ICFA Instrumentation School

June 17 – June 28, 2002

Istanbul Technical University
Istanbul, Turkey

Measurements

Helmuth Spieler

Physics Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

spieler@LBL.gov

These course notes and additional tutorials are available as pdf files at http://www-physics.lbl.gov/~spieler

Table of Contents

I. Detectors and Electronics Overview

1. A Representative Collider Detector

1.1 Measured Quantities

Measure directions, momenta, and signs of charged particles.

Measure energy carried by electrons and photons
in each direction

Measure energy carried by hadrons
(protons, pions, neutrons, etc.) in each direction.

Identify electrons, muons

Identify whether some of the charged particles originate from displaced vertices (i.e. don't originate from collision point)

example: B-tagging (see next page)

Infer (through momentum conservation) the presence of undetectable neutral particles such as neutrinos.

Data Acquisition

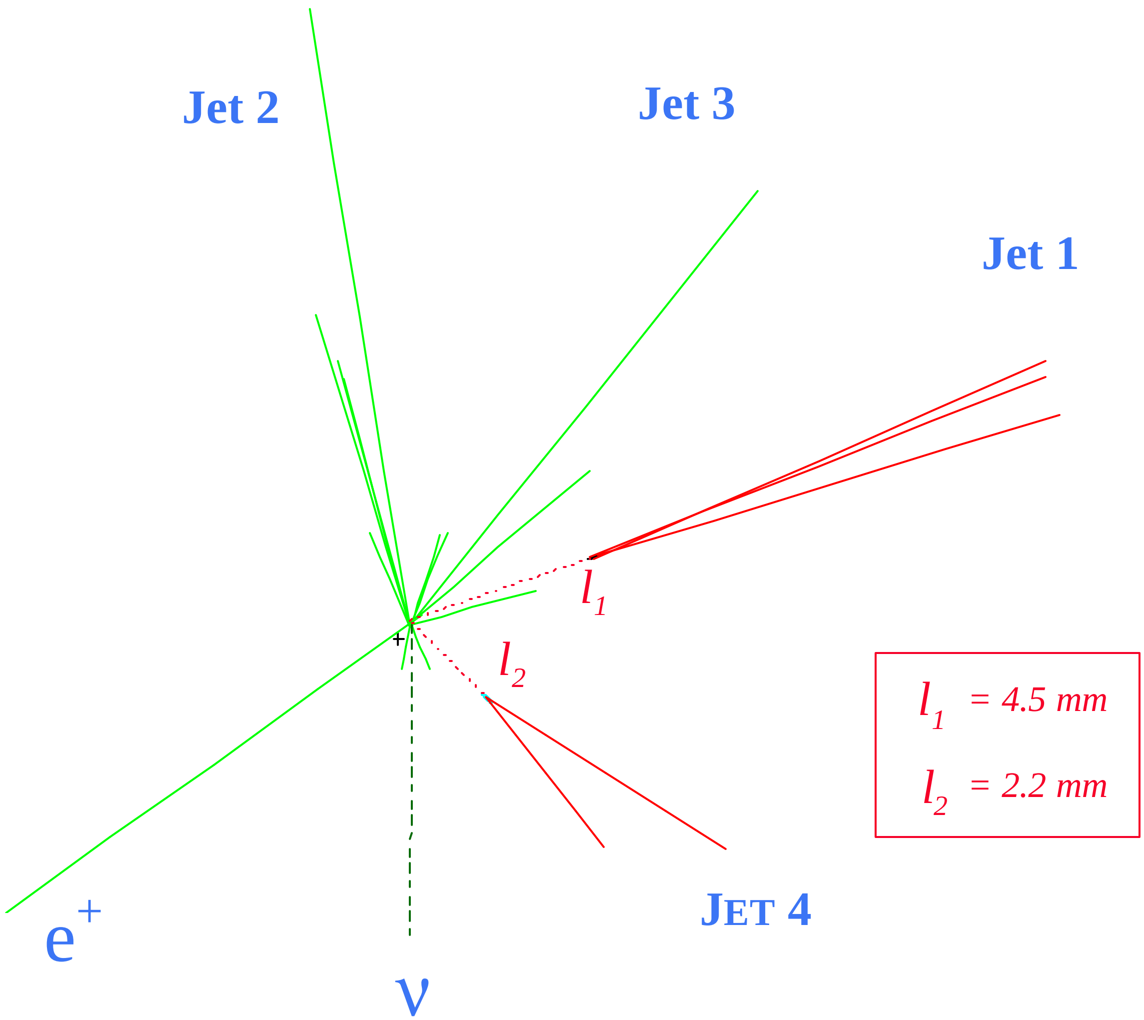
Process information fast enough to permit flagging about 10 – 100 potentially interesting events per second out of the billion collisions per second.

Other

Long and reliable operation in a hostile radiation environment

Must be affordable

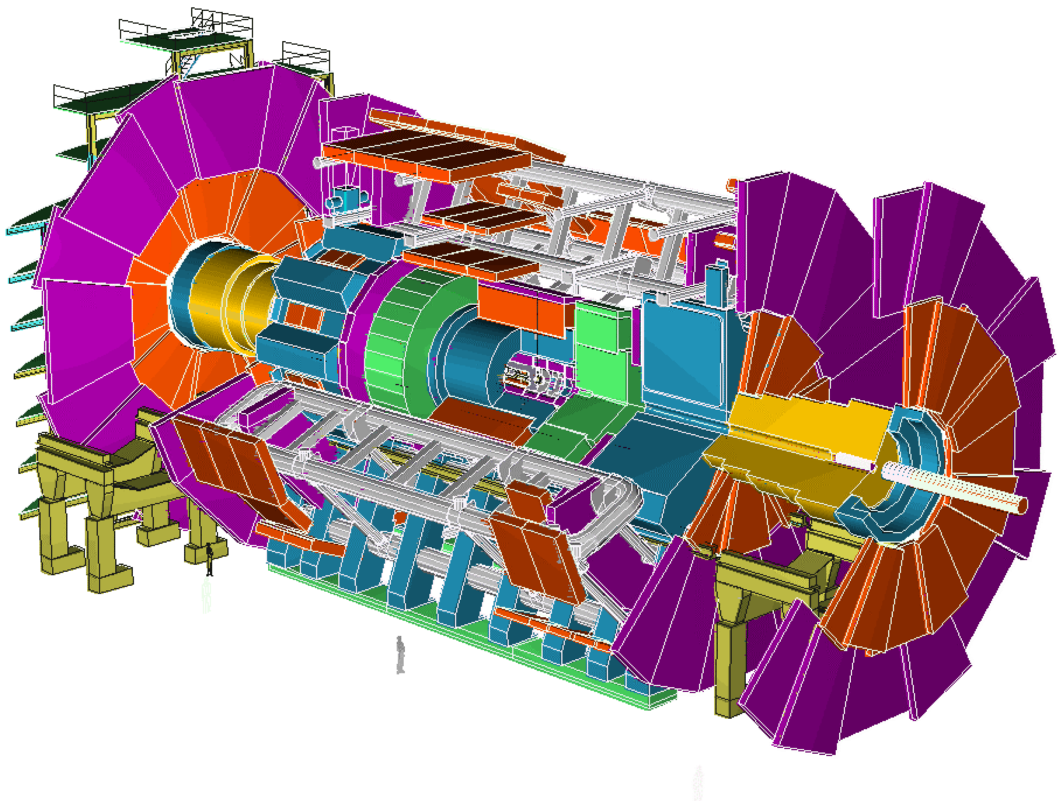
$t\bar{t}$ Event
SVX DISPLAY
CDF



$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

24 September, 1992
RUN #40758, EVENT #44414

1.2 The ATLAS detector



Together with CMS, one of two general-purpose detectors to be used at the LHC.

Approximate dimensions: Radius = 11 m

Length = 42 m

Overall weight is about 7000 tons.

