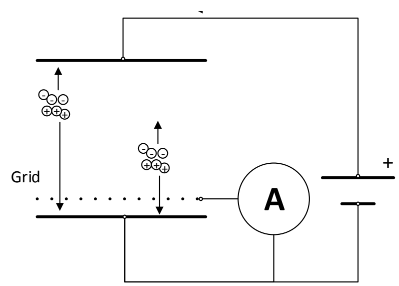
- *Current flows when charges move, not when "collected"*
- *Current detected when charge is induced on electrode*
  - Electrons, ions different drift times → *I(t)* varies, depends on position
  - Frisch grid "shields" signal electrodes → Delayed, single carrier current
  - Shockley-Ramo theorem: Current into an electrode is due to “weighting field”, derived when all other electrodes are grounded

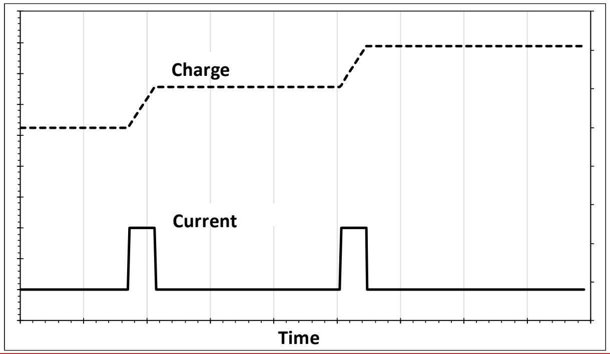
Variation in I(t)





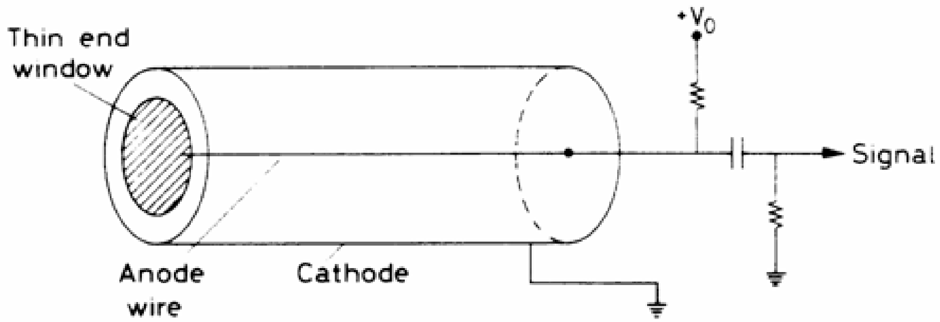
Electrodes → I(t)





Acquiring the signal

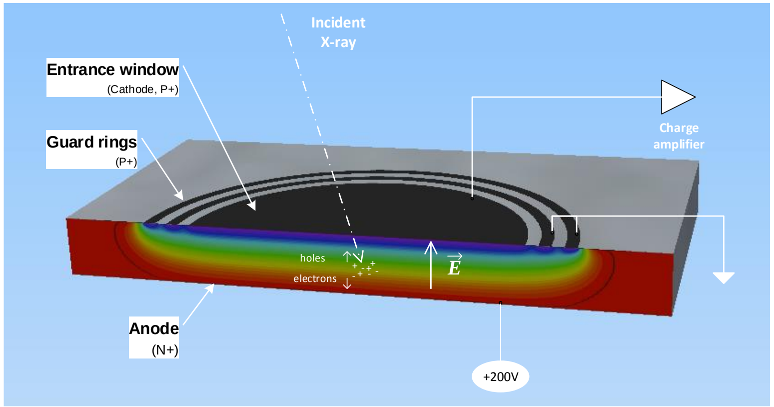
- **Ion Chamber**
  - *Planar chamber not actually used in pulse mode*
    - Too slow: 1 cm chamber → electrons take 100 μs to cross, ions many millisec
  - *Cylindrical ion chamber*
    - Field strong near wire → most of current at the end.
    - Current pulse is short, mostly electrons, independent of position
  - *Proportional counter*
    - If field near wire is strong enough, electrons ionize more, giving gain
    - Gives bigger charge and even shorter pulse
    - Cylindrical proportional counters are very common



Acquiring the signal

Semiconductor detector

- *Solid state ionization chamber*
  - Planar SiPIN is much like planar ion chamber
  - Lower ε_i, lower F_{Fano} → Better resolution   High density → Better stopping



  - Signal from X-ray

$$E_{dep} := 6\cdot keV \qquad \frac{E_{dep}}{\varepsilon_{pair}} = 1.7\times10^{3}\,q_e \qquad \frac{E_{dep}}{\varepsilon_{pair}} = 2.7\times10^{-16}\,C$$

$$v_e := \mu_e\cdot\frac{200V}{0.5\cdot mm} = 6\times10^{4}\,\frac{m}{s} \qquad T_e := \frac{0.5\cdot mm}{v_e} = 8.3\times10^{-9}\,s \qquad I_e := \frac{E_{dep}}{\varepsilon_{pair}\cdot T_e} = 3.2\times10^{-8}\,A$$

$$v_h := \mu_h\cdot\frac{200V}{0.5\cdot mm} = 1.8\times10^{4}\,\frac{m}{s} \qquad T_h := \frac{0.5\cdot mm}{v_h} = 2.8\times10^{-8}\,s \qquad I_h := \frac{E_{dep}}{\varepsilon_{pair}\cdot T_h} = 9.6\times10^{-9}\,A$$

  - Signal from alpha or beta particle

    Larger signal → Signal to noise ratio

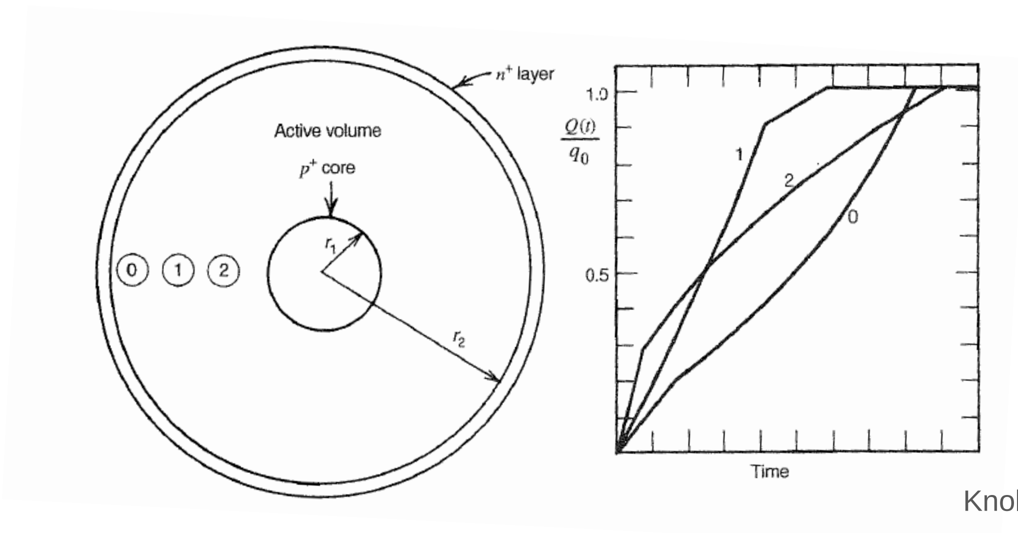
    Straggling → Electronics noise less important

Acquiring the signal

High Purity Germanium (HPGe)

- Large volume (many cm^3), high Z → Widely used in γ-ray spectroscopy
- Signals typically 100x larger than Si X-ray Coaxial geometry → Field varies with radius → Collection times of many μs, large variation in *I(t)*

- *Electronics*
  - Signals and signal to noise ratio 100x larger than X-rays in Si diode
  - Very narrow peak widths → Sensitive to "secondary" issues
  - Long collection time → Pulse shaping is critical
  - Pulse shape can tell you position



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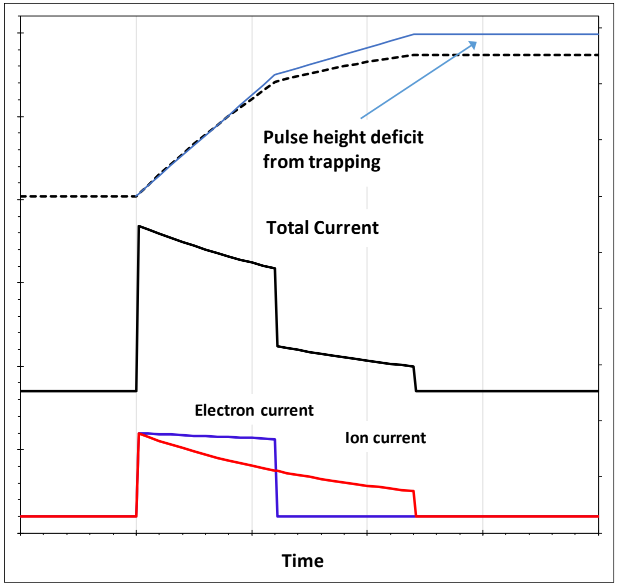
Acquiring the signal

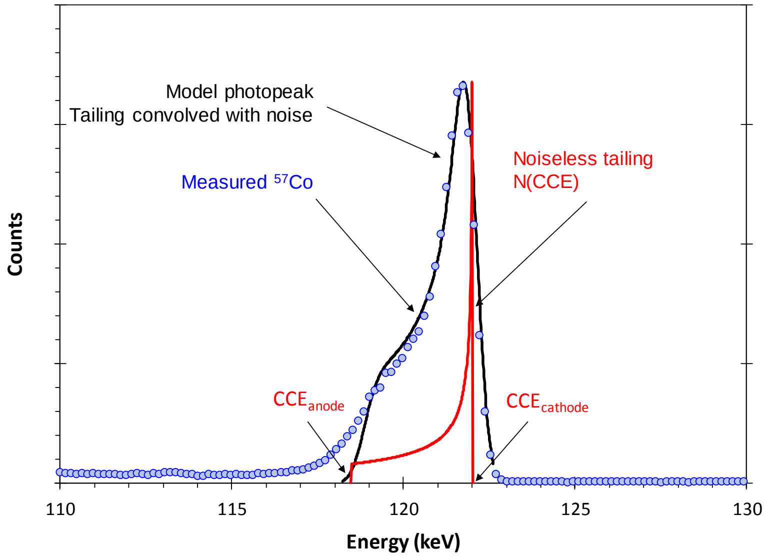
- $Cd_{1-x}Zn_xTe$
  - Crystals have high density of traps
  - Charges have short lifetime (100 ns)
  - Trapped while crossing detector
  - Creates pulse height deficit *CCE(x)*
  - Creates "tail“ in spectrum

$$CCE(x) = \left(\frac{\lambda_e}{L}\right)\left(1 - e^{-\left(\frac{x}{\lambda_e}\right)}\right) + \left(\frac{\lambda_h}{L}\right)\left(1 - e^{-\left(\frac{L-x}{\lambda_h}\right)}\right)$$

$$N(x) = 1 - e^{-\frac{x}{\lambda_{atten}}}$$

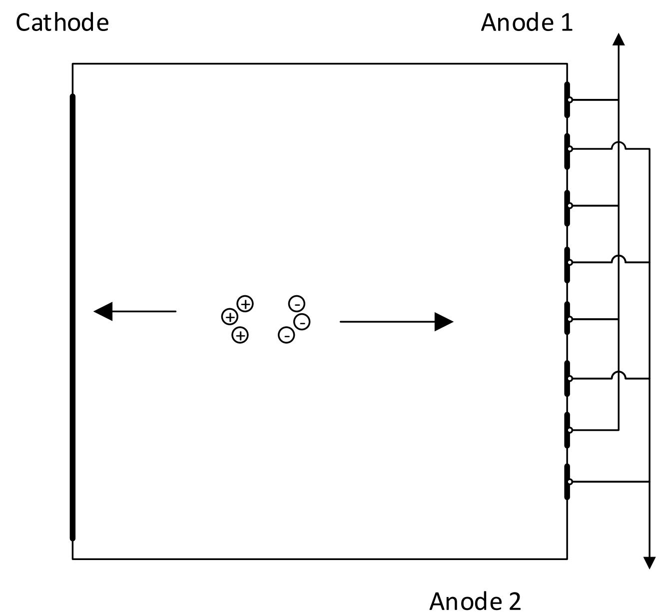
- *Electronics*
  - CCE more important than noise
  - Pulse shape → CCE
  - Correction but complexity

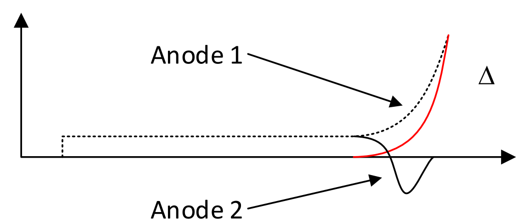




Acquiring the signal

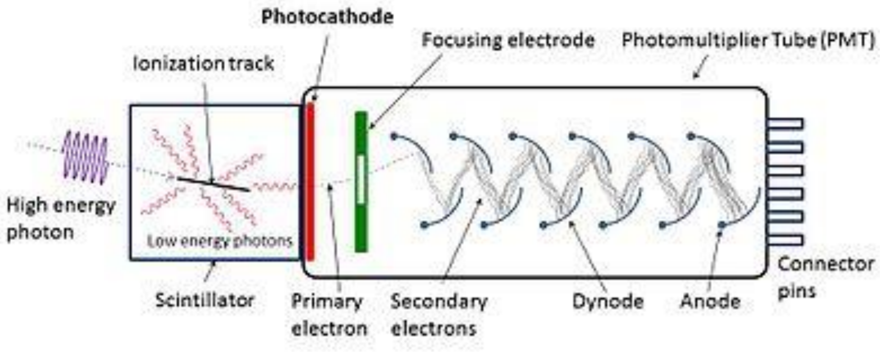
- **Semiconductor electrodes**
  - *Coplanar grid*
    - Similar to Frisch grid
    - Unipolar (electron only), quick rise
    - Reduces effects of trapping
    - Allows much larger volumes
    - Other electrode designs are similar
  - *Drift detectors*
  - *Strip detectors*
  - *Other electrode designs*
  - *All based on Shockly-Ramo theorem*
  - *Much active research*

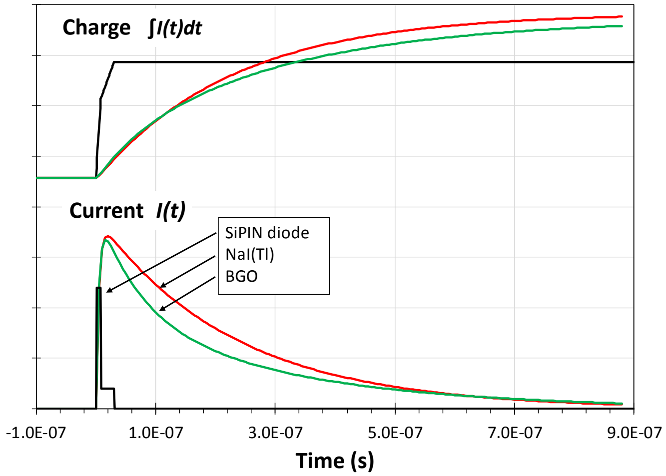




Acquiring the signal

- **Scintillation detector**
  - *Interaction produces excited state in crystal*
    - E_i is high (light yield low) → photosignal is small and F = 1
    - Light intensity is exponential with time (infinite impulse response)
  - *Photons interact in a photodetector*
    - Photodiodes are used but signal current is small
    - Photomultiplier with high gain (~10^5) common
  - *Electronics*
    - Large signal current, resolution limited by photostatistics,
    - Infinite impulse response (IIR)
    - Pulse shapes from scintillator



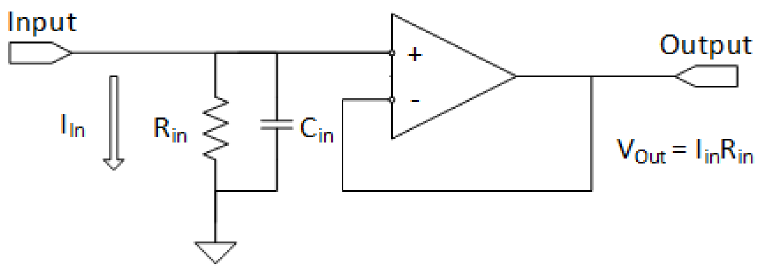


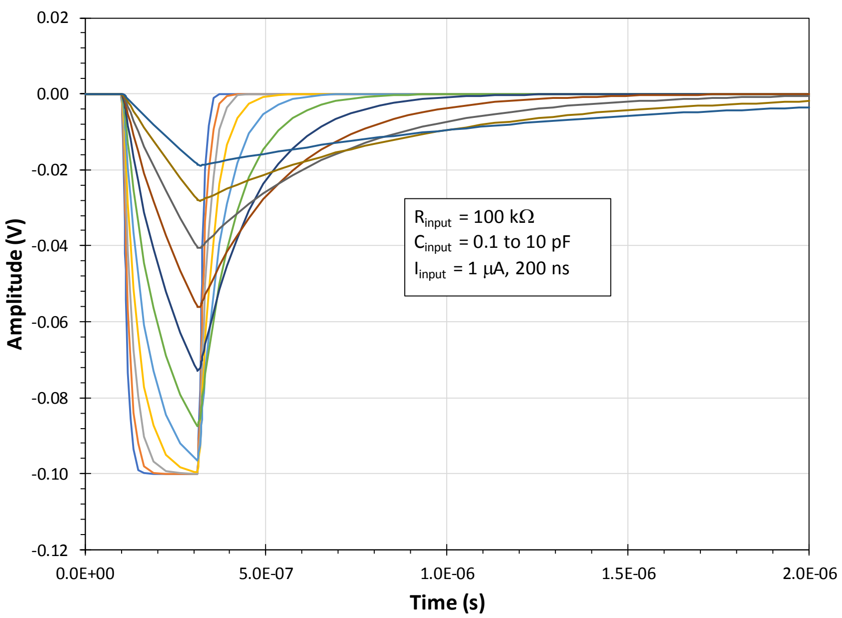
2.2 Preamplifier

How do we process the current pulse?

