TRIUMF Summer Institute

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Semiconductor Detectors and Electronics

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These course notes and additional tutorials at
http://www-physics.lbl.gov/~spieler

or simply Google "spieler detectors"

More detailed discussions in
H. Spieler: Semiconductor Detector Systems, Oxford University Press, 2005

Outline

Detector Applications and Requirements
- Energy Measurements
- Fast Timing
- Position Sensing
  - Strip and Pixel Detectors
- Signals and Noise

Sensor Physics I
- Signal Magnitude and Fluctuations
  - Fano Factor
- Signal Formation
  - Induced Current
  - Sensors + Amplifiers
- Semiconductor Diodes
  - pn-Junctions
  - Depletion Width

Sensor Physics II
- Signal Formation in
  pad detectors
- Signal Formation in strip and pixel
  detectors
- Trapping
- Sensor Materials

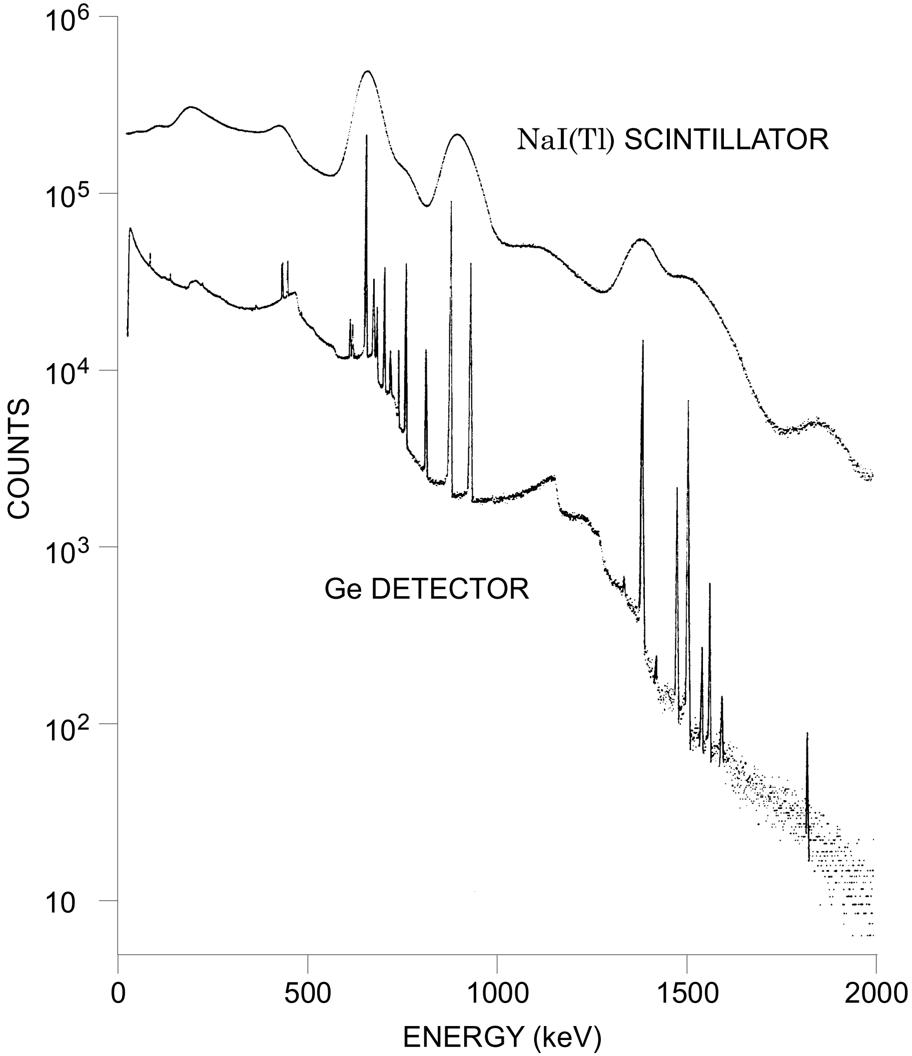
Electronics
- Amplifiers
- Electronic Noise
- Pulse Shaping
- Threshold Discriminator Systems
- Timing Measurements
- Digital Electronics
  - Analog-to-Digital Conversion
  - Pulse Processing
- Readout Systems

Detector Structures II – Pixel Devices
- Hybrid pixel devices, CCDs, Silicon Drift Chambers, DEPFETs, MAPS

Why Things Don’t Work

When first introduced in the 1960s, semiconductor detectors were used primarily for high-resolution x-ray and gamma spectroscopy.

Typical signal-to-noise ratio ~1000

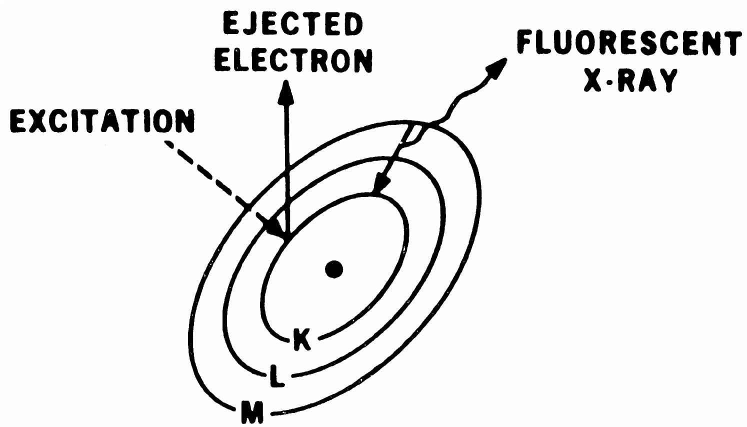


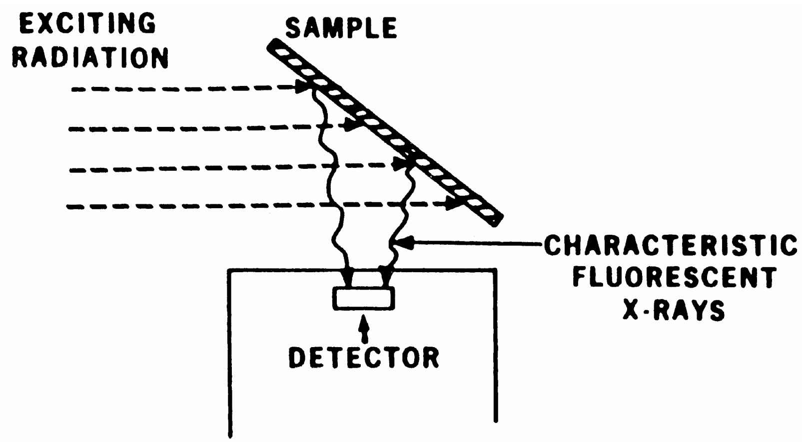
(J.Cl. Philippot, IEEE Trans. Nucl. Sci. **NS-17/3** (1970) 446)

A major scientific and industrial application is x-ray fluorescence

When excited by radiation of sufficient energy, atoms emit characteristic x-rays that can be used to detect trace contaminants.

Experimental Arrangement





The incident radiation can be broad-band, as long as it contains components of higher energy than the atomic transitions of the atoms to be detected.

High-rate high-resolution
x-ray fluorescence systems
opened a wealth of applications in science and industry.

Example:

Detection of trace contaminants

Human blood sample prior to introduction of unleaded gasoline:

log scale!