1.3 Accelerator Parameters and Event Rates

LHC: Colliding proton beams
7 TeV on 7 TeV (14 TeV center of mass)

Luminosity: 10^{34} cm^{-2}s^{-1}

Bunch crossing frequency: 40 MHz

Interactions per bunch crossing: 23

Charged particles per unit of rapidity: 150

$\Rightarrow$ hit rate $$n' = \frac{2 \cdot 10^9}{r_\perp^2} \; [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

where $r_\perp$ = distance from beam axis

If the detector subtends ±2.5 units of rapidity,
the total hit rate in the detector is $3 \cdot 10^{10}$ s^{-1}

Cannot read out all events continuously.

Use coarse criterion to generate trigger and only read out potentially interesting events

$\Rightarrow$ reduce readout rate to 10^5 s^{-1}

Requires about 2.5 μs to generate trigger

$\Rightarrow$ necessary to provide storage buffers in the detector

events time stamped to associate hits with beam crossing
(requires recording of time information to 25 ns accuracy)

on receipt of trigger read out only the relevant time bin

How to cope with ...

- High total event rate

  a) fast electronics
  high power required for both noise and speed

  b) segmentation
  reduce rate per detector element

  for example, at r = 30 cm the hit rate in an area of $5 \cdot 10^{-2}$ cm^2 is about 10^5 s^{-1}, corresponding to an average time between hits of 10 µs.

  ⇒ longer shaping time allowable

  ⇒ lower power for given noise level

- Large number of events per crossing

  a) fast electronics (high power)

  b) segmentation
  if a detector element is sufficiently small, the probability of two tracks passing through is negligible

  c) single-bunch timing
  reduce confusion by assigning hits to specific crossing times

⇒ Segmentation is an efficient tool to cope with high rates.

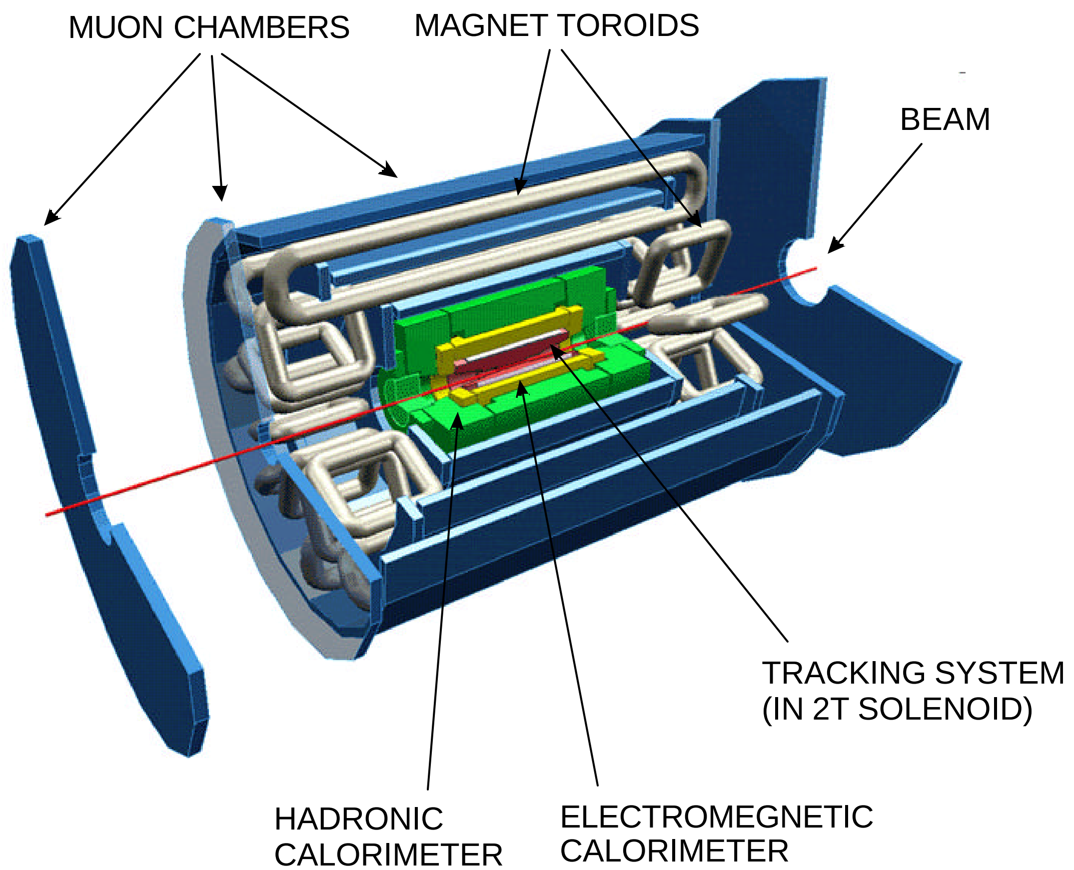
With careful design, power requirements don't increase.

⇒ Fine segmentation feasible with semiconductor detectors

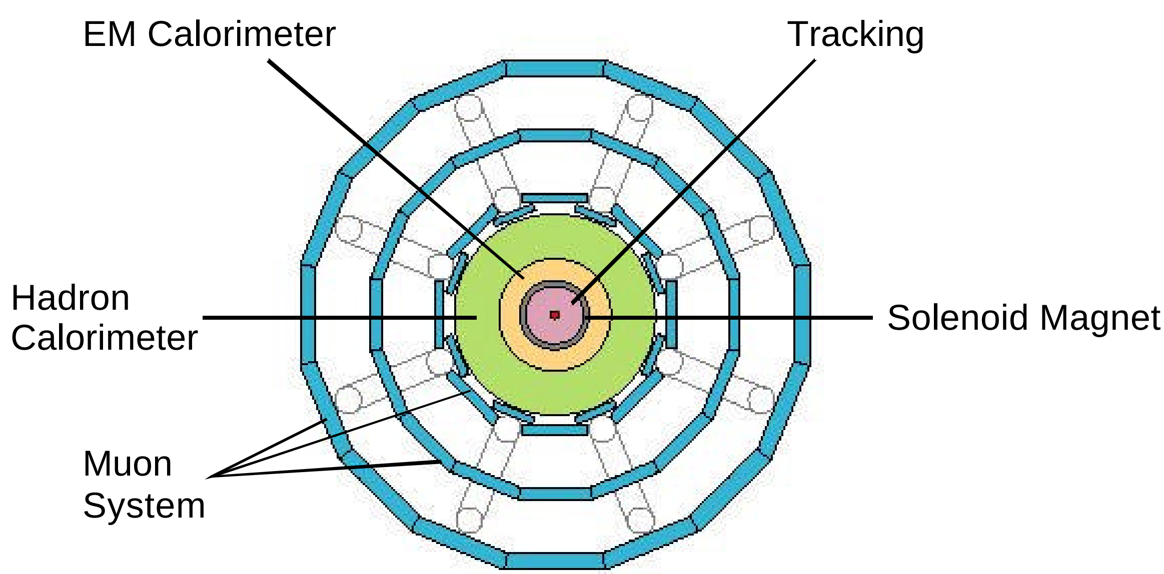
- "µm-scale" patterning of detectors
- monolithically integrated electronics mounted locally

Large number of front-end channels requires simple circuitry
Single bunch timing ⇒ collection times <25 ns