Acquiring the signal: Preamp

- **Resistor and amplifier**
  - *Current across a resistor produces a voltage*
    - If $RC << \tau_c \rightarrow$ proportional to current
      Pulse height is proportional to I_{max}, not Q_{sig}
    - If $RC >> \tau_c \rightarrow$ proportional to charge (integrated on C_{in})
    - Noise, timing, etc depend strongly on stray capacitance, cable, etc
    - Not recommended



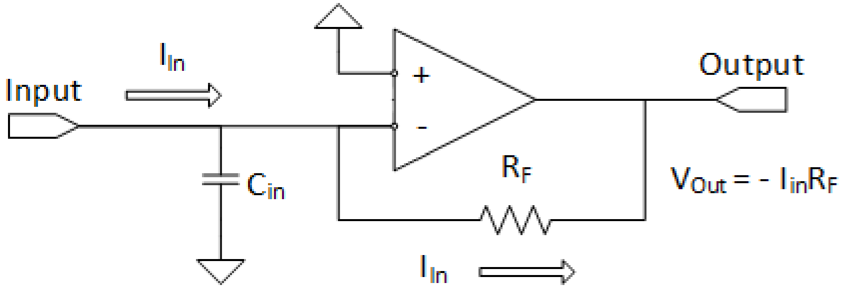


Acquiring the signal: Preamp

- **Transimpedance amplifier**
  - *Operation*
    - Inverting input is virtual ground → No current can flow into it
    - Input current must flow across feedback resistor, giving output voltage

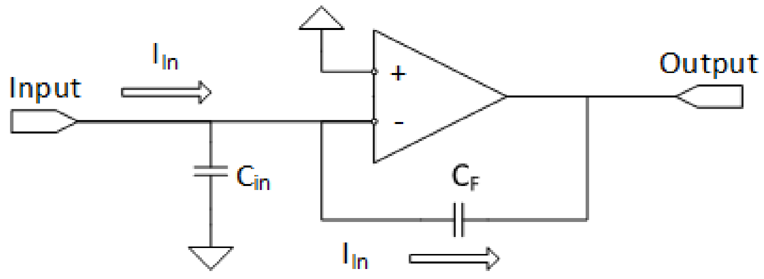
$$V_{out}(t) = -I_{in}(t)R_F$$

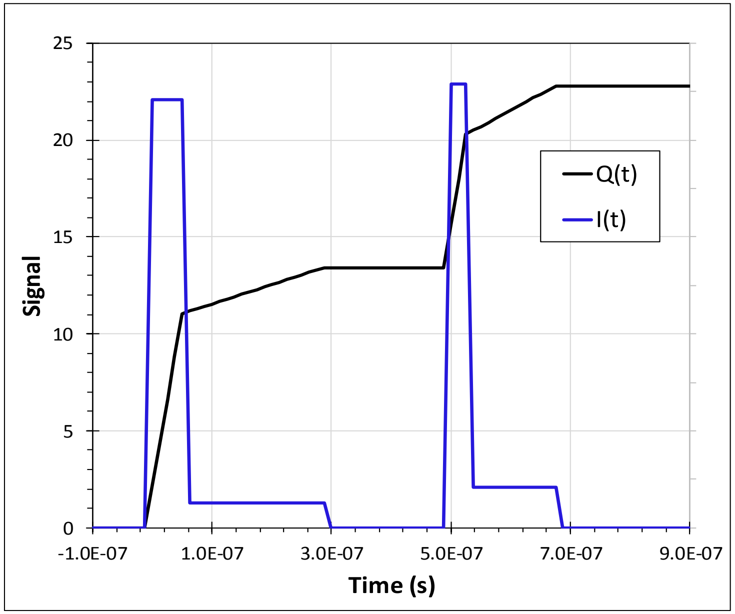
  - *Characteristics*
    - Much less dependent on C_{in}, etc
    - Pulse height is proportional to I_{max} rather than Q_{dep}
    - Used when pulse shapes unchanging or one wants to measure pulse shape



Acquiring the signal: Preamp

- **Charge amplifier**
  - *Operation*
    - Input current must flow across feedback capacitor
    - Voltage change across C_F drives current



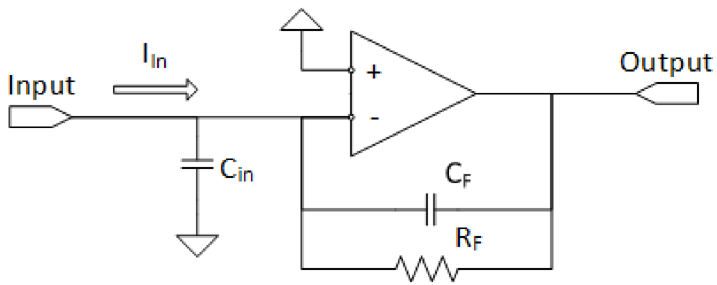


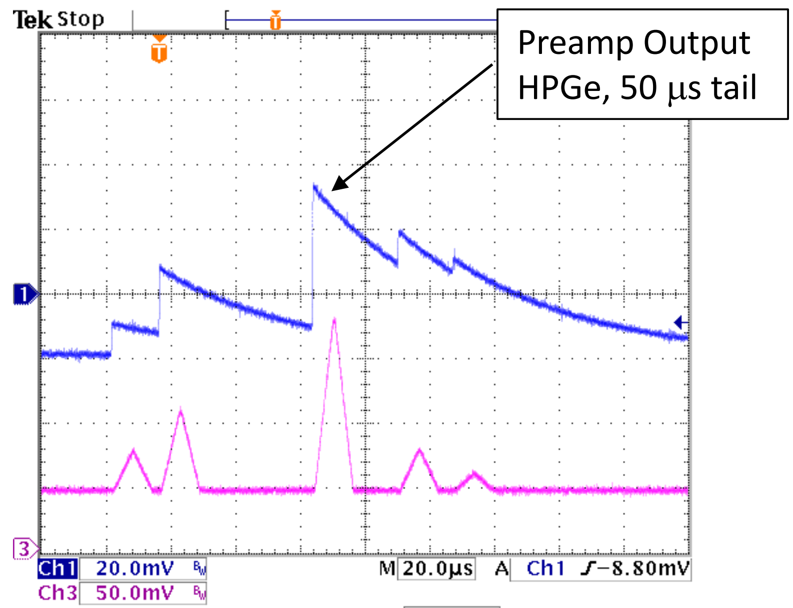
$$\frac{dV_{out}(t)}{dt} = -I_{in}(t)\left(\frac{1}{C_F}\right) \quad \Rightarrow \quad V_{out}(t) = \left(\frac{1}{C_F}\right)\int I_{in}(t)\,dt = \frac{Q_{in}}{C_F}$$

  - *Characteristics*
    - Output step is proportional to charge, not current
    - Independent of C_{in} (to with A_{OL})
    - Scales as $1/C_F$

Acquiring the signal: Preamp

- **Resistive feedback**
  - *With only C_F output goes to power rail → Must restore DC current*
  - *Feedback resistor*
    - RC >> τ_c → Rapid integration, slow exponential decay
    - Simple and commonly used

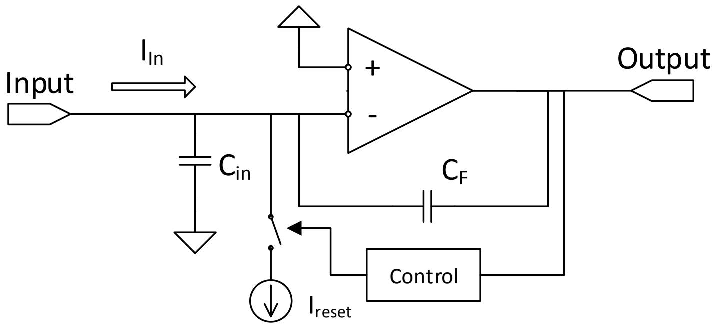


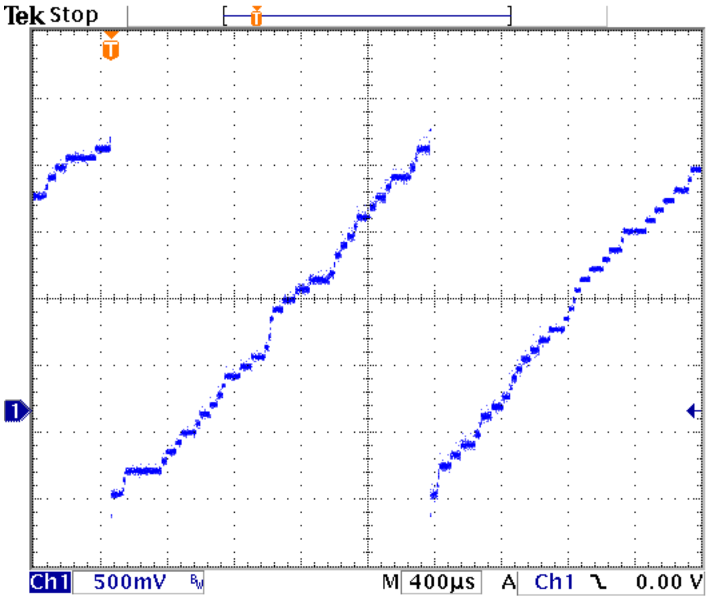


  - *Other options for continuous feedback*
    - R_F adds thermal noise
    - Feedback transistor, current into JFET drain, etc
    - All have pros and cons
    - Ongoing research

Acquiring the signal: Preamp

- **Reset preamps**
  - *Current pulse restores charge at input*
  - *Lowest noise (no sources for thermal noise or I_{dark}), high rates*
    - Used in lowest noise systems, e.g. high rate X-ray detectors
    - Several implementations: LED into JFET, reset diode, reset via HV





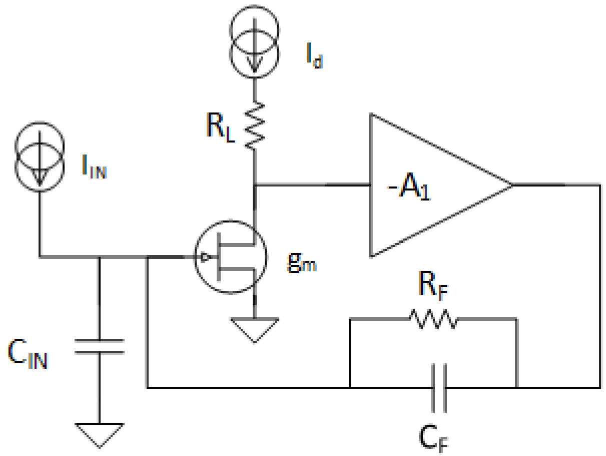
Acquiring the signal: Preamp

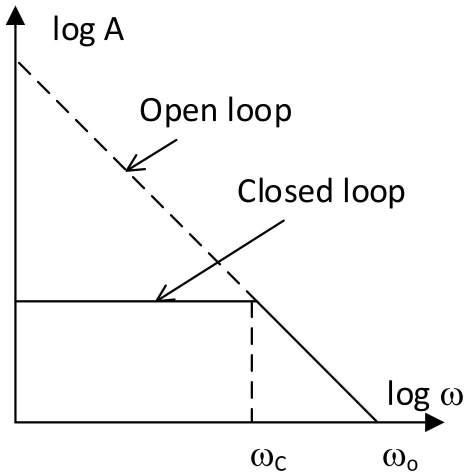
Realistic Preamp Input

- *Input stage is a FET (usually JFET)*
  - First stage dominates performance (noise, risetime, etc)
  - FET for low input current → low noise
  - FET's characteristics are key
- *Finite risetime*

$$\tau_{\mathrm{Preamp}} = C_{IN}\left(\frac{1}{\omega_0 C_F}\right)$$

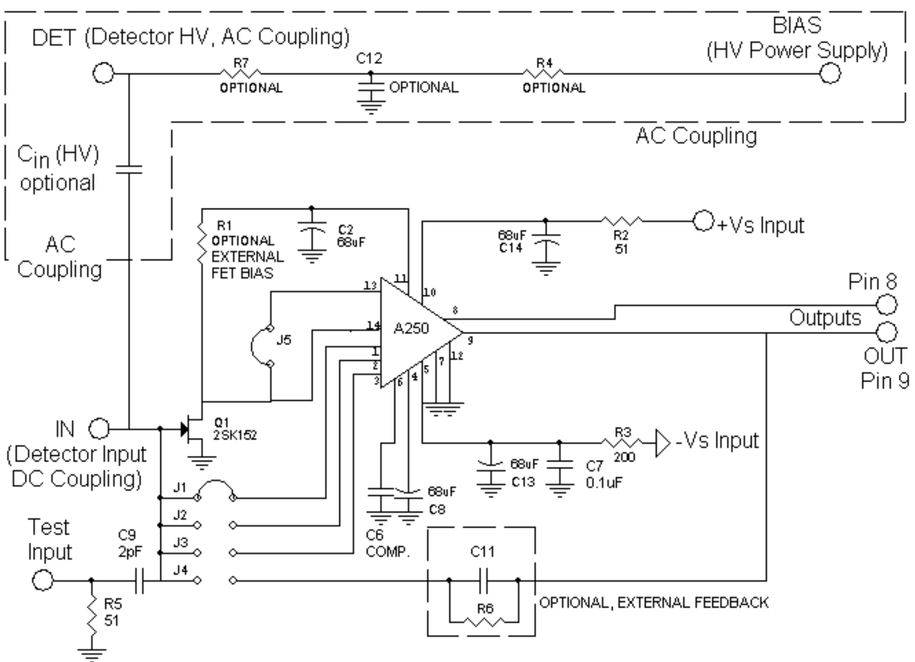
  - Risetime increases with C_{IN}

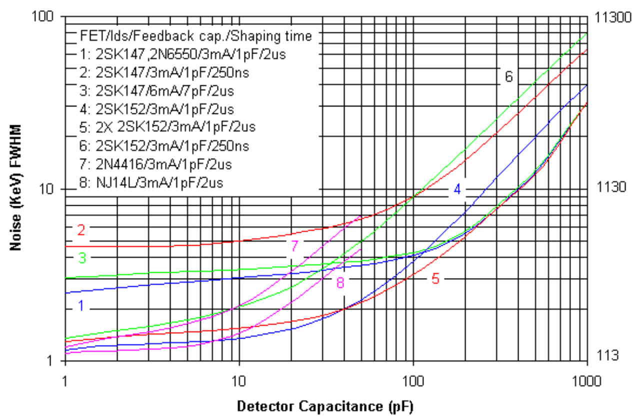


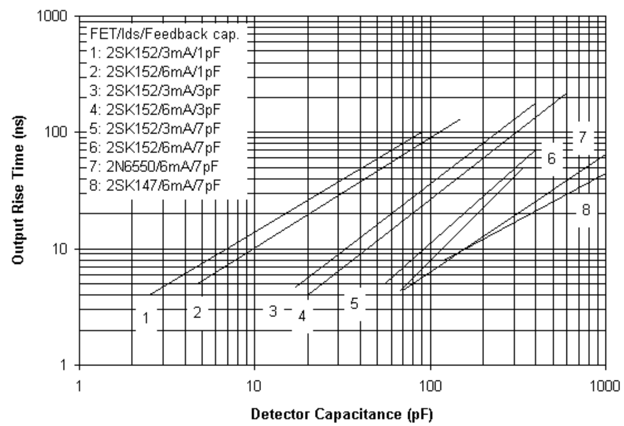


Acquiring the signal: Preamp

- **Real Preamp: Amptek A250 on test board**
  - *External JFET to match detector*
  - *Feedback cap gives charge gain, feedback resistor gives time constant*
  - *HV bias with filters*







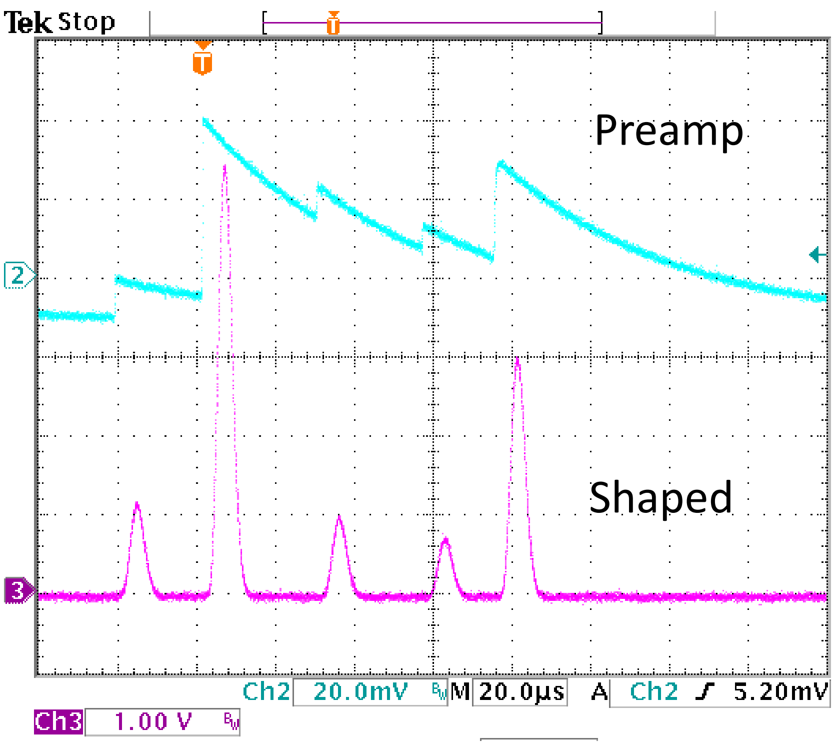
2.3 Pulse Shaping

What are the goals of pulse shaping?
How do we shape the pulses?

Acquiring the signal: Shaping

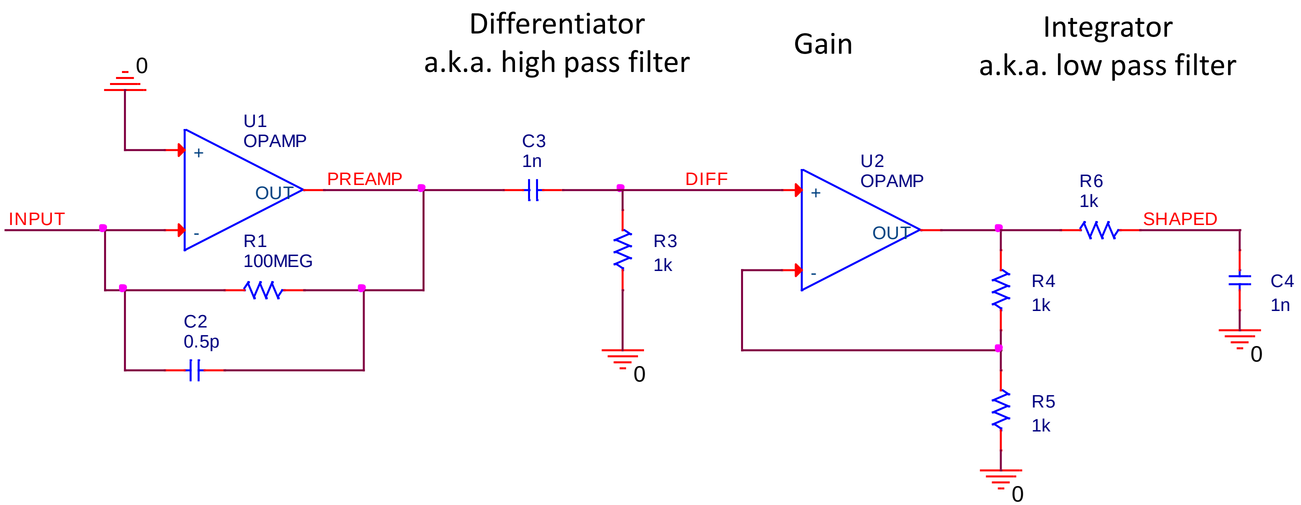
- **Goal of shaping**
  - *Optimize time response of system for*
    - Measurement of signal amplitude or count rate, or timing, or shape, or …

- **Key objectives**
  1) *Remove preamp tail (prevent tail pileup)*
  2) *Limit pulse duration (limit dead time & pileup)*
  3) *Filter noise (improve S/N ratio)*
  4) *Minimize pulse shape effects (ballistic deficit)*
  5) *Apply gain*



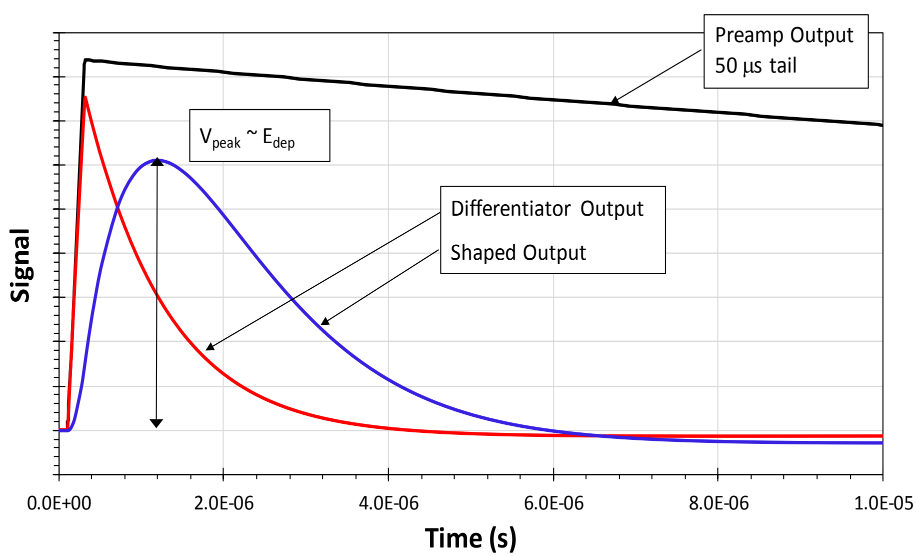
Acquiring the signal: Shaping

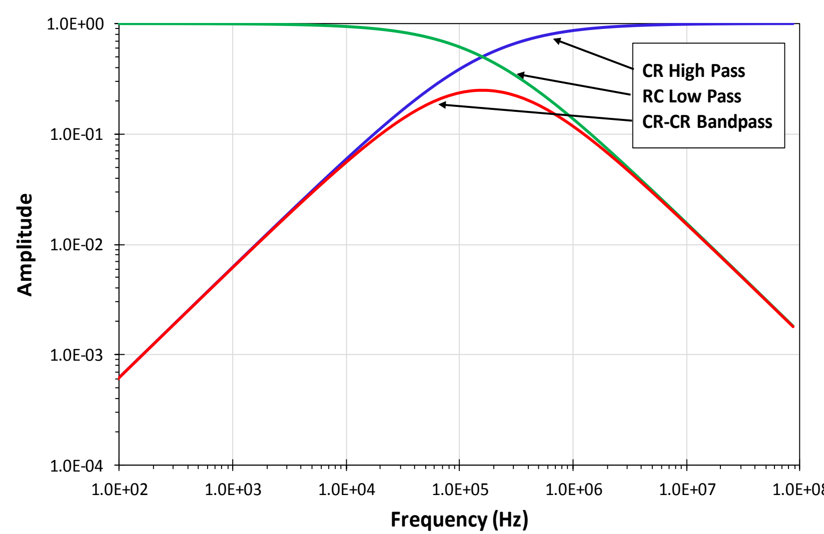
Simple Example: CR-RC Shaper



$$V(t) = \left(\frac{t}{\tau}\right) e^{-\left(\frac{t}{\tau}\right)}$$

$$V(\omega) = \left(\frac{1}{1+\omega\tau}\right)\left(\frac{\omega\tau}{1+\omega\tau}\right)$$



