IV. Signal Processing I

1. The Problem

"Optimum" Filtering

Pulse Shaping Objectives

2. Pulse Shaping and Signal-to-Noise Ratio

Equivalent Noise Charge

Ballistic Deficit

Noise vs. Shaping Time

Analytical Analysis of a Detector Front-End

Other Types of Shapers

Examples

Detector Noise Summary

3. Noise vs. Power Dissipation

1. The Problem

Radiation impinges on a sensor and creates an electrical signal.

The signal level is low and must be amplified to allow digitization and storage.

Both the sensor and amplifiers introduce signal fluctuations – noise.

1. Fluctuations in signal introduced by sensor
2. Noise from electronics superimposed on signal

The detection limit and measurement accuracy are determined by the signal-to-noise ratio.

Electronic noise affects all measurements:

1. Detect presence of hit: Noise level determines minimum threshold.
   If threshold too low, output dominated by noise hits.
2. Energy measurement: Noise "smears" signal amplitude.
3. Time measurement: Noise alters time dependence of signal pulse.

How to optimize the signal-to-noise ratio?

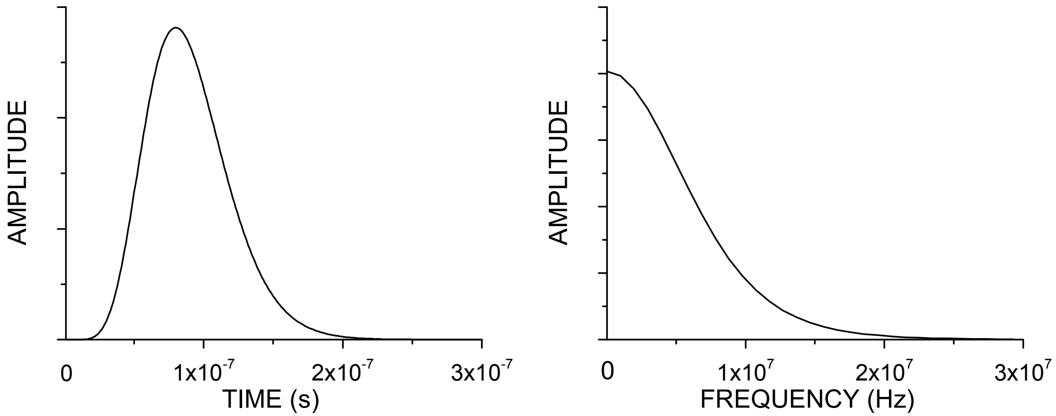
1. Increase signal and reduce noise
2. For a given sensor and signal: reduce electronic noise

Assume that the signal is a pulse.

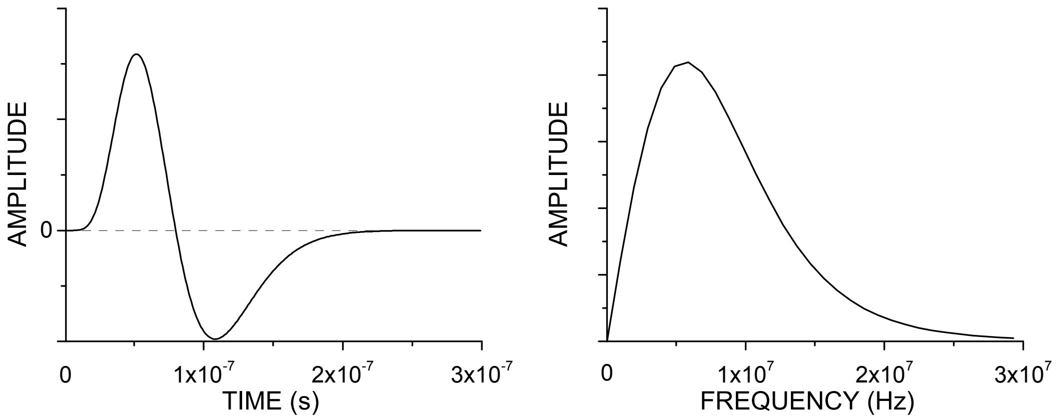
The time distribution of the signal corresponds to a frequency spectrum (Fourier transform).

Examples: Time Domain Frequency Domain

1. The pulse is unipolar, so it has a DC component and the frequency spectrum extends down to zero.

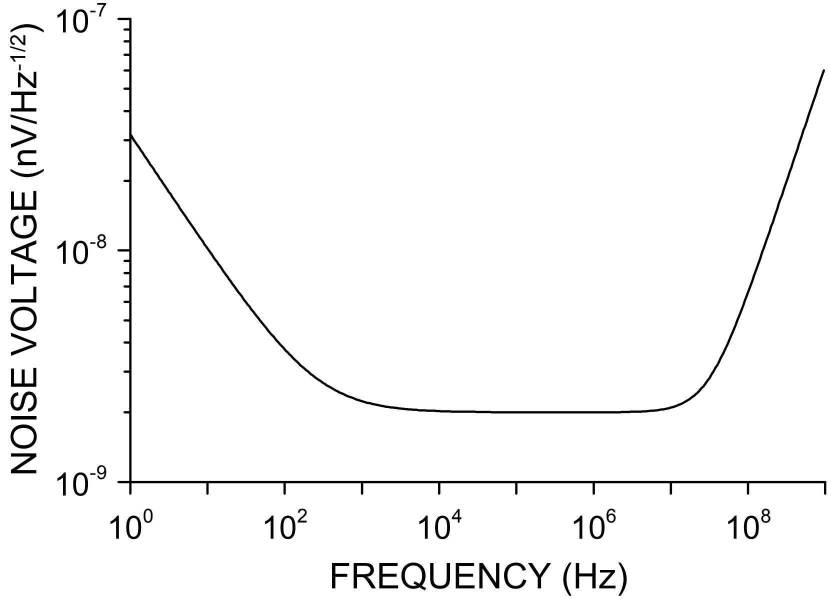


2. This bipolar pulse carries no net charge, so the frequency spectrum falls to zero at low frequencies, but extends to higher frequencies because of the faster slope.



The noise spectrum is generally not the same as the signal spectrum.

Typical Noise Spectrum:



$\Rightarrow$ Tailor frequency response of measurement system to optimize signal-to-noise ratio.

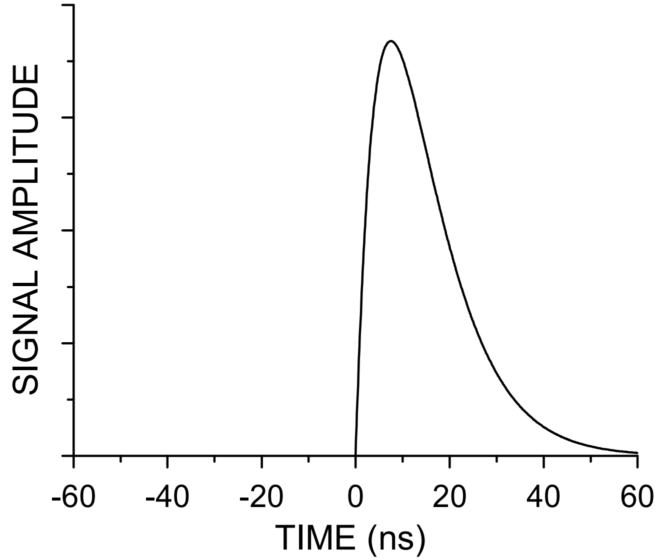
Frequency response of the measurement system affects both

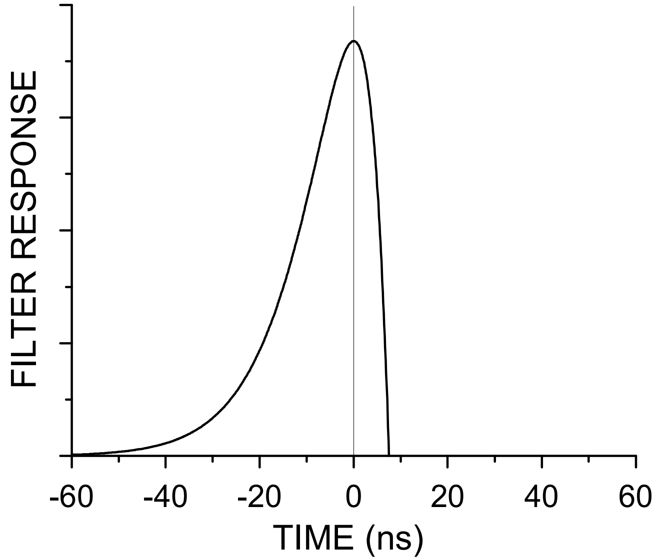
- signal amplitude and
- noise.

There is a general solution to this problem:

Apply a filter to make the noise spectrum white (constant over frequency). Then the optimum filter has an impulse response that is the signal pulse *mirrored in time* and shifted by the measurement time.

For example, if the signal pulse shape is: $\Rightarrow$ The response of the optimum filter:





This is an "acausal" filter, i.e. it must act before the signal appears.

$\Rightarrow$ Only useful if the time of arrival is known in advance.

Not good for random events
Need time delay buffer memory $\Rightarrow$ complexity!

Does that mean our problem is solved (and the lecture can end)?

1. The “optimum filter” preserves all information in signal, i.e. magnitude, timing, structure.

   Usually, we need only subset of the information content,
   i.e. area (charge) or time-of-arrival.

   Then the raw detector signal is not of the optimum form for the information that is required.

   For example, a short detector pulse would imply a fast filter function. This retains both amplitude and timing information.
   If only charge information is required, a slower filter is better, as will be shown later.

2. The optimum filter is often difficult or impractical to implement

   Digital signal processing would seem to remove this restriction, but this approach is not practical for very fast signals or systems that require low power.

4. Simpler filters often will do nearly as well

5. Even a digital system requires continuous (“analog”) pre-processing.

6. It’s often useful to understand what you’re doing, so we’ll spend some more time to bring out the physical background of signal formation and processing.

Signal Processing Objectives

Two conflicting objectives:

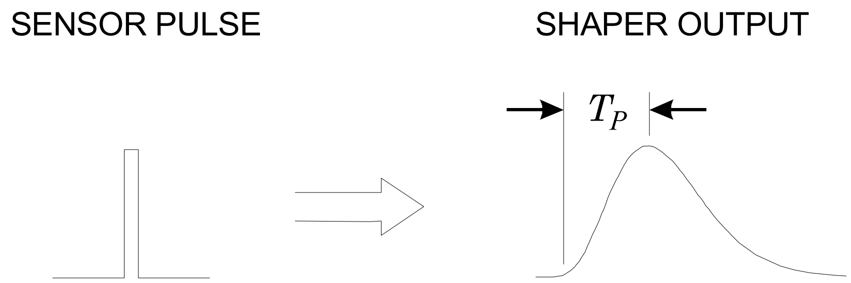
1. Improve Signal-to-Noise Ratio S/N

Restrict bandwidth to match measurement time $\Rightarrow$ Increase pulse width

Typically, the pulse shaper transforms a narrow detector current pulse to

a broader pulse (to reduce electronic noise),

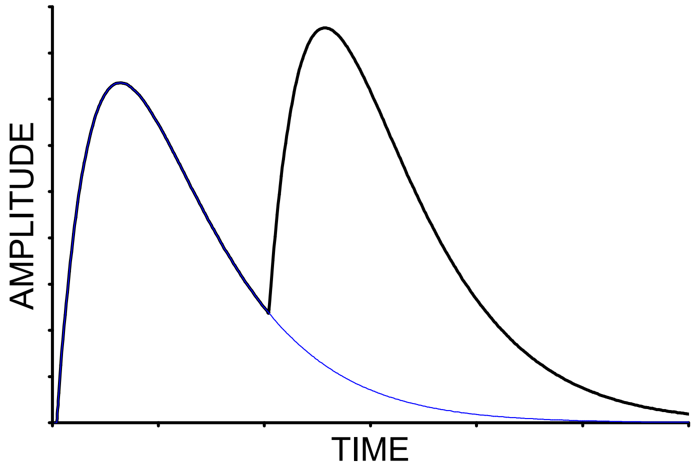
with a gradually rounded maximum at the peaking time T_P
(to facilitate measurement of the peak amplitude)



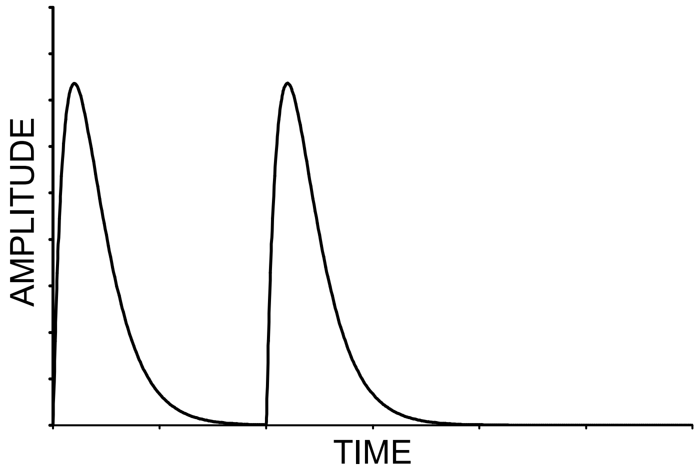
If the shape of the pulse does not change with signal level, the peak amplitude is also a measure of the energy, so one often speaks of pulse-height measurements or pulse height analysis. The pulse height spectrum is the energy spectrum.