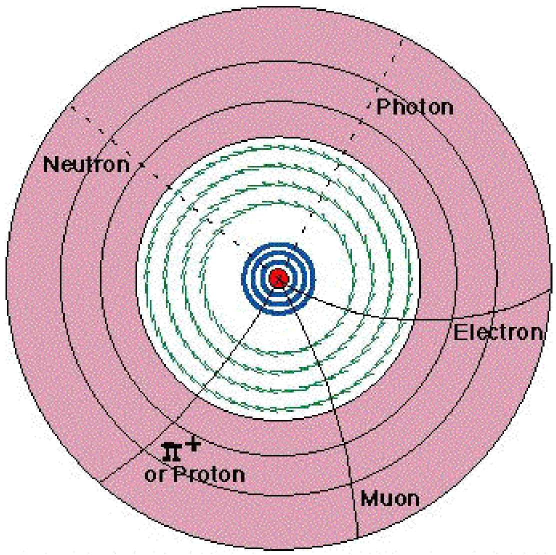
1.4 Schematic Overview



Schematic End-View



Tracking in 2T magnetic field



Separate particles by

sign of charge

magnetic rigidity q/m

A particle of momentum P passing through a magnetic field B forms an orbit with radius

$$r = \frac{P}{qB}$$

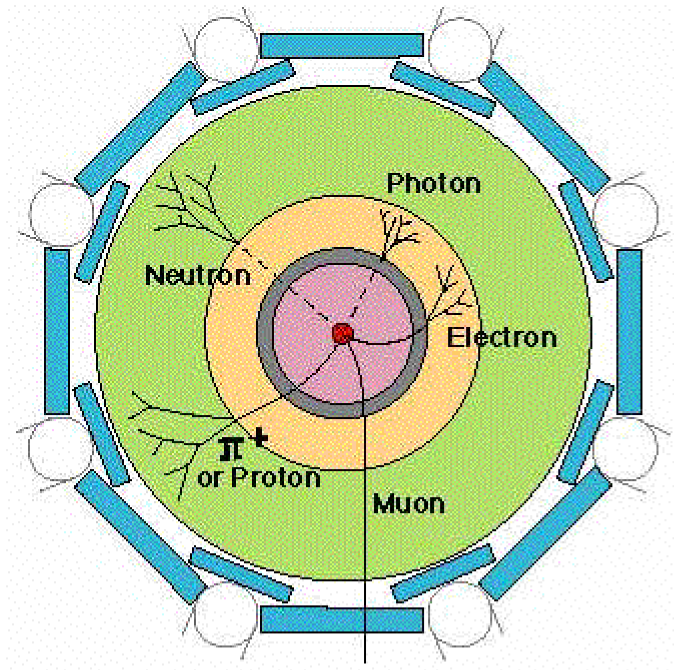
However, since the radius of the tracking volume R is chosen to be smaller, the particles are deflected by an angle

$$2\sin\frac{\Theta}{2} = \frac{R}{r} = -\frac{qBR}{P}$$

The deflection angle measures the sign of the charge and the momentum.

If magnetic field is non-uniform, must calculate $\int B dr$ along track.

Calorimetry



Particles generate showers in calorimeters

Electromagnetic Calorimeter (yellow):

Absorbs and measures the energies of all electrons, photons

Hadronic Calorimeter (green)

Absorbs and measures the energies of hadrons, including protons and neutrons, pions and kaons

(electrons and photons have been absorbed in EM calorimeter)

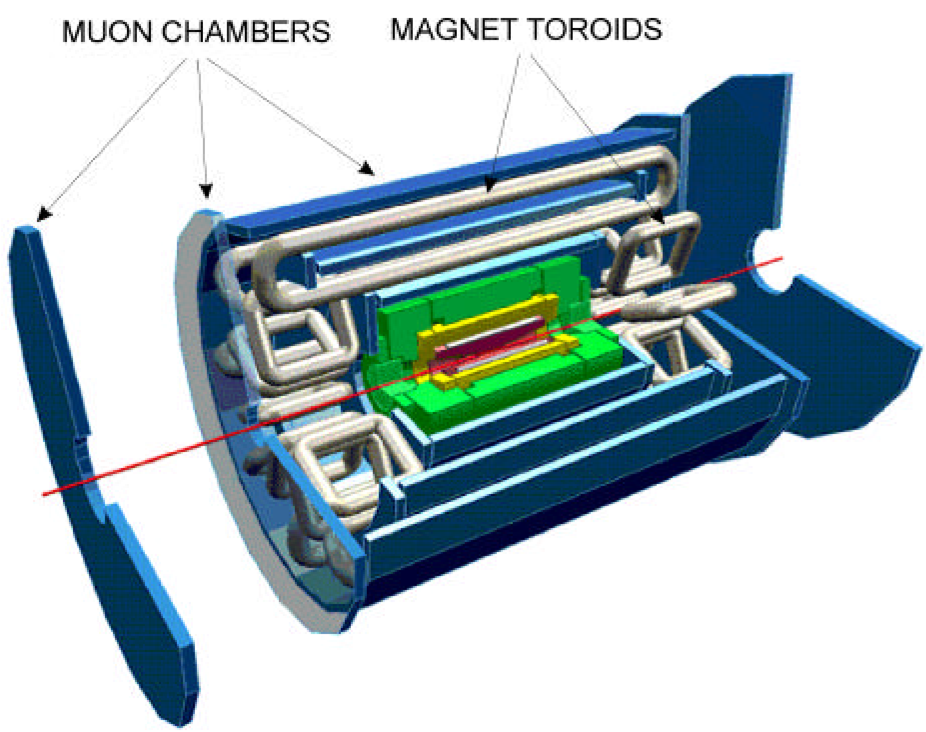
Muon System

Muons are about 200 times more massive than electrons and interact less with material so they do not produce the same kind of electromagnetic shower.

Muons are the only charged particle that can travel through all of the calorimeter material and reach the outer layer.

To improve momentum resolution, introduce additional magnetic field:

field lines concentric to beam line (unlike barrel solenoid) firmed by set of toroid magnets



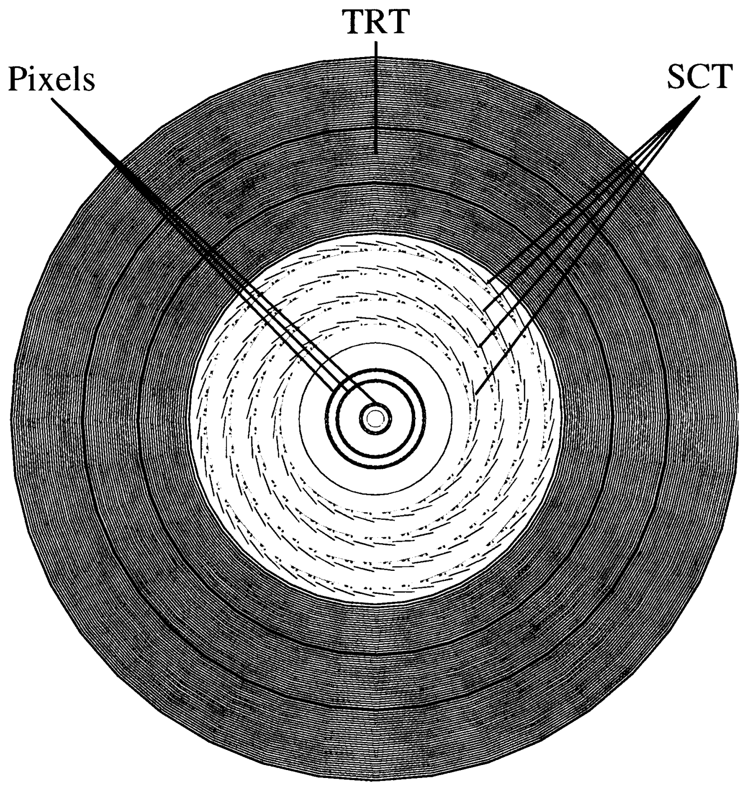
Muon System determines the signs and momenta of muons with better precision than the inner tracking system.

Sub-Detectors

Tracking System

The tracking system measures the directions, momenta, and signs charged particles

immersed in a 2T magnetic field parallel to the beam axis.