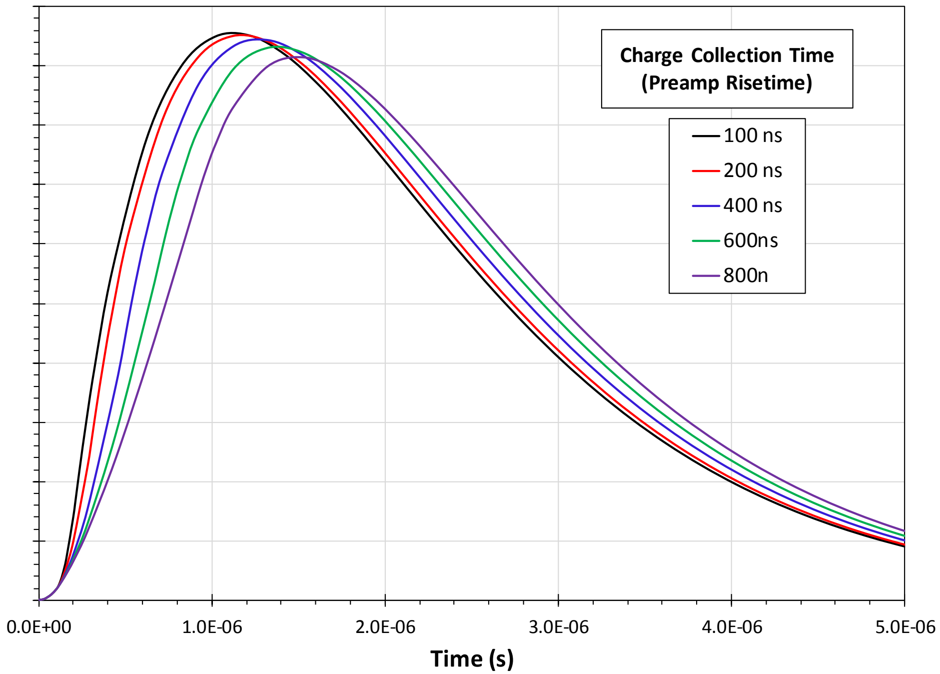


Acquiring the signal: Shaping

- **Simple Example: CR-RC Shaper**
  - *Key Characteristics*
    - Differentiator (a.k.a. high pass filter)
      1) Removes baseline and preamp tail
      2) Reduces low frequency noise
    - Integrator (a.k.a. low pass filter)
      1) Slows the leading edge and flattens pulse to reduce ballistic deficit
      2) Reduces high frequency noise
    - Characteristic time duration – "dead time"
    - Peak voltage attenuated by shaping
  - *Compromises*
    - Highest count rates → narrow pulse (short τ)
    - Best resolution → most noise filtering → long pulse (long τ)

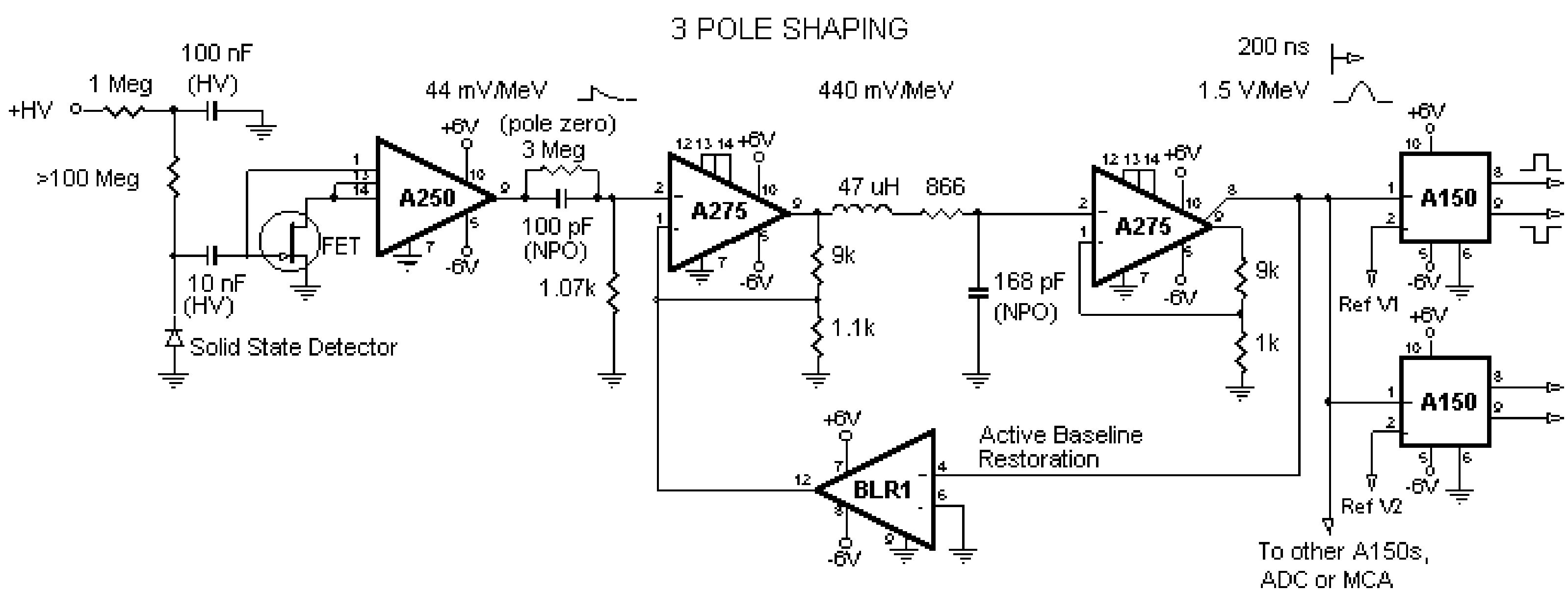
Acquiring the signal: Shaping

- **Ballistic Deficit**
  - *Charge collection time affects pulse amplitude*
  - *Pulse height depends on $I_{in}(t)$ → slow pulses have pulse height deficit*
  - *Creates a "tail" in the spectrum*



Acquiring the signal: Shaping

- **Real shaping circuit: Amptek hybrids**
  - *For solid state particle detector*
  - *A250 preamp with matched JFET and resistive feedback*
  - *CR-(RC)^2 shaping with active baseline restore*
  - *Will discuss details in next sections*



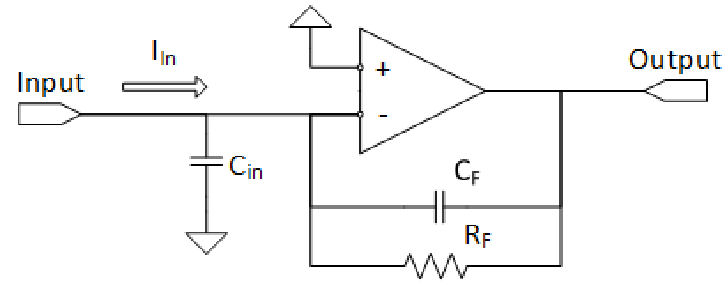
2.4 Gain

Acquiring the signal: Gain

- **Preamp conversion gain**

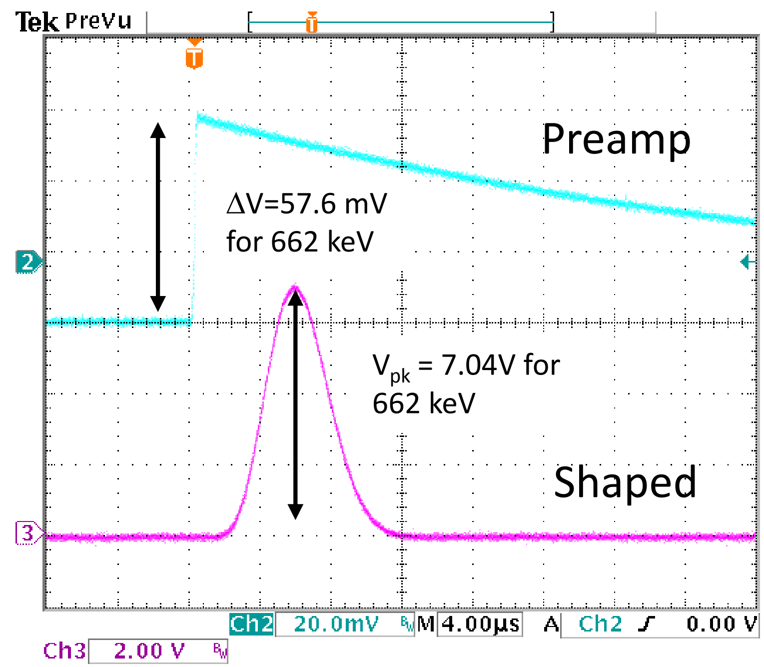
$$\Delta V_{preamp} = \left(\frac{E_{dep}}{\varepsilon_{pair}}\right)\left(\frac{1}{q_e C_F}\right)$$

  - *mV per eV (or keV or …)*
  - *Depends on ε_i and C_F*
  - *1 pF → 44 mV/MeV (Si) or 0.16 μV/e-h*



- **Shaper gain**
  - *V/keV of the peak of the shaped pulse*
  - *Product of a shaping factor and any voltage gain*
  - *Needs to match subsequent circuits*

$$V_{peak} = \Delta V_{preamp}\left(G_{shape} G_{gain}\right)$$

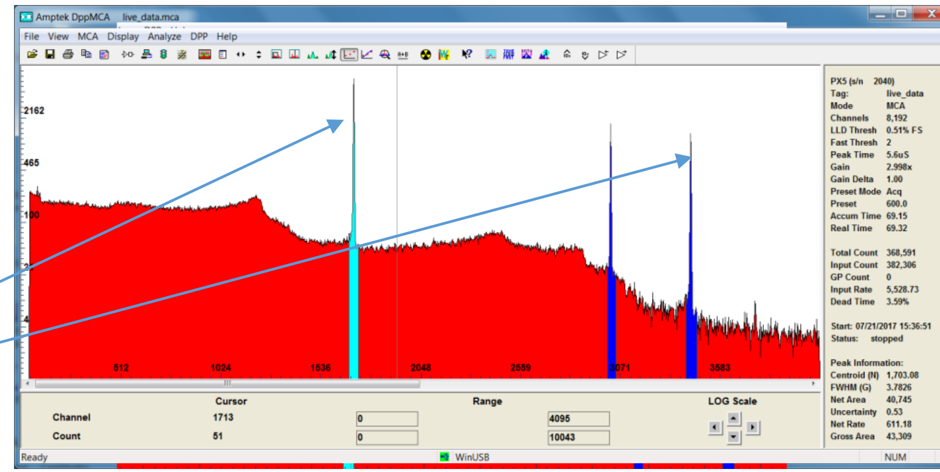


Acquiring the signal: Gain

- **MCA System Conversion Gain**
  - *Input range (e.g. 5V) and number of channels (e.g. 4096) → 1.22 mV/channel*
  - *Combines with shaper gain to get "system conversion gain", eV/ channel*

$$Channel = \left(\frac{E_{dep}}{\varepsilon_{pair}}\right)\left(\frac{1}{q_e C_F}\right)\left(G_{shape}G_{gain}\right)\left(\frac{N_{chann}}{V_{\max\_chann}}\right)$$

Channel 1703: 662.7 keV
Channel 3428: 1332.5 keV

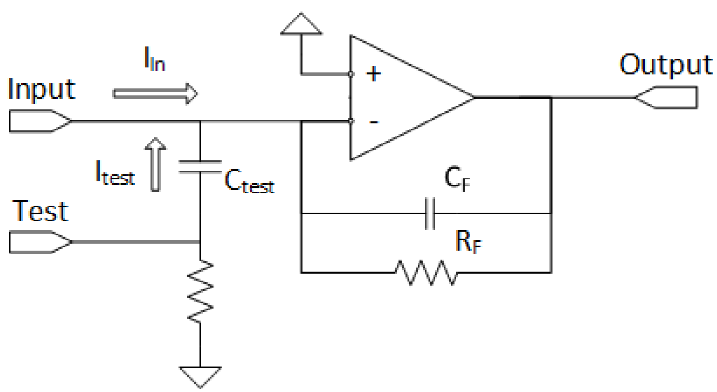


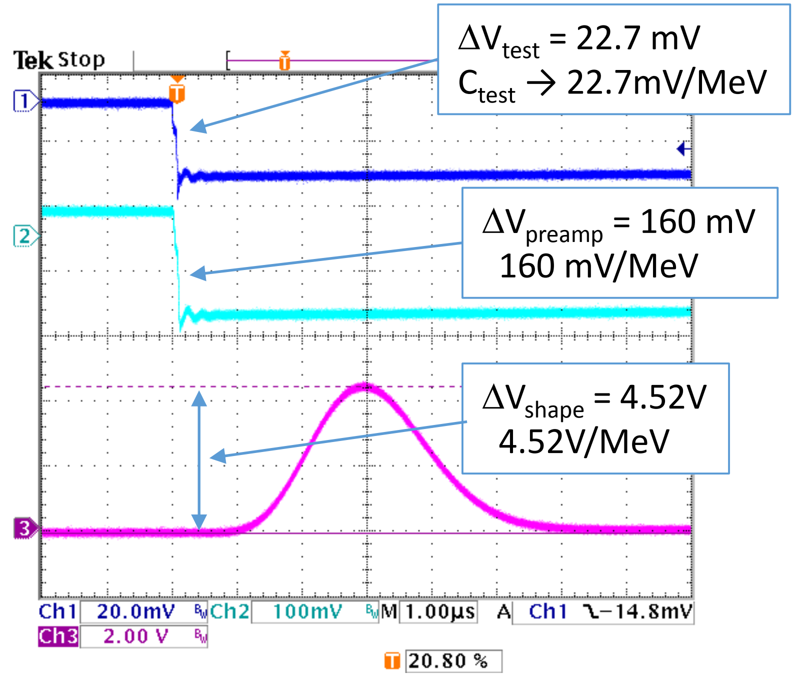
- **Offset**
  - *Many people assume zero offset, e.g. zero eV in channel zero.* ***Not true!***
- **Related topics**
  - *Gain stability is important*
    - HPGe, FWHM ~ 1 part in 1,000 → 100 ppm change affect measurements
  - *Linearity is important*

Acquiring the signal: Gain

Calibrating the gain

- *Best solution: source with known energies (prior slide)*
  - Emission energies from physical constants, no standards needed
  - Photopeaks are ideal but you can use Compon edges, β endpoints, etc
- *Alternate method: test pulse*
  - Inject pulse ΔV_{test} into C_{test}, delivers $Q=C_{test}\Delta V_{test}$
  - Accuracy limited by C_{test}, C_{stray}, ΔV_{test}
  - Pulse shape may not match detector
  - Circuit may be affected by pulser





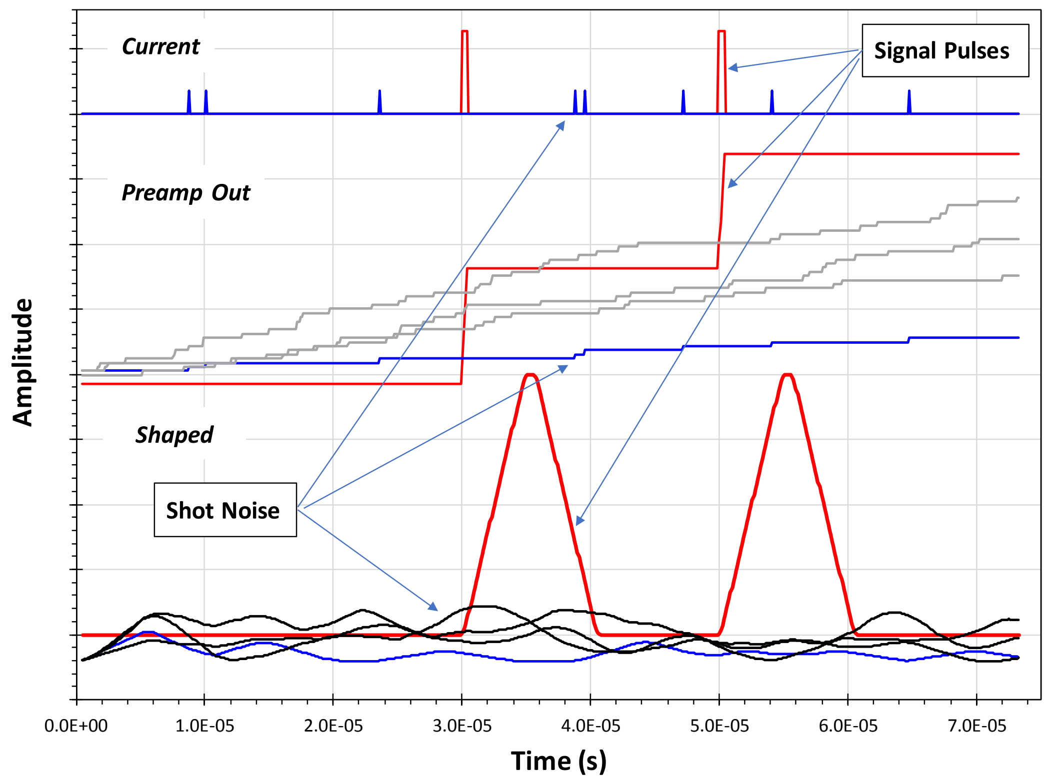
3. Resolution & Electronic Noise

3.1 Example: Shot Noise

An intuitive picture of intrinsic noise

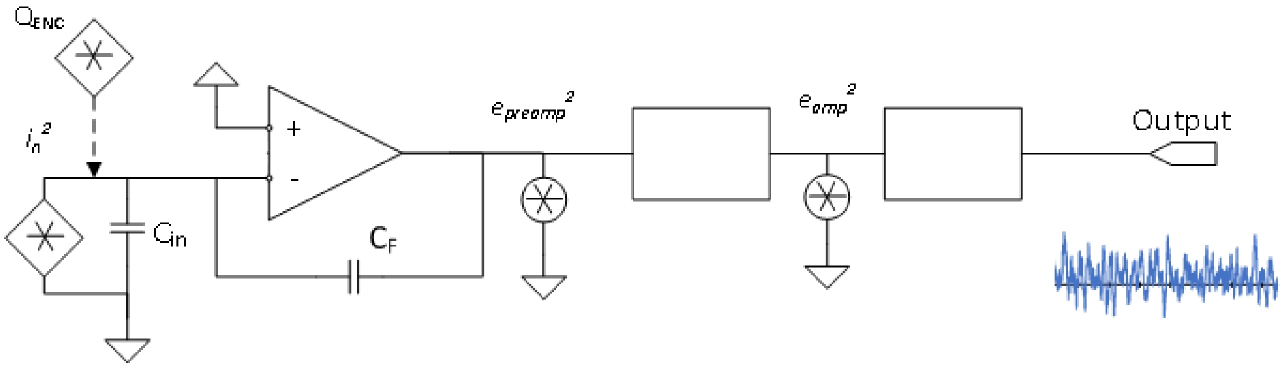
Resolution & Noise: Shot Noise

- **Intuitive Picture**
  - *Current pulse from detector gives output shape $S_{out}(t)$*
  - *Every electron "leaking" through detector gives same shape but smaller*
  - *These impulses, at random times, cause random output fluctuations*
  - *Analogous to balls (shot) falling on a tin roof*



Resolution & Noise

- **Equivalent Noise Charge (ENC)**
  - *Noise sources throughout circuit combine to give rms output voltage*
  - *Most of the noise at the output does not arise from a physical current or voltage at the preamp input.*
  - *We define an input equivalent noise: Equivalent Noise Charge (Q_{ENC})*
  - *Q_{ENC} is the rms input charge that would give observed output rms voltage*
  - *Defined as the input charge needed to give S/N=1*

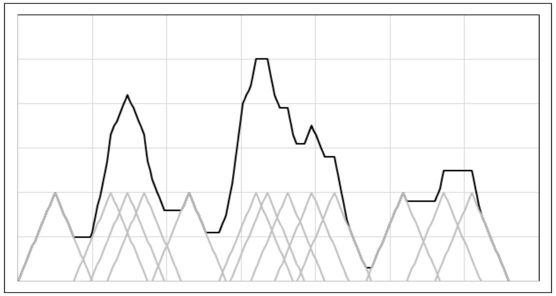


Resolution & Noise: Shot Noise

Noise Index: Time Domain

- *Each electron yields an output pulse $S_{out}(t)$*
- *Electrons occur at time t_k, average rate ν, amplitude a_k, rms $\langle a^2 \rangle$*
- *Output waveform is*

$$V_{out}(t) = \sum_k a_k S_{out}(t - t_k)$$



- *Variance in output (from Campbell's theorem) is*

$$\sigma_V^2 = \nu \left\langle a^2 \right\rangle \int_0^\infty \left| S_{out}(t) \right|^2 dt$$

- *Separate intensity of noise source from circuit response*
- *We define a noise index, property of the shaper,*

$$N_{step}^2 = \int_0^\infty \left| S_{out}(t) \right|^2 dt$$

$$\sigma_V^2 = \nu \left\langle a^2 \right\rangle N_{step}^2$$

Resolution & Noise: Shot Noise

Noise Index: Time Domain CR-RC

- *For CR-RC,*

$$N_{step}^2 = \int_0^\infty \left|S_{out}(t)\right|^2 dt = e^2 \int_0^\infty \left[\frac{t}{\tau} e^{-\frac{t}{\tau}}\right]^2 dt = \left(\frac{e^2}{4}\right)\tau$$

- *In general, for noise impulses into the preamp*

$$N_{step}^2 = \int_0^\infty \left|S_{out}(t)\right|^2 dt = A_{step}^2 \tau$$

  - A_{step} is characterizes of the shaping network, $S_{out}(t)$
  - τ is a characteristic time constant