2. Improve Pulse Pair Resolution ⇒ Decrease pulse width

Pulse pile-up distorts amplitude measurement.



Reducing pulse shaping time to 1/3 eliminates pile-up.



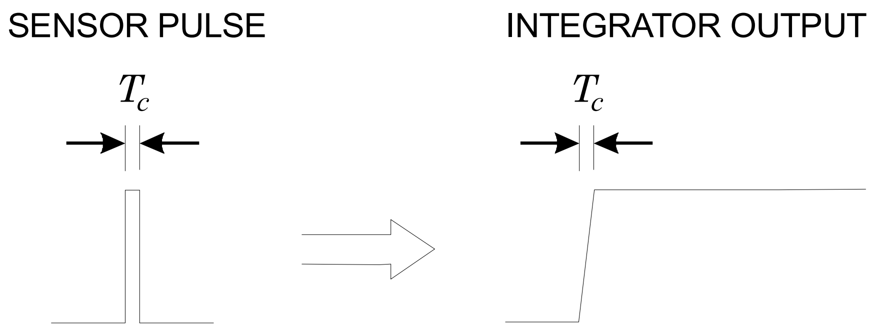
Necessary to find balance between these conflicting requirements. Sometimes minimum noise is crucial, sometimes rate capability is paramount.

Usually, many considerations combined lead to a “non-textbook” compromise.

- *“Optimum shaping” depends on the application!*
- Shapers need not be complicated – *Every amplifier is a pulse shaper!*

Goal: Improve energy resolution

Procedure: Integrate detector signal current $\Rightarrow$ Step impulse



Commonly approximated as "step" response (zero rise time).

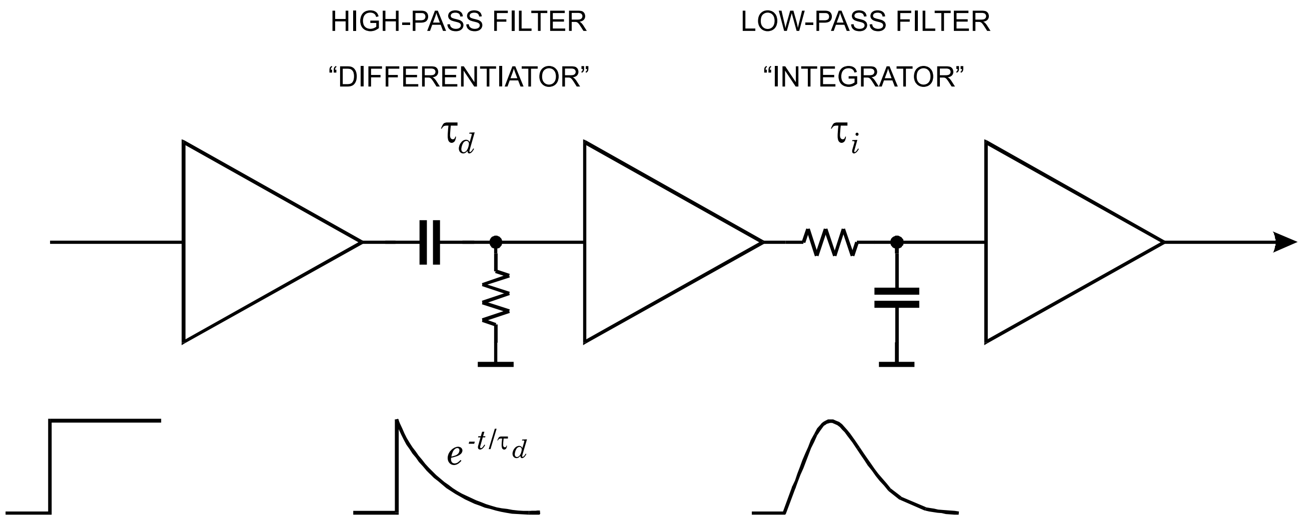
Long "flat top" allows measurements at times well beyond the collection time T_C.

$\Rightarrow$ Allows reduced bandwidth and great flexibility in selecting shaper response.

Optimum for energy measurements, but not for fast timing!

"Fast-slow" systems utilize parallel processing chains to optimize both timing and energy resolution (see Timing Measurements).

Simple Example: CR-RC Shaping



Simple arrangement: Noise performance only 36% worse than optimum filter with same time constants.

⇒ Useful for estimates, since simple to evaluate

Key elements:

- lower frequency bound ($\hat{=}$ pulse duration)
- upper frequency bound ($\hat{=}$ rise time)

are common to all shapers.

2. Pulse Shaping and Signal-to-Noise Ratio

Pulse shaping affects both the

- total noise

and

- peak signal amplitude

at the output of the shaper.

Equivalent Noise Charge

Inject known signal charge into preamp input
(either via test input or known energy in detector).

Determine signal-to-noise ratio at shaper output.

Equivalent Noise Charge $\equiv$ Input charge for which $S/N = 1$

Ballistic Deficit

When the rise time of the input pulse to the shaper extends beyond the nominal peaking time, the shaper output is both stretched in time and the amplitude decreases

Shaper output for an input rise time

$t_r = 1$

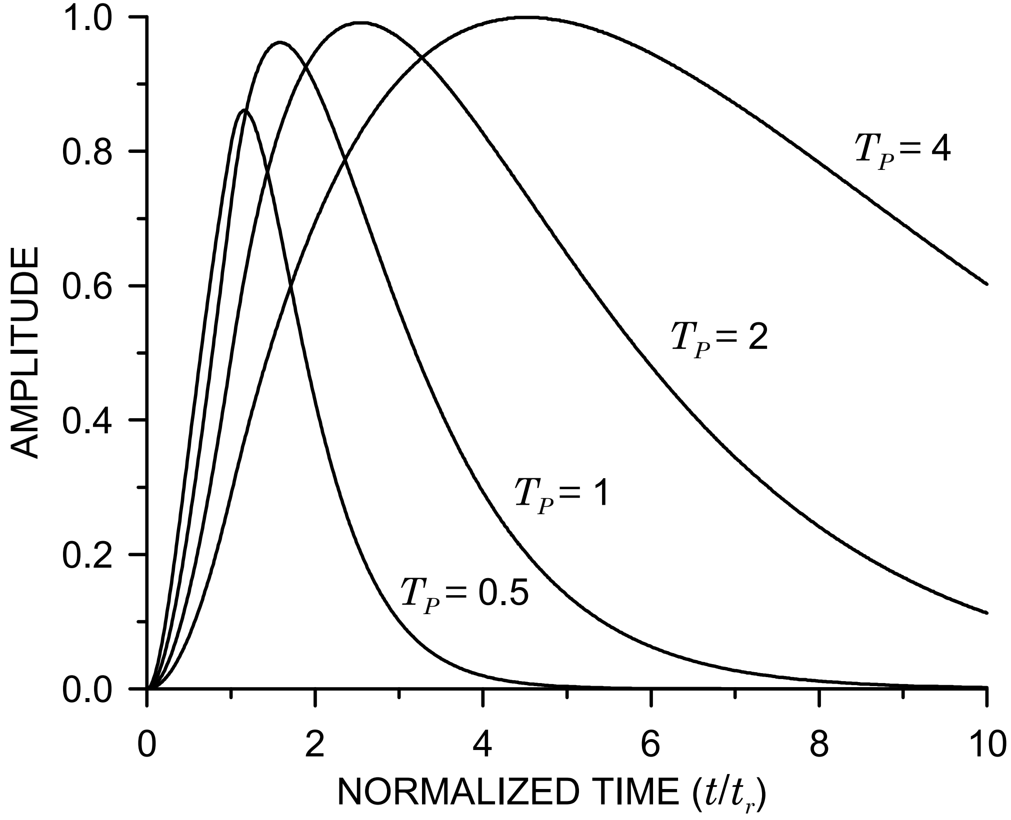
for various values of nominal peaking time.

Note that the shaper with $T_P = 0.5$

- peaks at $t = 1.15 t_r$

and

- attains only 86% of the pulse height achieved at longer shaping times.



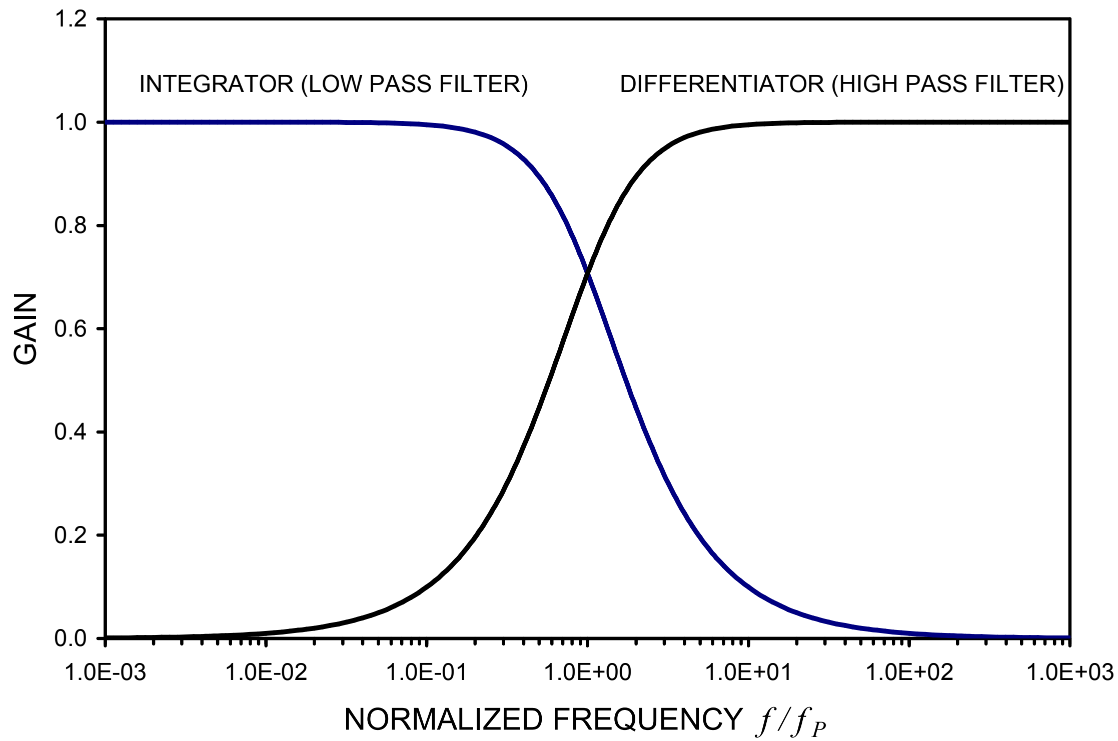
$\Rightarrow$ Increased equivalent noise charge

