# Pulse Processing: Preamplifiers and Noise

Nuclear Instrumentation

Lecture 2

UNIVERSITY OF LIVERPOOL

## Learning Objectives

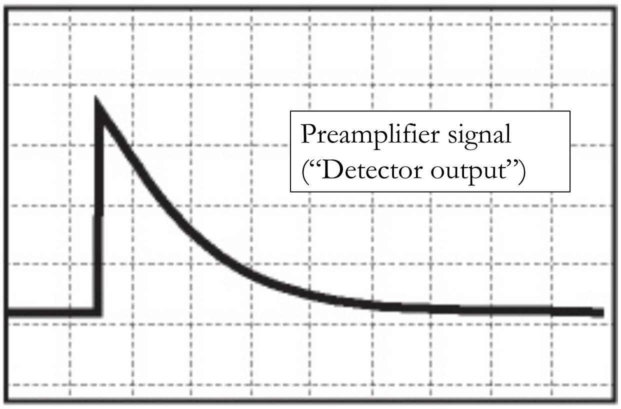
**After this lecture you should understand:**

- Operation of charge-sensitive and current-sensitive preamplifiers
- Pulse pile-up and recovery
- Sources of electronic noise
- Energy resolution factors

# Preamplifiers

**Primary function:**

- To extract the signal from the detector with minimum signal-to-noise degradation



Preamplifier signal
("Detector output")

# Preamplifiers

- Locate close to the detector (to minimize capacitive loading).

Several types of detector produce moderately large outputs. e.g:

- Photodiodes operating in intense light
- Photomultiplier tubes (PM tubes)
- Scintillation detectors mounted on a PM tube
- Microchannel plates

For such detectors, use a **current-sensitive** preamplifier

## High-resolution systems

More care needs to be taken for **high-resolution systems**. Detectors in this category include:

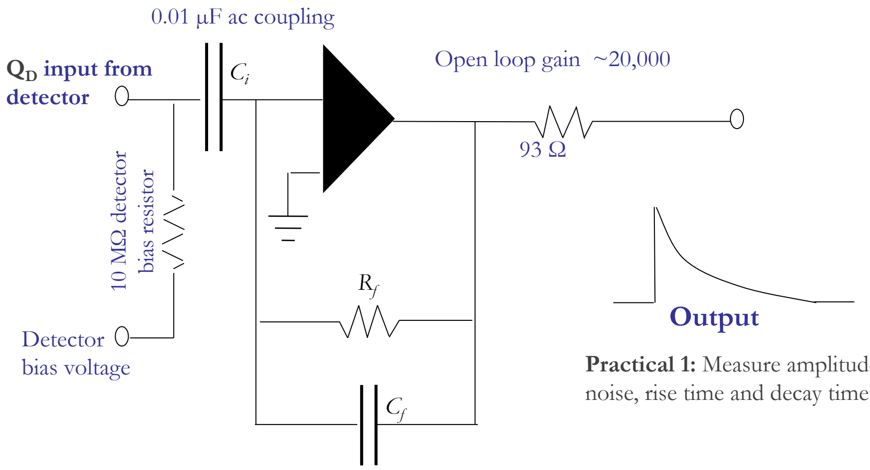
- Silicon (Si) detectors
- Germanium (Ge) detectors
- Gas proportional counters.

These produce very small output signals. Therefore, the preamp input stage should contribute little noise.

This requirement is often met by using a **charge-sensitive** preamplifier:

- with FET input stage.
- cooled FET (reduce thermal noise).