Necessary to measure low intensity peaks adjacent to very strong signals

concentrations in ppm

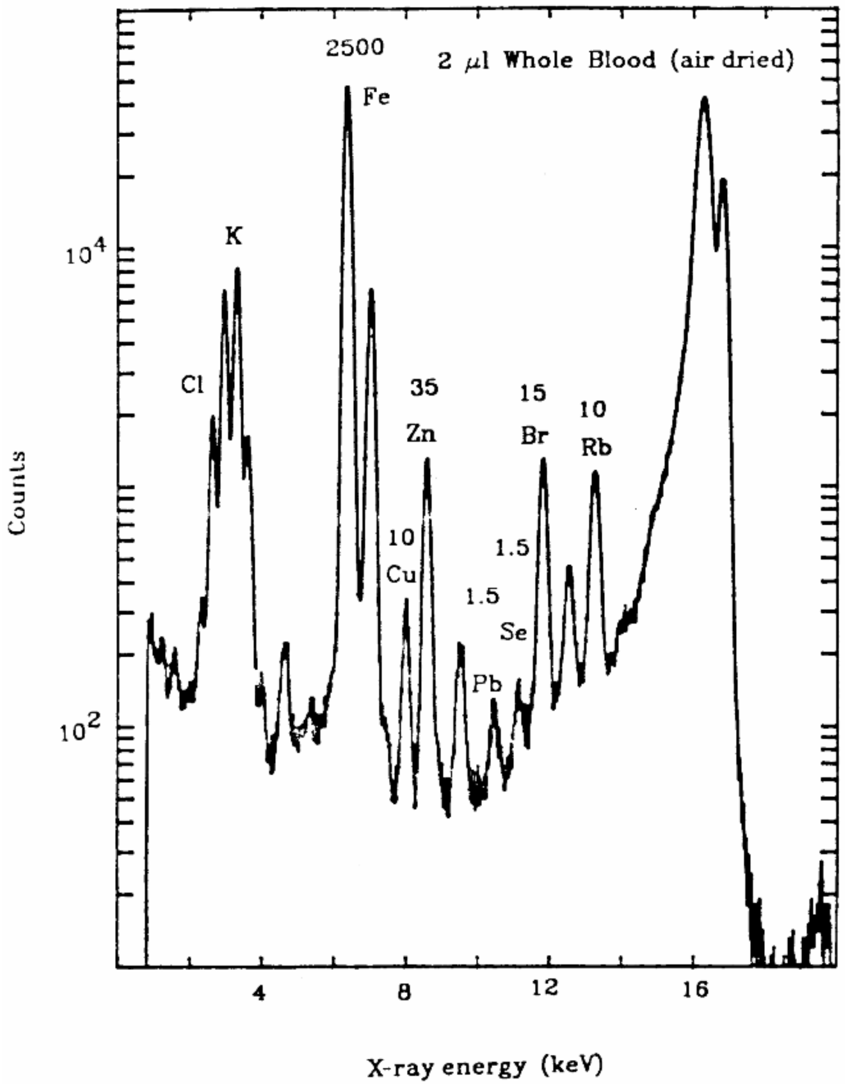
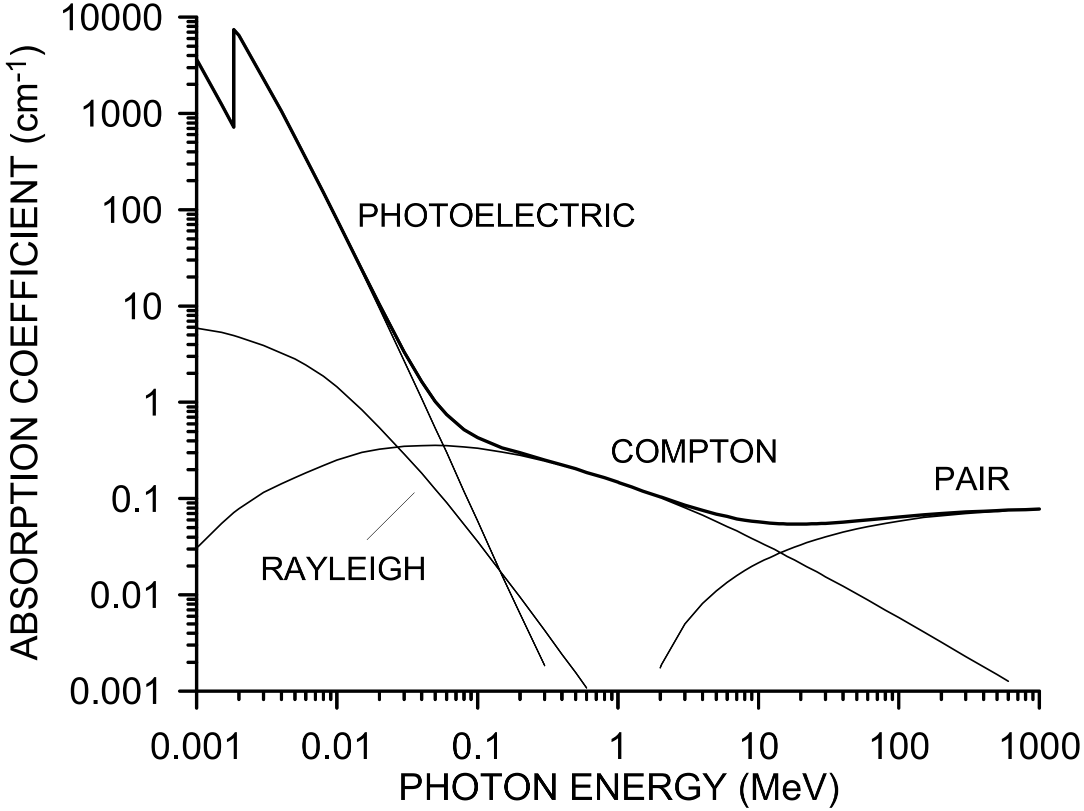


Fig. courtesy of Joe Jaklevic, LBNL

As explained in previous lectures, the interaction mechanisms of gamma rays depend on energy. Absorption coefficient μ in Si:



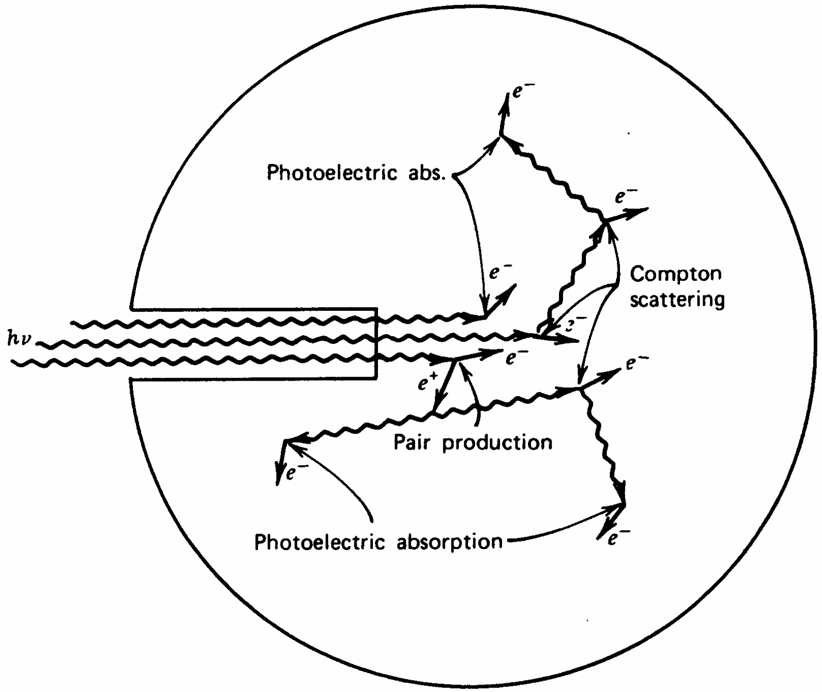
Fraction of particle interactions: $$\frac{N}{N_0} = 1 - \exp(-\mu x)$$

Distinguish between

- Detection
- Energy measurement

Detection possible with fraction of photon energy.

For full energy absorption, typically multiple processes are involved.