Noise Charge vs. Shaping Time

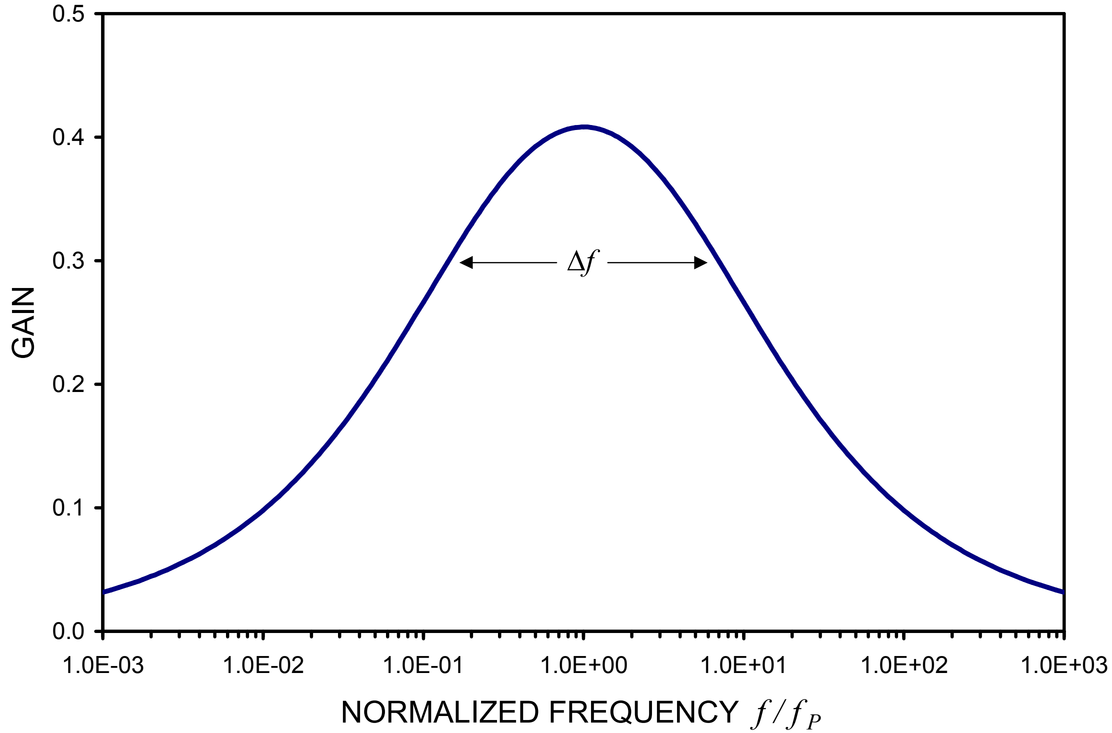
Assume that differentiator and integrator time constants are equal $\tau_i = \tau_d \equiv \tau$.

$\Rightarrow$ Both cutoff frequencies equal: $f_U = f_L \equiv f_P = 1/2\pi\tau$.

Frequency response of individual pulse shaping stages



Combined frequency response

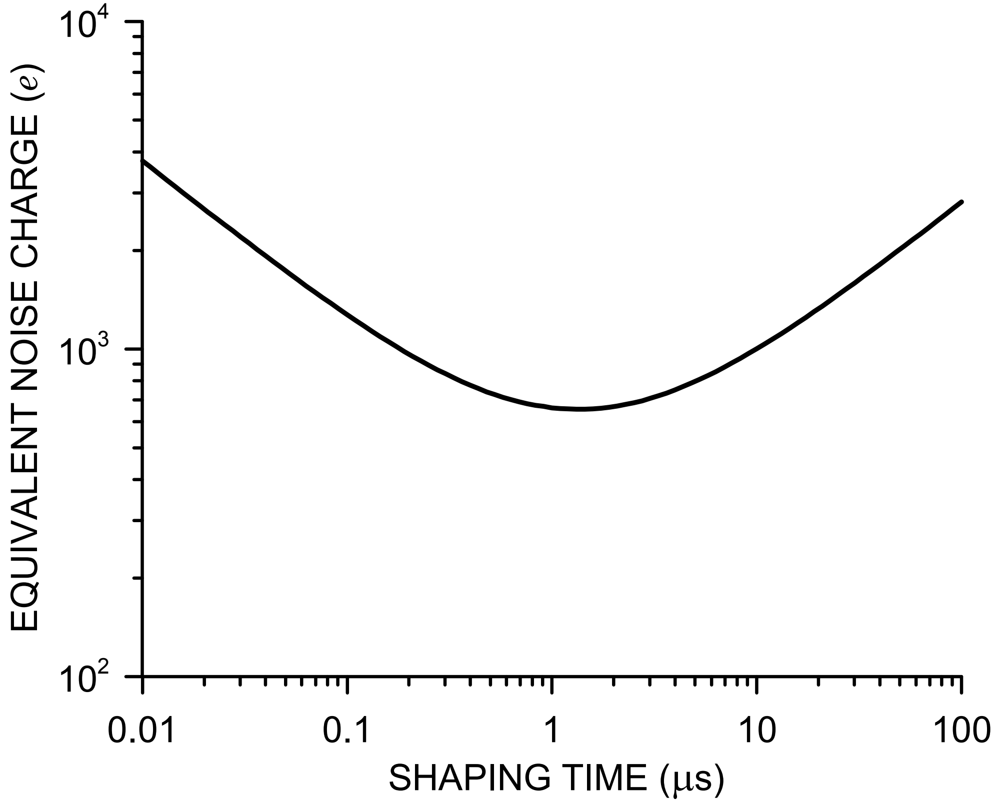


Logarithmic frequency scale $\Rightarrow$ shape of response independent of τ .

However, bandwidth Δf decreases with increasing time constant τ.

$\Rightarrow$ for white noise sources expect noise to decrease with bandwidth, i.e. decrease with increasing time constant.

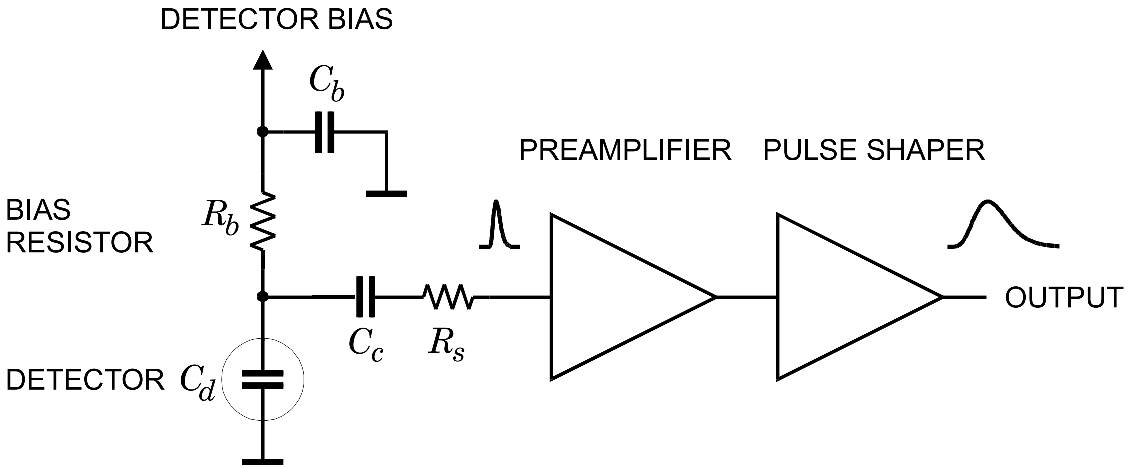
Result of typical noise measurement vs. shaping time



Noise sources (thermal and shot noise) have a flat ("white") frequency distribution.

Why doesn't the noise decrease monotonically with increasing shaping time (decreasing bandwidth)?

Analytical Analysis of a Detector Front-End



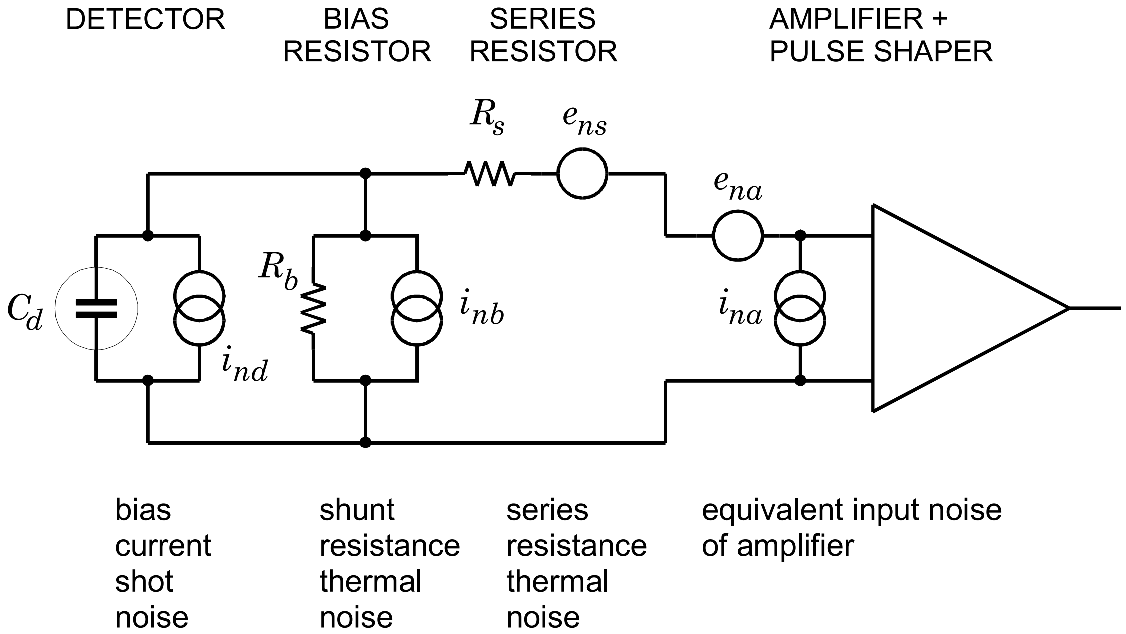
Detector bias voltage is applied through the resistor R_B. The bypass capacitor C_B serves to shunt any external interference coming through the bias supply line to ground. For AC signals this capacitor connects the "far end" of the bias resistor to ground, so that R_B appears to be in parallel with the detector.

The coupling capacitor C_C in the amplifier input path blocks the detector bias voltage from the amplifier input (which is why this capacitor is also called a "blocking capacitor").

The series resistor R_S represents any resistance present in the connection from the detector to the amplifier input. This includes

- the resistance of the detector electrodes
- the resistance of the connecting wires
- any resistors used to protect the amplifier against large voltage transients ("input protection")

Equivalent circuit for noise analysis



In this example a voltage-sensitive amplifier is used, so all noise contributions will be calculated in terms of the noise voltage appearing at the amplifier input.

Resistors can be modeled either as voltage or current generators.

- Resistors in parallel with the input act as current sources.
- Resistors in series with the input act as voltage sources.

Steps in the analysis:

1. Determine the frequency distribution of the noise voltage presented to the amplifier input from all individual noise sources

2. Integrate over the frequency response of a CR-RC shaper to determine the total noise output.

3. Determine the output signal for a known signal charge and calculate equivalent noise charge (signal charge for S/N= 1)

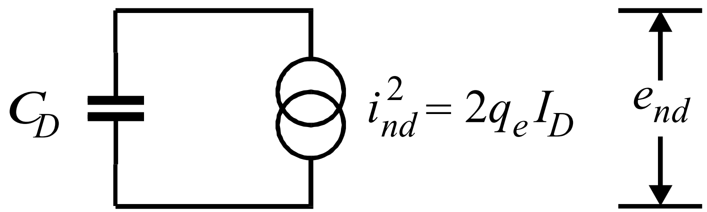
First, assume a simple CR-RC shaper with

equal differentiation and integration time constants $\tau_d = \tau_i = \tau$,

which in this special case is equal to the peaking time.