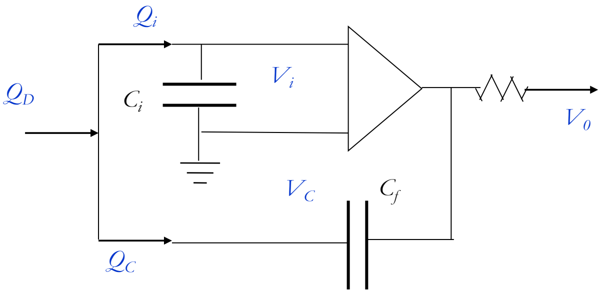
## Charge-sensitive preamplifier



**Practical 1:** Measure amplitude, noise, rise time and decay time

A charge-sensitive preamplifier integrates the detector charge pulse $Q_D$ (duration $10^{-5}$ – $10^{-6}$ s), collected on a capacitor $C_i$ and then discharged by a feedback resistor $R_f$

# Charge-sensitive preamplifier



- The diagram shows charges, voltages and essential elements in a charge-sensitive preamp.
- Output voltage proportional to total integrated charge: $V_0=Q_D/C_f$
- Risetime depends on the charge collection characteristics of the detector
- Decay time constant $\tau_0=R_fC_f$

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# Charge-sensitive preamplifier

- $R_f$ is a **source of electronic noise:** It should be as **large** as possible.
- Electronic noise in charge-sensitive preamps is generally controlled by **four** components:
  1. The input field-effect transistor (FET).
  2. The total capacitance of the input (detector capacitance, cables etc.).
  3. The resistance connected to the input.
  4. Input leakage currents from the detector and FET.
- The FET is selected for low-noise performance and often is cooled to almost LN$_2$ temperature to reduce thermal noise.

# Preamplifier sensitivity

- **Preamplifier sensitivity** given as output voltage per unit of deposited energy e.g. mV/MeV.
- Charge delivered by a detector to its preamp:

$$Q_D = [Ee \times 10^6]/\varepsilon$$

E = energy in MeV deposited in the detector,
ε= avg energy (eV) to produce an electron-hole (e-h) pair
e = electronic charge ($1.6\times10^6$ C).

Output voltage: $V_0 = Q_D/C_f = Ee\times10^6/\varepsilon C_f$
Hence, sensitivity: $V_0/E = e\times10^6/\varepsilon C_f$ .

**Example:** For $C_f = 10^{-12}$ F and $\varepsilon = 3.62$ eV/e-h (for a silicon detector)

$$\underline{V_0/E = 44\ \text{mV/MeV}}$$

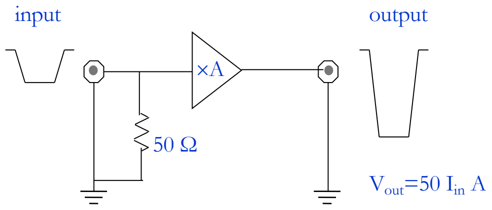
# Current-sensitive preamplifier

For less demanding requirements:

- When the detector gives ~ large, fast rising pulses, use a terminated 50-ohm cable attached to the detector output.
- The current pulse develops the desired voltage across the load presented by the cable).
- For scintillators mounted on PM tubes, this signal is usually large enough to drive a fast discriminator without additional amplification.

For smaller pulses (single-photon counting, etc), additional amplification may be provided by a **current-sensitive preamplifier**.

# Current-sensitive preamplifier



- The 50-ohm input impedance is chosen to match the impedance of the cable.
- Current pulse is converted to a voltage pulse:

$$V_{out} = 50\ I_{in}\ A$$

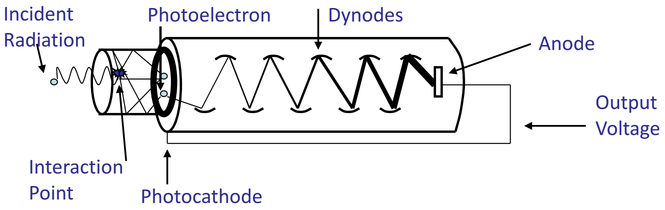
A = preamp gain

$I_{in}$ = amplitude of the detector current pulse

For timing applications, this signal can drive input of a counter/rate meter

# Limitation on timing resolution with PM tubes

- Fluctuation in the transit time of the electrons through the PM tube causes jitter in the arrival time of the pulse at the detector output.