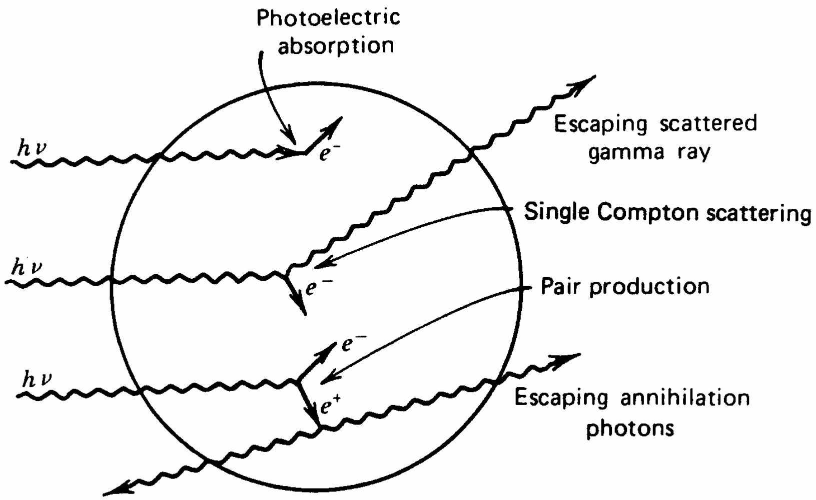


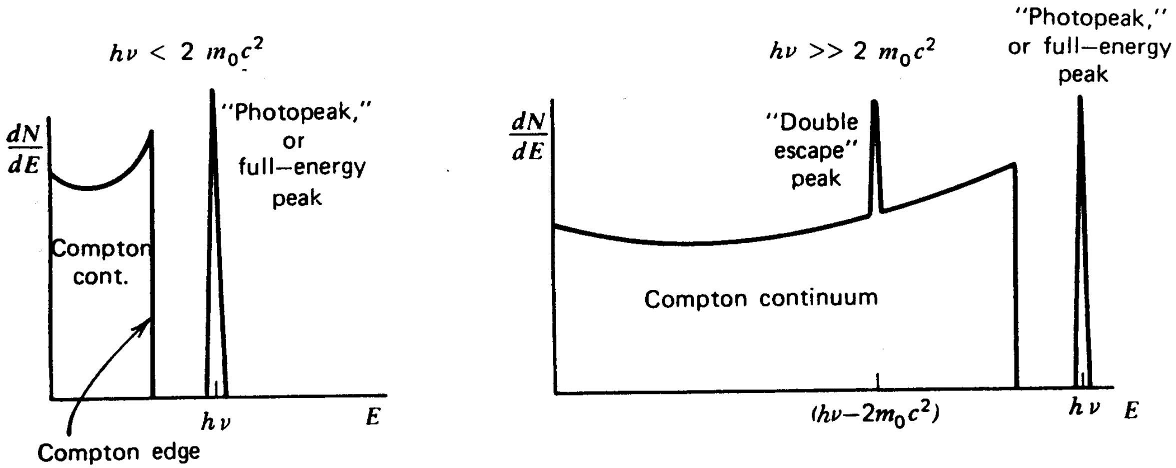
If the detector volume is sufficiently large, the full photon energy will be measured.

"Full energy peak":

From Knoll,
Radiation Detection and Measurement

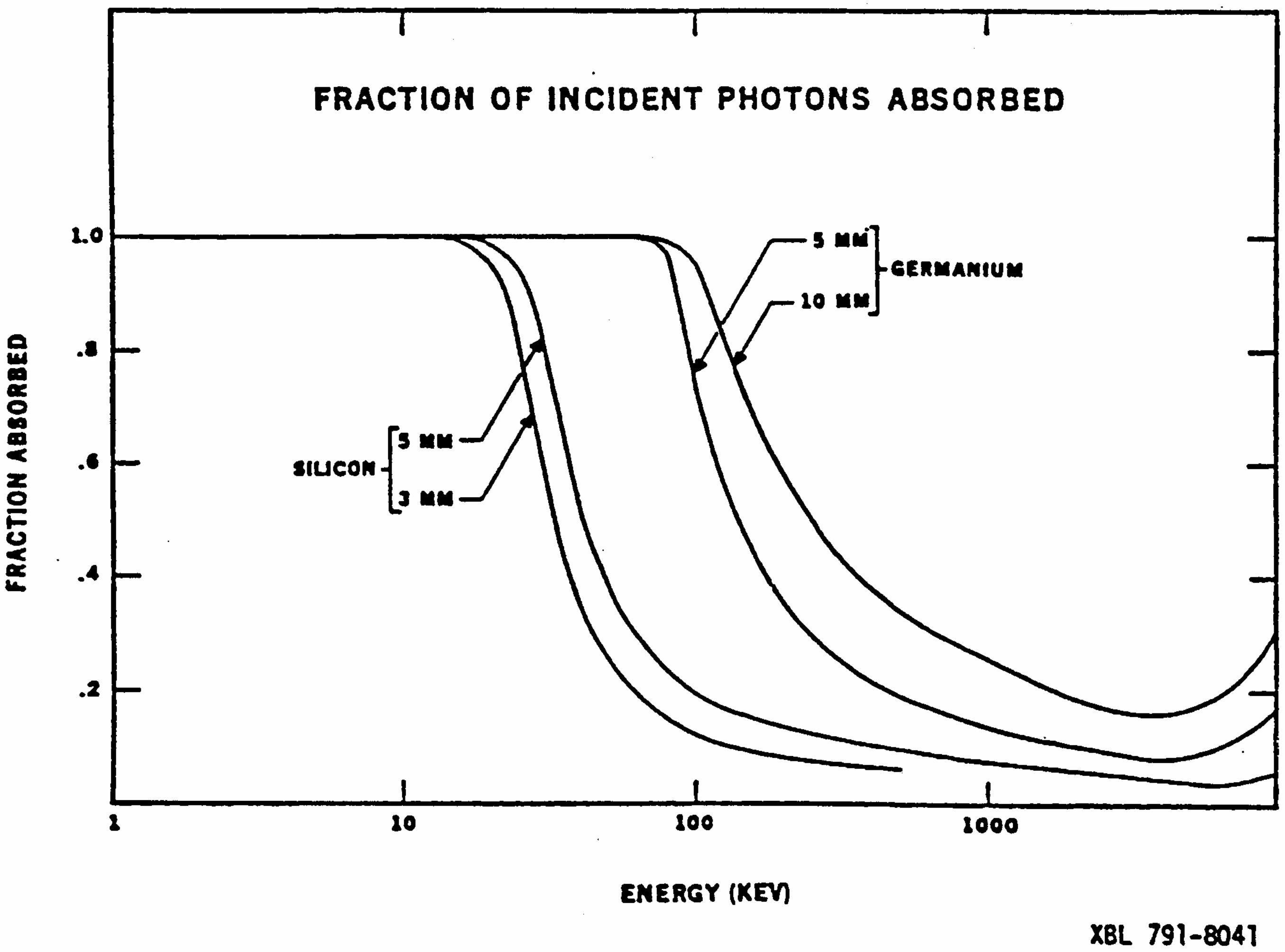
With a small detector volume,
secondary particles can
leave the detector volume,
so only a fraction of the
incident photon energy
is measured.