Noise Contributions

a) Detector bias current



This model results from two assumptions:

1. The input impedance of the amplifier is infinite
2. The shunt resistance R_P is much larger than the capacitive reactance of the detector in the frequency range of the pulse shaper.

Does this assumption make sense?

If R_P is too small, the signal charge on the detector capacitance will discharge before the shaper output peaks. To avoid this

$$R_P C_D \gg T_P \approx \frac{1}{\omega_P},$$

where ω_P is the midband frequency of the shaper.

Therefore, $R_P \gg \dfrac{1}{\omega_P C_D}$ as postulated.

Under these conditions the noise current will flow through the detector capacitance, yielding the voltage

$$e_{nd}^2 = i_{nd}^2 \frac{1}{(\omega\, C_D)^2} = 2q_e I_D \frac{1}{(\omega\, C_D)^2}$$

$\Rightarrow$ The noise contribution decreases with increasing frequency (shorter shaping time)

Note: Although shot noise is “white”, the resulting noise spectrum is strongly frequency dependent.

In the time domain this result is more intuitive. Since every shaper also acts as an integrator, one can view the total shot noise as the result of "counting electrons".

Assume an ideal integrator that records all charge uniformly within a time T. The number of electron charges measured is

$$N_e = \frac{I_D T}{q_e}$$

The associated noise is the fluctuation in the number of electron charges recorded

$$\sigma_n = \sqrt{N_e} \propto \sqrt{T}$$

Does this also apply to an AC-coupled system, where no DC current flows, so no electrons are "counted"?

Since shot noise is a fluctuation, the current undergoes both positive and negative excursions. Although the DC component is not passed through an AC coupled system, the excursions are. Since, on the average, each fluctuation requires a positive and a negative zero crossing, the process of "counting electrons" is actually the counting of zero crossings, which in a detailed analysis yields the same result.

b) Parallel Resistance

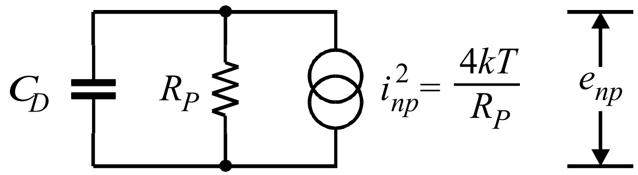
Any shunt resistance R_P acts as a noise current source. In the specific example shown above, the only shunt resistance is the bias resistor R_b.

Additional shunt components in the circuit:

1. bias noise current source (infinite resistance by definition)
2. detector capacitance

The noise current flows through both the resistance R_P and the detector capacitance C_D.

⇒ equivalent circuit



The noise voltage applied to the amplifier input is

$$e_{np}^2 = \frac{4kT}{R_P} \left(\frac{R_P \cdot \frac{-\mathbf{i}}{\omega C_D}}{R_P - \frac{\mathbf{i}}{\omega C_D}} \right)^2$$

$$e_{np}^2 = 4kTR_P \frac{1}{1 + (\omega R_P C_D)^2}$$

Comment:

Integrating this result over all frequencies yields

$$\int_0^\infty e_{np}^2(\omega)d\omega = \int_0^\infty \frac{4kTR_P}{1+(\omega\, R_P C_D)^2}\, d\omega = \frac{kT}{C_D}\ ,$$

which is independent of R_P. Commonly referred to as "kTC" noise, this contribution is often erroneously interpreted as the "noise of the detector capacitance".

An ideal capacitor has no thermal noise; all noise originates in the resistor.

So, why is the result independent of R_P?

R_P determines the primary noise, but also the noise bandwidth of this subcircuit. As R_P increases, its thermal noise increases, but the noise bandwidth decreases, making the total noise independent of R_P.

However,
If one integrates e_{np} over a bandwidth-limited system (such as our shaper),

$$v_n^2 = \int_0^\infty 4kTR_P \left| \frac{G(i\omega\ )}{1 - i\omega\, R_P C_D} \right|^2 d\omega$$

the total noise decreases with increasing R_P.

c) Series Resistance

The noise voltage generator associated with the series resistance R_S is in series with the other noise sources, so it simply contributes

$$e_{nr}^2 = 4kTR_S$$

d) Amplifier input noise

The amplifier noise voltage sources usually are not physically present at the amplifier input. Instead the amplifier noise originates within the amplifier, appears at the output, and is referred to the input by dividing the output noise by the amplifier gain, where it appears as a noise voltage generator.

$$e_{na}^2 = \underset{\text{“white noise”}}{\underset{\uparrow}{e_{nw}^2}} + \underset{1/f \text{ noise}}{\underset{\uparrow}{\frac{A_f}{f}}}$$

(can also originate in external components)

This noise voltage generator also adds in series with the other sources.

- Amplifiers generally also exhibit input current noise, which is physically present at the input. Its effect is the same as for the detector bias current, so the analysis given in 1. can be applied.
- In a well-designed amplifier the noise is dominated by the input transistor (fast, high-gain transistors generally best). Noise parameters of transistors are discussed in Chapter 6.

  Transistor input noise decreases with transconductance $\Rightarrow$ increased power

- Minimum device noise limited both by technology and fundamental physics.

Equivalent Noise Charge

$$Q_n^2 = \left(\frac{\mathbf{e}^2}{8}\right)\left[\left(2q_e I_D + \frac{4kT}{R_P} + i_{na}^2\right)\cdot\tau + \left(4kTR_S + e_{na}^2\right)\cdot\frac{C_D^2}{\tau} + 4A_f C_D^2\right]$$

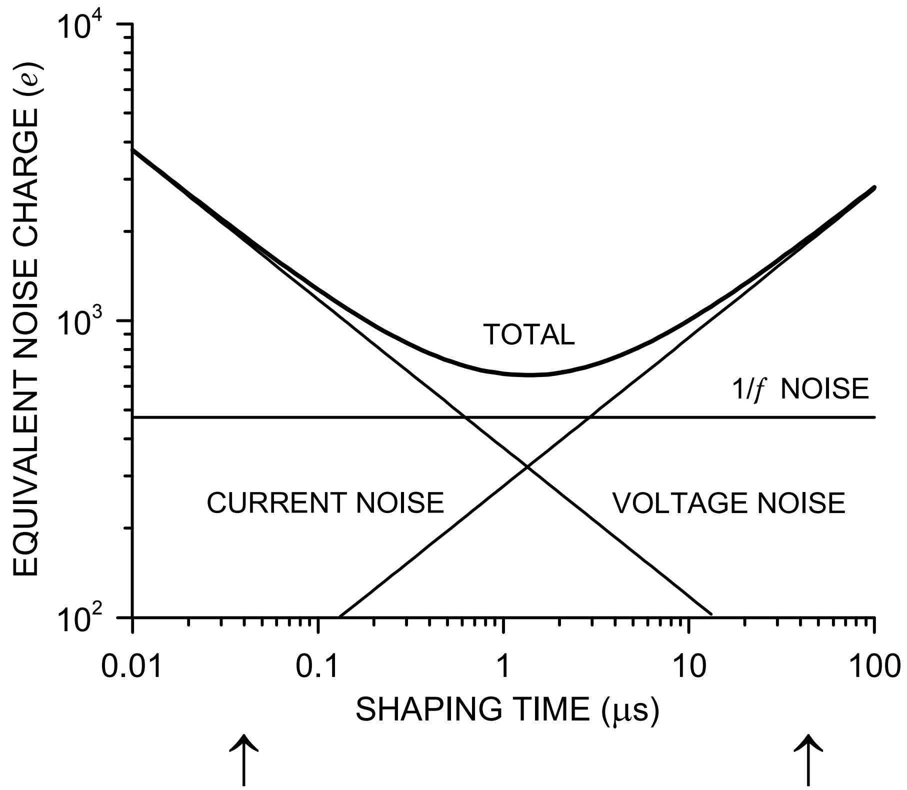
	↑	↑	↑
$\mathbf{e} = \exp(1)$	current noise	voltage noise	$1/f$ noise
	$\propto \tau$	$\propto 1/\tau$	independent of τ
	independent of C_D	$\propto C_D{}^2$	$\propto C_D{}^2$

- Current noise is independent of detector capacitance, consistent with the notion of "counting electrons".
- Voltage noise increases with detector capacitance (reduced signal voltage)
- $1/f$ noise is independent of shaping time.

  In general, the total noise of a $1/f$ source depends on the ratio of the upper to lower cutoff frequencies, not on the absolute noise bandwidth. If τ_d and τ_i are scaled by the same factor, this ratio remains constant.
- Detector leakage current and FET noise decrease with temperature

  $\Rightarrow$ High resolution Si and Ge detectors for x-rays and gamma rays operate at cryogenic temperatures.

The equivalent noise charge Q_n assumes a minimum when the current and voltage noise contributions are equal. Typical result:



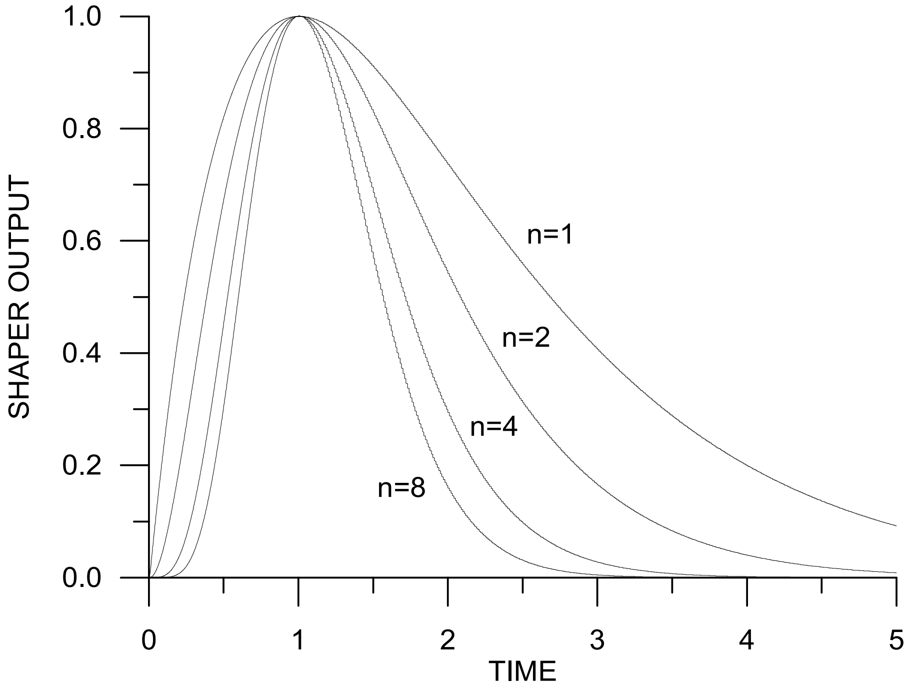
dominated by voltage noise current noise

For a CR-RC shaper the noise minimum obtains for $\tau_d = \tau_i = \tau$.

This criterion does not hold for more sophisticated shapers.

Other Types of Shapers

Shapers with Multiple Integrators



Start with simple CR-RC shaper and add additional integrators
($n=$ 1 to $n=$ 2, ... $n=$ 8).

Change integrator time constants to preserve the peaking time $\tau_n = \tau_{n=1} / n$

Increasing the number of integrators makes the output pulse more symmetrical with a faster return to baseline.