- *For CR-RC, A_{step}=e/2, τ=RC and T_{peak}=2.4τ*

- *For shot noise in a CR-RC shaper,*

$$\nu = \frac{I_{dark}}{q_e} \qquad a = q_e \qquad \Rightarrow \qquad Q_{ENC}^2 = \left(q_e I_{dark}\right)\left(\frac{e^2}{4}\right)\tau$$

Resolution & Noise

- **Noise Index: Frequency Analysis**
  - *Take Fourier transform (Carson's theorem) and find*

$$\sigma_V^2 = \nu\left\langle a^2\right\rangle \int_0^\infty \left|S_{out}(t)\right|^2 dt = \frac{\nu\left\langle a^2\right\rangle}{\pi} \int_0^\infty \left|S_{out}(\omega)\right|^2 d\omega$$

  - *This is true for random, uncorrelated, noise impulses – white noise*
  - *If noise sources are correlated in time, or filtered to have some intensity distribution, we generalize to*

$$\sigma_V^2 = \frac{1}{\pi} \int_0^\infty e_n^2(\omega)\left|H(\omega)\right|^2 d\omega$$

  - *$H(\omega)$ is the response of the circuit to that noise source*
  - *$e_n^2(\omega)$ is the "noise spectral density", with units V^2/Hz*
    - For "white" noise, $e_n^2(\omega)$ is constant $\leftrightarrow$ noise represented as impulse $\delta(t)$
  - *$i_n^2(\omega)$ is the "current noise spectral density", units A^2/Hz*

Resolution & Noise

Frequency Analysis

- *Effect on circuit*
  - Assume a filter has gain $A(\omega)$, which peaks at some value A_{peak}
  - Output noise is

$$V_{on}^2 = \int_0^\infty e_n^2(\omega) A^2(\omega) d\omega$$

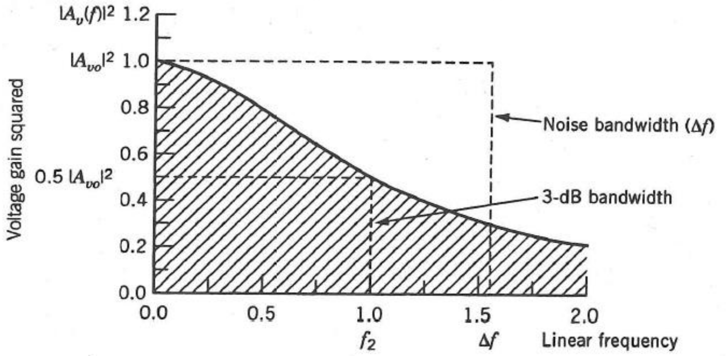
- *White noise effect*
  - e_n^2 independent of frequency so

$$V_{on}^2 = e_n^2 \int_0^\infty A^2(\omega) d\omega$$

  - We define a "noise bandwidth"

$$\Delta\omega = \frac{1}{A_{peak}^2} \int_0^\infty A^2(\omega) d\omega$$

$$V_{on}^2 = \left(e_n^2\right)\left(\Delta\omega\right)$$



From Motchenbacher

  - Reducing bandwidth reduces output noise. Key to noise filtering
  - Noise bandwidth is from integral
  - Noise bandwidth ≠ signal bandwidth

3.2 Noise in General

What are the general characteristics of intrinsic electronic noise?

Resolution & Noise

Noise

- *Unwanted disturbances superposed on a signal that obscure its information content (IEEE Dictionary of Elec. & Electronic Terms)*
- *<u>Intrinsic noise</u> is generated within a circuit itself*
- *<u>Extrinsic noise</u> is generated outside a circuit and coupled in*
- *In nuclear electronics, noise modulates the baseline: signal pulses ride on top of the randomly fluctuating baseline.*

Intrinsic noise mechanisms

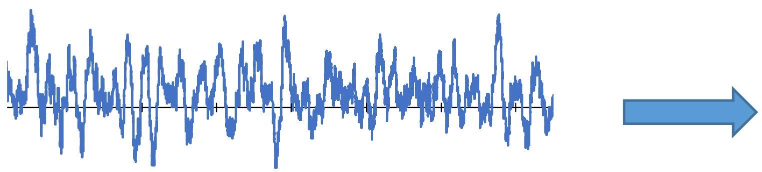
$$i = n_e q_e v \qquad \Rightarrow \qquad \sigma_i^2 = \left(n_e q_e\right)^2 \sigma_v^2 + \left(v q_e\right)^2 \sigma_n^2$$

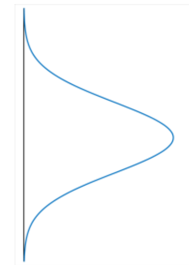
- *Intrinsic noise arises from fluctuations in (1) number of the carriers or (2) velocity of the carriers*
- *Every component in a circuit can generate intrinsic noise*

Resolution & Noise

General properties of intrinsic noise

- *Noise amplitude varies randomly with time*
- *Probability distribution of amplitude is Gaussian*

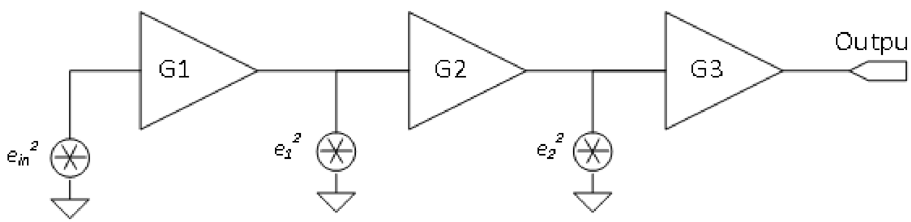




- *Sources add "in quadrature" IF UNCORRELATED*

$$\langle \sigma_{TOT}^2 \rangle = \langle \sigma_1^2 \rangle + \langle \sigma_2^2 \rangle + \langle \sigma_2^2 \rangle + \ldots$$

- *Noise at input, before gain, dominates*



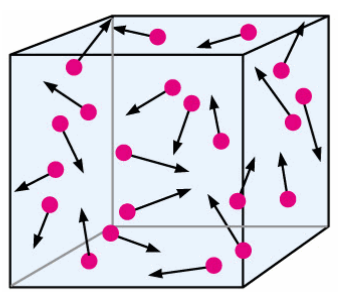
$$\langle V_{output}^2 \rangle = (G_1 G_2 G_3)^2 \langle V_{in}^2 \rangle + (G_2 G_3)^2 \langle V_1^2 \rangle + (G_3)^2 \langle V_2^2 \rangle$$

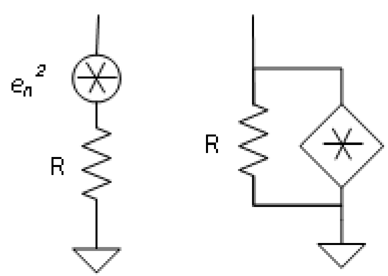
- *Can be minimized (by changing noise sources or noise filtering) but can never be eliminated.*

Resolution & Noise

Thermal noise

- *Mechanism*
  - Electrons in a conductor form a gas and exhibit Brownian motion.
  - Even when average current is zero, fluctuating velocities of individual carriers lead to an instantaneous fluctuating current
- *Statistical fluctuation in velocity of carriers*
  - No current flow needed: a resistor on a bench exhibits thermal noise
  - Depends only on the resistance: every 1kΩ resistor has 4 nV/√Hz noise
  - Occurs in anything dissipative (dissipation fluctuation theorem)
  - Slope of IV curve has units ohms but no dissipation → no shot noise
- *Properties*
  - Model as voltage noise source in series with resistor or current source in parallel
  - Increases with temperature
  - Uniform spectral density (white noise) ↔ uncorrelated in time





$$e_n^2 = 4kTR \qquad i_n^2 = \frac{4kT}{R}$$

Resolution & Noise

- **Thermal noise in radiation detection**
  - *Resistors in input circuit*
    - Feedback resistor, HV bias resistor

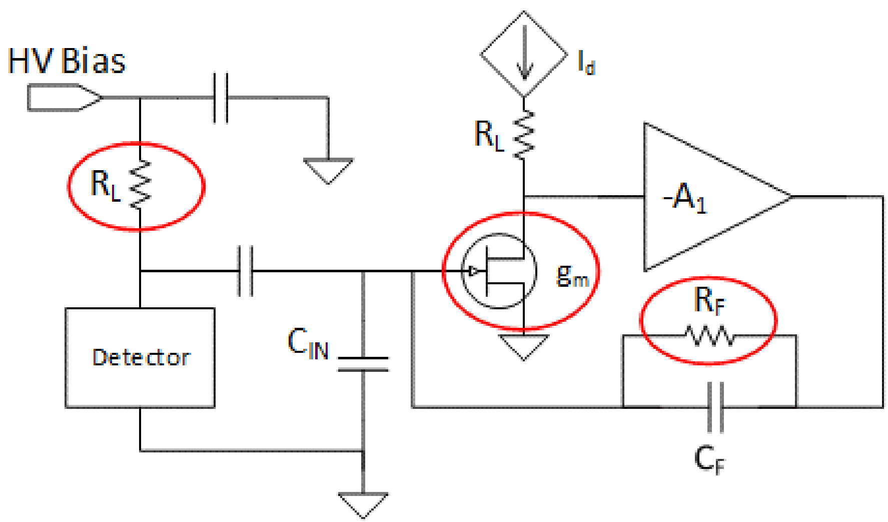
$$i_n^2 = \frac{4kT}{R_{\|}}$$

  - *Channel of input transistor*
    - Fluctuations of velocity of carriers in the channel

$$i_n^2 = \frac{N_{chann} q_e}{L^2} \mu_0 4kT = \gamma g_m (4kT)$$

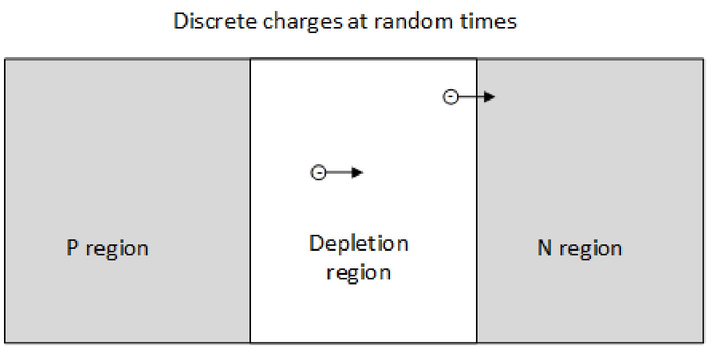
  - *Input capacitor*
    - Dielectric dissipation → noise scales as 1/ω

$$e_n^2(\omega) = \frac{4kT}{\omega C \tan\delta}$$



Resolution & Noise

- **Shot noise**
  - *Statistical fluctuation in number of carriers in current flow*
    - Associated with current flow
    - Occurs when charge cross a barrier (junction, vacuum tube)
    - Occurs when carrier motion is independent (not correlated)
    - Does not occur in "ohmic" conductor
  - *Shot noise is independent of temperature*
    - The current causing it may depend on temperature
  - *Uniform spectral density*
    - In time domain, represented as an impulse
    - In frequency domain, it is white (Fourier transform of impulse)



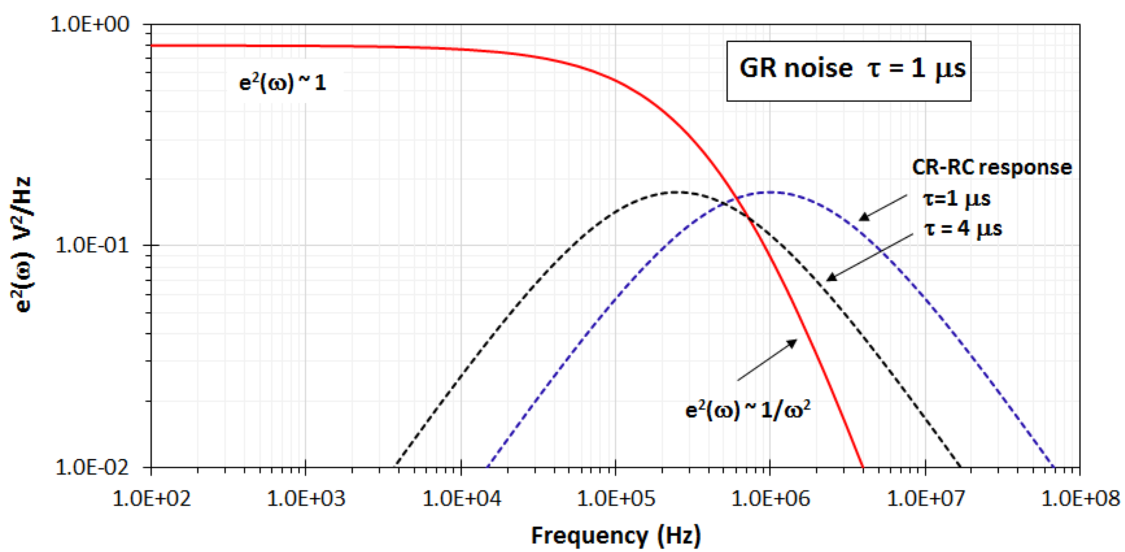
$$i_n^2 = 2q_e I_{DC}$$

Resolution & Noise

- **Generation-Recombination noise**
  - *Statistical fluctuation in number of carriers generated and recombining*
    - Associated with a characteristic lifetime τ
    - At time intervals $T < \tau$, number is correlated so $e^2(\omega)$ decreases with as ω increases
  - *Non-uniform spectral density*
    - $I_n^2(\omega)$ follows a Lorentzian distribution

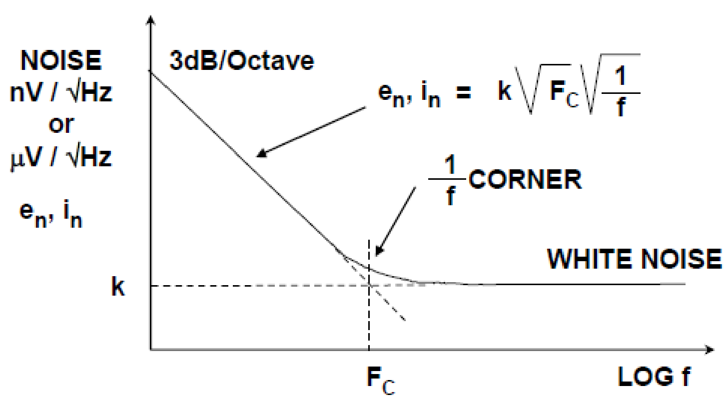
$$i_n^2(\omega) = \left(\frac{4I_{DC}^2}{N}\right)\left(\frac{\tau}{1+(\omega\tau)^2}\right)$$

where g is generation rate, so number of carriers is $N = g\tau$

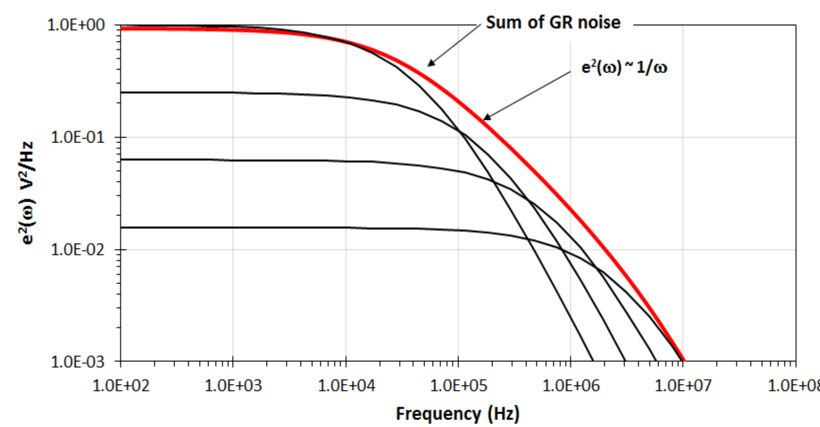


Resolution & Noise

- **1/f noise**
  - *Various origins*
    - All active devices also exhibit 1/f noise
    - MOSFETs theory → 1/f fluctuations in number and velocity
    - Resistors exhibit material dependent 1/f noise (a.k.a. excess noise)
    - Not always strictly 1/f. Can be $1/f^2$ or to another power
    - Sum of GR lifetimes give 1/f over some band
  - *Key properties*
    - Difficult to suppress. Usually important .



From Analog Devices

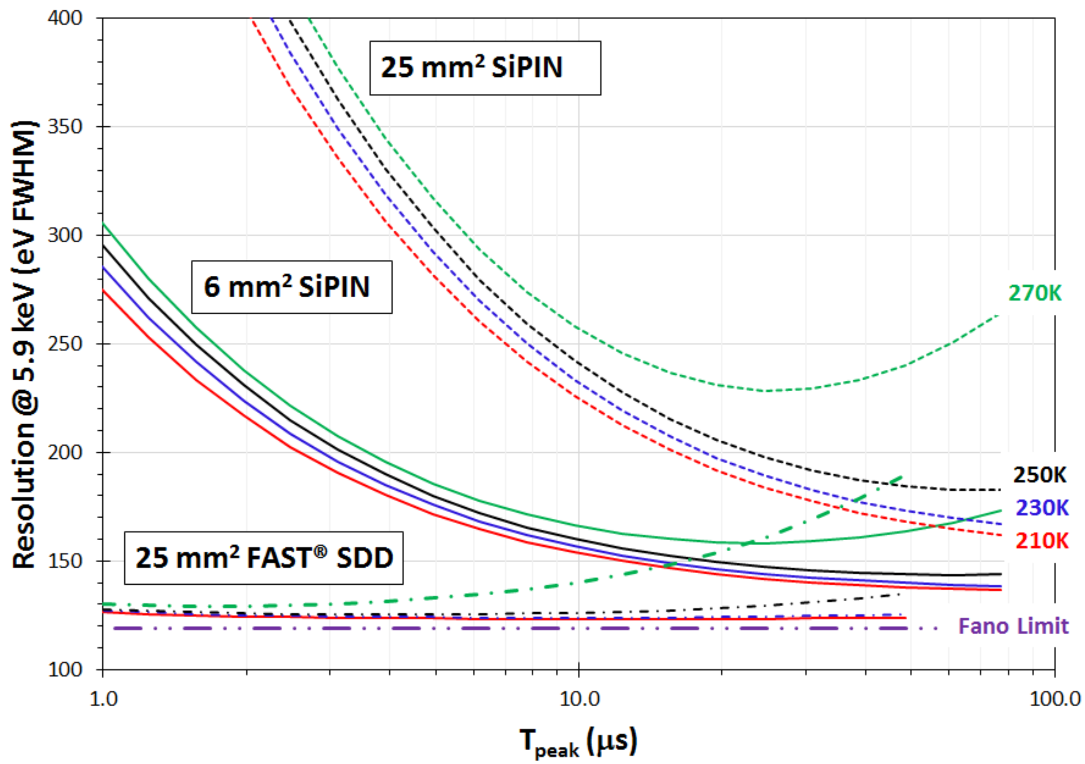


3.3 Noise and Pulse Shaping

How does pulse shaping filter noise?