Pixels at small radii (4, 11, 14 cm) to cope with

- high event rate (2D non-projective structure)
- radiation damage

  small capacitance ~ 100 fF ⇒ low noise $Q_n \approx$ 100 el

Strips at larger radii (30, 37, 45, 52 cm) - minimize material, cost

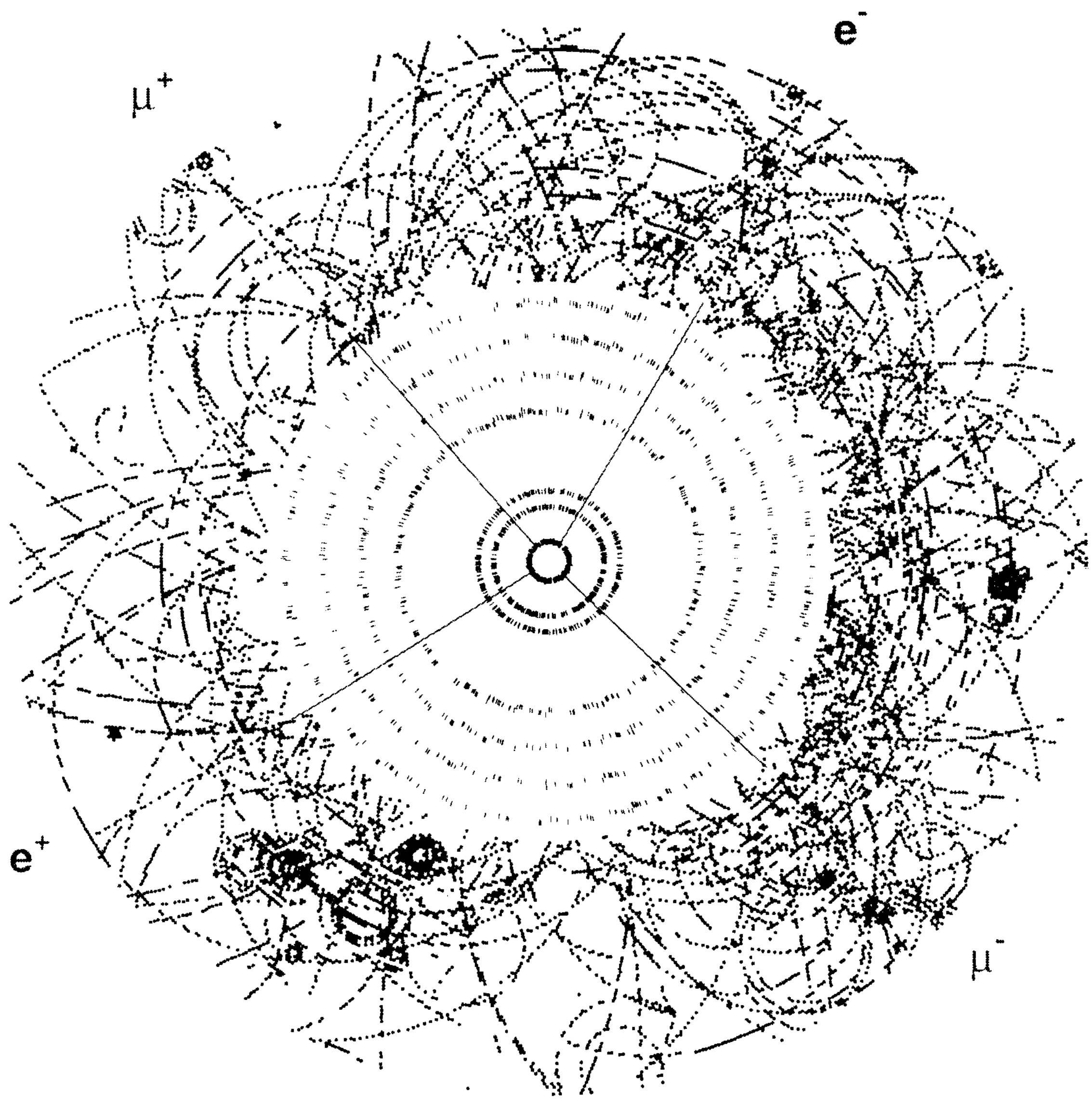
Pixels and strips provide primary pattern recognition capability

Straw drift chambers at outer radius (56 – 107 cm)

~70 layers yield 40 space points at large R and augment pattern recognition by continuous tracking (least expensive solution)

"Typical Event" in Tracker

$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-e^+e^-$ (m_H= 130 GeV)

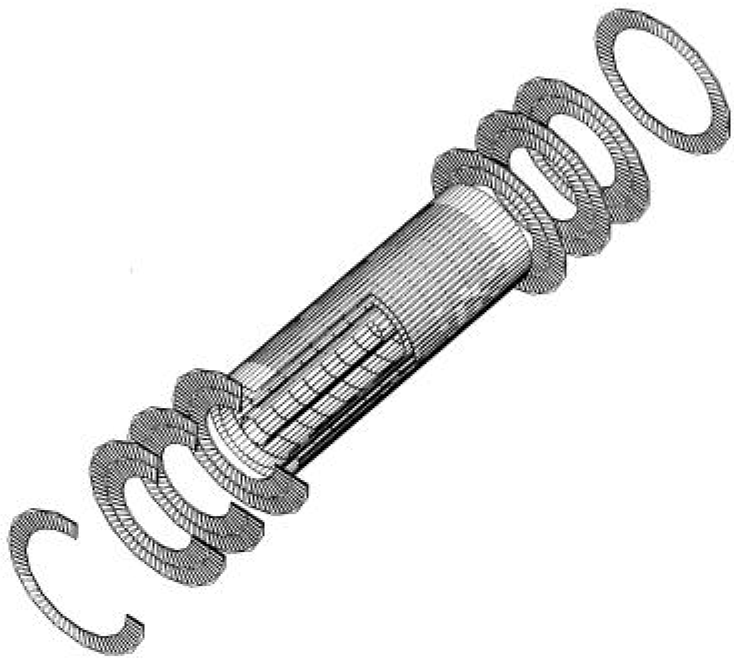


Typical Si Tracker Arrangement

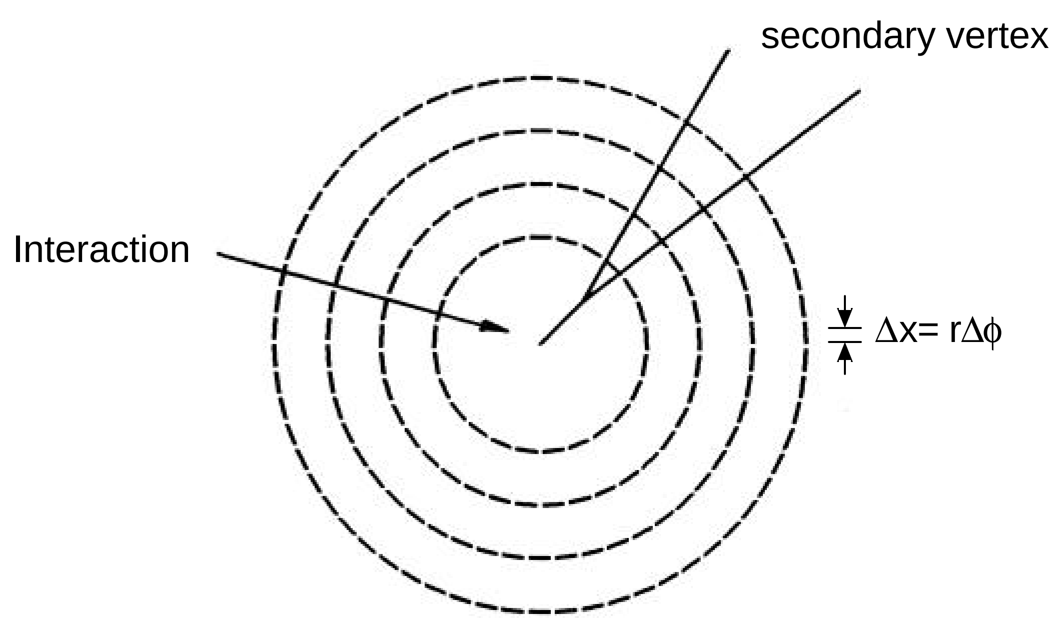
Resolution is provided primarily in azimuth, i.e.

a) barrel in central region: strip electrodes parallel to beam

b) disks in forward regions: strip electrodes arranged radially



Provides rapidity coverage with minimum Si area



Impact parameter resolution

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

b) the resolution of the inner layer s_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 $\sigma_1 = \sigma_2 = \sigma$

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

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

The obtainable impact parameter resolution decreases rapidly from

s_b/s = 7.8 at r_2/r_1 =1.2 to
s_b/s = 2.2 at r_2/r_1= 2 and
$s_b/s < 1.3$ at $r_2/r_1 > 5$.