From Knoll,
Radiation Detection and Measurement

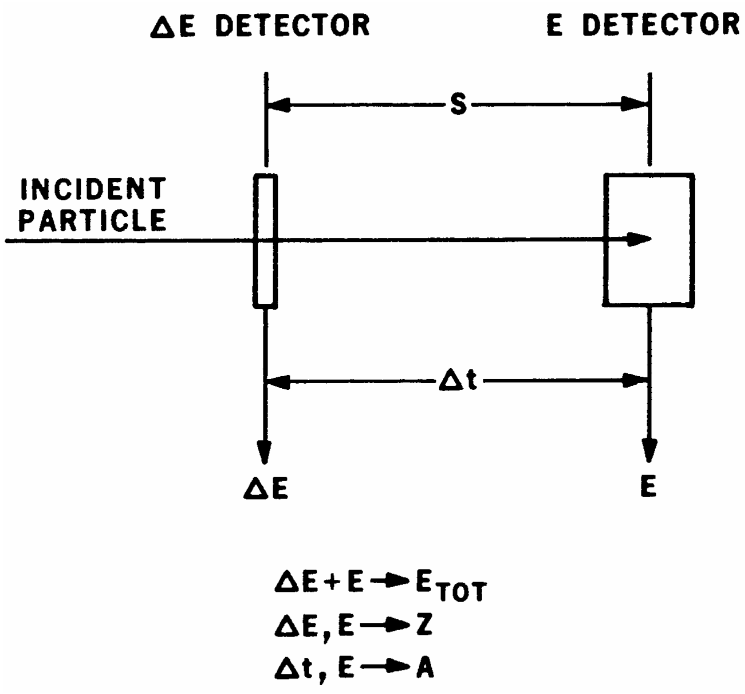
Fraction of photons fully absorbed vs. energy for different thicknesses of Si and Ge.

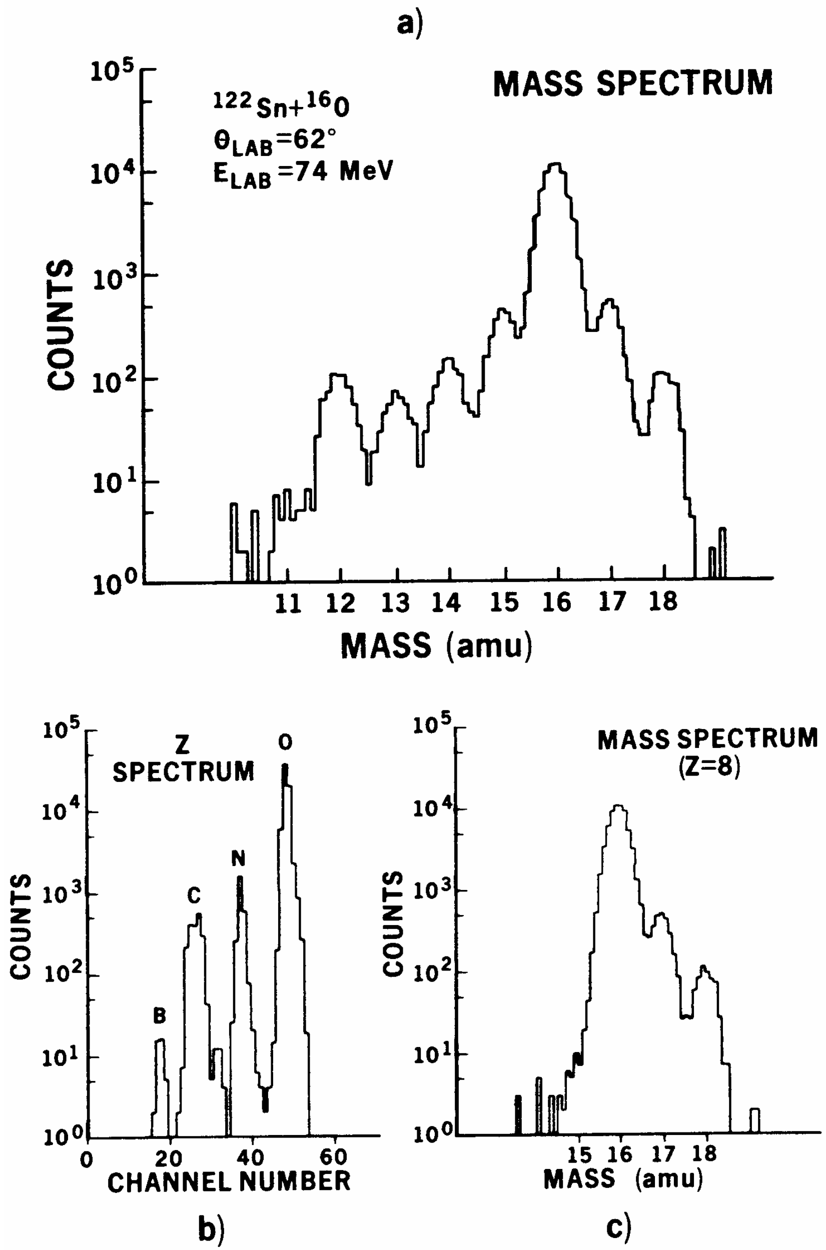


Thin Si detectors have ns collection times and provide ps time resolution.

Nuclear time-of-flight system:

Flight path s= 20 cm, $\sigma_t \approx 20$ ps

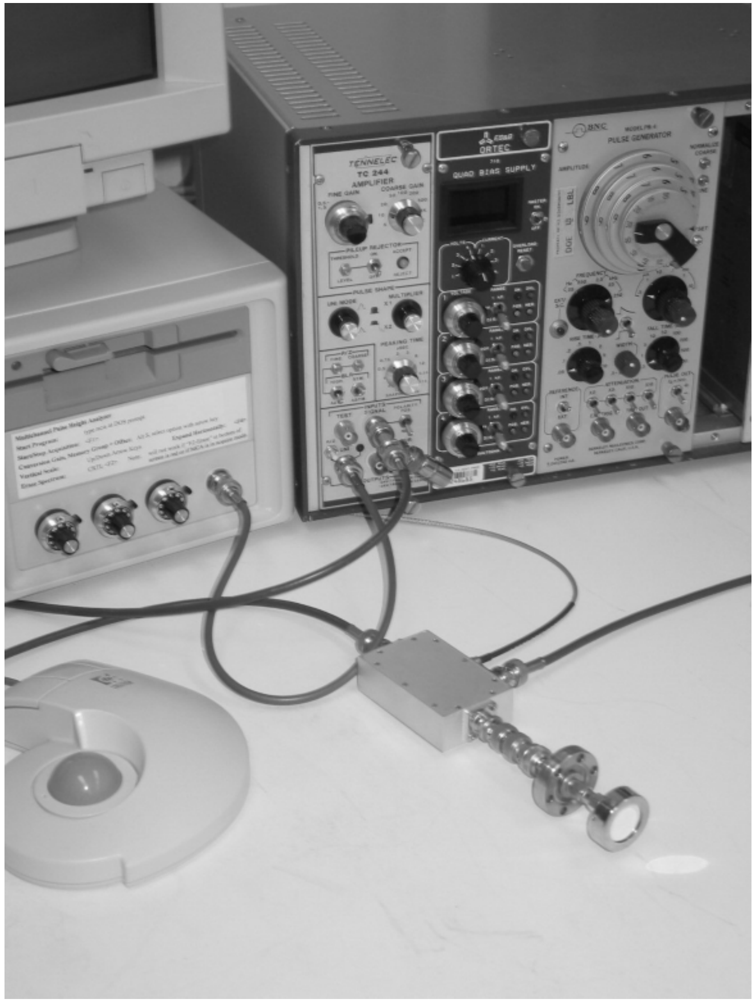




Spieler et al., Z. Physik **A278** (1976) 241

Position Sensing – Rethinking Requirements

“Traditional” Si detector system
for charged particle measurements



Tracking Detector Module (CDF SVX)
512 electronics channels on 50 μm pitch

Spectroscopy systems highly optimized!

By the late 1970s improvements were measured in %.