$\Rightarrow$ improved rate capability at the same peaking time

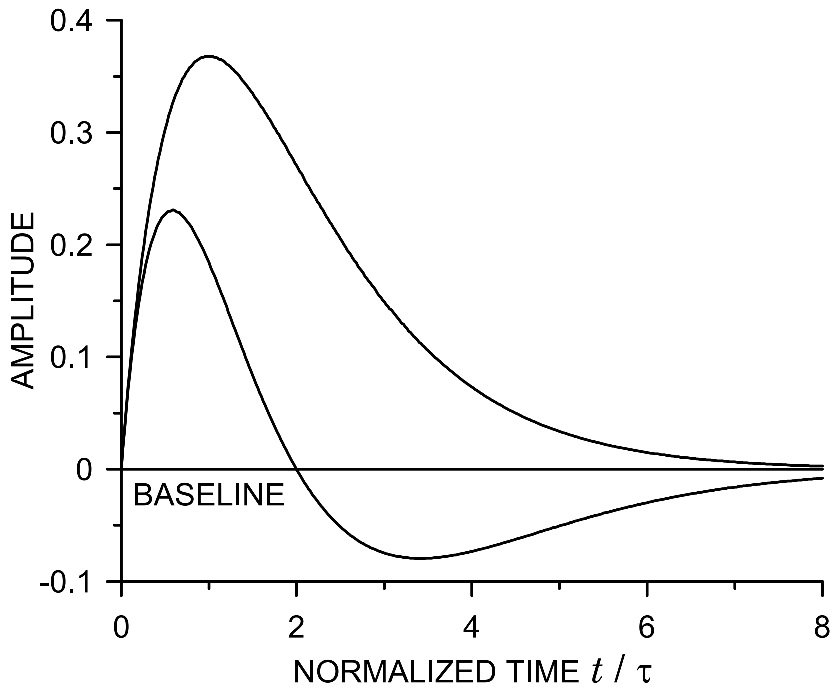
Shapers with the equivalent of 8 RC integrators are common.
Usually, this is achieved with active filters

(i.e. circuitry that synthesizes the bandpass with amplifiers and feedback networks).

Bipolar Shaping

Unipolar pulse + 2nd differentiator

→ Bipolar pulse



Electronic resolution with bipolar shaping typ. 25 – 50% worse than for corresponding unipolar shaper.

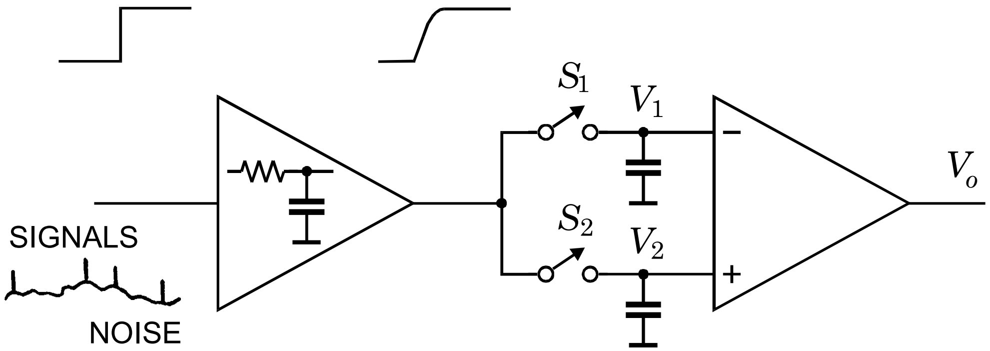
However …

- Bipolar shaping eliminates baseline shift
  (as the DC component is zero).
- Pole-zero adjustment less critical
- Added suppression of low-frequency noise.
- Not all measurements require optimum noise performance.
  Bipolar shaping is much more convenient for the user (important in large systems!)
  – often the method of choice.

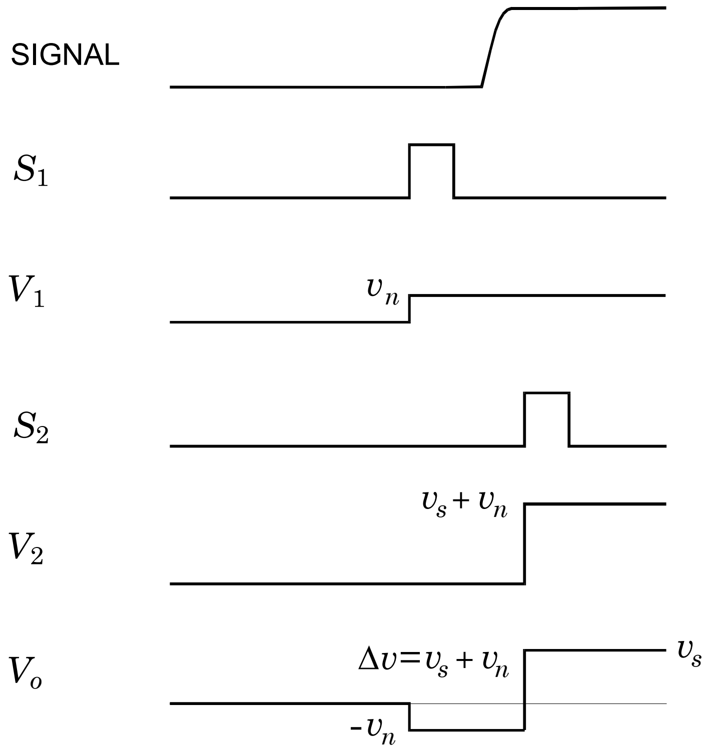
Time-Variant Shapers

Time variant shaper change the filter parameters during the processing of individual pulses.

A commonly used time-variant filter is the correlated double-sampler.



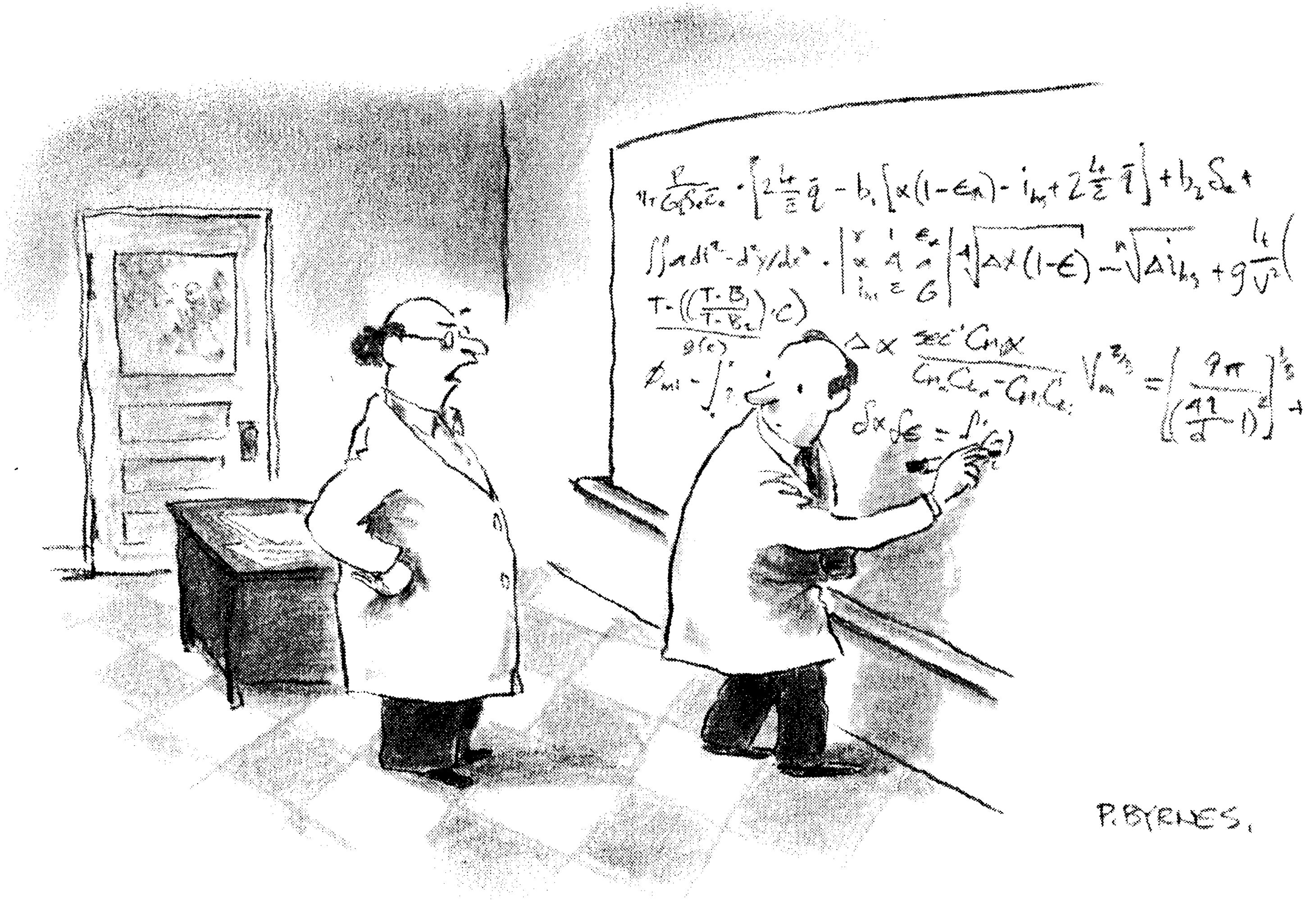
1. Signals are superimposed on a (slowly) fluctuating baseline
2. To remove baseline fluctuations the baseline is sampled prior to the arrival of a signal.
3. Next, the signal + baseline is sampled and the previous baseline sample subtracted to obtain the signal



S/N depends on

1. time constant of prefilter
2. time difference between samples

See "Semiconductor Detector Systems" for a detailed noise analysis. (Chapter 4, pp 160-166)

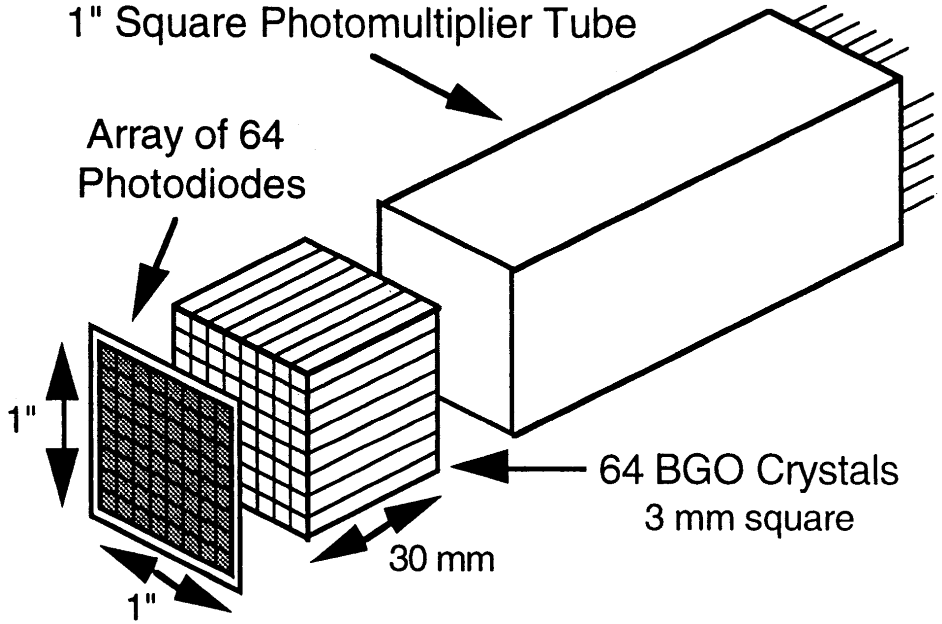


"Duh."