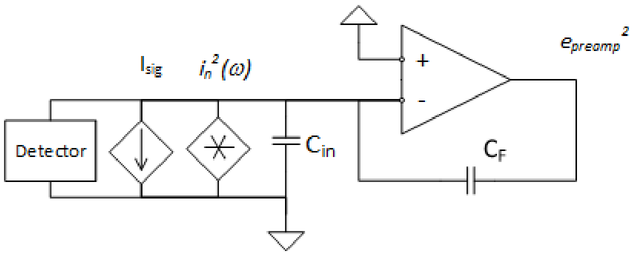
Resolution & Noise

- **Noise dependence**
  - *Varies with shaping time*
  - *Varies with temperature (different at long and short τ)*
  - *Varies with detector area and technology*
  - *Varies with type of pulse shaping (not shown here)*



Noise and Pulse Shaping

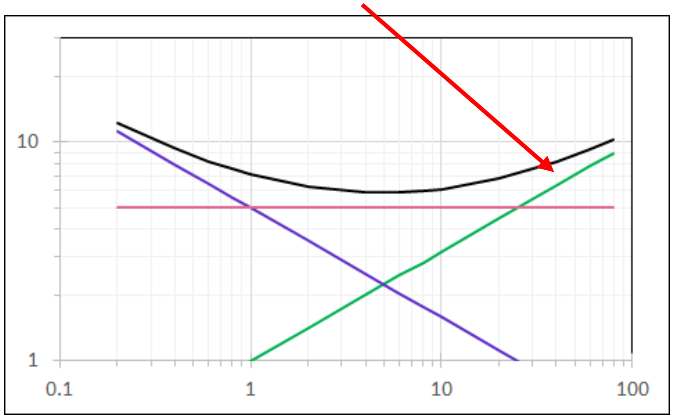
- **Parallel noise (a.k.a. current noise)**
  - *There are current noise sources in parallel with signal current*
    - Detector leakage current shot noise, feedback resistor thermal noise, etc.
    - Actual, physical fluctuating currents into the preamp input
    - Mostly shot noise from I_{dark} and thermal noise from $R_{||}$ (both white)
  - *These are integrated by the feedback capacitor*
    - This is a low pass filter (integration ↔ $1/\omega C_F$)
    - White parallel noise → low frequency at preamp output



$$e_{preamp}(\omega) = \frac{i_n(\omega)}{\omega C_F}$$

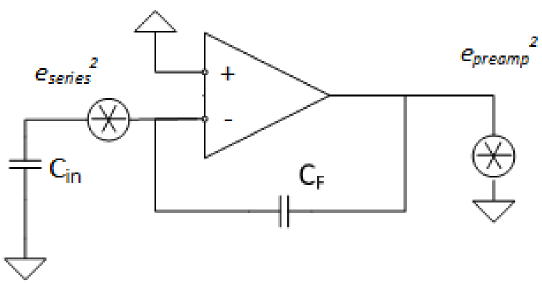
$$Q_{ENC} = \left(2qI_d + \frac{4kT}{R_{||}} + i_{amp}^2\right)\left(A_{step}^2 \tau\right)$$

White current noise

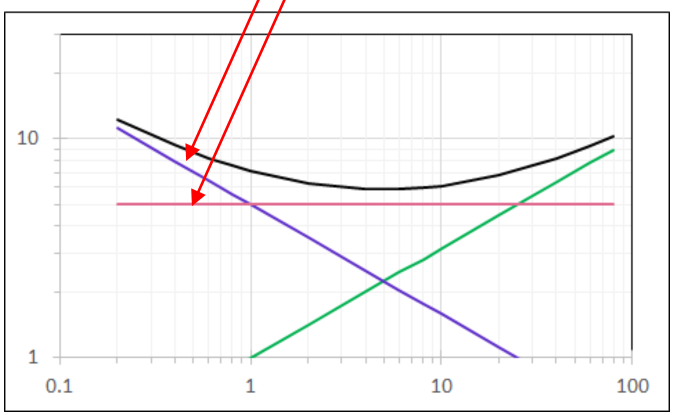


Noise and Pulse Shaping

- **Series noise (a.k.a. voltage noise)**
  - *Noise sources in the preamp → noise at preamp output*
  - *Model these as a voltage noise source in series with input*
    - An input equivalent noise source. The fluctuations are not actually there
    - Input equivalent noise increases with C_{in}. <u>Low capacitance is important</u>
  - *Not integrated by feedback capacitor*
    - White noise sources lead to white noise at preamp
    - Mostly white and 1/f noise from FET



White voltage noise
1/f voltage noise

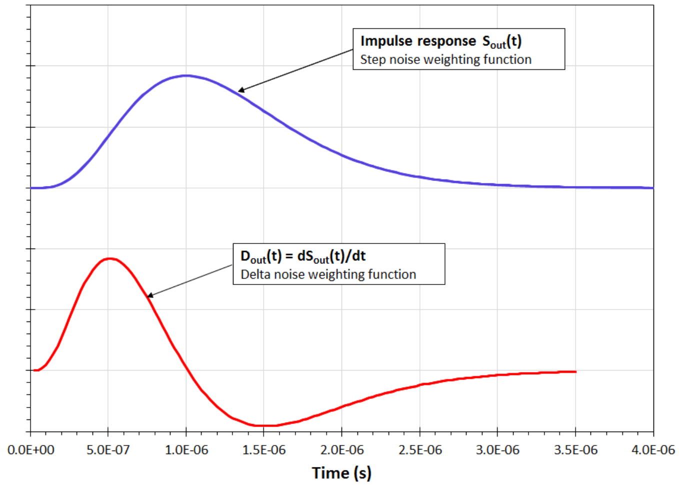


$$e_{preamp}(\omega) = e_{series}(\omega)\left(1+\frac{C_{in}}{C_F}\right) = e_{series}(\omega)\frac{(C_{in}+C_F)}{C_F}$$

$$Q_{ENC}^2 \cong C_{in}^2\left\{\left(v_{1/f}^2\right)A_{pink}^2 + \left(4kT\left(\frac{\gamma}{g_m}\right)+i_{preamp}^2\right)\left(\frac{A_{delta}^2}{\tau}\right)\right\}$$

Noise Weighting Functions

- *Parallel white noise a.k.a. "Step noise"*
    - Impulse at preamp input → step at preamp out → Output impulse is $S_{out}(t)$
    - Noise scales as $A^2_{step}\tau$
- *Series white noise a.k.a. "Delta noise"*
    - Impulse (or "delta") at preamp output
    - Not integrated → Output impulse is $D_{out}(t) = \frac{d}{dt} S_{out}(t)$
    - Noise scales as A^2_{delta}/τ
- *Series 1/f noise a.k.a. "Pink noise"*
    - Noise is independent of τ



$$N^2_{step} = \int_0^\infty \left|S_{out}(t)\right|^2 dt = e^2 \int_0^\infty \left[\frac{t}{\tau} e^{-\frac{t}{\tau}}\right]^2 dt = \left(\frac{e^2}{4}\right)\tau$$

$$N^2_{delta} = \int_0^\infty \left|D_{out}(t)\right|^2 dt = e^2 \int_0^\infty \left[\left(\frac{1}{\tau} - \frac{t}{\tau^2}\right) e^{-\frac{t}{\tau}}\right]^2 dt = \left(\frac{e^2}{4}\right)\frac{1}{\tau}$$

$$N^2_{pink} = \int_0^\infty \frac{\left|D(\omega)\right|^2}{\omega} d\omega \sim \ln\left(\frac{f_u}{f_l}\right)$$

Resolution & Noise

Noise in a practical circuit

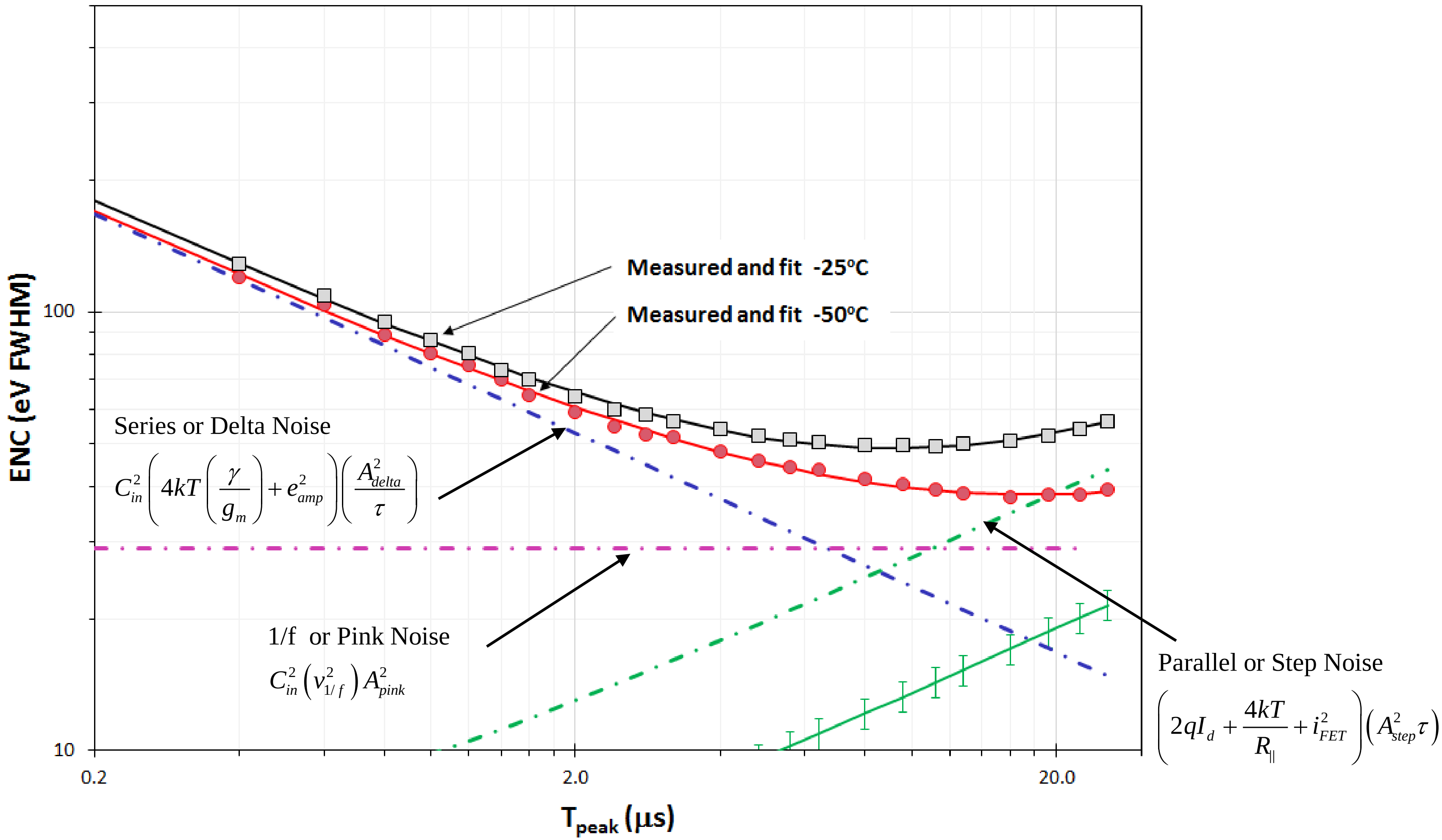
$$Q_{ENC}^2 \cong \left(2qI_d + \frac{4kT}{R_{\|}} + i_{FET}^2\right)\left(A_{step}^2\tau\right) + C_{in}^2\left(v_{1/f}^2\right)A_{pink}^2 + C_{in}^2\left(4kT\left(\frac{\gamma}{g_m}\right) + e_{amp}^2\right)\left(\frac{A_{delta}^2}{\tau}\right)$$

- *Parallel noise*
  - Depends on dark current and parallel resistance
  - I_d increases with detector size, strongly depends on detector temperature
  - Dominates at long shaping times
- *1/f noise*
  - Scales with detector capacitance
  - Depends on input FET and on materials at input
  - Independent of shaping time. Dominates at minimum
- *Series noise*
  - Scales with detector capacitance
  - Depends on FET properties

    $g_m \sim C_{FET} \rightarrow$ Optimum when $C_{FET} \sim C_{det}$
  - Dominates at short shaping times (needed for high count rates)
- *Indices depend on pulse shaping: CR-RC versus others*

Resolution & Noise

- **Example**



4. Timing

4.1 Dead Time

What is dead time?

How does it affect a measurement?

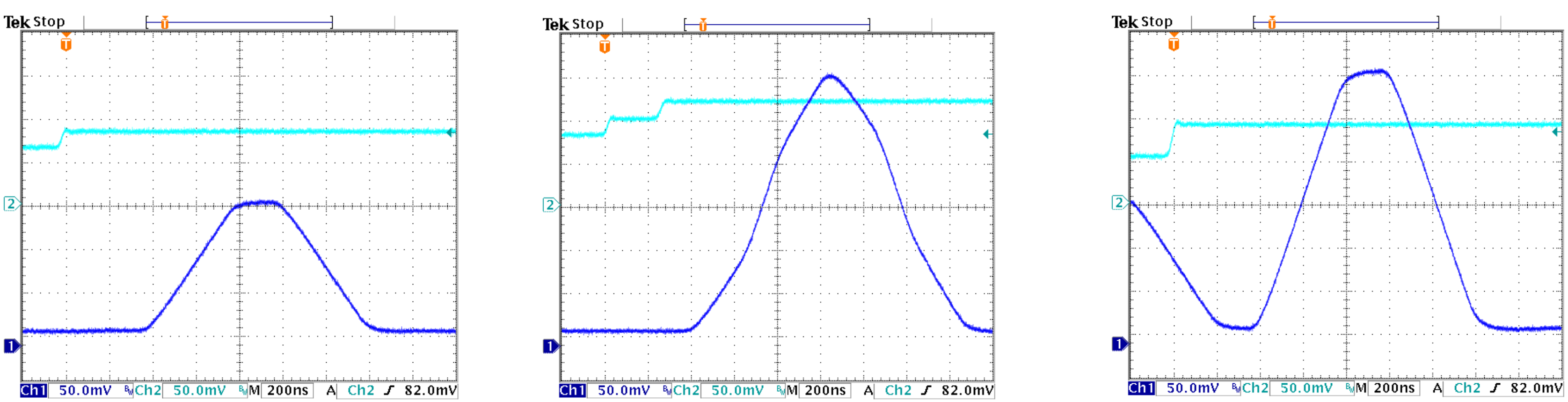
Timing: Dead Time

What is dead time?

- *Time after each event during which the system cannot record another event*
- *Since events occur at random times, some events are always "lost"*
- *True input rate is R_{IN}. Measured output rate is R_{OUT}*
- *Want to know R_{IN} → minimize and correct for dead time losses*

What causes dead time?

- *Intrinsic detector response time*
    - If detector current pulse is 10 to 50 ns, cannot detect a second if ΔT *= 20 ns*.
- *Time associated with pulse shaping*
    - Exact dead time depends on how events are identified
- *Time associated with data acquisition, storage, and conversion*



Timing: Dead Time

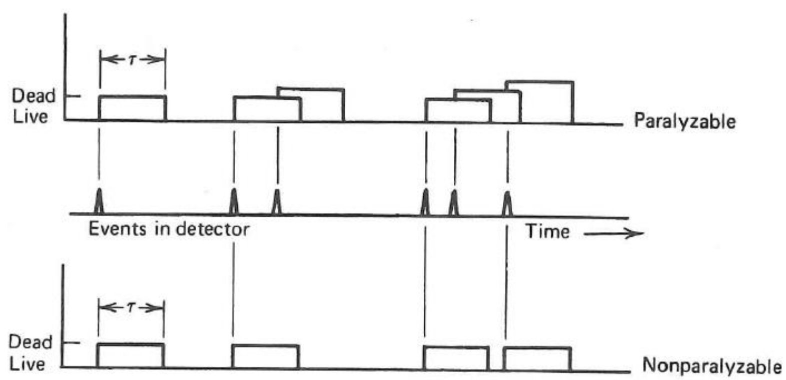
Dead Time Models

- *Non-paralyzable*
  - An event happening during the dead time is simply lost
  - At high rates, saturates at $R_{OUT}=1/T_{dead}$

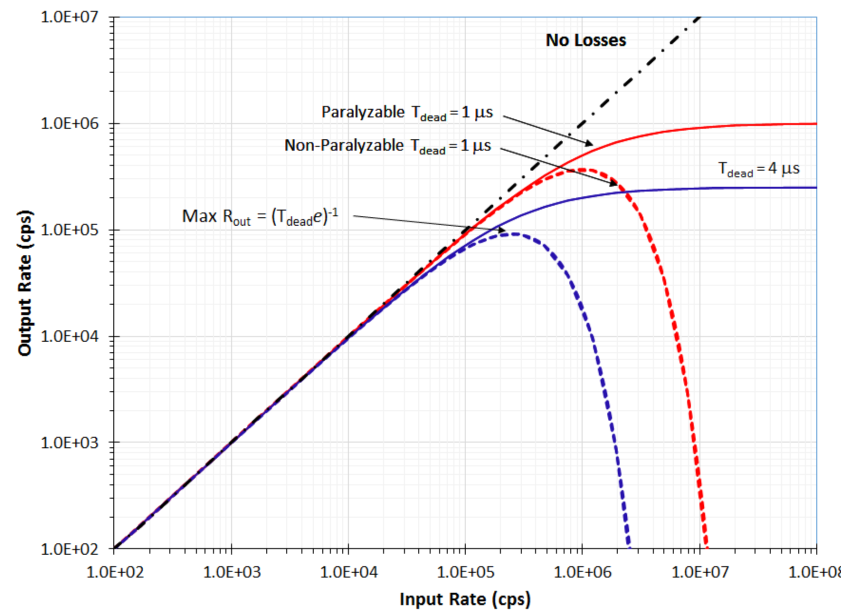
$$R_{out} = R_{in}\left(\frac{1}{1-R_{in}T_{dead}}\right)$$

- *Paralyzable*
  - Event happening during dead time restarts dead time
  - At high rate, saturates as $R_{out} \rightarrow 0$
  - Peak R_{out} occurs at $R_{in}=1/T_{dead}$ and 68% ($1/e$) dead time

$$R_{out} = R_{in}\left(e^{-R_{in}T_{dead}}\right)$$



From Knoll



Timing: Dead Time

- **How do we correct for dead time losses?**
  - *Computation*
    - If you know the dead time per pulses, and which model applies, then you can measure R_{out} and compute R_{in}
    - Works well in many systems but requires careful characterization
  - *Live time clock*
    - Count rate comes from measured counts divided by measurement time
    - Can stop the clock while the system is dead, yielding live time
    - Must be able to define well the dead time of each pulse. Worked well in analog systems, where ADC acquisition time dominated
    - There are many sophisticated variations on this approach
  - *Measuring input rate*
    - Can use a faster channel, with little dead time, and measure its rate directly
    - Must make sure all events are registering in both channels. Noise will be different in fast and slow; can get spurious noise pulses or events lost in noise, causing errors
  - *Note*
    - We CAN correct for dead time losses with good accuracy
    - All corrections are approximate. Lower dead losses give better accuracy

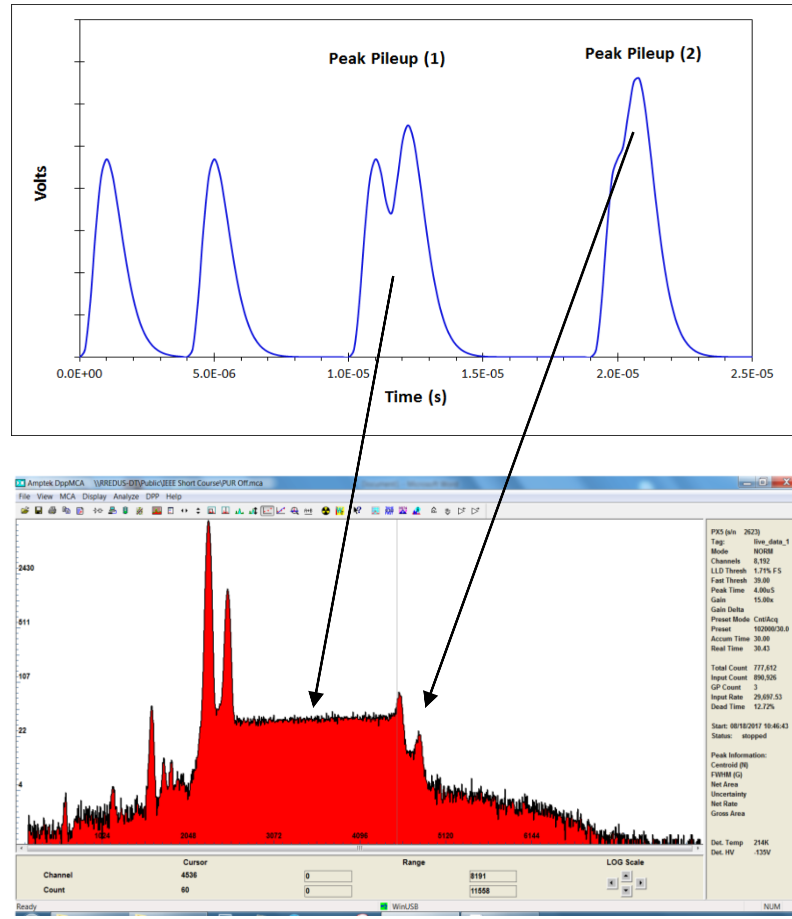
4.2 Pile-Up

What is pile-up?

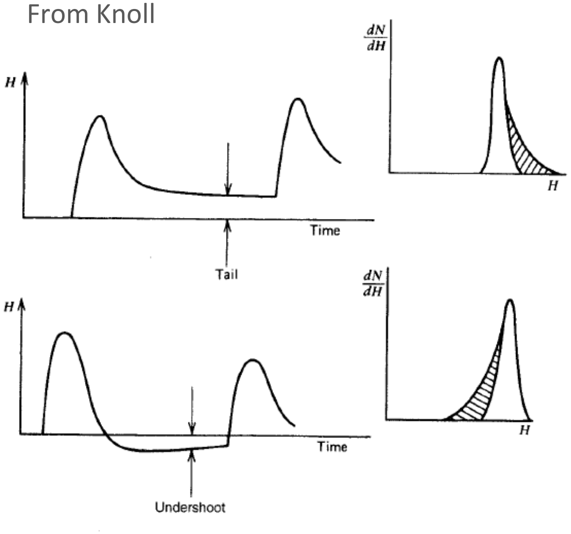
How does it affect a measurement?