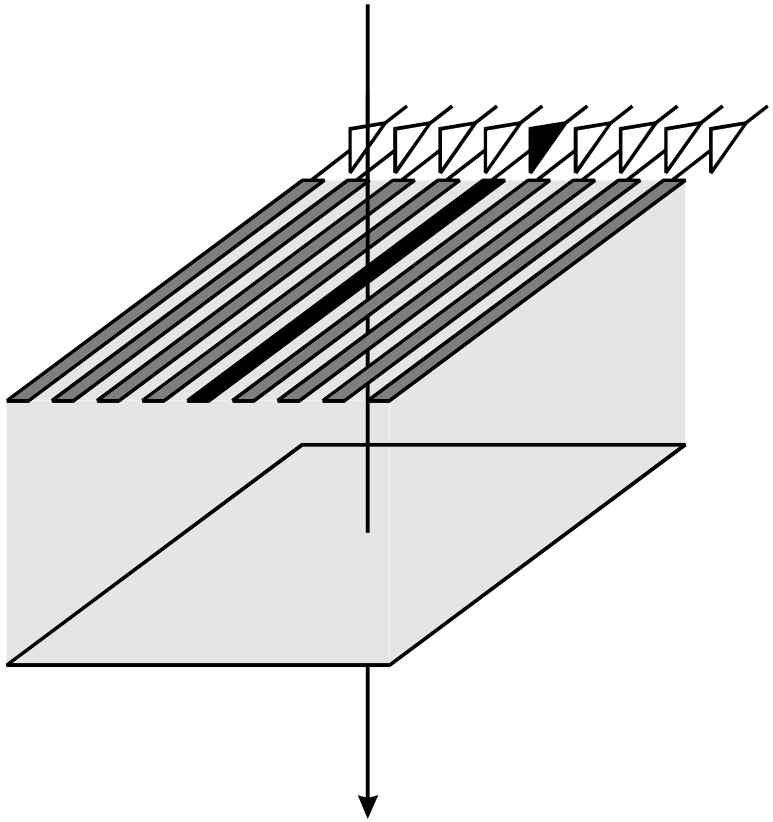
Separate system components:

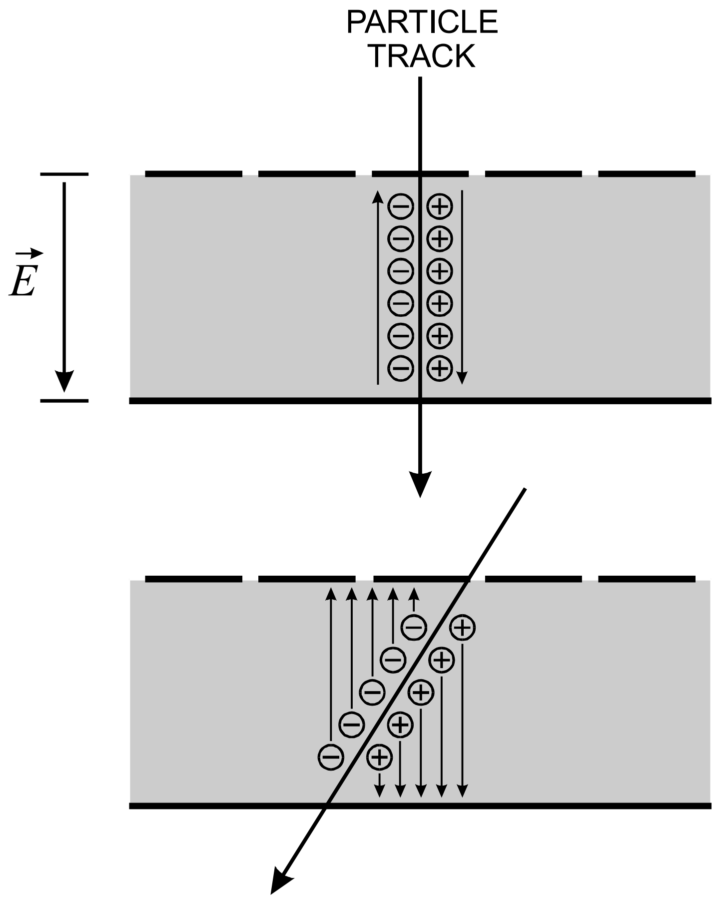
1. detector
2. preamplifier
3. amplifier
    - adjustable gain
    - adjustable shaping
        - (unipolar + bipolar)
    - adjustable pole-zero cancellation
    - baseline restorer

Beam times typ. few days with changing configurations, so equipment must be modular and adaptable.

In large systems as in HEP power dissipation and size are critical, so systems are not designed for optimum noise, but *adequate* noise, and circuitry designed for specific detector requirements.

In high energy physics the largest Si detector arrays are used for position sensing.



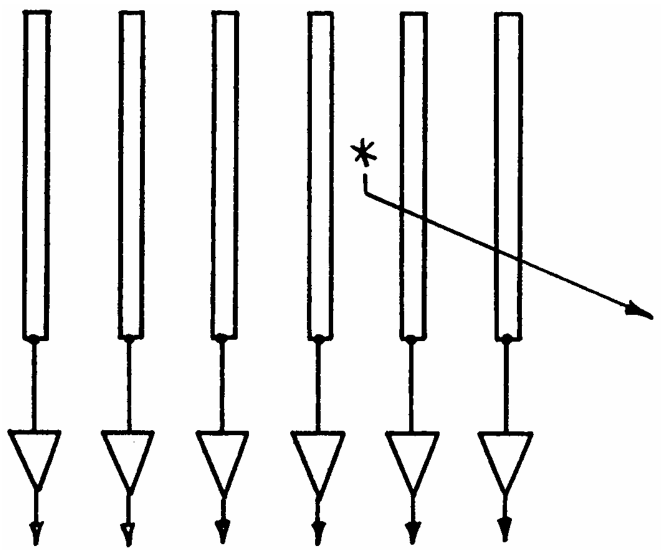


The ability to pattern electrodes on micron scales coupled with high rate capability and radiation resistance makes semiconductor detectors the system of choice for at small radii. Robust operation also facilitates large area systems (ATLAS: 60 m^2, CMS: 260 m^2).

Resolution determined by precision of micron scale patterning

Two options:

1. Binary Readout

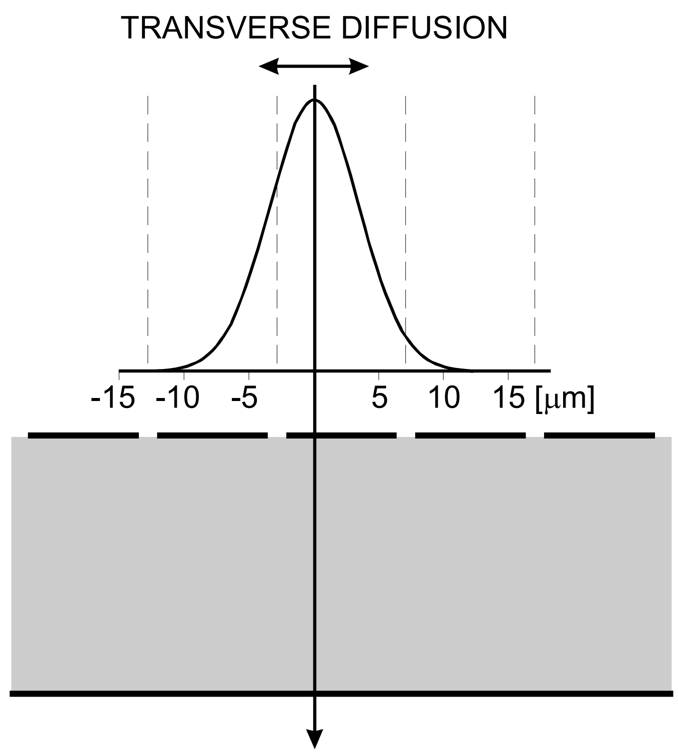


To Threshold Discriminators

Position resolution set directly by strip pitch, i.e. strip center-to-center distance:

$$\sigma_x = \frac{pitch}{\sqrt{12}}$$

2. Analog Readout



Relies on transverse diffusion: $\sigma_x \propto \sqrt{t_{coll}}$

e.g. $t_{coll} \approx 10$ ns $\Rightarrow$ $\sigma_x = 5\ \mu$m

Interpolation precision depends on S/N and strip pitch

In tracking systems the biggest challenge is reducing mass.