Examples: Photodiode Readout

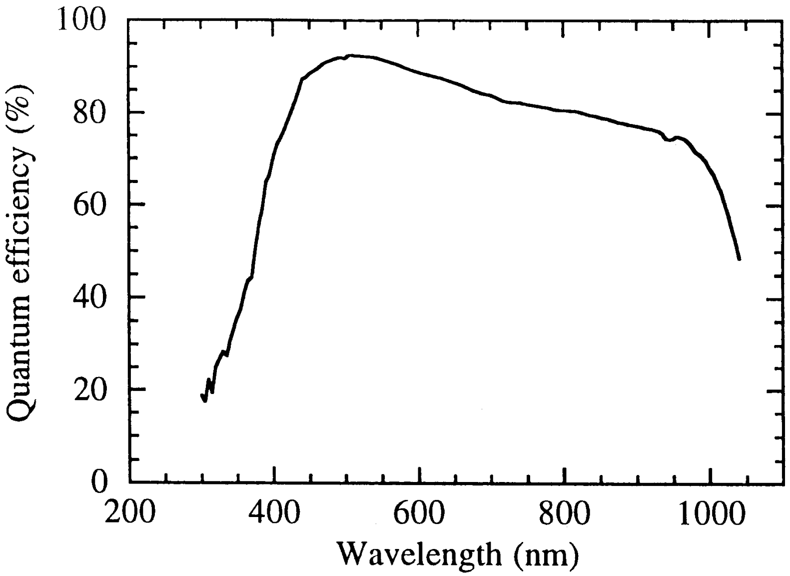
(S. Holland, N. Wang, I. Kipnis, B. Krieger, W. Moses, LBNL)

Medical Imaging (Positron Emission Tomography)



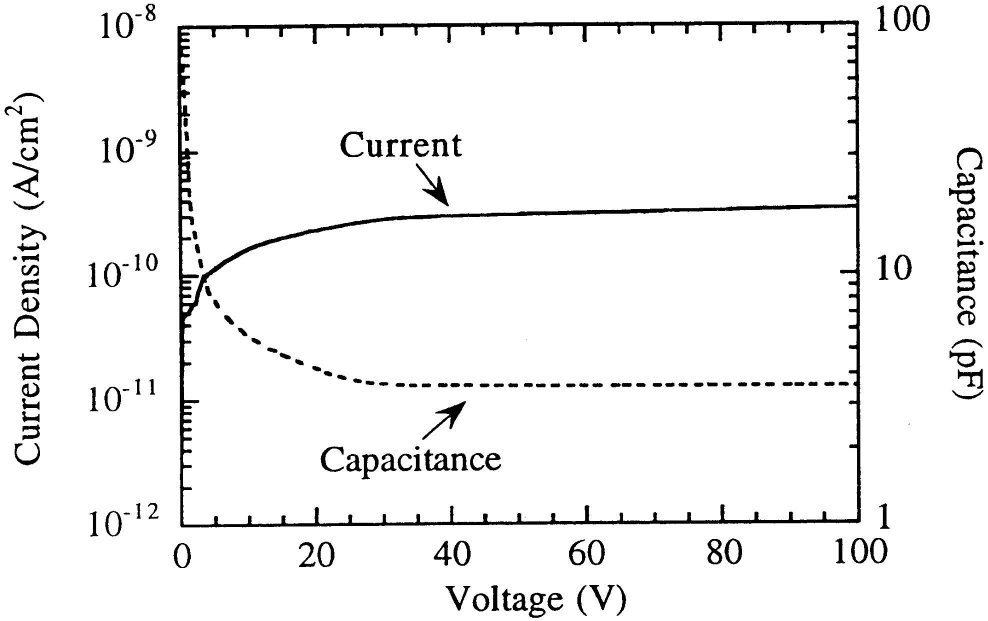
Read out 64 BGO crystals with one PMT (timing, energy) and tag crystal by segmented photodiode array.

Requires thin dead layer on photodiode to maximize quantum efficiency.



Thin electrode must be implemented with low resistance to avoid significant degradation of electronic noise.

Furthermore, low reverse bias current critical to reduce noise.

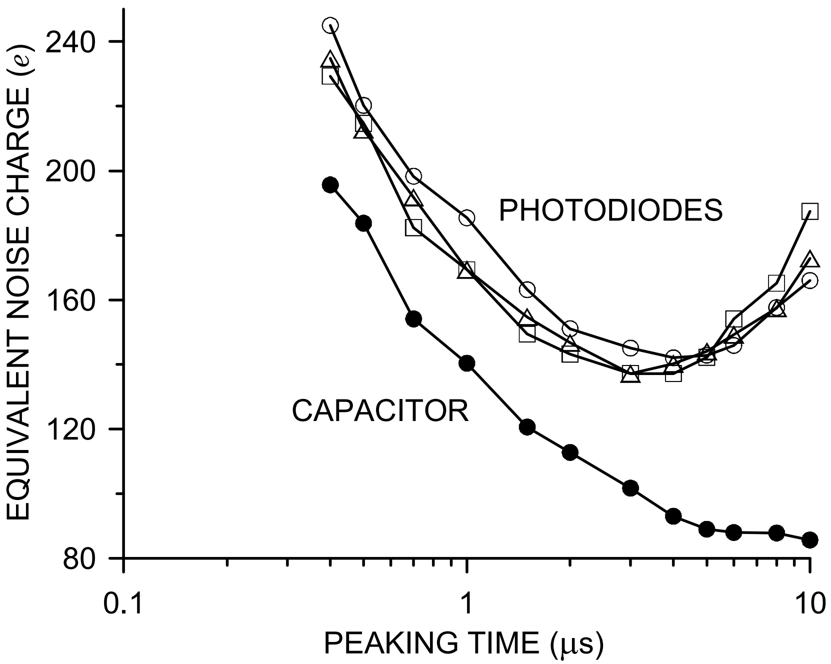


Photodiodes designed and fabricated in LBNL Microsystems Lab.

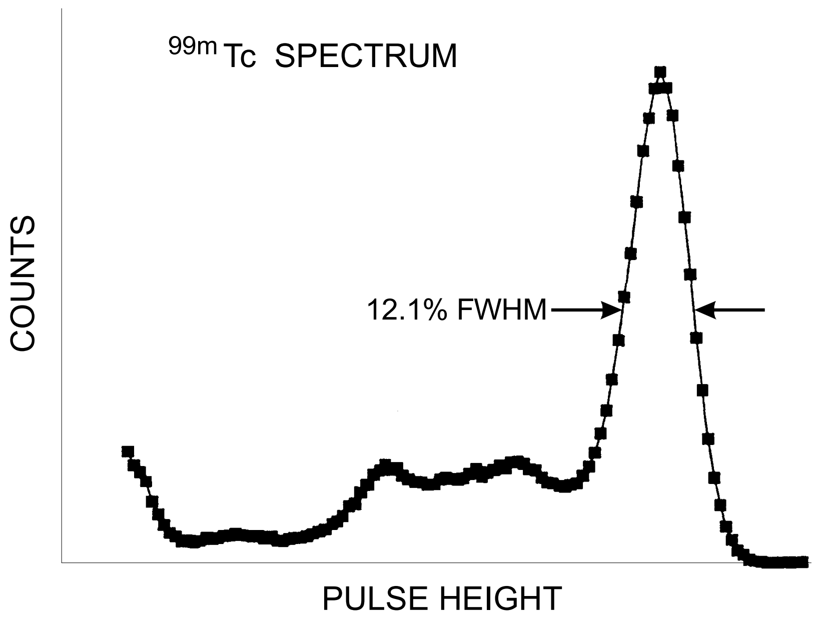
Front-end chip (preamplifier + shaper): 16 channels per chip, die size: 2 x 2 mm^2,
1.2 μm CMOS

continuously adjustable shaping time (0.5 to 50 μs)

Noise vs. shaping time



Energy spectrum with BGO scintillator



Note increase in noise at long shaping times when photodiode is connected - shot noise contribution.

Examples: Short-Strip Si X-Ray Detector

(B. Ludewigt, C. Rossington, I. Kipnis, B. Krieger, LBNL)

Use detector with multiple strip electrodes not for position resolution,

but for segmentation ⇒ distribute rate over many channels

⇒ reduced capacitance

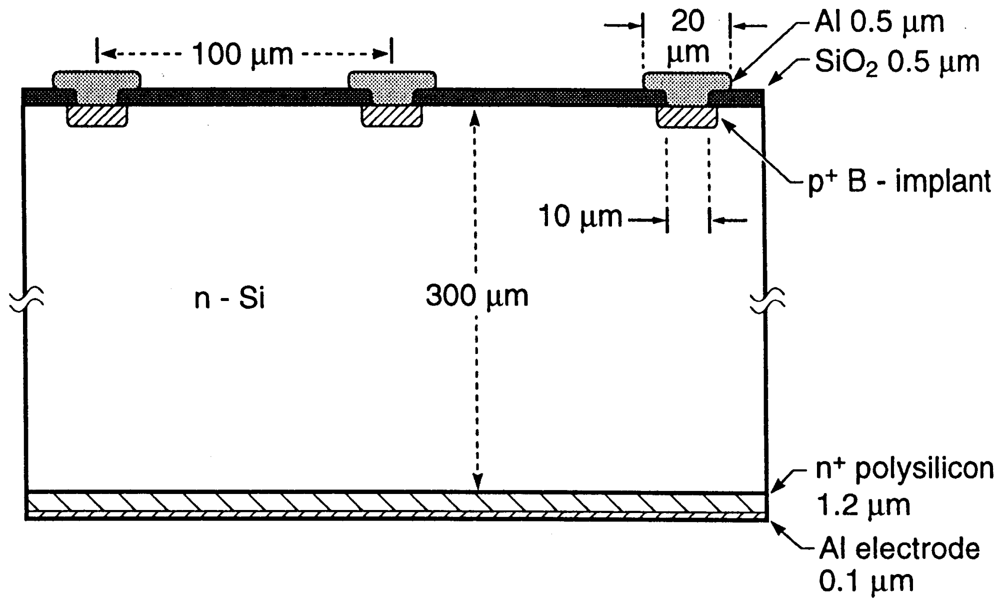
⇒ low noise at short shaping time

⇒ higher rate per detector element

For x-ray energies 5 – 25 keV ⇒ photoelectric absorption dominates (signal on 1 or 2 strips)

Strip pitch: 100 μm

Strip Length: 2 mm
(matched to ALS beam)



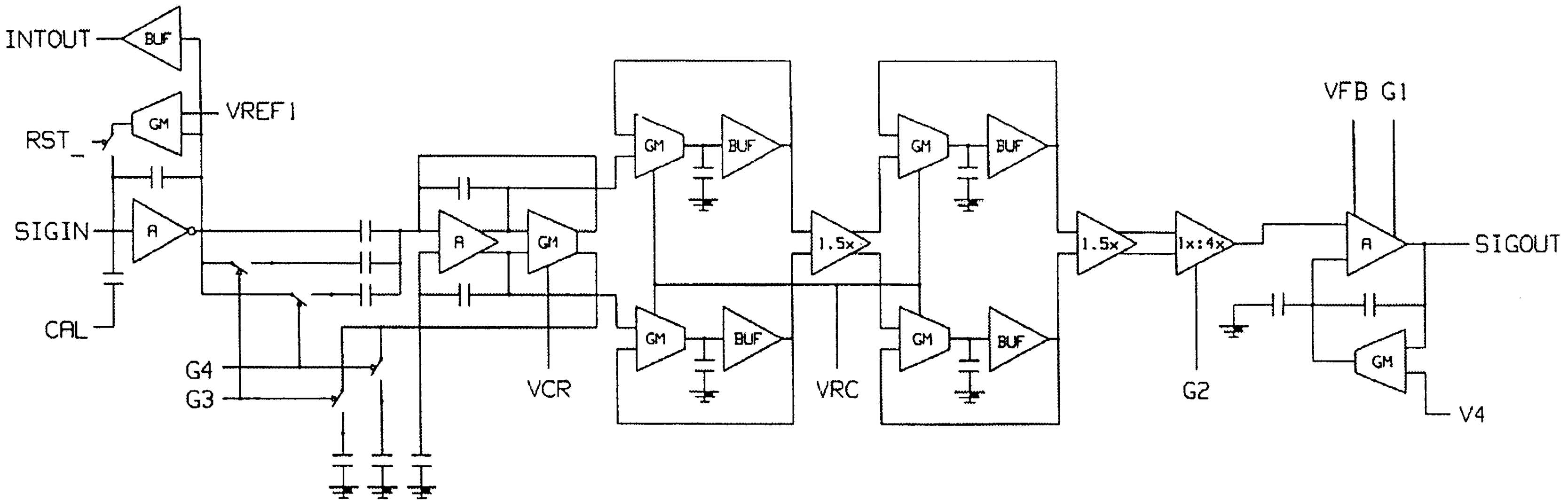
Readout IC tailored to detector

Preamplifier + CR-RC^2 shaper + cable driver to bank of parallel ADCs (M. Maier + H. Yaver)

Preamplifier with pulsed reset.