For s = 10 µm and $r_2/r_1 \approx 2$: $s_b \approx 20$ µm.

Similar conclusions apply for the momentum resolution.

The inner radius is limited by the beam pipe, typically r = 5 cm.

At the high luminosity of the LHC radiation damage is a serious concern, which tends to drive the inner layer to greater 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, so that x/X_0= $2.8 \cdot 10^{-3}$ and at $p_\perp$= 1 GeV/c the scattering angle Θ_{rms}= 0.56 mrad.

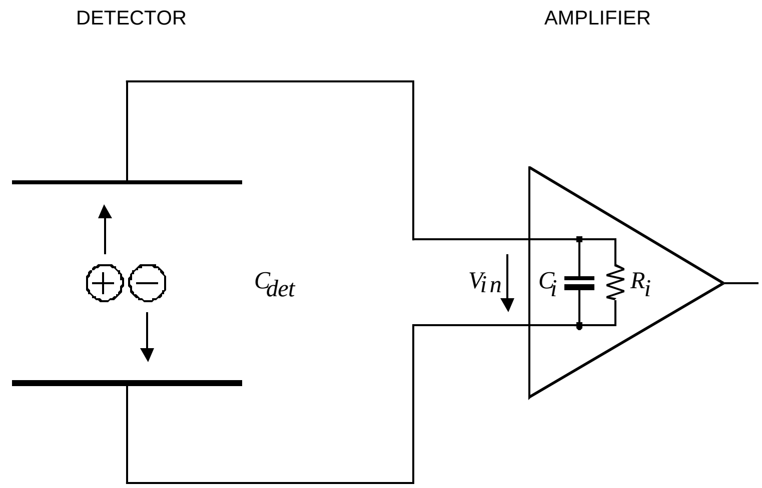
This corresponds to $s_b = R\Theta_{rms}$= 28 μm, which exceeds the impact parameter resolution.

Scattering originating at small radii is more serious, so it is important to limit material especially at small radii.

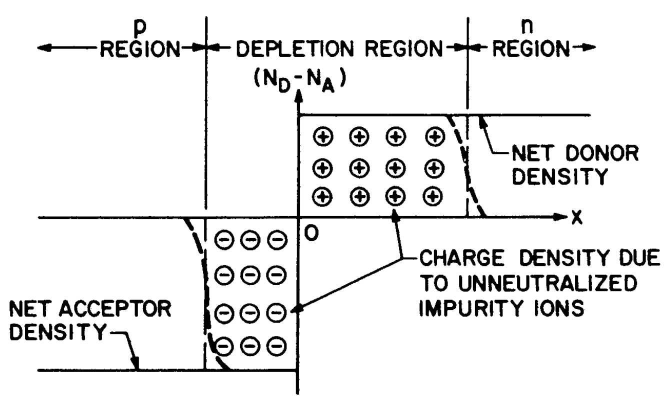
For comparison: 300 μm of Si $\rightarrow$ 0.3% X_0

Silicon Detectors

Silicon are ionization chambers, where the absorbing medium is Si.



Dopants introduce mobile charge carriers into bulk
– electrons in n-type region, holes in p-region



Forms a p-n junction

Apply reverse bias voltage:
positive to n-region and negative to p-region
Þ draws electrons and holes away from junction

Forms high-field region free of **mobile** charge
(host atoms still remain, so region has space charge)

Electron-hole pairs are formed when a particle deposits energy
(Minimum Ionizing Particle forms ~70 e-h pairs per micron)

The electric field sweeps electrons to the positive electrode
and holes to the negative electrode

Þ induce an electric current.

measure in amplifier

In typical HEP detectors the silicon is ~300 mm thick. Unlike conventional diodes, the doping is chosen so that the depletion region extends throughout the thickness of the silicon

Þ 22000 e-h pairs per MIP (3.5 fC)

A small current still flows in the absence of incident radiation due to thermal excitation of electrons across the band-gap

Þ reverse bias current
“dark current” or “leakage current”

source of electronic noise – will be discussed later

Radiation Damage

Two sources of particles

a) beam collisions

b) neutron albedo from calorimeter

Fluences per year (equivalent 1 MeV neutrons)

r ~ 10 cm	typ. $5 \cdot 10^{13}$ cm^{-2}
r ~ 30 cm	typ. $2 \cdot 10^{13}$ cm^{-2}

Ionizing Dose per year

r ~ 10 cm	30 kGy (3 Mrad)
r ~ 30 cm	4 kGy (400 krad)

In reality, complex maps are required of the radiation flux, which is dependent on local material distribution.

Gas and Si detectors in tracking system especially subject to radiation damage (small radii – high rate per cm^2)

Radiation damage affects both detectors and electronics.

Radiation damage is a critical problem in semiconductor detectors:

a) detector leakage current

$$I_R = I_{R0} + a\Phi Ad$$

Þ shot noise

$$Q_{ni}^2 = 2q_e I_R F_i T_S$$

Þ self-heating of detector

reduce current by cooling

$$I_R(T) \propto T^2 e^{-E/2k_B T}$$

reduce shaping time T_S

reduce area of detector element

b) Increase in depletion voltage

Þ thin detector

Þ allow for operation below full depletion

Þ less signal

Requires lower noise to maintain minimum S/N

Þ decrease area of detector element (capacitance)

Note: gas-proportional chambers are also subject to radiation damage

plasma-assisted polymerization in avalanche region

Þ deposits on electrodes

Use of a highly-developed technology, i.e. Si rather than “exotic” materials, provides performance reserves and design flexibility to cope with radiation damage.

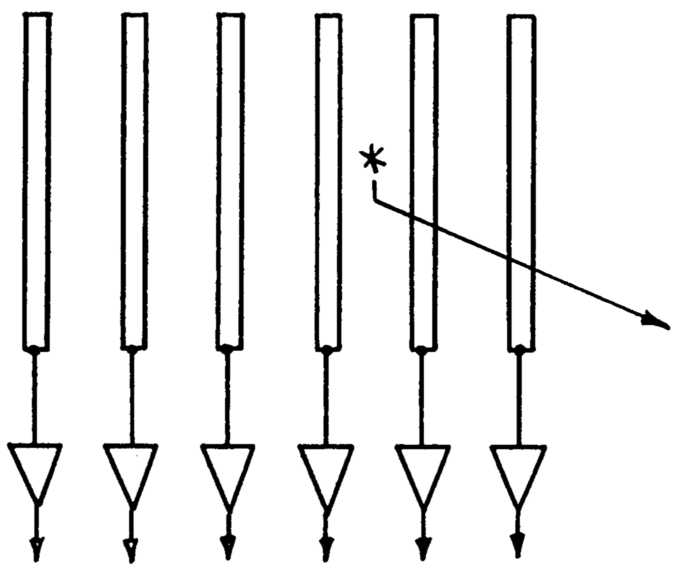
Þ Need to understand detector physics and electronics

Silicon Strip Detectors

Resolution determined by precision of micron scale patterning of the detector electrodes (e.g. strips on 50 µm pitch).