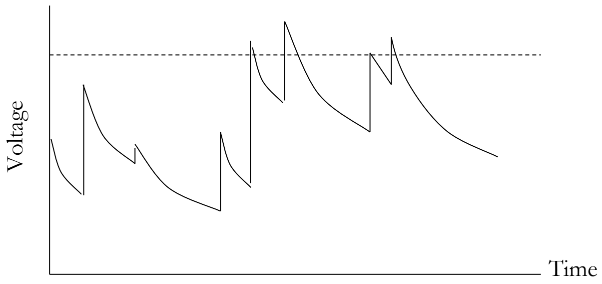
- Preamplifier input noise: causes uncertainty (jitter) in the time at which the pulse crosses the threshold of a timing discriminator. To minimize this effect: choose a preamplifier rise time $\tau_{rise}$ ~ or < detector rise time.

Choosing $\tau_{rise}$ << than that of the detector output does not help.

In fact, it is a source of **additional** noise.

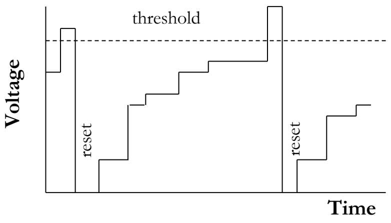
# Overload recovery and pile-up

- The amplitude of preamp pulses is proportional to the energy deposited but at high count rates, the train of pulses can ride on each other
- Even though they are shaped later, they must not be allowed to exceed the linear range of the preamp or amplitude information is lost.



Solution: Reduce feedback resistance → gives faster decay but **increased noise**.

# Overload recovery and pile-up



At high count-rates use an **automatic reset** preamp:

- Feedback resistor is removed so the output voltage builds up until limit is reached.
- At that point the voltage is rapidly reset to zero after which the process repeats.

There are several ways of resetting the system:

- For low-energy X-ray systems, reset using **pulsed optical device** (LED triggering a light-sensitive switch)
- For higher energies and/or at high rates, use a **transistor reset.**
- Have a dead time during the reset period:

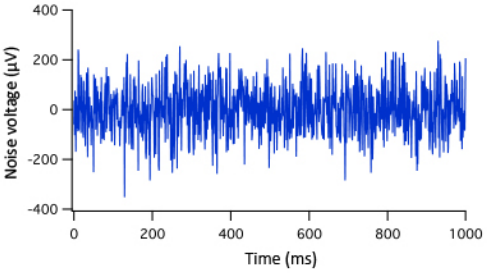
$$\textbf{\% dead time} = 100[E\, r\, T_{reset}]/E_{reset}$$

E = Energy per event; r = rate; $E_{reset}$ = reset threshold; $T_{reset}$ = dead time per reset

# Electronic noise

Noise in a measurement system arises from

- the detector
- the electronics processing the signal - mainly from the preamp.



Electronic noise is generally more important for low-energy measurements

There are 3 main categories:

**(1) Parallel noise, (2) Series noise and (3) Flicker noise.**

# Parallel noise

There are two main sources of parallel noise

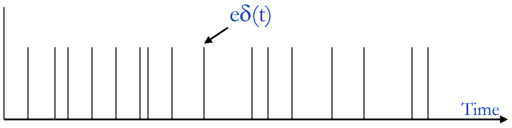
- **Shot noise:** Leakage currents through the detector and its circuitry
- **Thermal noise:** Thermal motion of electrons in critical resistors, (preamplifier feedback resistor and the detector bias resistor)

Each source is treated as an **effective noise-current generator** at the input to the preamplifier.

# Shot noise

Current = a series of discrete pulses of equal height arriving randomly in time.

- 1 pulse ≡ unit of charge e (an electron or hole)
- Current pulse ≡ $e\delta(t)$, where $\delta(t)$ is the delta function and . $\int e\delta(t)dt = e$



- Leakage current $i_L = ne$, where n = average pulse rate.

- If amplifier shaping time = $\tau$, approx. $N \approx n\tau$ pulses will have elapsed during the period of the signal pulse.

- Thus, the **average leakage charge** collected in time $\tau$: $Q_{av} = Ne$.