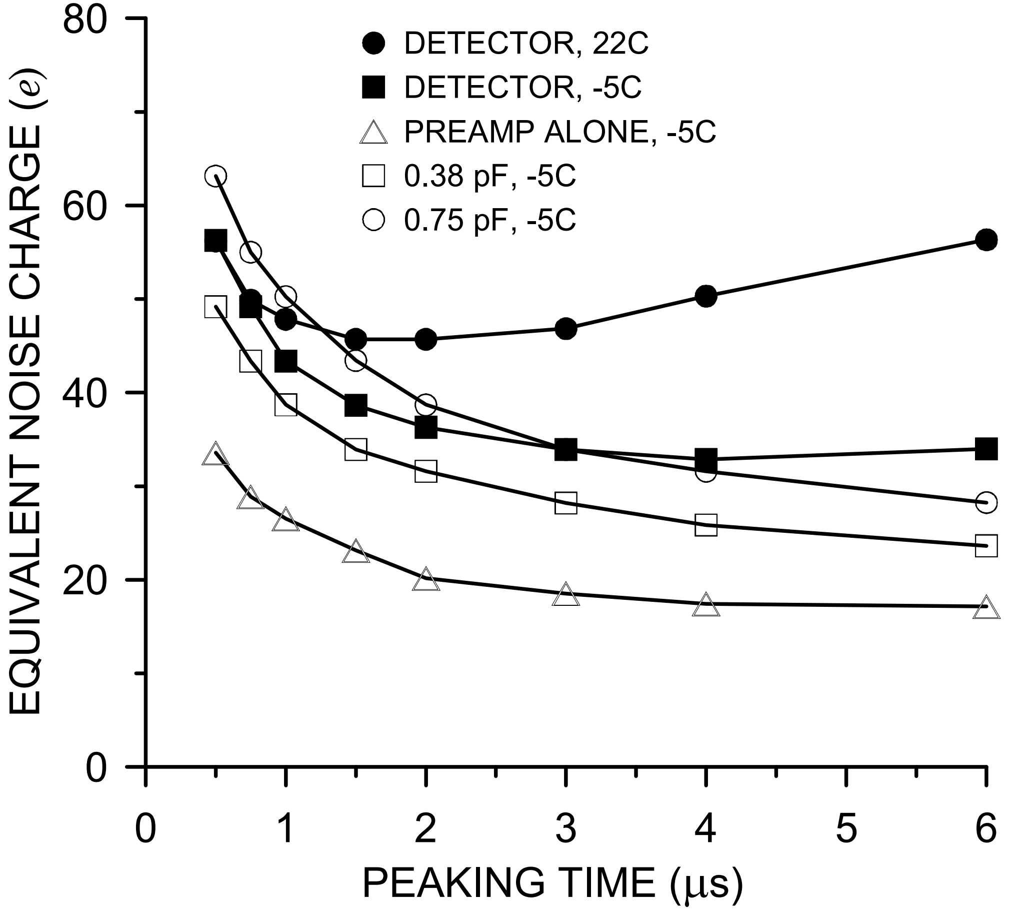
Shaping time continuously variable 0.5 to 20 μs.

CHARGE-SENS. PREAMPLIFIER | CR | RC | RC | VARIABLE GAIN | OUTPUT



Noise Charge vs. Peaking Time

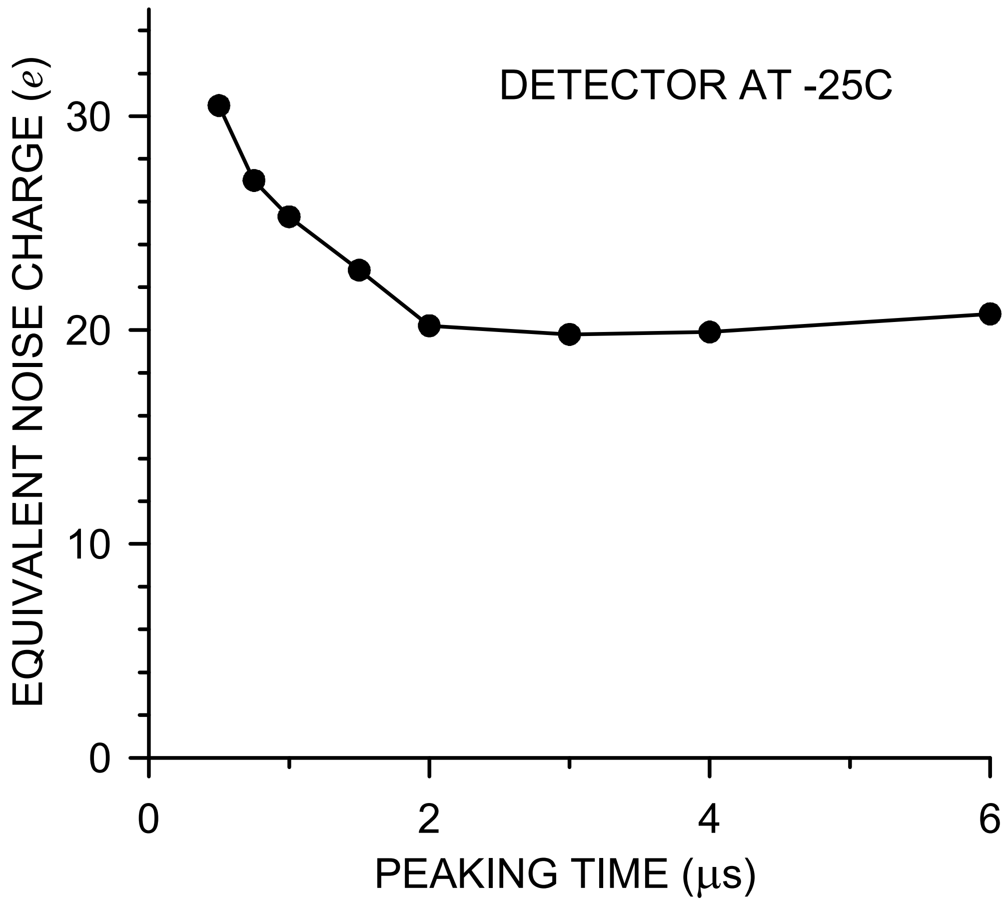
- Open symbols: preamplifier alone and with capacitors connected instead of a detector.
- Connecting the detector increases noise because of added capacitance and detector current (as indicated by increase of noise with peaking time).
- Cooling the detector reduces the current and noise improves.



Second prototype

Current noise negligible because of cooling.

"Flat" noise vs. shaping time indicates that $1/f$ noise dominates.



Numerical expression for the noise of a CR-RC shaper
(amplifier current noise negligible)

(note that some units are "hidden" in the numerical factors)

$$Q_n^2 = 12\, I_B\, \tau \;+\; 6\cdot 10^5 \frac{\tau}{R_P} \;+\; 3.6\cdot 10^4\, e_n^2\, \frac{C^2}{\tau} \quad \text{[rms electrons}^2\text{]}$$

where

τ	shaping time constant [ns]
I_B	detector bias current + amplifier input current [nA]
R_P	input shunt resistance [kΩ]
e_n	equivalent input noise voltage spectral density [nV/√Hz]
C	total input capacitance [pF]

$Q_n = 1\, e$ corresponds to 3.6 eV in Si
2.9 eV in Ge

“Series” and “Parallel” Noise

For sources connected in parallel, currents are additive.

For sources connected in series, voltages are additive.

⇒ In the detector community voltage and current noise are often called “series” and “parallel” noise.

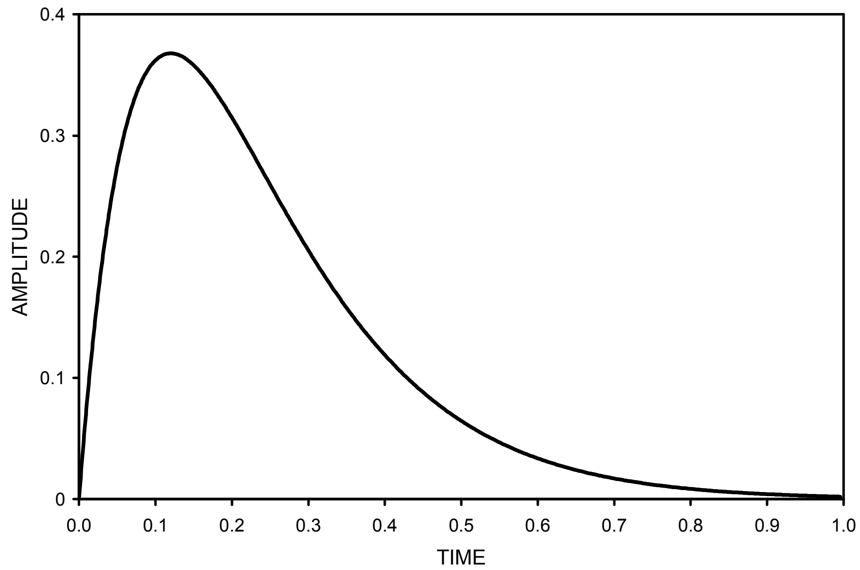
The rest of the world uses equivalent noise voltage and current.

Since they are physically meaningful, use of these widely understood terms is preferable.

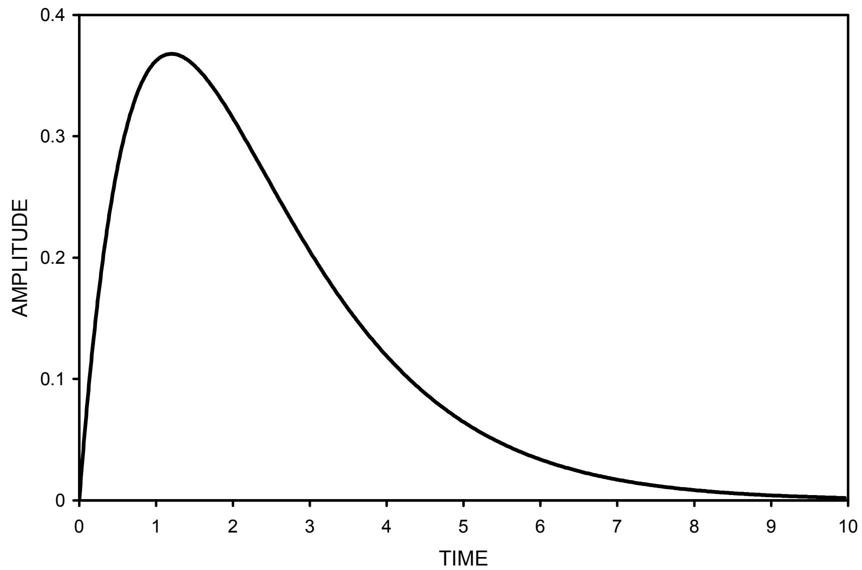
Scaling of Filter Noise Parameters

Pulse shape is the same when shaping time is changed.

shaping time = τ



shaping time = 10τ



Shaper can be characterized by a "shape factor" which multiplied by the shaping time sets the noise bandwidth.

The expression for the equivalent noise charge

$$Q_n^2 = \left(\frac{\mathbf{e}^2}{8}\right)\left[\left(2q_e I_D + \frac{4kT}{R_P} + i_{na}^2\right)\cdot\tau + \left(4kTR_S + e_{na}^2\right)\cdot\frac{C_D^2}{\tau} + 4A_f C_D^2\right]$$

	↑	↑	↑
$\mathbf{e} = \exp(1)$	current noise	voltage noise	$1/f$ noise
	$\propto \tau$	$\propto 1/\tau$	independent of τ
	independent of C_D	$\propto C_D{}^2$	$\propto C_D{}^2$

can be put in a more general form that applies to all type of pulse shapers:

$$Q_n^2 = i_n^2 \; T_s \; F_i \; + \; C^2 \; e_n^2 \; \frac{F_v}{T_s} + \; F_{vf} \; A_f \; C^2$$

- The current and voltage terms are combined and represented by i_n^2 and e_n^2.
- The shaper is characterized by a shape and characteristic time (e.g. the peaking time).
- A specific shaper is described by the “shape factors” F_i, F_v, and F_{vf}.
- The effect of the shaping time is set by T_S.