Two options:

Binary Readout



to discriminators

Position resolution determined directly by pitch

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

Analog Readout

Interpolation yields resolution < pitch p

Relies on transverse diffusion

$$\sigma_x \propto \sqrt{t_{coll}}$$

e.g. in Si

$t_{coll} \approx$ 10 ns

$\Rightarrow$ σ_x = 5 µm

Interpolation precision depends on S/N and p

p = 25 µm and S/N=50

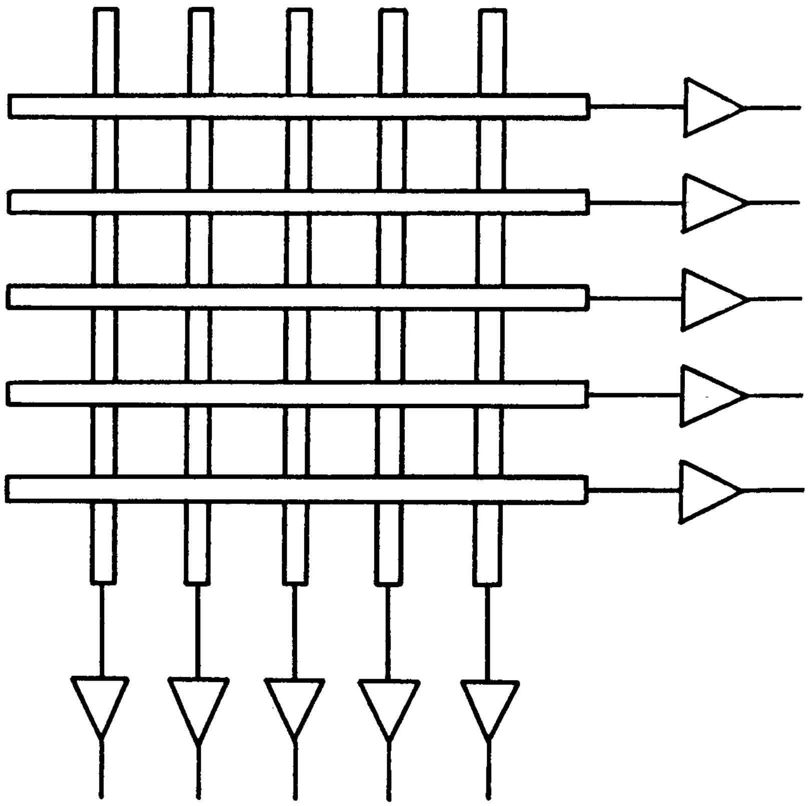
$\Rightarrow$ 3 – 4 µm resolution

ATLAS uses binary readout
(reduce power consumption, cabling, cost)

Two-Dimensional Detectors

1. Two-Dimensional Projective Devices

Example: Crossed strips on opposite sides of Si wafer



n readout channels Þ n^2 resolution elements

Problem: ambiguities with multiple hits

n hits in acceptance field Þ *n x*-coordinates
n y-coordinates

Þ n^2 combinations

of which
$n^2 - n$ are “ghosts”

High track density in ATLAS precludes 90° crossed strips
(OK for lower backgrounds, i.e. BaBar)

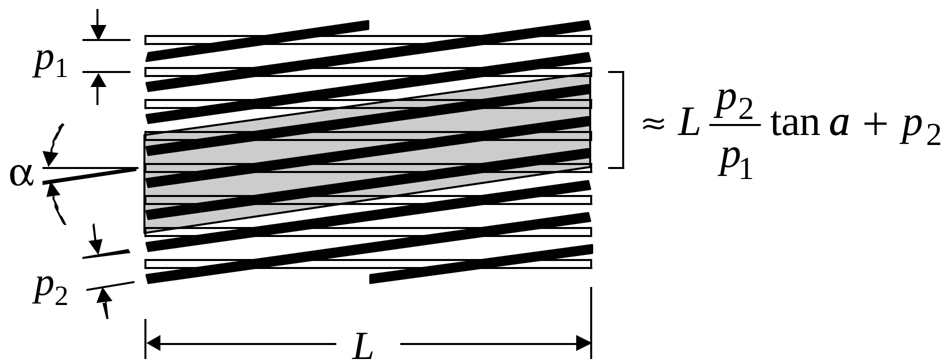
⇒ use small-angle stereo to reduce ghosting

Small-Angle Stereo

The area subtended by two sensing elements (strips) of length L_1 and L_2 arranged at an angle 90º is $A = L_1 L_2$, so a hit in a given strip can form combinations with hits on all of the transverse strips – the probability of "ghosting" is maximal.

However, if the angle α subtended by the two strip arrays is small (so that their lengths L are approximately equal), then the capture area

$$A \approx L^2 \frac{p_2}{p_1} \tan \alpha + L p_2$$



Consider a given horizontal strip struck by a particle. To determine the longitudinal coordinate all angled strips that cross the primary strip must be checked and every hit that deposits on these strips adds a coordinate that must be considered in conjunction with the coordinate defined by the horizontal strip.

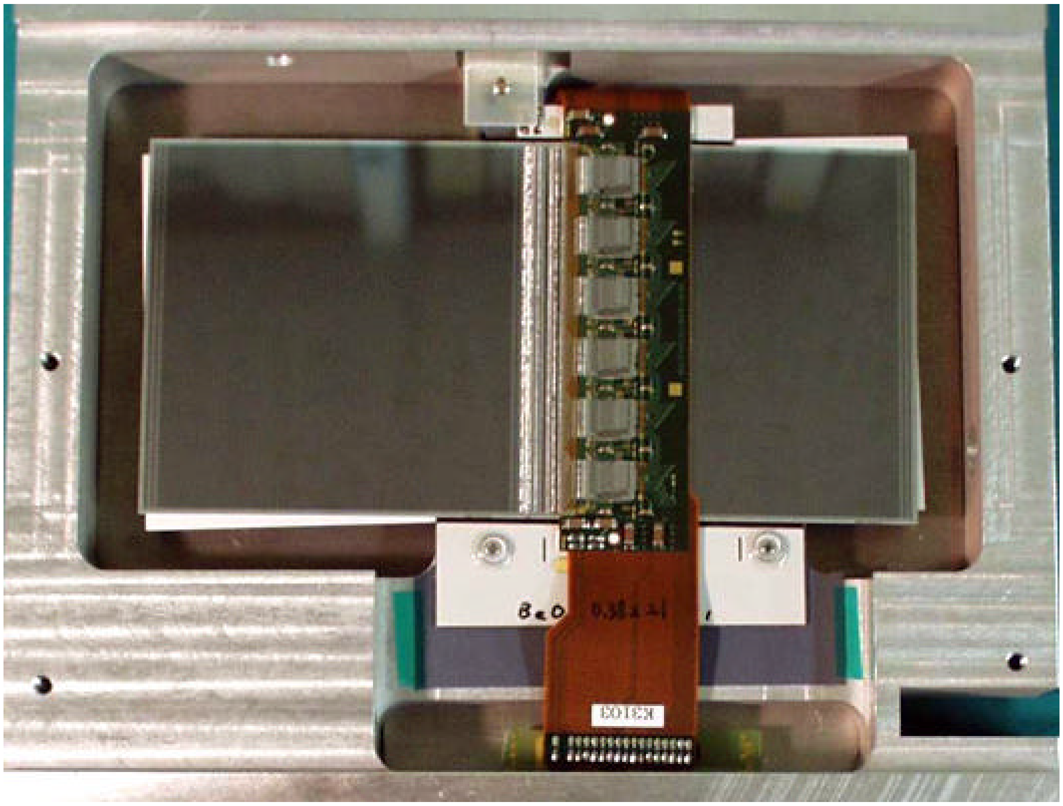
Since each strip captures charge from a width equal to the strip pitch, the exact width of the capture area is an integer multiple of the strip pitch.

The probability of multiple hits within the acceptance area, and hence the number of "ghosts", is reduced as α is made smaller, but at the expense of resolution in the longitudinal coordinate.

$$\Delta z = \frac{p_1}{\tan \alpha} + p_2 \sin \alpha$$

ATLAS Silicon Strip Detector Module

(mounted in fabrication fixture)



Two 6 x 6 cm^2 single-sided Si strip detectors butted edge-to-edge to form 12 cm long detector

Two 6 x 12 cm^2 detectors glued back-to-back and rotated to one another by 40 mrad to form small-angle stereo

Readout ICs – 128 channels each – mounted on detectors and connected at middle.