Timing: Pileup

- **What causes pulse pileup?**
  - *If two pulses are too close together in time, pulse height of second is affected.*
  - *Result is an error in measured pulse height → Distortion in spectrum*
- **Three pile-up cases**
  - *Tail Pile-up*
  - *Peak Pile-up continuum, $\Delta T > T_{flat}$*
  - *Peak Pile-up sum, $\Delta T < T_{flat}$*



Tail Pile-up
From Knoll

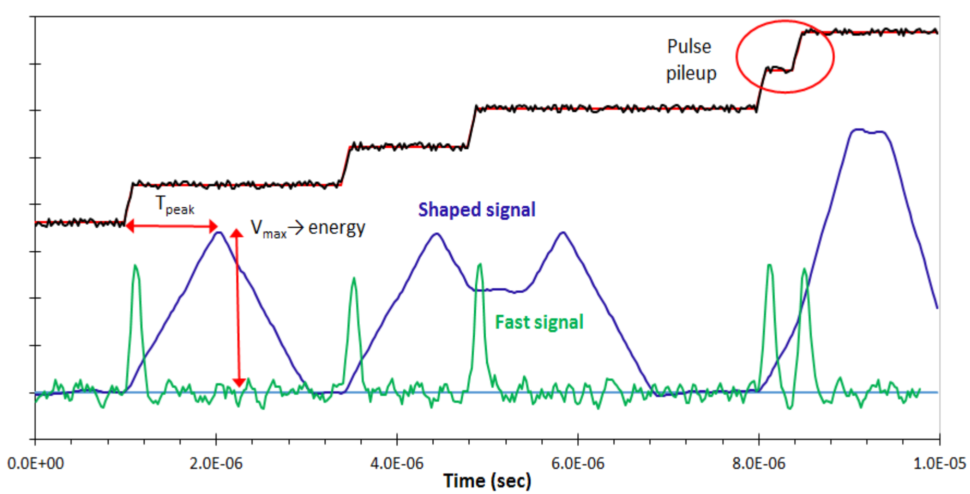


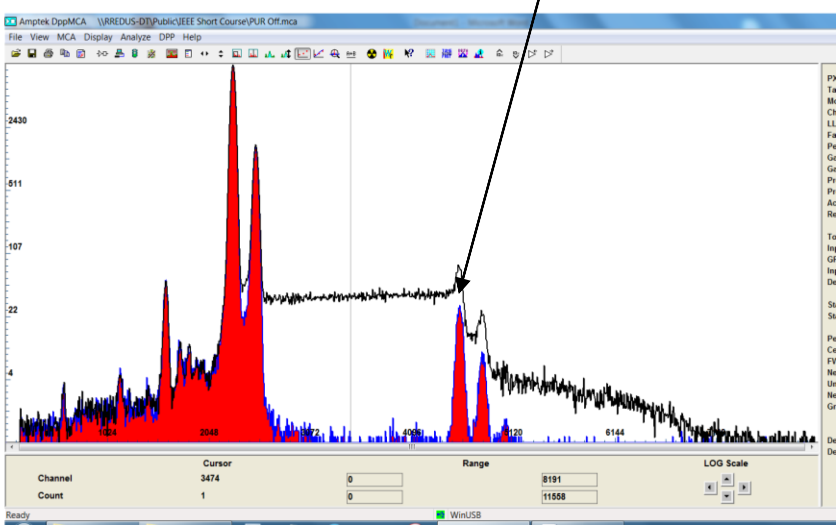
Timing: Pileup

AMPTEK®

- **Pile-up Rejection**
  - *A parallel fast channel is used, optimized to detect pulses quickly*
  - *Identify pulses distinguishable in fast channel but overlapped in slow*
  - *Rejects all pulses which would have pulse height error*
  - *Reduces total count rate (double dead time per pulse) but cleans spectrum*
- **Sum Peak**
  - *Does not remove sum peak*
  - *"Pulse pair resolving time"*

$$R_{sum} = R_1 R_2 T_{PPRT}$$





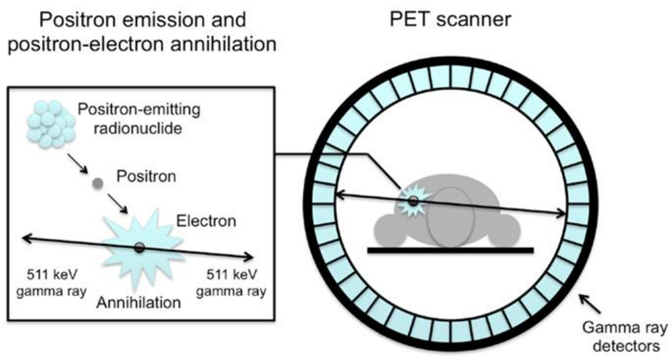
4.3 Timing Measurements

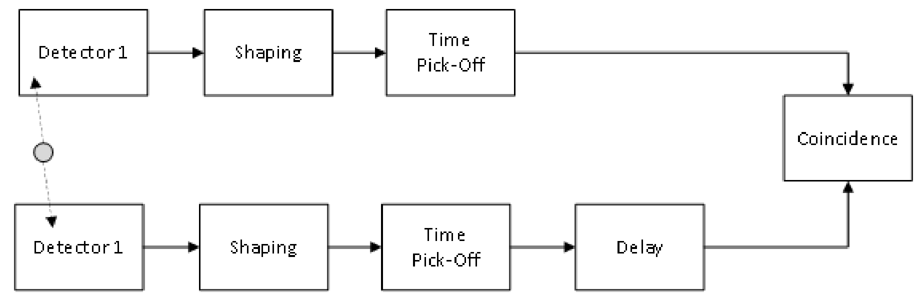
How do we measure pulse timing?

Timing Measurement

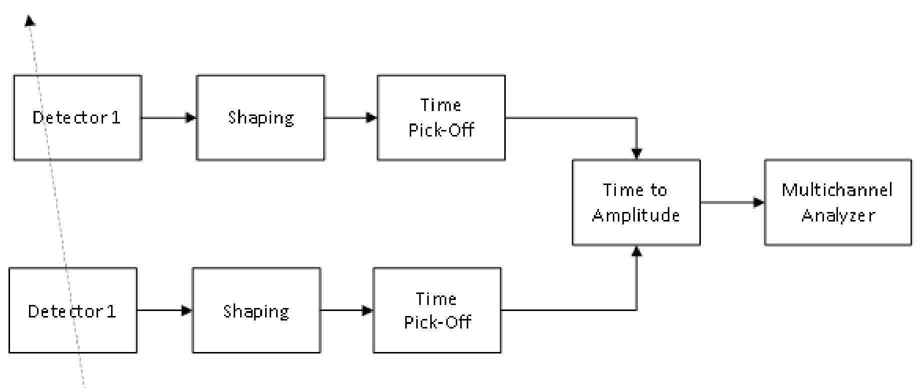
Applications

- *Positron Emission Tomography*
  - Were detectors triggered at some time (coincidence)?



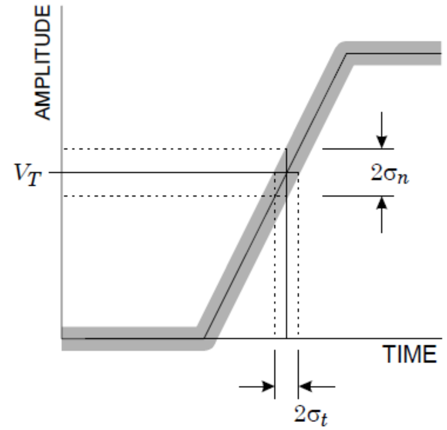


- *Delay Measurement*
  - Velocity in accelerator, half-life of excited state



Timing Measurement

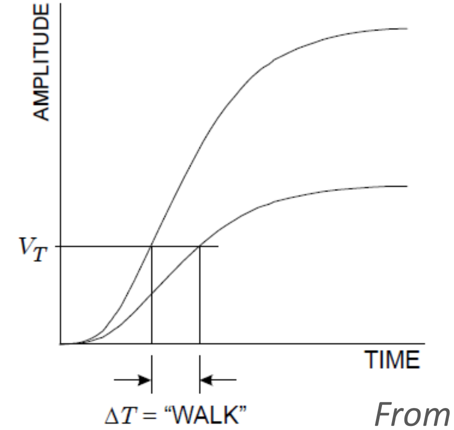
- **Leading Edge timing**
  - *Pulse "time" defined by leading edge crossing a threshold*
  - *Two sources of timing uncertainty*



  - *Timing "jitter" (random)*
    - ENC → fluctuation in timing measurement
    - Slope to noise ratio that matters

$$\sigma_{time} = \sigma_{noise} \left(\frac{dV}{dt} \right) \Bigg|_{V = thresh}$$

  - *Timing "walk" (systematic)*
    - Time depends on pulse amplitude
    - Time crossing depends on shape of signal current

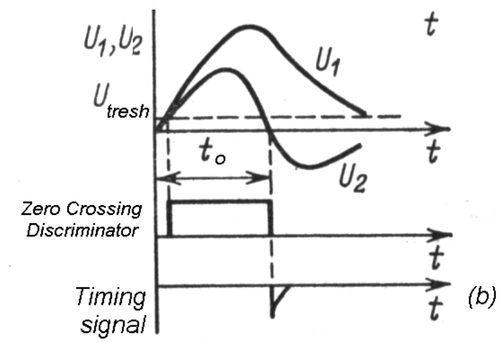


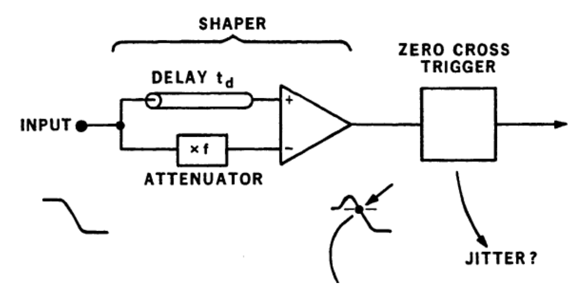
From Spieler

Timing Measurements

- **Key timing characteristics**
  - *There is always a delay: trigger happens after the event*
  - *Timing properties depend on derivative, slope of shape pulse*
    - Derivative → noise
    - Fast pulses often better → noisy

- **Other timing pick-off methods**
  - *Trigger at peak*
    - Find derivative of pulse, into zero crossing
    - Need to AND with a threshold
  - *Constant fraction*
    - Sum signal and delayed, attenuated
    - Fires at a constant fraction of risetime
    - Independent of amplitude (no walk)
  - *-Digital*
    - Fit waveform or run other algorithms
    - Limited by ADC clock

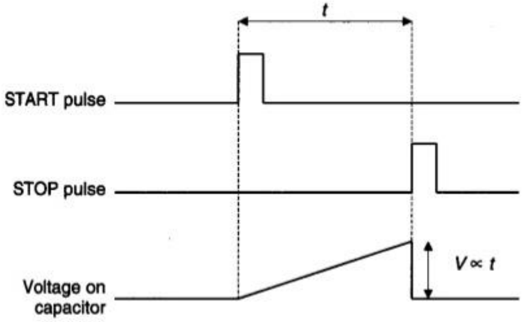




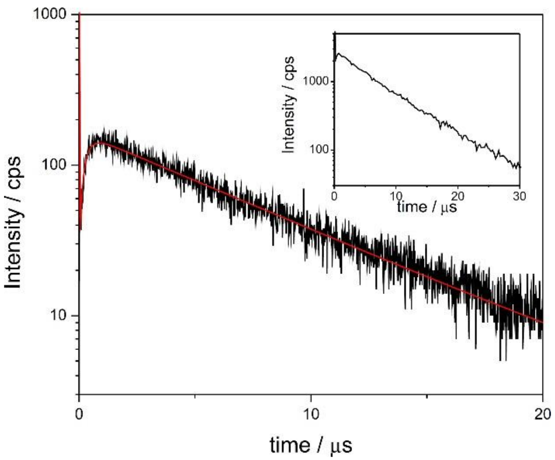
From Ortec

Timing Measurements

- **Other Timing Components**
  - *Delay units*
    - One always needs to adjust delays between channels
  - *Coincidence units*
    - Looks for logic signals to be simultaneous
  - *Time to amplitude converter*
    - Linear ramp from START to STOP
    - Use pulse height electronics for timing
  - *Multichannel scaler (MCS)*
    - Records counts in successive time bins
    - Gives timing spectrum
    - Measure half-life



From Ortec



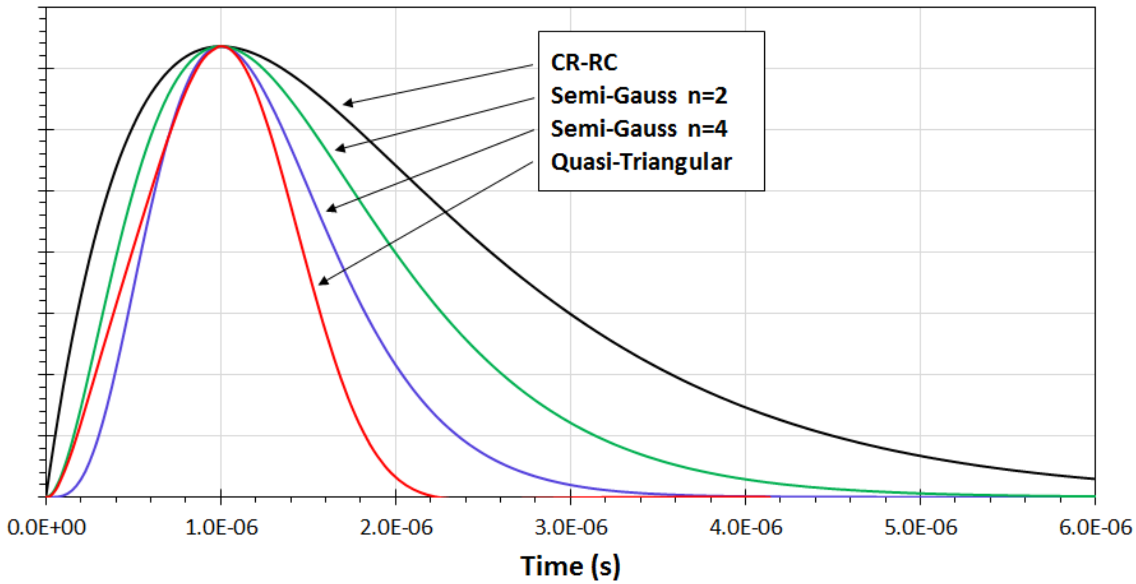
5. Pulse Shaping Revisited

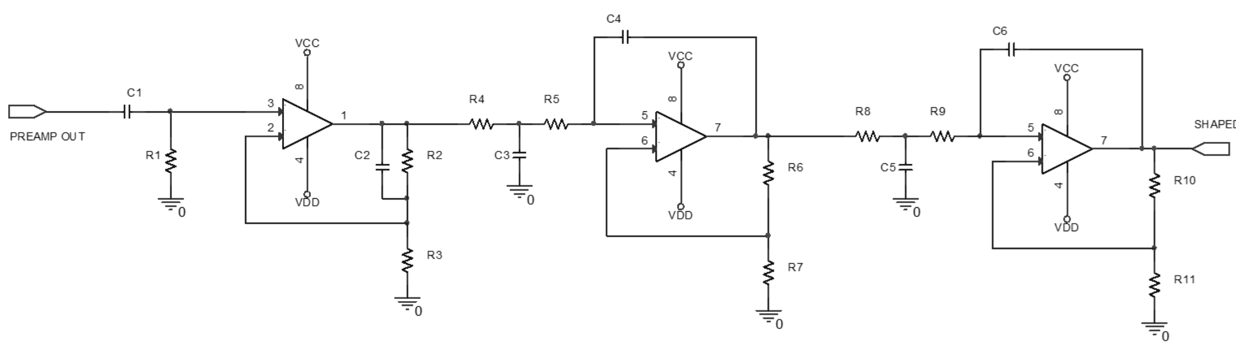
Why are there different pulse shapers?
Which one should I use?

Other shaping topics

Pulse Shaping Revisited

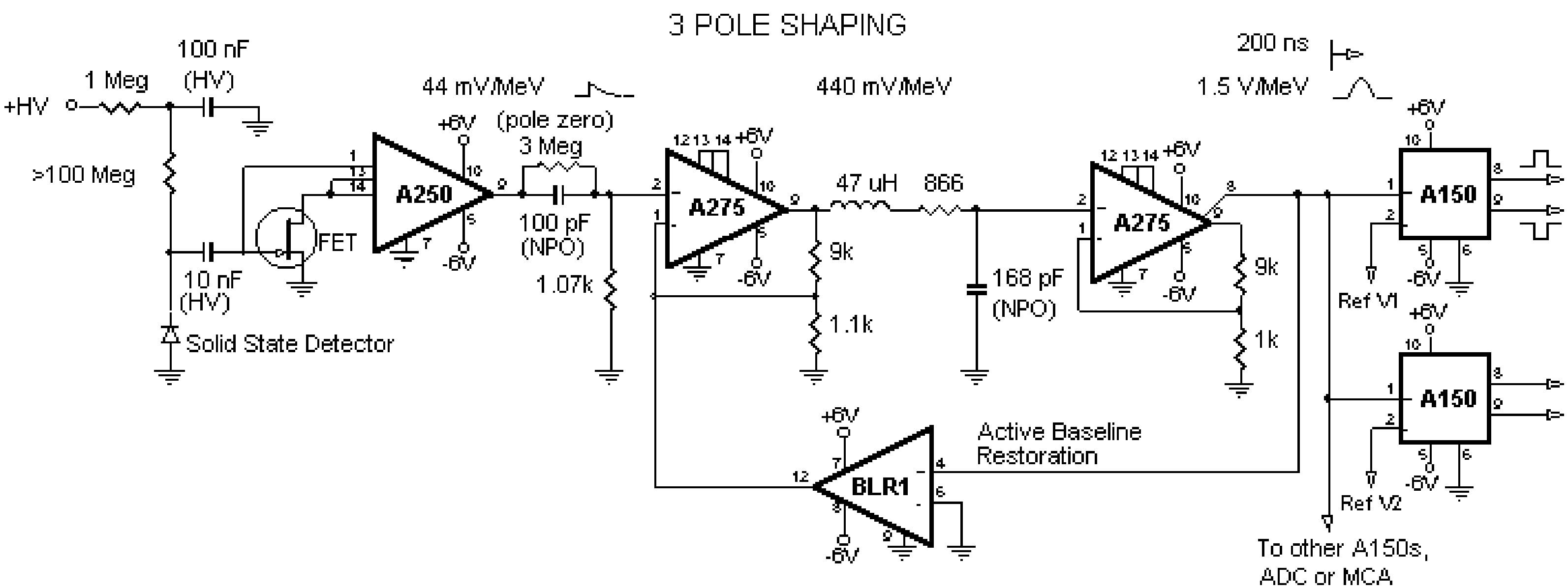
- **Analog pulse shapers**
  - *More low pass filtering → Faster return to baseline & lower noise bandwidth*
  - *Can also use "active" filters, Sallen-Key circuit with complex poles*





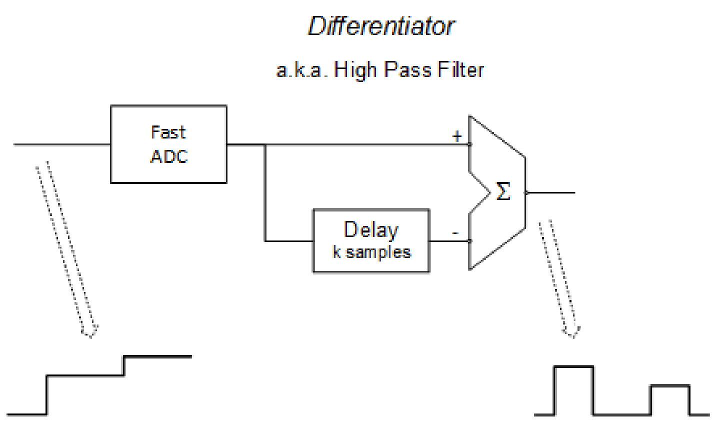
Pulse Shaping Revisited

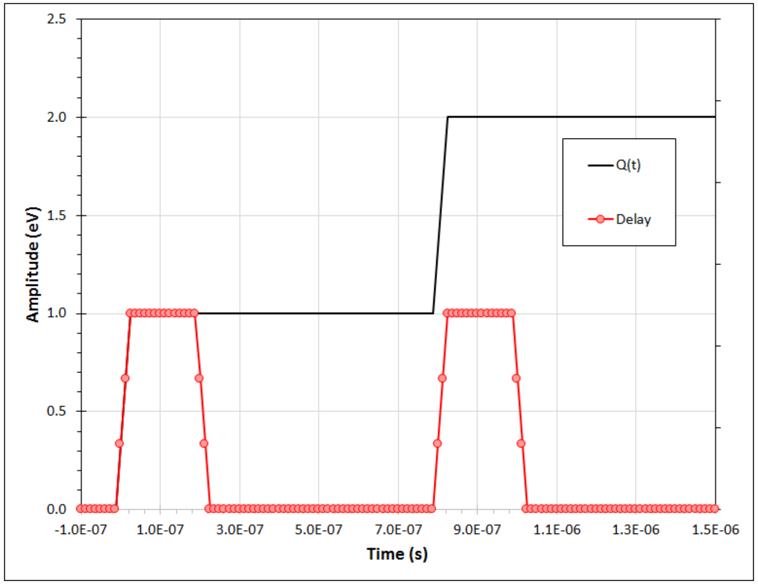
- **Real shaping circuit: Amptek hybrids**
  - *For solid state particle detector*
  - *A250 preamp with matched JFET and resistive feedback*
  - *CR-(RC)^2 shaping with active baseline restore*