# Shot noise

- Pulses arrive randomly in time and so $N$ is subject to Poisson statistics, i.e. $N$ has a standard deviation of $\sqrt{N}$ and a relative standard deviation of $1/\sqrt{N}$.
- Therefore, the actual charge collected will exhibit a **statistical variation** - observed as **noise** on the signal.
- Noise is quoted as the **variance** (standard deviation)$^2$ of $Q_{av}$:

$$(\omega)^2_{\mathrm{shot}} = (Q_{av} / \sqrt{N})^2 = N e^2$$

which can be written as

$$(\omega)^2_{\mathrm{shot}} = n\, e^2\, \tau = e\, i_L \tau$$

after substituting for $N$ and $i_L$

Note that the units are (charge)$^2$

## Shot noise

**Example**: We use the above general arguments and our knowledge of detectors to estimate the effect of shot noise on the signal from a germanium detector.

- Suppose the detector leakage current is 1 nA. This is equivalent to a flow rate $n \sim 6\times10^9$ electrons per second.
- If we have set a shaping time constant $\tau$ of 6 μs, $N = n\tau \sim 4\times10^4$ and $\sqrt{N} \sim 200$.
- In a germanium detector, about 3 eV is required to create an electron-hole pair. So, a variation of 200 charge carriers is equivalent to **600 eV** of noise on the energy signal.

## Thermal noise

Arises from the thermal motion of charge carriers in a resistor, the most important being the preamplifier feedback resistor R.

- The motion is driven by thermal energy kT where k = Boltzmann's constant.
- kT is the thermal energy of an electron in the resistor R.
- Consider motion (energy) to be due to a varying (effective) voltage V across the resistor, giving energy eV = kT to the electrons
- The voltage V generates a (thermal) current $i_{th} = V/R$.
- This current can be treated as an **effective input source** - like shot noise.
- Thermal noise variance:

$$(\omega)^2_{th} \approx e\, i_{th}\, \tau = [eV/R]\, \tau = [kT/R]\, \tau$$

after substituting for $i_{th}$ and eV.

# Thermal noise

A proper calculation gives

$$(\omega)^2_{th} \approx [4kT/R]\ \tau$$

Combining shot noise and thermal noise:

$$(\omega)^2_{parallel} \approx e\, i_L\, \tau + [4kT/R]\ \tau$$

NB both terms have **same** dependence on the shaping time constant $\tau$.

Parallel noise is minimized by

- Reducing T (cooling the feedback and bias resistors).
- Using a large feedback resistor (or an autoset preamplifier).
- Using a short shaping time constant $\tau$.

# Series Noise

- Due to leakage current $i_D$ in the preamplifier FET.
- Has a different dependence on $\tau$ to that of shot noise or thermal noise.
- This is because $i_D$ is a property of the transistor (and its temperature) and is **not** dependent on $\tau$.

Consider $i_D$ = electrons flowing at a rate n per unit time, i.e.

$$i_D = ne.$$

During the shaping time $\tau$, a number $N = n\tau$ electrons will have been collected.

N will fluctuate (Poisson statistics), hence, the output current will fluctuate:

$$i_D = ne = N e/\tau \pm \sqrt{N}\, e/\ \tau = ne\ \pm \sqrt{n}\, e/ \sqrt{\tau}$$

- Variance: (standard deviation)$^2$ of the FET current $\propto ne^2/\tau$.

Output voltage due to FET leakage is proportional to $i_D$ and so the variance in the output (series noise) will also vary as $1/\tau$ (not directly with $\tau$ as we found with parallel noise).

# Series noise

Thus we have

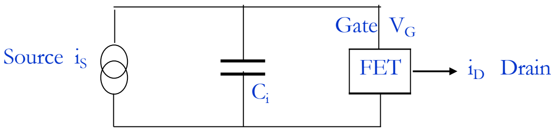
$$(\omega)^2_{\text{series}} \approx ne^2/\tau$$

Series noise depends on

- **Temperature** → because FET leakage depends on temperature.
- **Input capacitance $C_{i.}$**
- FET **transconductance g.**

To see this, we calculate $i_D$ as if it were due to an **effective noise source** $i_S$ at the **input** to the preamplifier.