Strip pitch: 80 µm
no. of channels: 2 x 768

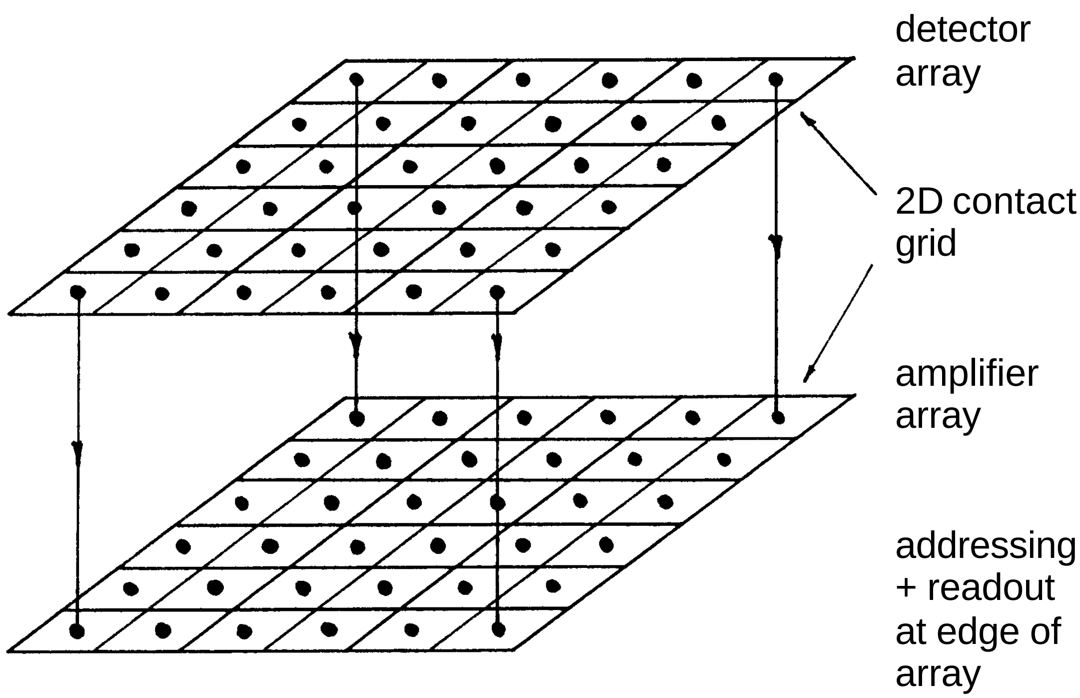
Binary readout with on-chip pipeline and readout sparsification

Kapton pigtail connects to local opto-module for clock, control, data transmission

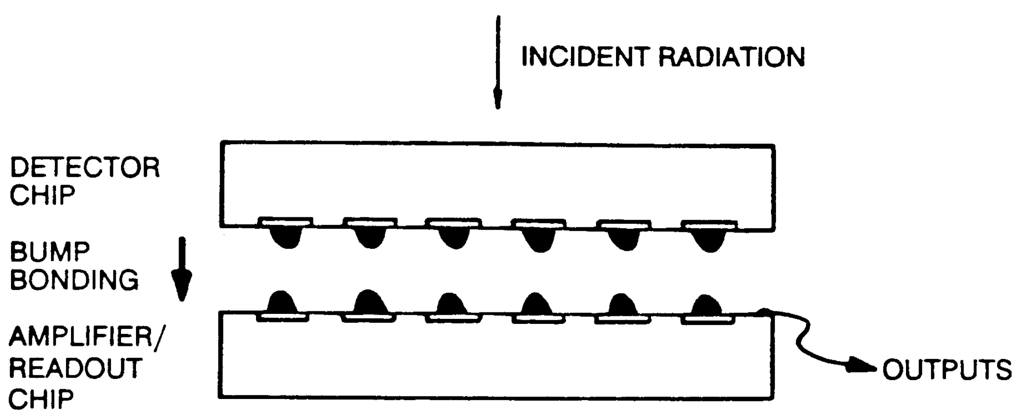
Innermost layers use Si Random–Access Pixel Arrays

Amplifier per pixel, store time, address of hit in buffers

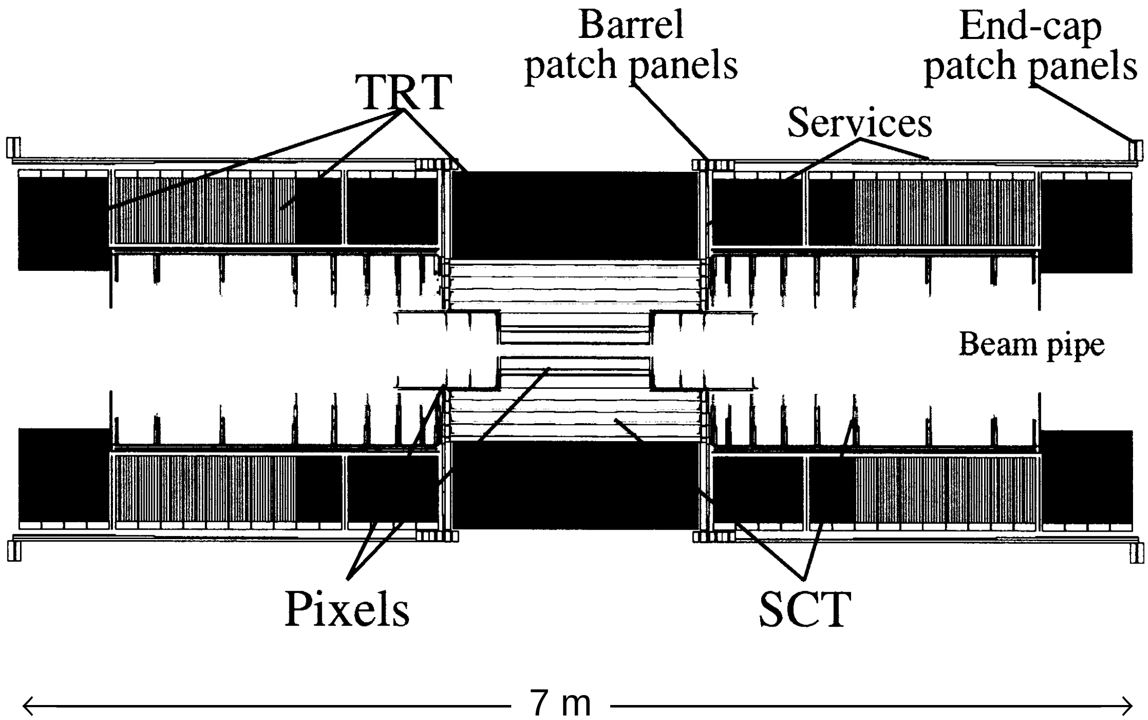
Pixels individually addressed for read out
⇒ unambiguous position information



2D contact via “bump bonds”



More resistant to radiation damage because small pixel capacitance increases signal-to-noise ratio.



Strip modules use back-to-back single-sided detectors with small-angle stereo (40 mr) to provide z-resolution with negligible “ghosting”.

Resolution provided by 3 detector types in barrel

	$R\phi$	z
Pixels	12 μm	66 μm
Strips	16 μm	580 μm
Straws	170 μm	—

Electromagnetic Calorimeter

The Electromagnetic Calorimeter absorbs the energies of all incident electrons and photons
(this constitutes the "electromagnetic energy").

It is finely subdivided so that it can measure the directional dependence of the electromagnetic energy.

EM calorimeter consists of thin lead plates (about 1.5 mm thick) separated by sensing devices.

Sensing system: Liquid Ar Ionization Chamber

To provide directional information and locate jets,
collection electrodes are segmented.

Many connections to warm front-end electronics at outside of cryostat

design challenges to control capacitance, pickup

Hadronic Calorimeter

The hadronic calorimeter surrounds the EM calorimeter.

Absorbs and measures the energies of hadrons
– protons and neutrons, pions and kaons

(electrons and photons have been stopped before reaching it).