Impact parameter resolution

$$\sigma_b^2 \approx \left(\frac{\sigma_1 r_2}{r_2 - r_1} \right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1} \right)^2 = \left(\frac{\sigma_1}{1 - r_1 / r_2} \right)^2 + \left(\frac{\sigma_2}{r_2 / r_1 - 1} \right)^2$$

⇒ a) the ratio of outer to inner radius should be large

b) the resolution of the inner layer σ_1 sets a lower bound on the overall resolution

c) the acceptable resolution of the outer layer scales with r_2 / r_1.

If the layers have equal resolution $\sigma_1 = \sigma_2 = \sigma$

$$\left(\frac{\sigma_b}{\sigma} \right)^2 \approx \left(\frac{1}{1 - r_1 / r_2} \right)^2 + \left(\frac{1}{r_2 / r_1 - 1} \right)^2$$

The geometrical impact parameter resolution is determined by the ratio of the outer to inner radius.

The obtainable impact parameter resolution decreases rapidly from

$\sigma_b / \sigma = 7.8$ at $r_2 / r_1 = 1.2$ to $\sigma_b / \sigma = 2.2$ at $r_2 / r_1 = 2$ and $\sigma_b / \sigma < 1.3$ at $r_2 / r_1 > 5$.

The inner radius is limited by the beam pipe, typically $r = 5$ cm.
At high luminosities, e.g. LHC, radiation damage is a serious concern, which tends to drive the inner layer to larger radii.

Amount of material and its distribution is critical:

Small angle scattering: $$\Theta_{rms} = \frac{0.0136\ [GeV/c]}{p_\perp} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \cdot \ln\left(\frac{x}{X_0} \right) \right]$$

Assume a Be beam pipe of x= 1 mm thickness and R= 5 cm radius:

The radiation length of Be is X_0= 35.3 cm $\Rightarrow$ x/X_0= $2.8 \cdot 10^{-3}$

$\Rightarrow$ For $p_\perp$= 1 GeV/c the scattering angle $\Theta_{\rm rms}$= 0.56 mrad.

This corresponds to $\sigma_b = R\Theta_{\rm rms}$= 28 μm

Exceeds the impact parameter resolution typically achievable by the detector:

For σ= 10 μm and $r_2/r_1 \approx 3$: $\sigma_b \approx$ 25 μm.

Scattering originating at small radii is more serious $\Rightarrow$

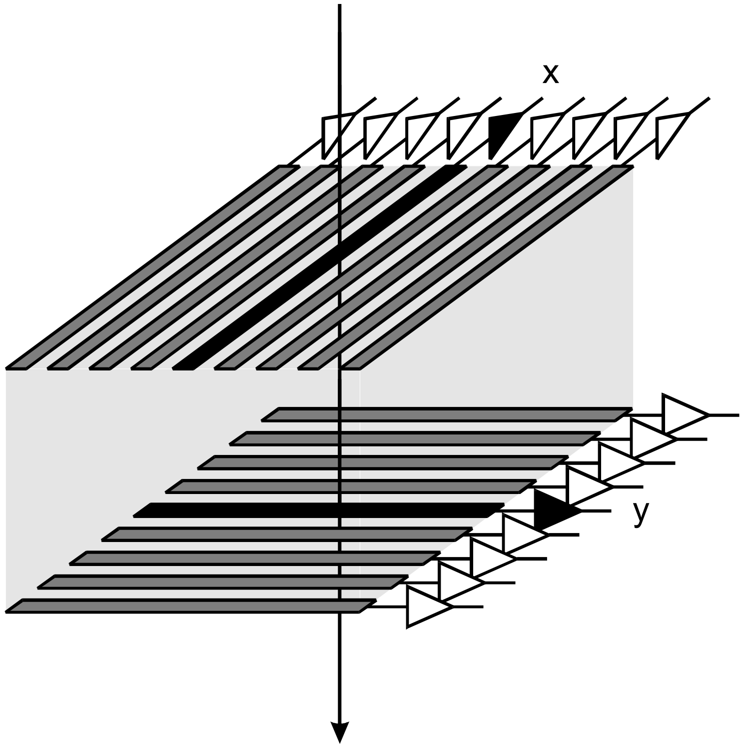
Important to limit material at small radii.

Especially critical at ILC!

For comparison: 300 μm of Si (typ. strip detector) $\rightarrow$ 0.3% X_0

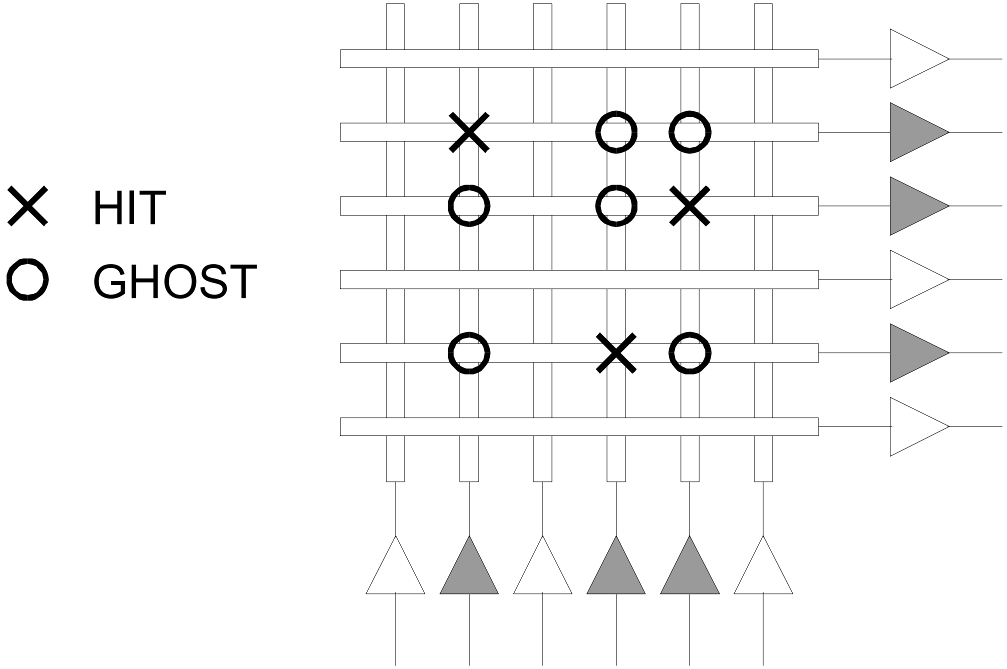
Two-Dimensional Position Sensing

Crossed Strips



n readout channels $\Rightarrow$ n^2 resolution elements

Problem: Ambiguities with multiple simultaneous hits (“ghosting”)



n hits in acceptance field $\Rightarrow$ n x-coordinates
n y-coordinates

$\Rightarrow$ n^2 combinations

of which $n^2 - n$ are “ghosts”

Reduce ambiguities by small-angle stereo

In collider geometries often advantageous, as z resolution less important than $r\varphi$.