Detector Noise Summary

Two basic noise mechanisms: input noise current i_n
input noise voltage e_n

Equivalent Noise Charge:
$$Q_n^2 = i_n^2 \; T_s \; F_i \; + \; C^2 \; e_n^2 \; \frac{F_v}{T_s}$$

T_S Characteristic shaping time (*e.g.* peaking time)

F_i , F_v "Shape Factors" that are determined by the shape of the pulse.

C Total capacitance at the input (detector capacitance + input capacitance of preamplifier + stray capacitance + …)

Typical values of F_i , F_v

CR-RC shaper	F_i = 0.924	F_v = 0.924
CR-(RC)^4 shaper	F_i = 0.45	F_v = 1.02
CR-(RC)^7 shaper	F_i = 0.34	F_v = 1.27
CAFE chip	F_i = 0.4	F_v = 1.2

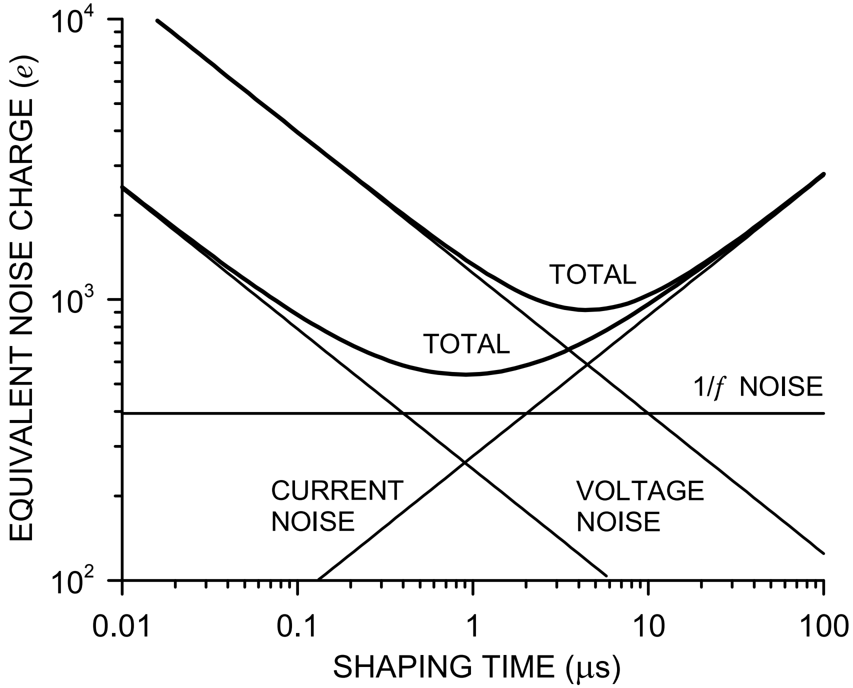
Note that $F_i < F_v$ for higher order shapers.

Shapers can be optimized to reduce current noise contribution relative to the voltage noise (mitigate radiation damage!).

Minimum noise obtains when the current and voltage noise contributions are equal.

Current noise

- detector bias current
  increases with detector size, strongly temperature dependent
- noise from resistors shunting the input
  increases as resistance is decreased
- input transistor –
  low for FET, higher for BJTs



Voltage noise

- input transistor –
  noise decreases with increased current
- series resistance, e.g. detector electrode, protection circuits

FETs commonly used as input devices – improved noise performance when cooled ($T_{opt} \approx$ 130 K)

Bipolar transistors advantageous at short shaping times (<100 ns).
When collector current is optimized, bipolar transistor equivalent noise charge is independent of shaping time (see Chapter 6).

Equivalent Noise Charge vs. Detector Capacitance ($C = C_d + C_a$)

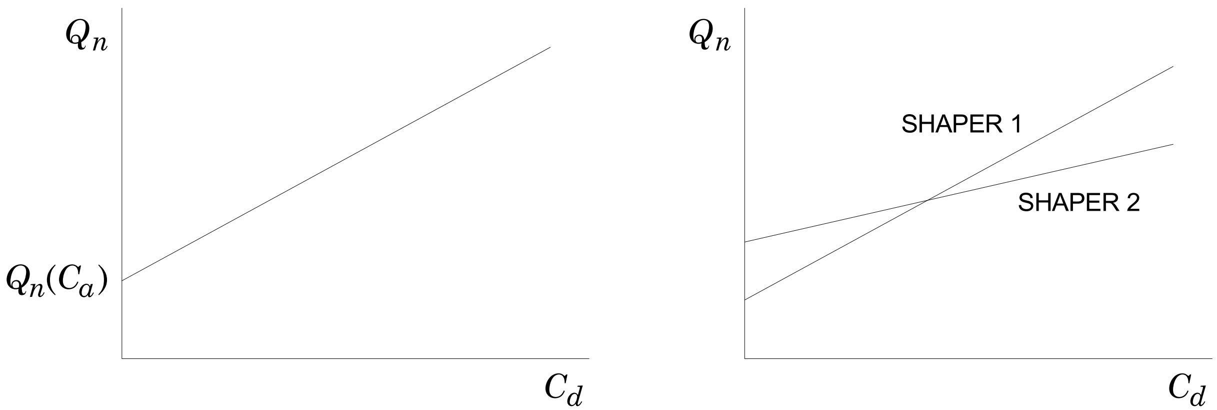
$$Q_n = \sqrt{i_n^2 F_i T + (C_d + C_a)^2 e_n^2 F_v \frac{1}{T}}$$

$$\frac{dQ_n}{dC_d} = \frac{2C_d e_n^2 F_v \frac{1}{T}}{\sqrt{i_n^2 F_i T + (C_d + C_a)^2 e_n^2 F_v \frac{1}{T}}}$$

If current noise $i_n^2 F_i T$ is negligible, i.e. **voltage noise dominates:** $\frac{dQ_n}{dC_d} \approx 2e_n \cdot \sqrt{\frac{F_v}{T}}$

↑ input stage ↑ shaper

Zero intercept: $Q_n\big|_{C_d=0} = C_a e_n \sqrt{F_v / T}$



Noise vs. Power Dissipation

Under optimum scaling to maintain signal-to-noise ratio,

input transistor power (≈ preamp power) scales with $(S/N)^2$.

Power Reduction

1. Segmentation reduces detector capacitance

   ⇒ lower noise for given power

2. Segmentation reduces the hit rate per channel

   ⇒ longer shaping time, reduce voltage noise

3. Segmentation reduces the leakage current per channel (smaller detector volume)

   ⇒ reduced shot noise, increased radiation resistance

Segmentation is a key concept in large-scale detector systems.
(also to increase radiation resistance)

Example: Optimization of Si detector strip length

Assume reduced signal charge S_{rad}/S_0 due to trapping:

Under optimum scaling to maintain signal-to-noise ratio,

input transistor power (≈ preamp power) scales with $(S_0/S_{rad})^2$.

see Spieler, *Semiconductor Detector Systems*, Ch. 6

Alternative: reduce sensor capacitance

Best to scale strip length by S_{rad}/S_0.

Increases number of readout ICs by S_0/S_{rad}, so

increases power by S_0/S_{rad}

- Digital readout power per channel independent of strip length
- Front-end power dominated by input transistor – scales with $\propto C_{strip}^2 \propto L_{strip}^2$

Total power: $$P_{tot} = N_{strip} \left(P'_{analog} L^2 + P_{digital} \right)$$

Number of strips: $$N_{strip} = \frac{A}{p \cdot L}$$ where $A =$ Area and $p =$ strip pitch

$\Rightarrow$ Power per unit area $$\frac{P_{tot}}{A} = \frac{1}{p} \left(P'_{analog} L + \frac{P_{digital}}{L} \right)$$

Assume analog power for 10 cm strip length: 0.2 mW

(SiGe design by E. Spencer, UCSC submitted for fab)

For comparison

ABCD chip digital power: 1.1 mW/ch at 40 MHz clock frequency, $V_{DD} =$ 4V

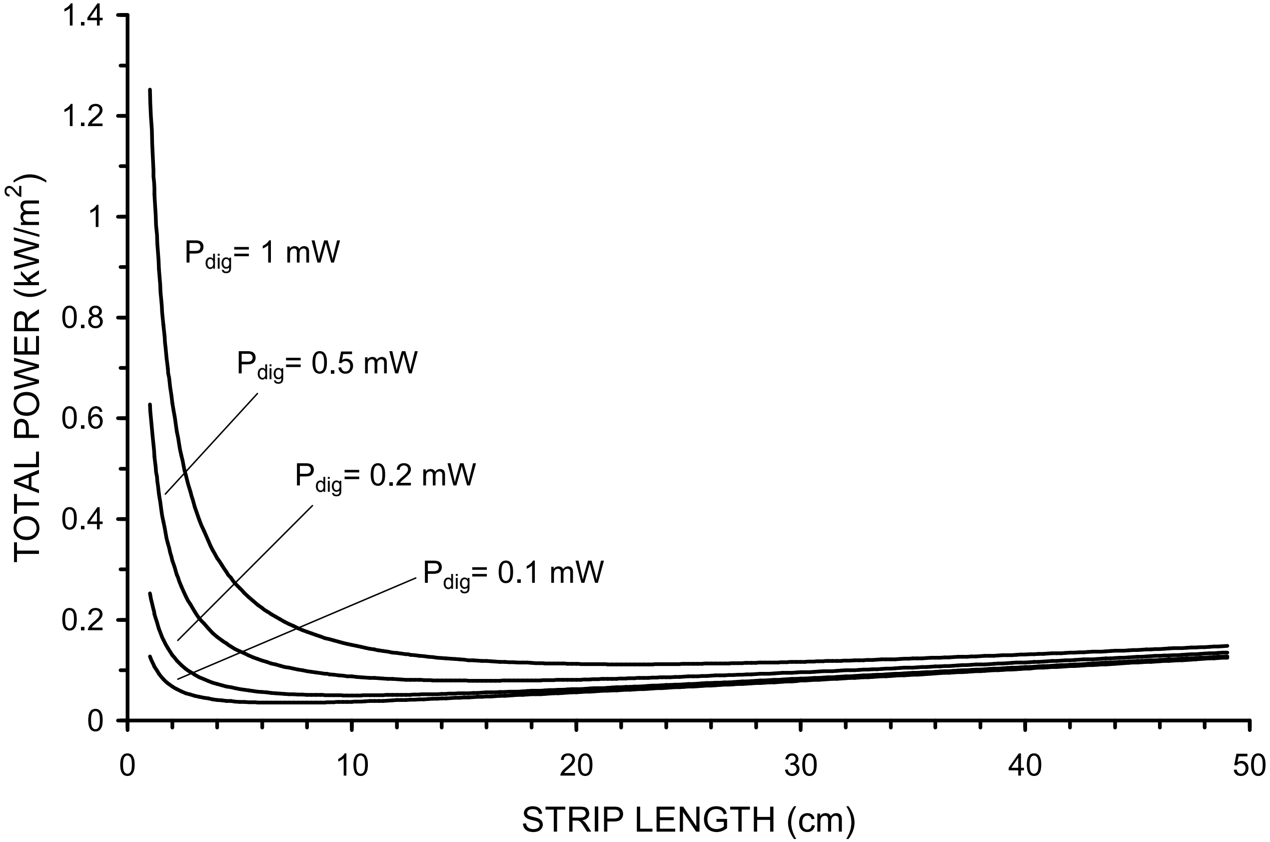
Digital power scales $\propto$ clock frequency and $\propto 1/(\text{supply voltage})^2$

Note: max strip length also constrained by occupancy

(probably the first science result at LHC!)

Total Power (kW) per Square Meter vs. Strip Length and Digital Power P_{dig}

(strip pitch = 80 μm, analog power 0.2 mW for 10 cm strip length)



- Power increases rapidly at strip lengths below about 3 cm.
  (Dominated by digital circuitry)
- Important to streamline digital circuitry to reduce its contribution.
  e.g. analyze contributions of individual circuit blocks and assess usefulness.