# Series noise



Schematic equivalent circuit, showing an input source $i_S$, which generates an FET drain current $i_D$.

- Consider an input current pulse i(t) = eδ(t).
- This pulse contains charge e.
- It generates $\Delta V_G = e/C_i$ at the FET gate, where $C_i$ is the input capacitance.

# Series noise

The transconductance of a transistor is

$$g = \partial i_D/\partial V_{G.}$$

Thus, $\Delta V_G$ at the FET input generates an FET drain current:

$$\Delta i_D = g\Delta V_G = ge/\ C_i.$$

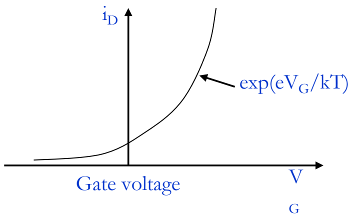
Alternatively, an FET drain current $\Delta i_D = e$ would result from an amount of charge $C_i\, e/g$, from an effective input source, collected on $C_i$.

Hence, we rewrite $(\omega)^2_{\text{series}}$ as being due to effective shot noise at the preamp input, by replacing e with $C_i\, e/g$. i.e.

$$(\omega)^2_{\text{series}} \propto \left(\frac{C_i}{g}\right)^2 \frac{e^2 n}{\tau}$$

# Series noise

The temperature dependence is contained in the quantity n, and is obtained from an approximate relationship between transistor drain current $i_D$ and gate voltage $V_G$: $i_D \approx \exp(e\, V_G\, /kT\,)$



- Differentiating gives $\partial i_D/\partial V_G = (e/kT)i_{D,}$
- This can be written as $g = (e^2n/kT)$, using Equations (3.9) and (3.11).

Substituting for $e^2n$ in Equation (3.12):

$$(\omega)^2_{\text{series}} \propto \left(\frac{C_i}{g}\right)^2 \frac{gkT}{\tau} = C_i^2\left(\frac{kT}{g\tau}\right) \qquad (3.14)$$

N.B. This is **not** a proper derivation of series noise. However, apart from numerical constants, it is the expression for series noise given by a more rigorous calculation.

# Series noise

Series noise is minimized by

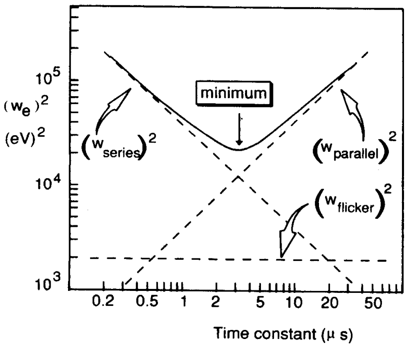
- Reducing the input impedance $C_i$ (length of connecting leads etc.).
- Lowering the temperature (cooling the FET and feedback resistor).
- Using a high gain ($g$), low-noise FET.
- Increasing the shaping time.

# Flicker noise

There is a third noise source, flicker noise, ~ independent of $\tau$.

- It arises from currents in all active components and increases with count rate.
- It is generally << parallel or series noise.

# Noise and amplifier shaping time

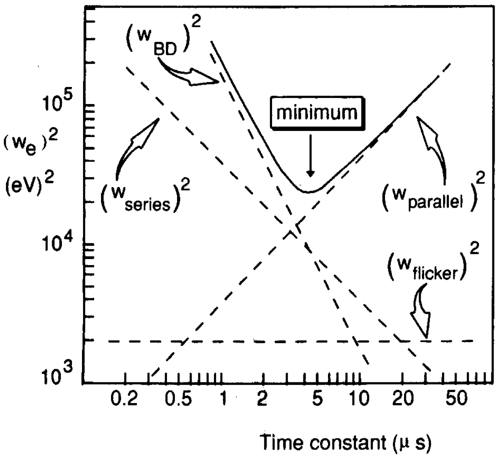


- $(\omega)^2_{series}$ decreases with τ.
- $(\omega)^2_{parallel}$ increases with τ.
- Optimum τ gives a **minimum** in the total electronic noise level.