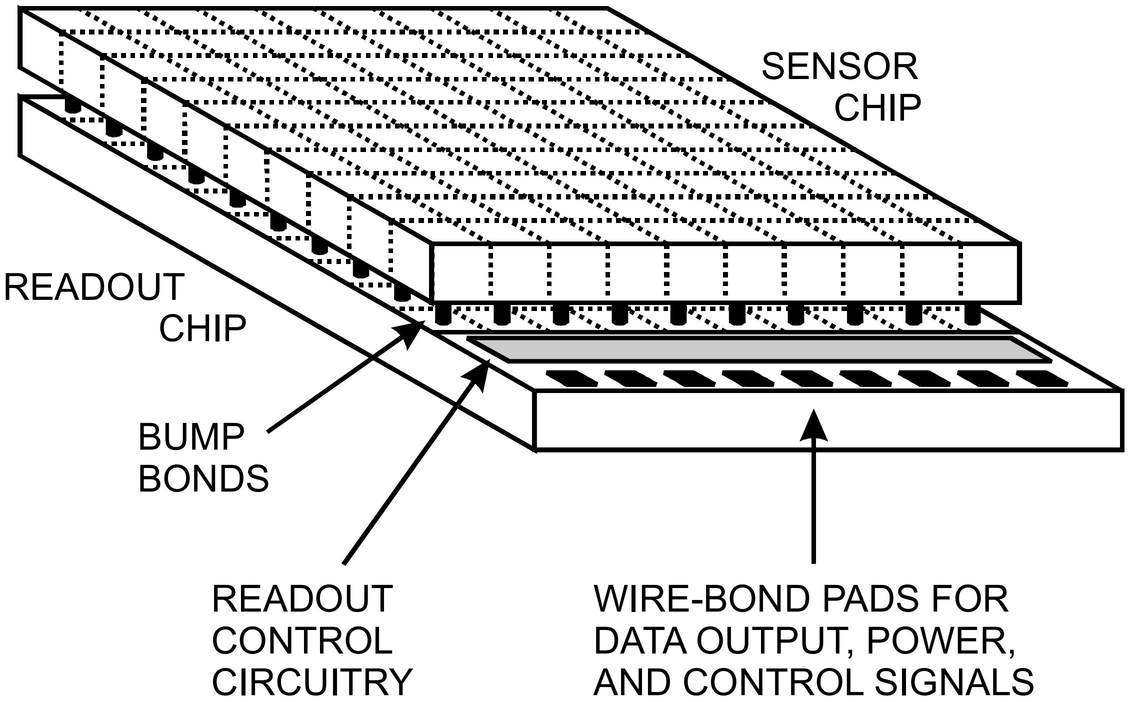
The width of the shaded area subject to confusion is $L\dfrac{p_2}{p_1}\tan\alpha + p_2$

Example: ATLAS SCT uses 40 mrad small-angle stereo

Two single-sided strip detectors glued back-to-back

Eliminate “ghosting” in non-projective configurations.

Example: hybrid pixel detector (also CCDs, MAPS)



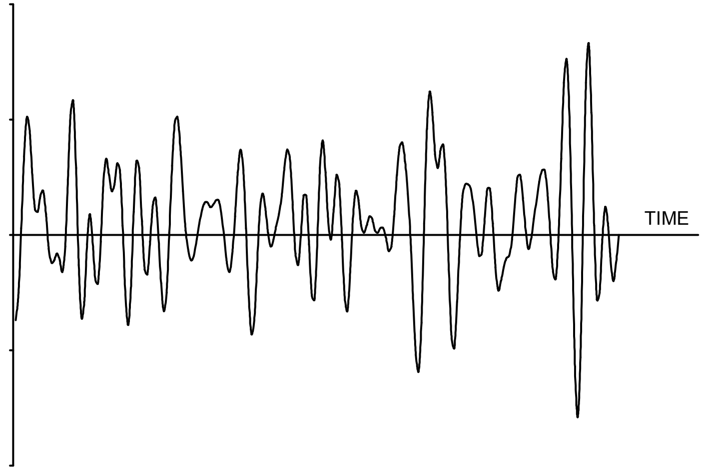
Example: ATLAS pixel detector (just installed), ~1m^2, 80 million channels

Challenge: power dissipation, but with optimized design power per m^2 comparable to strip detector systems.

Baseline Fluctuations (Electronic Noise)

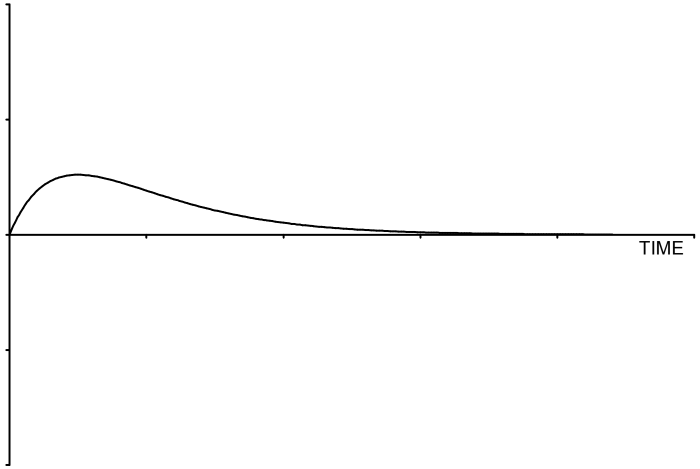
Choose a time when no signal is present.

Amplifier's quiescent output level (baseline):

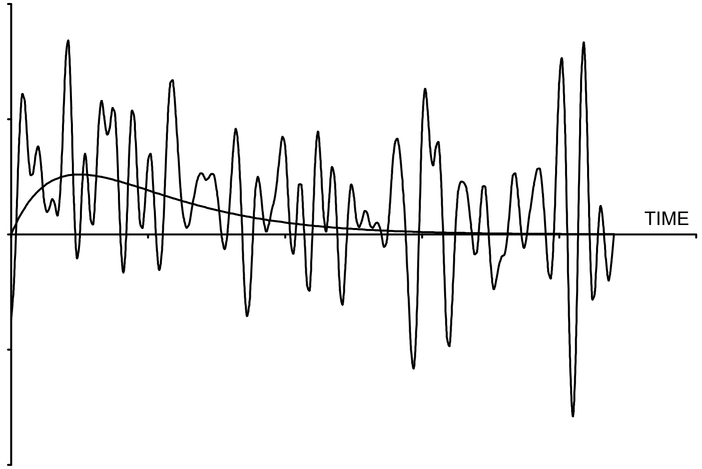


In the presence of a signal, noise + signal add.

Signal:



Signal+Noise (S/N = 1)



$S/N \equiv$ peak signal to rms noise

Measurement of peak amplitude yields signal amplitude + noise fluctuation

The preceding example could imply that the fluctuations tend to increase the measured amplitude, since the noise fluctuations vary more rapidly than the signal.

In an optimized system, the time scale of the fluctuation is comparable to the signal peaking time.

Then the measured amplitude fluctuates positive and negative relative to the ideal signal.

Measurements taken at 4 different times:

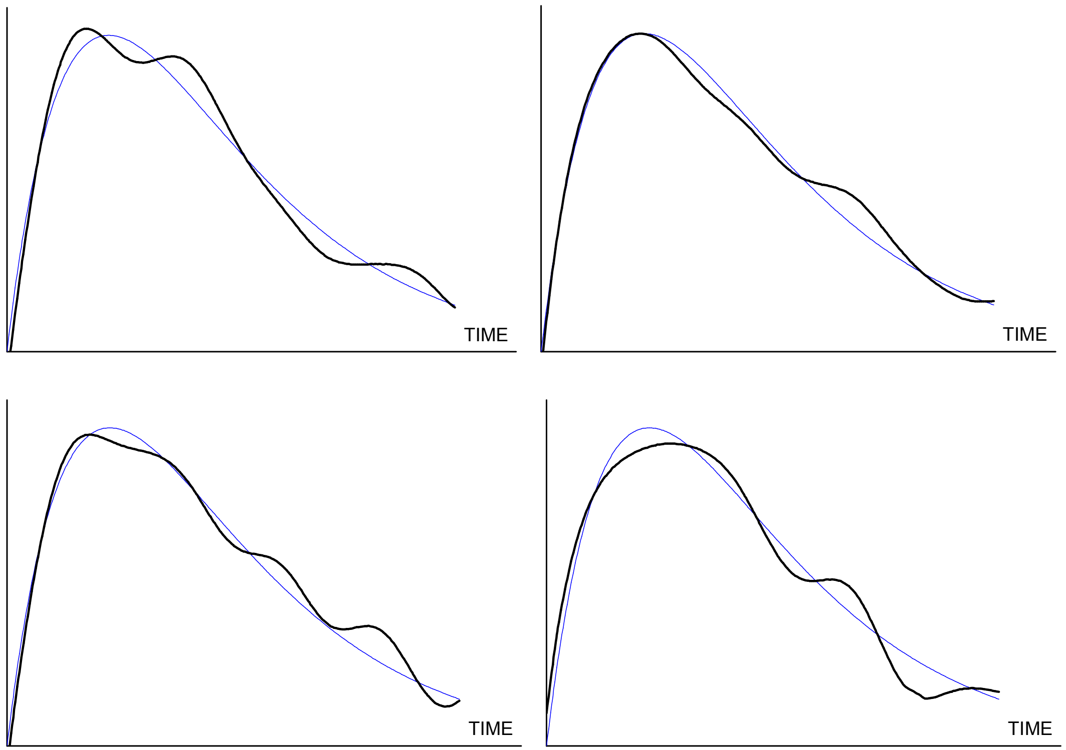
noiseless signal superimposed for comparison

$S/N = 20$

Noise affects

Peak signal

Time distribution



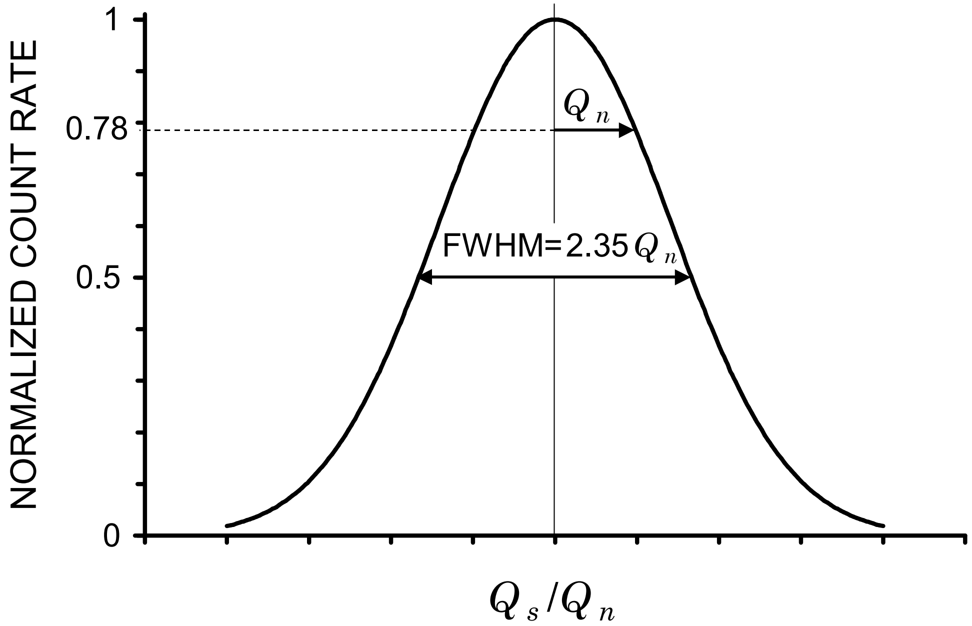
Electronic noise is purely random.

⇒ amplitude distribution is Gaussian

⇒ noise modulates baseline

⇒ baseline fluctuations superimposed on signal

⇒ output signal has Gaussian distribution



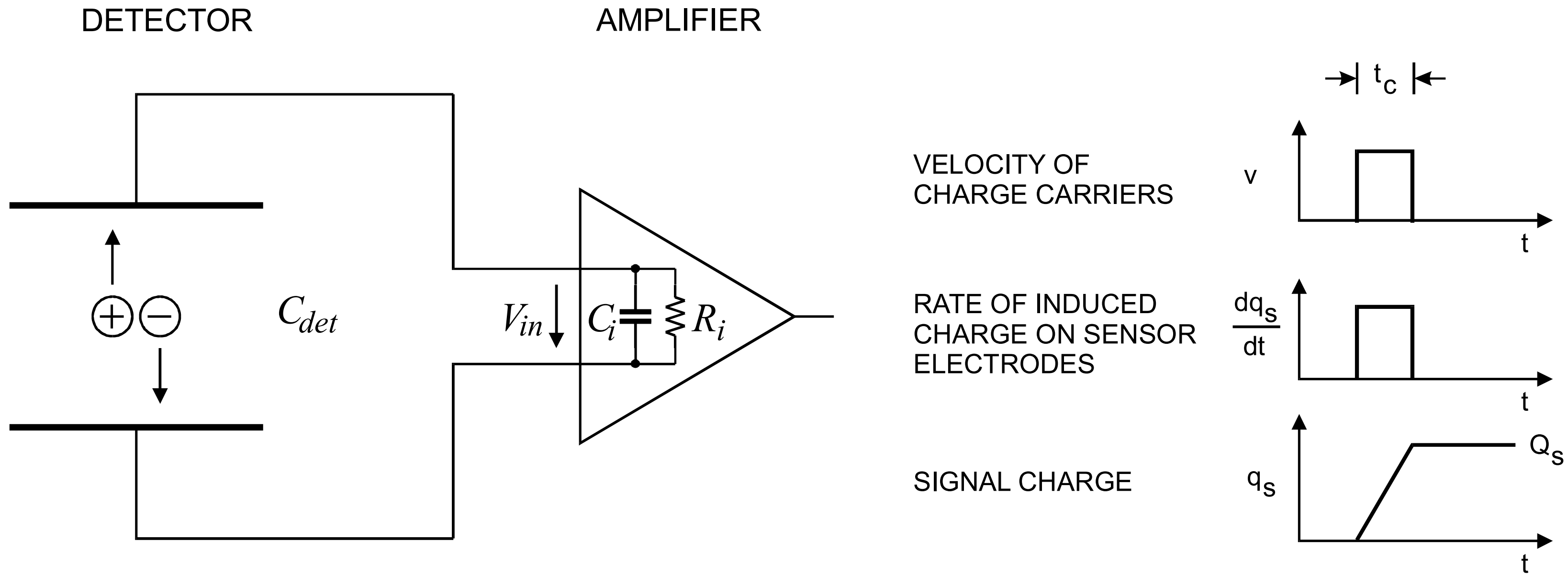
Measuring Resolution

Inject an input signal with known charge using a pulse generator set to approximate the detector signal shape.

Measure the pulse height spectrum.

peak centroid ⇒ signal magnitude
peak width ⇒ noise (FWHM= 2.35 Q_n)

Signal-to-Noise Ratio vs. Detector Capacitance



if R_i x (C_{det} + C_i) >> collection time,

peak voltage at amplifier input $V_{in} = \dfrac{Q_s}{C} = \dfrac{\int i_s dt}{C} = \dfrac{Q_s}{C_{det} + C_i}$

↑

Magnitude of voltage depends on total capacitance at input!

The peak amplifier signal V_S is inversely proportional to the **total capacitance at the input**, i.e. the sum of

1. detector capacitance,
2. input capacitance of the amplifier, and
3. stray capacitances.

Assume an amplifier with a noise voltage v_n at the input.

Then the signal-to-noise ratio

$$\frac{S}{N} = \frac{V_S}{v_n} \propto \frac{1}{C}$$

- However, S/N does not become infinite as $C \to 0$
  (then front-end operates in current mode)

- The result that $S/N \propto 1/C$ generally applies to systems that measure signal charge.