Pulse shaping revisited

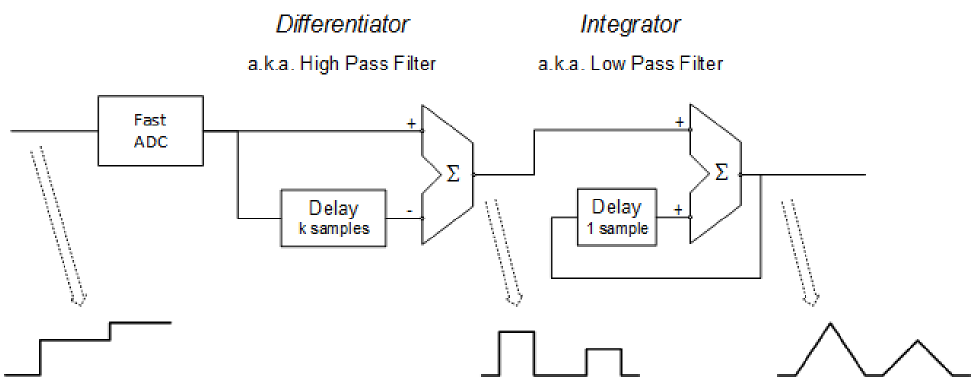
- **Digital High Pass: Finite Impulse Response**
  - *Problem with CR filter*
    - It decays exponentially to zero → "Infinite Impulse Response" or IIR
    - It gets small but persists "forever" → long dead time, pile-up
  - *Solution is delay subtract (digital high pass filter)*
    - An impulse input leads to an output which goes to zero after some time
    - "Finite Impulse Response" or **FIR**. Yields higher count rates

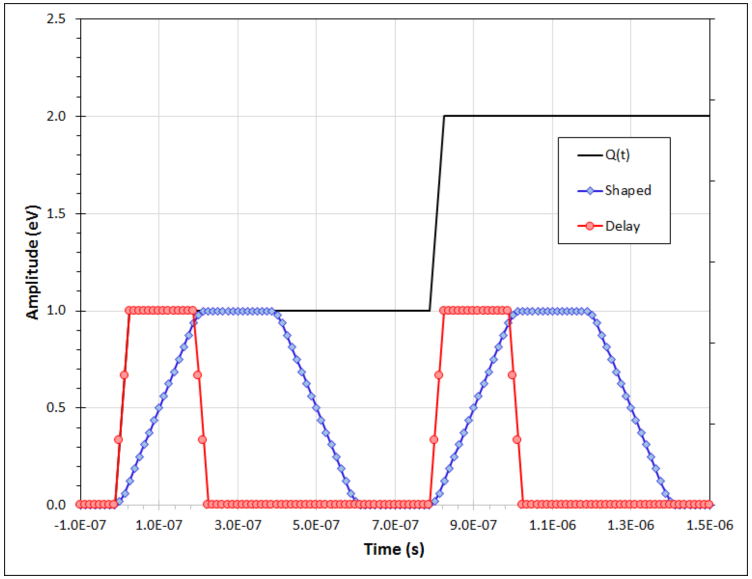




Pulse shaping revisited

- **Digital Low Pass**
  - *Apply running average (integrator) after differentiator*
    - Pulse shape is trapezoid
    - Flat top means no ballistic deficit, clean sum peak
    - FIR means highest possible throughput
    - Noise indices are minimum
  - *More complex digital shapes possible: pseudo-cusp, etc*



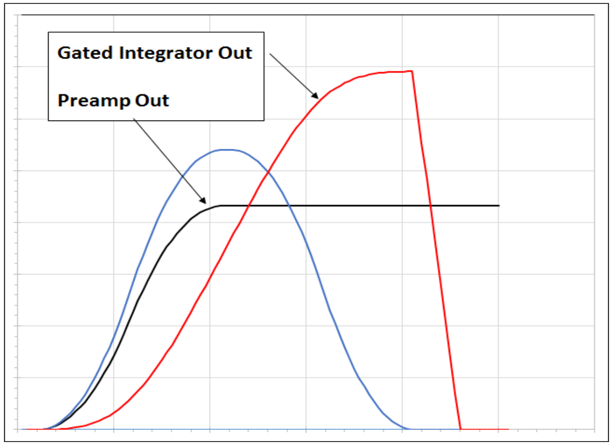


Pulse Shaping Revisited

- **What is the ideal pulse shape?**

	Step (parallel) noise	Delta (series) noise	Duration (FWHM)	Duration (FWTM)
RC - CR	$\frac{e^2}{4}\tau_{peak} = 1.87\tau_{peak}$	$\frac{e^2}{4\tau_{peak}} = \frac{1.87}{\tau_{peak}}$	$2.45\tau_{peak}$	$4.8\tau_{peak}$
Semi-Gaussian	$\frac{2}{3}\tau_{peak}$	$\frac{2.5}{\tau_{peak}}$	$1.1\tau_{peak}$	$2.5\tau_{peak}$
Pseudo-Gaussian	$0.58\tau_{peak}$	$\frac{2.9}{\tau_{peak}}$	τ_{peak}	$2.2\tau_{peak}$
Infinite cusp	τ_0	$\frac{1}{\tau_0}$		
Digital Triangle	$\frac{2}{3}\tau_{peak}$	$\frac{2}{\tau_{peak}}$	τ_{peak}	$2\tau_{peak}$
Digital Trapezoid	$\frac{2}{3}\tau_{peak} + \tau_{flat}$	$\frac{2}{\tau_{peak}}$	$\tau_{peak} + \tau_{flat}$	$2\tau_{peak} + \tau_{flat}$

Pulse shaping revisited

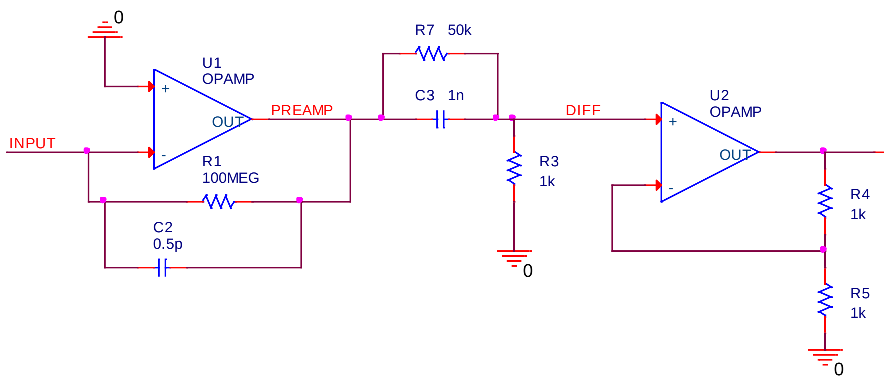


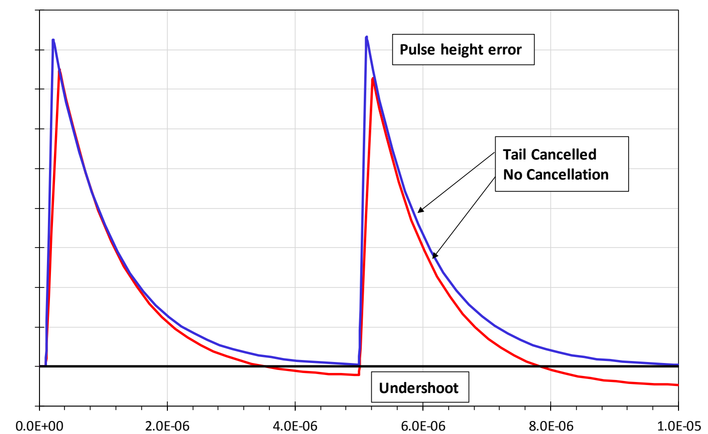
- **Analog Time Variant: Gated Integrator**
  - *Adjust the integration time for every pulse*
    - Completely eliminates ballistic deficit
    - Noise depends on integration time
      - → Depends on spectrum – not known a priori
      - → Cannot be modeled in frequency domain
    - Peak shapes are not Gaussian (sum of Gaussian) and always varying
  - *Other time variant circuits are in use*

- **Digital Time Variant: Adaptive shaping**
  - *Adjust the peaking time on every pulse*
    - Use the longest time that avoids overlap
    - Provides highest possible resolution for good throughput
    - Resolution depends on count rate so always varying
    - Peak shapes are not Gaussian (sum of Gaussian) and always varying
  - *Very active topic in research today*

Pulse shaping: Additional topics

- **Pole Zero Cancellation**
  - *Problem*
    - CR passes attenuated slow tail → tail undershoot → error for next pulse
  - *Solution*
    - Pass an attenuated fraction of the actual tail (via R7)
    - (R7 C3) = (R1 C2)



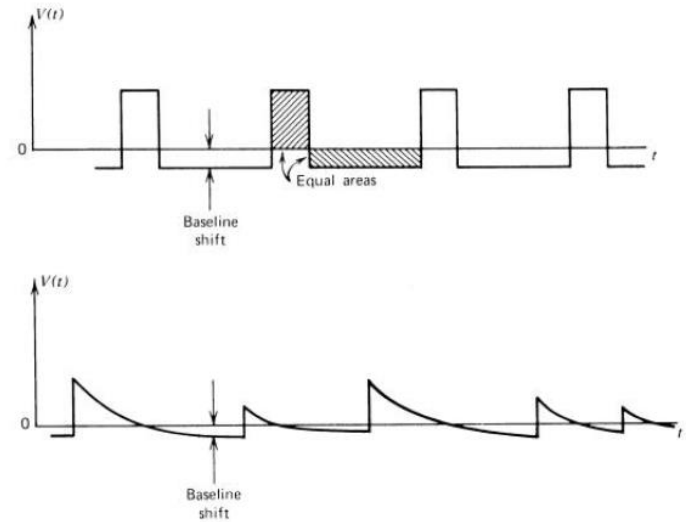


  - *Why is this called "pole zero cancellation"?*
    - The "pole" from the preamp is "cancelled" to get a single pole response

$$\left[\frac{s\tau_{preamp}}{1+s\tau_{preamp}}\right]\left[\frac{s\tau_{CR}}{1+s\tau_{CR}}\right] \Rightarrow \left[\frac{s\tau_{preamp}}{1+s\tau_{preamp}}\right]\left[\frac{\tau_{CR}\left(1+sR_{PZ}C\right)}{\tau_{CR}+R_{PZ}C+R_{PZ}C}\right]=\left[\frac{s\tau_1}{1+s\tau_1}\right] \quad \text{if} \quad R_{PZ}C=\tau_{preamp}$$

Pulse shaping: Additional topics

- **Baseline restoration**
  - *Problem*
    - Capacitor blocks DC. A sequence of unipolar pulses has a DC component, so baseline shifts
    - Shift depends on count rate and energy spectrum

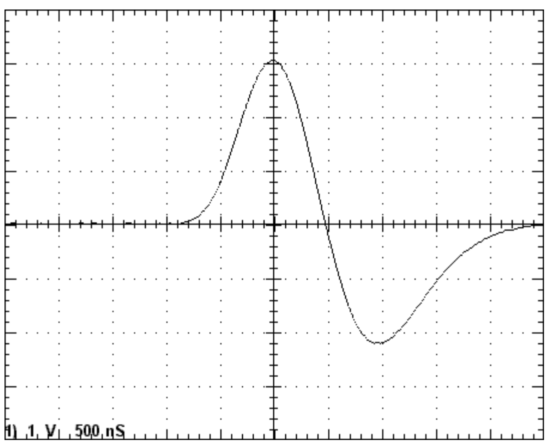


(from Knoll)

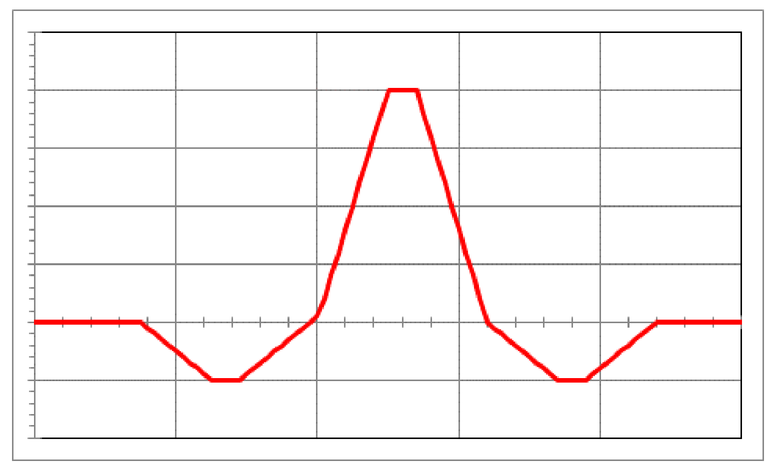
  - *Solution*
    - Pull the signal to ground in the absence of a signal
    - Initially done with diodes, now typically uses a feedback loop
    - Fast loops recover quickly but can add noise

Pulse shaping: Additional topics

- **Bipolar Shaping**
  - *Alternate solution for baseline shift*
    - Use a double-lobed pulse, with net area zero
    - Stable baseline and better rejects low frequency noise (e.g. 60 Hz)
    - But shaping factors A_{delta}, A_{step} worse (√2 analog, √1.5 digital)
    - Used where intrinsic noise not critical, stability and simplicity are



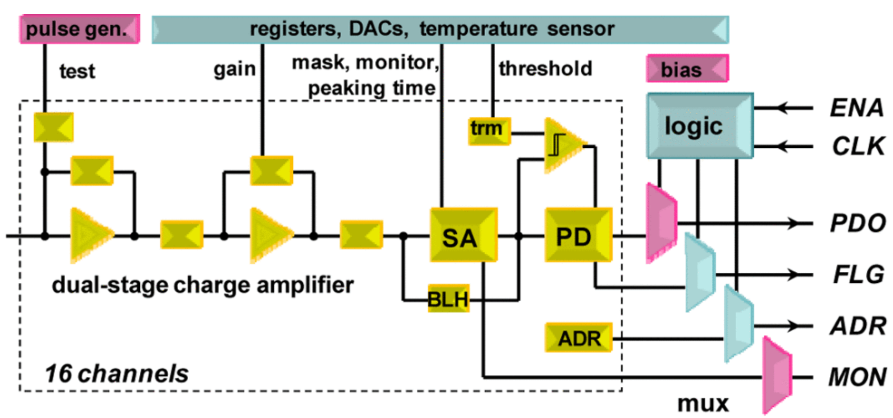
Analog bipolar pulse

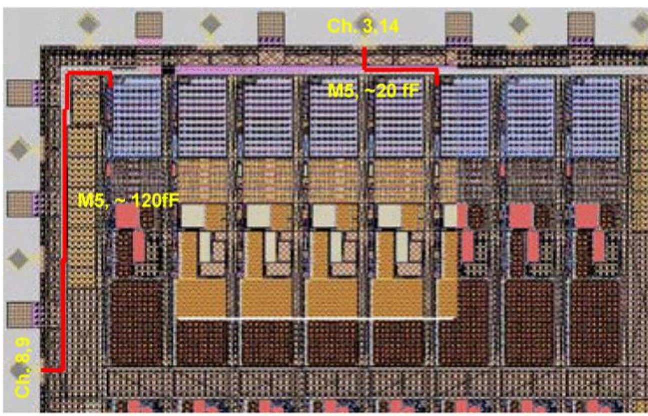


Digital bipolar pulse

Pulse shaping: Additional topics

- **Application Specific ICs**
  - *Compact multichannel systems*
    - De Geronimo, *ASIC for SDD-Based X-Ray Spectrometers*, IEEE TNS 2010
    - 16 channels, each with preamp, shaper, and peak detect
    - Single IC, 2 x 5 mm, <2 mW per channel, rad-hard
    - Advantage: Compare to digital spectrometer: 2"x2", 1W per channel
    - Disadvantage: Must customize for detector and application
    - ASIC development is a very active field!





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6. Digitizing the Output

Digitizing

- **Threshold discriminator**
  - *Logic output if signal over threshold*
  - *Only has lower threshold*

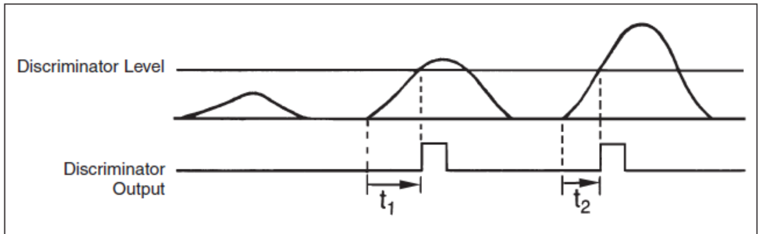


Fig. 1. Integral Discriminator Output Triggering.

- **Single Channel Analyzer**
  - *Logic output if signal in window*
  - *Has lower and upper level*
  - *Timing SCA generates output at a well-defined time relative to pulse*
  - *Can stack several SCAs*

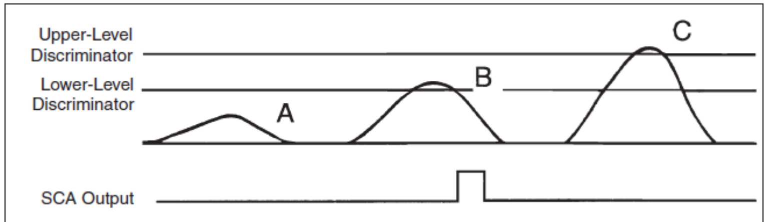
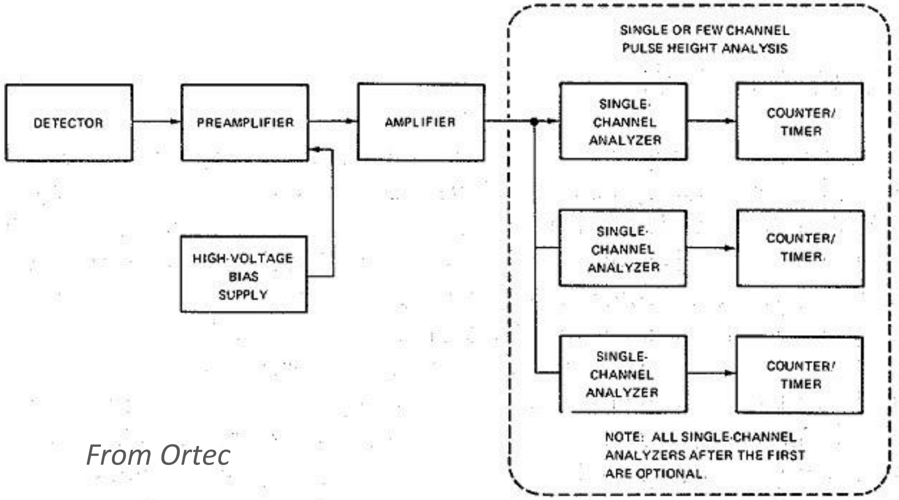


Fig. 2. Single-Channel Analyzer Function.