The plots vary depending on particular detector & electronics used.

- e.g. $(\omega)^2_{parallel}$ is reduced by using an auto-reset preamplifier (no feedback resistor).
- Reducing $(\omega)^2_{parallel}$ shifts the minimum to a longer time constant.
- This may be undesirable if the counting rate is very high.

# Ballistic deficit



- There may be noise from ballistic deficit, when the charge collection time in the detector is not << τ.
- $(\omega)^2_{BD}$ is shown to be ∝ $1/\tau^2$ (no real justification).

- If $(\omega)^2_{BD}$ > or ~ $(\omega)^2_{series}$, minimum will be skewed (not symmetric).
- Or, a skewed noise curve suggests a possible significant ballistic deficit.

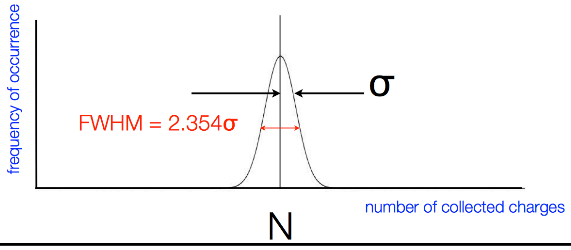
# Energy Resolution

Interaction of radiation with matter a statistical process (probability for any given collision/excitation/absorption)

After all energy is deposited, charge collection is also statistical (Poisson)

$$\Omega = \sqrt{N}$$

At large N, distribution becomes Gaussian



# Energy Resolution

Statistical fluctuations in the number of charge carriers per interaction event ($N_{pair}$) is given by

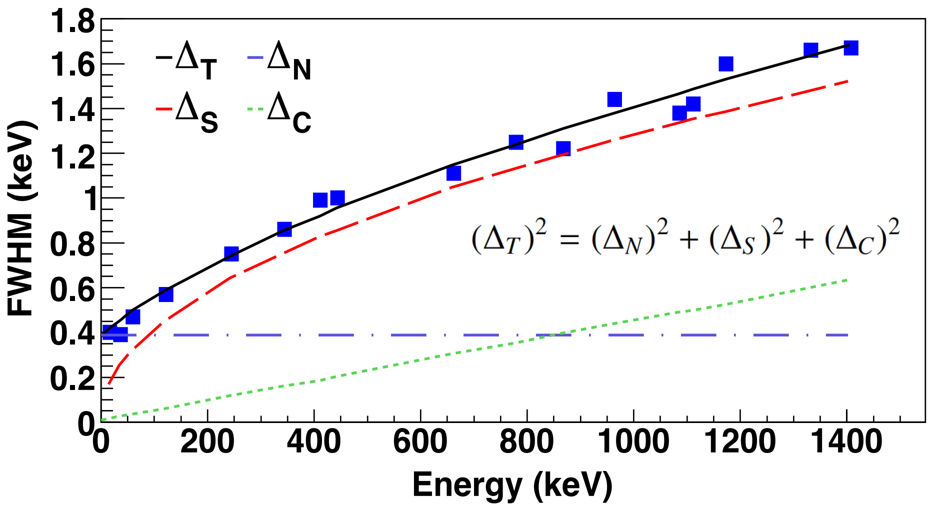
$$(\Delta E_S)^2 = \frac{(2.35)^2 F}{N_{pair}}$$

F is the fano factor accounting for deviation from Poisson statistics of experimentally observed statistical fluctuations

**T**otal energy resolution: electronic **N**oise, **S**tatistical fluctuations in # of charge carriers and incomplete **C**harge collection

$$(\Delta_T)^2 = (\Delta_N)^2 + (\Delta_S)^2 + (\Delta_C)^2$$

## Energy Resolution



## Summary

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- Pulse pile-up and recovery
- Sources of electronic noise
- Energy resolution factors