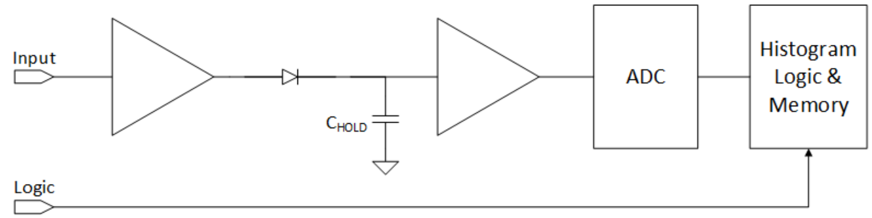
- **Counters & Timers**
  - *Used with discriminators & SCAs*



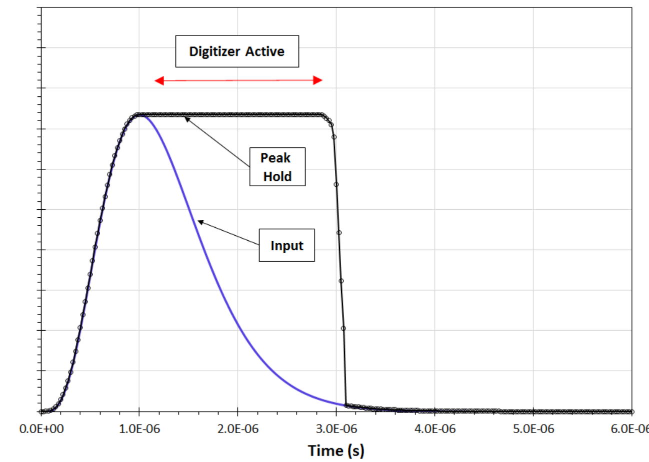
From Ortec

Digitizing

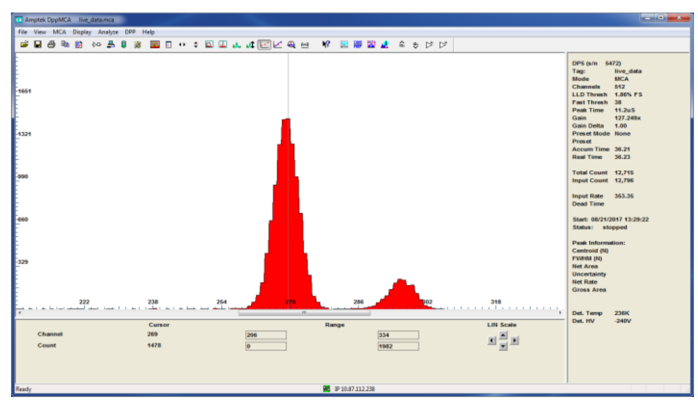
- **Multi-Channel Analyzer**
  - *Equivalent to many SCAs*
  - *Get histogram of pulse heights*



- **MCA Components**
  - *Peak detect & hold*
  - *ADC*
  - *Acceptance logic (pile-up, gate)*
  - *Histogram memory*
  - *Readout*



- **ADC**
  - *Critical to MCA*
  - *Many options*

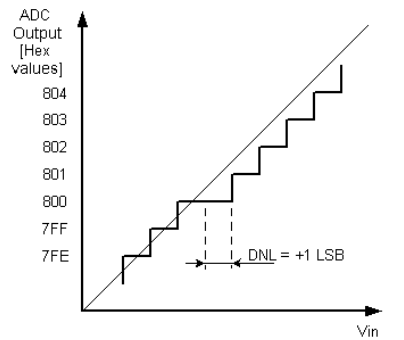


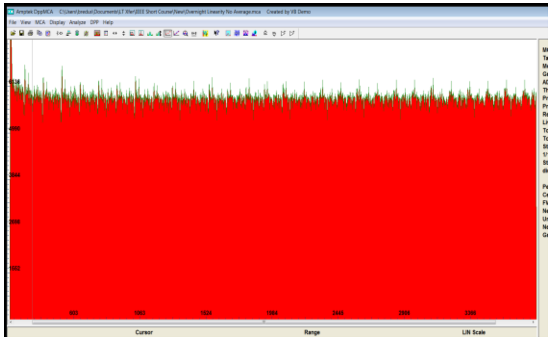
Digitizing

- **ADC parameters**
  - *Resolution*
    - Granularity of the output
    - Adds noise (white voltage noise)

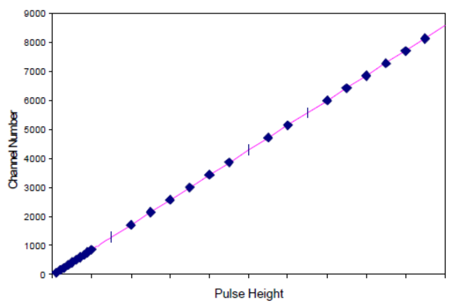
$$\sigma_V = \frac{1}{2\sqrt{3}}\left(\Delta V_{LSB}\right)$$

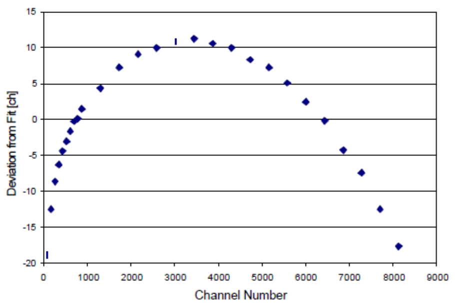
  - *Non-linearity*
    - Differential: How uniform are the digitization increments?





    - Integral: Is the digitized output proportional to the analog inut

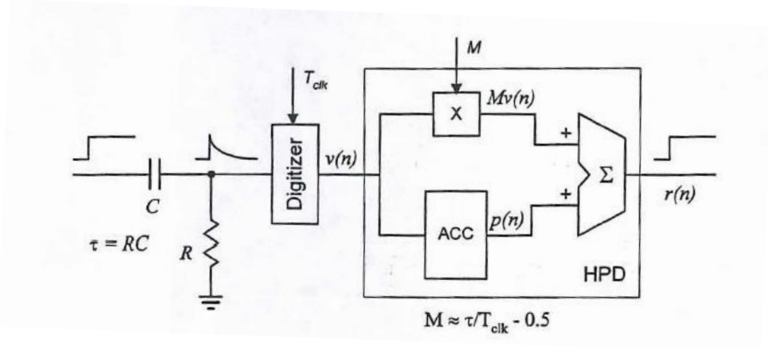




From Spieler

Digital Pulse Processing

- *Analog Prefilter*
  - Signal from preamp must be prepared for digitization
  - Basic problem: Millivolt preamp signal poorly matched to ADC bits
  - Several different algorithms with different prefilters
- *Jordanov prefilter (NIM 1994)*
  - CR high pass filter removes offset, then apply gain to match ADC
  - Must then cancel (digitally) the tail thus introduced



$$d_n = ADC_n - ADC_{n-k} - ADC_{n-l} + ADC_{n-(k+l)}$$

$$p_n = p_{n-1} + d_n$$

$$r_n = p_n + Md_n$$

$$s_n = s_{n-1} + r_n$$

$$k \to risetime \qquad (k-l) \to flat$$

- *For all DPPs, analog prefilter must be matched to detector and preamp*
- *Analog pulse shaping is key to a successful DPP*

6. Why things don't work

6.1 Practical considerations

After assembling a detector system, a common experience is that it doesn't work as expected. H Spieler

Why noise theory often does not seem to matter.

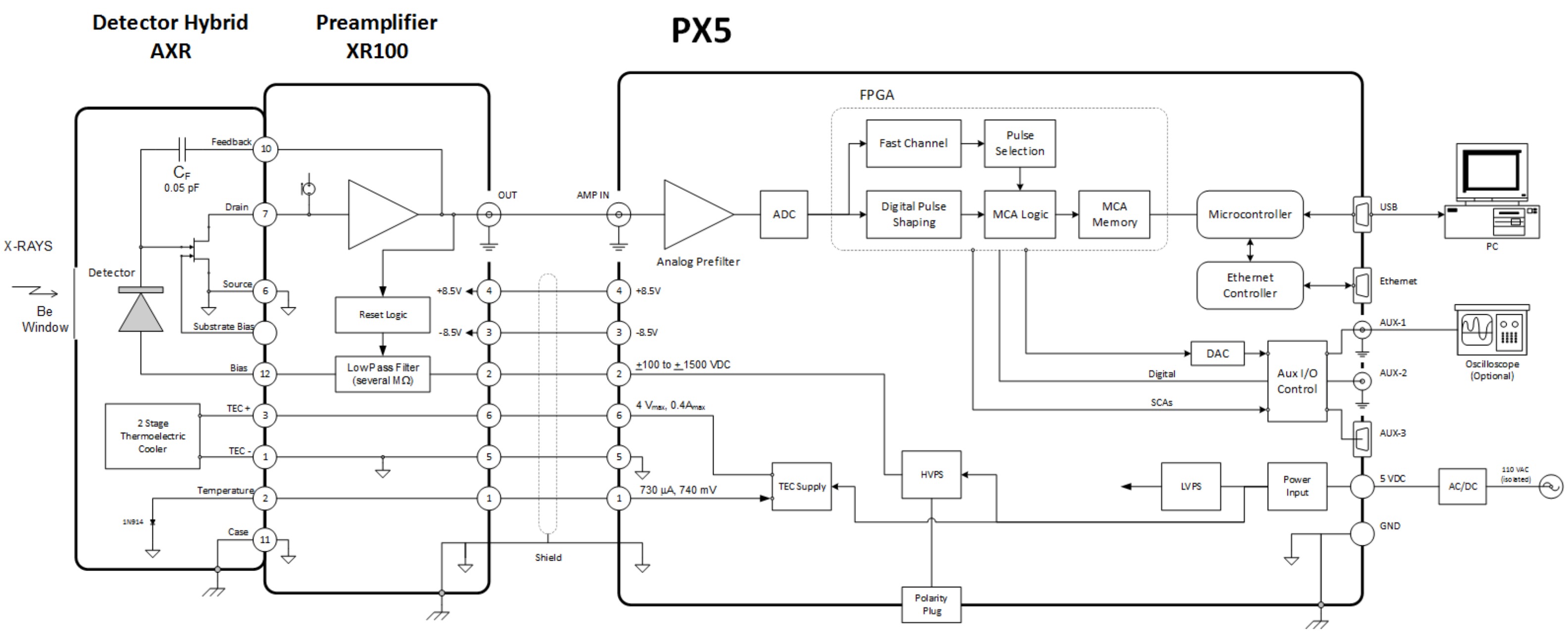
Why things don't work: Practical matters

- Shea's Law: The ability to improve a design occurs primarily at the interfaces. This is also the prime location for screwing it up.

- **Connections**
  - *Check that everything is connected*
  - *Check that the power is turned on*
  - *Cables and termination*
    - Improper termination can attenuate the signal
    - Improper termination can cause ringing → Amplified high frequency noise
    - Long cables are susceptible to reflections, resistive losses, and interference
    - USE THE RIGHT CONNECTORS AND CABLES
    - KEEP CONNECTIONS AS SHORT AS POSSIBLE
  - *Check mechanical interfaces*
    - Good heat sinking matters
    - Mechanical stability matters

Why things don't work: Practical matters

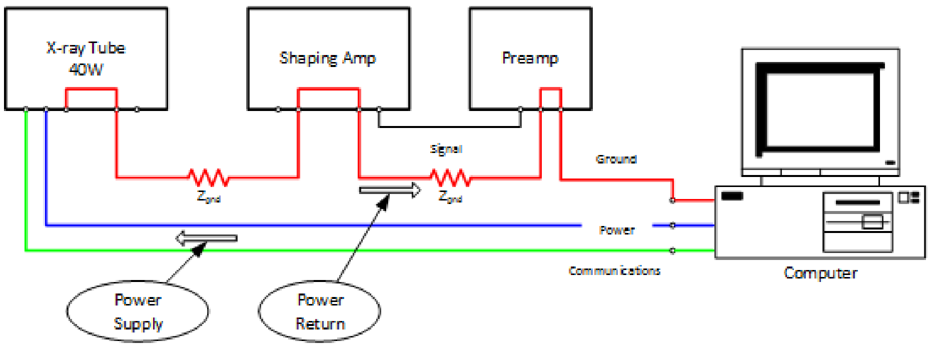
- **Consider the WHOLE system**
  - *Power supplies*
    - Nuclear systems include HVPS, several low voltages, etc
    - Can have 1/3rd the parts. Don't underestimate!
  - *Communications interfaces*
    - You have to get the data from the digitizer to a computer
    - Can have 1/3rd the parts. Don't underestimate!

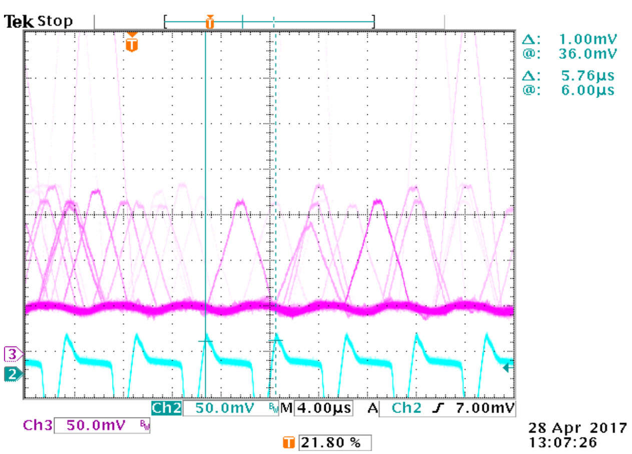


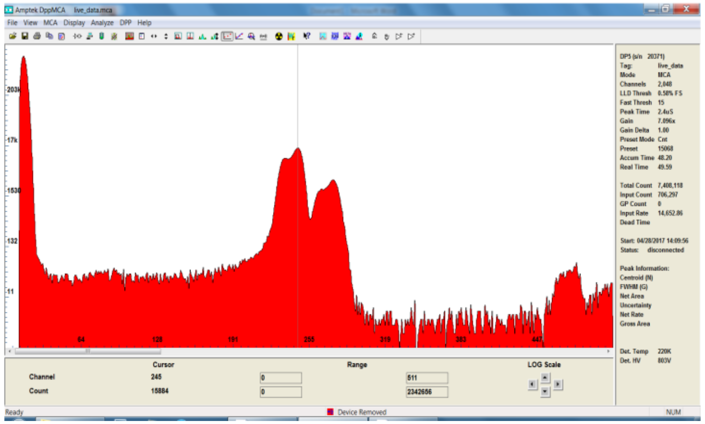
6.2 Interference

Why things don't work: Interference

- **What is interference?**
  - *Noise arising from energy coupling into the circuit from outside*



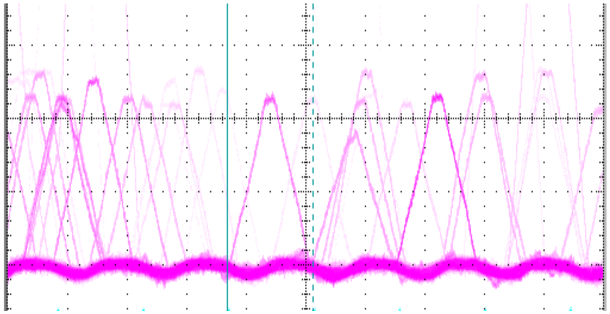




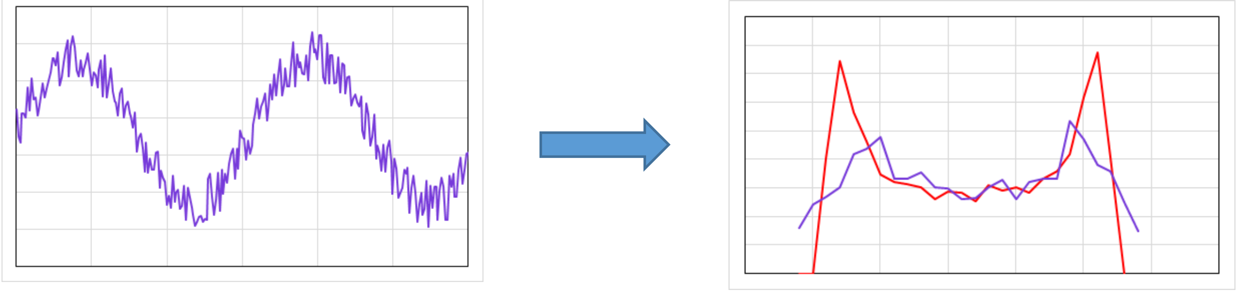
Why things don't work: Interference

General properties of interference

- *Output voltage is periodic, not random*
- *Affects pulse heights, count rate (above threshold), timing measurements*



- *Limited to certain frequency bands*
- *Pulse height distribution is not Gaussian*



- *FWHM does NOT go as sum of squares*
- *In principle, it can be eliminated totally*

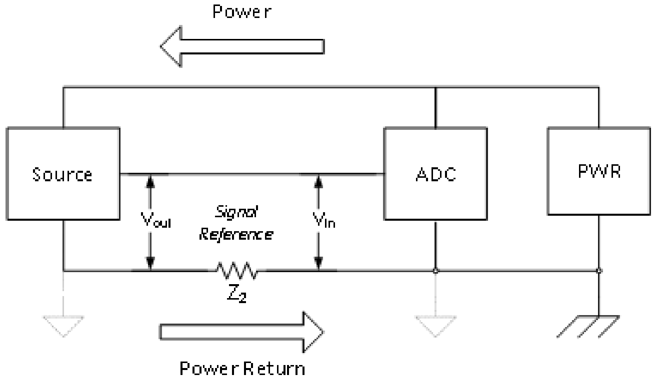
Why things don't work: Interference

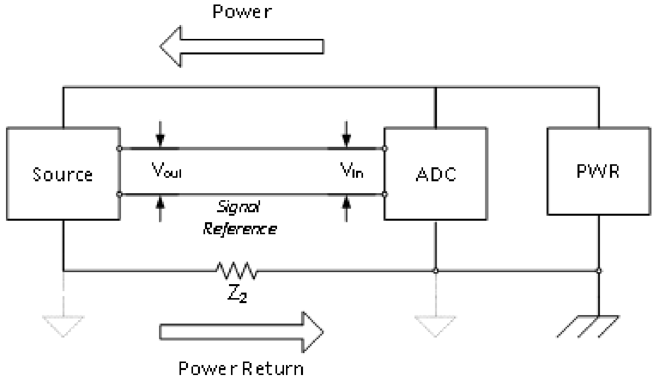
- **What is required to have interference?**
  - *(1) Source of energy, (2) coupling mechanism, (3) susceptible component*
  - *To solve an interference problem, you must address one of the three*
    - Eliminate the source of energy
    - Reduce the coupling
    - Change the susceptibility of your circuit
- **What are the key classes of interference?**
  - *Conducted currents*
    - Ground currents are the most common problem
    - Ripple on power lines, fluctuations on communication lines
  - *EM radiation*
    - Capacitive coupling, usually between adjacent wires
    - Magnetic coupling, usually into a loop (sometimes a ground loop)
  - *Acoustic radiation*
    - Vibrating biased wires create a current
  - *Photocoupling*
    - Radiation detectors pick up light

$$Q = CV \quad \Rightarrow \quad I = \frac{dQ}{dt} = C\frac{dV}{dt} + V\frac{dC}{dt}$$

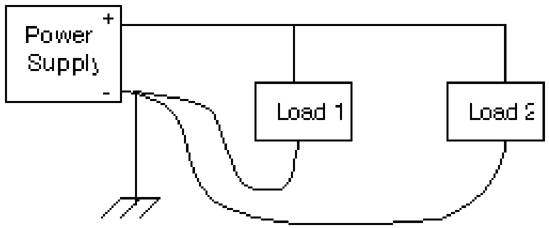
Why things don't work: Interference

- **Grounding**
  - *NEVER TRUST YOUR GROUND*
  - *Always have a REAL ground connection*
  - *Separate power return from signal reference*





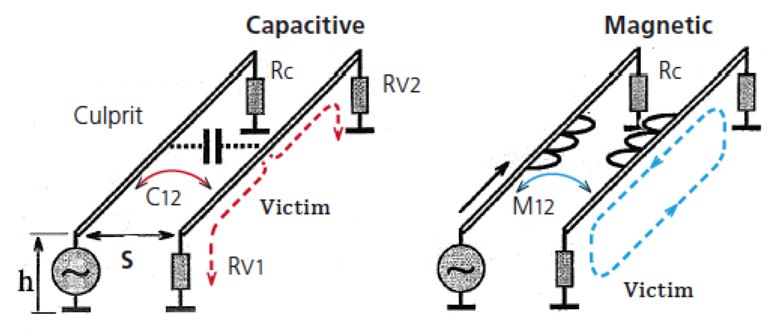
  - *Single point ground is usually best*

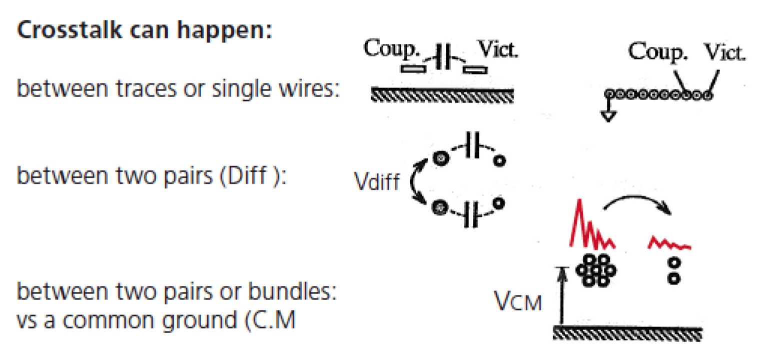


  - *Consider where ground currents flow and ground impedance*

Why things don't work: Interference

- **Radiated**
  - *Capacitive or magnetic coupling*
  - *Reduce coupling*
    - Shielding
    - Minimize loop size
    - "Ground loop"
    - Twisted pair
  - *Reduce emission*
    - Change frequency
    - FOLLOW MANUFACTURER'S RULES
    - Bypass caps, trace lengths, etc





Summary

Summary

- **Front end electronics are critical for good performance**

- **There are fundamental limits affecting every system**
  - *Stochastic pulse times*
  - *Fluctuations from intrinsic noise & charge creating*
  - *Variations in current profiles*
  - *Practical matters: size, cost, the "ilities"*

- **Start by considering system needs & signal from detector**
  - *What are you measuring?*
  - *What resolution & rate do you need?*
  - *What are the characteristics of the current pulse from the detector?*

Summary

- **Pulse shaping is a compromise between low noise and high rate**
  - *Fast shaping ↔ Higher noise*
  - *Digital shaping → Best performance, high cost and power*
  - *Analog shaping → Size, cost, power critical, performance less o*
  - *Many options for each*

- **Keys to performance**
  - *Low input capacitance (detector & connections), match JFET to detector*
  - *Low leakage currents, high parallel resistances*

- **Successful systems rely on many details that go beyond "headline specs"**

For more information

- **Textbooks**
  - *H. Spieler, **Semiconductor Detector Systems**, Oxford University Press, 2005*
  - *G. Knoll, **Radiation Detection and Measurement** (4th ed), Wiley & Sons, 2010*
  - *C. Motchenbacher & J. Connelly, **Low-Noise Electronic System Design**, Wiley & Sons, 1993*
  - *H. Ott, **Noise Reduction Techniques in Electronic Systems** (2nd ed), AT&T Bell Labs, 1988*

- **Online**
  - *Spieler tutorials: http://www-physics.lbl.gov/~spieler/*