ATLAS hadronic calorimeters consist of steel absorbers separated by tiles of scintillating plastic.

Shower particles traversing the scintillating tiles, causes emission of light proportional to the incident energy.

Tile structure provides position information. Add signals from all the tiles within "towers" aimed at the collision point.

Hadronic calorimeter has two major functions.

1. Measure the energies and directions of jets.

Generally the energies of individual hadrons in the jet are uninteresting – total jet energy is important quantity.

2. Infer the presence of particles that are not directly detectable because they have only a very weak interaction with matter.

measure missing momentum

If the transverse components of momentum do not add to zero (within errors), infer presence of one or more undetected neutral particles.

requires full coverage – “hermiticity”

Since hadrons can initiate their shower in the EM calorimeter, the signals from both calorimeters must be combined to get the full hadronic energy and momentum.

To provide the needed hermiticity (full coverage), it is necessary to extend the calorimeter to detect jets at angles as small as 1 degree from the beam axis.

⇒ Also End-Cap and Forward Calorimeters

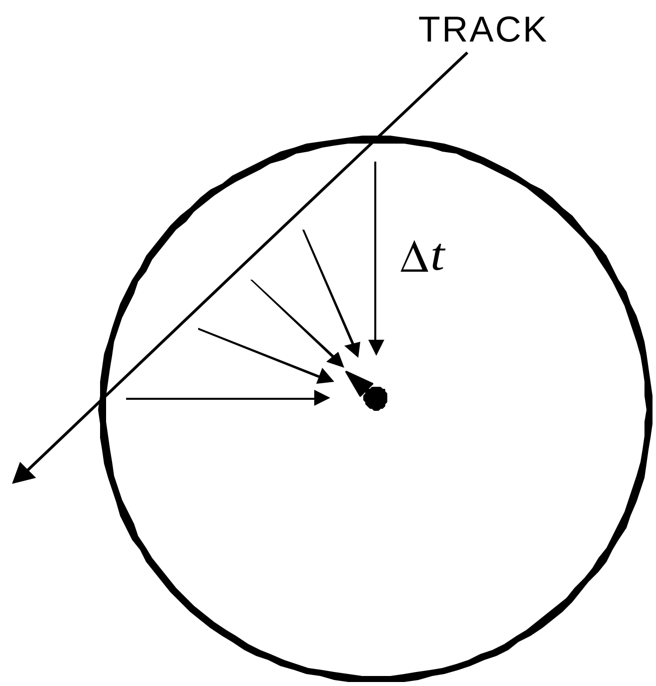
Muon System

Muons are the only charged particle that can travel through all of the calorimeter material and reach the outer layer.

muons with energy above, say, 5 GeV will penetrate about 5 meters of steel, whereas hadrons of almost any energy are completely absorbed in about 1.5 meters of steel.

The muon sensors are gas proportional drift chambers,

3 cm in diameter, ~ 1 – 6 m long.



Electrons formed along the track drift towards the central wire.
The first electron to reach the high-field region initiates the avalanche, which is used to derive the timing pulse.

Since the initiation of the avalanche is delayed by the transit time of the charge from the track to the wire, the time of the avalanche can be used to determine the radial position.

Principle also used in straw tracker – need fast timing electronics

Summary of Measured Quantities

1. Si Tracking	position to ~10 μm accuracy in rφ (through segmentation) timing to 25 ns accuracy to separate bunch crossings
2. Straw Tracker	position to 170 μm at r > 56 cm
3. EM calorimeter	energy via LAr ionization chambers position through segmentation
4. Hadron calorimeter	energy via plastic scintillator tiles position through segmentation
5. Muon System	signal via ionization chambers position through timing measurement

Although these various detector system look very different, they all follow the same principles.

Sensors must determine

1. presence of a particle
2. magnitude of signal
3. time of arrival

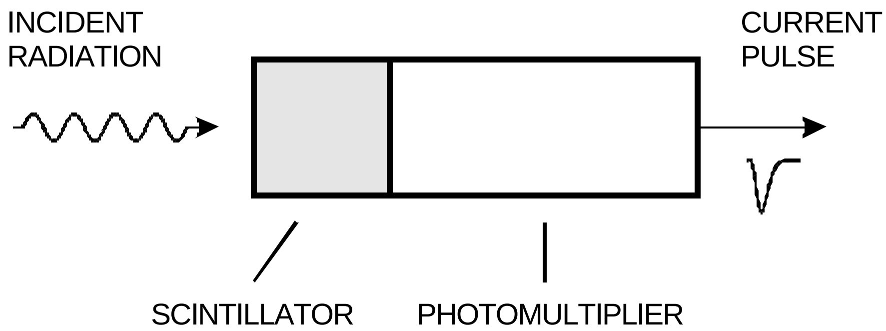
Some measurements depend on sensitivity, i.e. detection threshold.
example: silicon tracker, to
detect presence of a particle in a given electrode

Others seek to determine a quantity very accurately, i.e. resolution
example: calorimeter – magnitude of absorbed energy
muon chambers – time measurement yields position

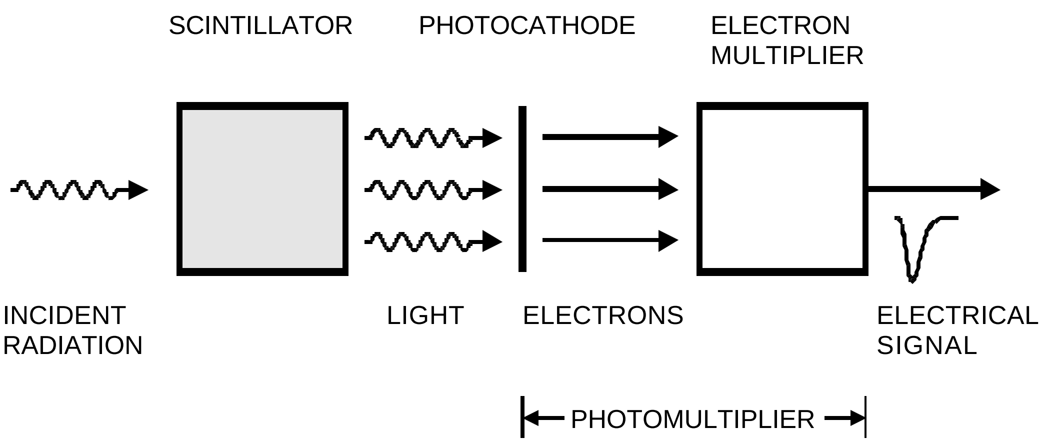
All have in common that they are sensitive to

1. signal magnitude
2. fluctuations

2. Detector Functions – Example: Scintillation Detector



Processes in Scintillator – Photomultiplier

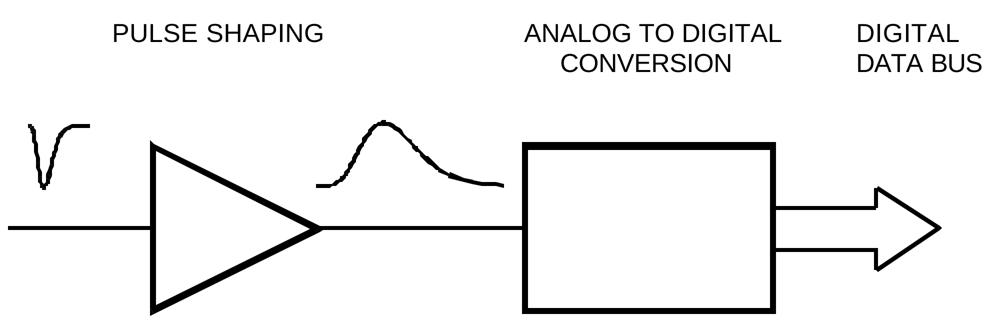


number of photons
∝ absorbed energy

number of photoelectrons
∝ absorbed energy

charge in pulse
∝ abs. energy

Signal Processing



charge in pulse
∝ abs. energy

pulse height
∝ absorbed energy

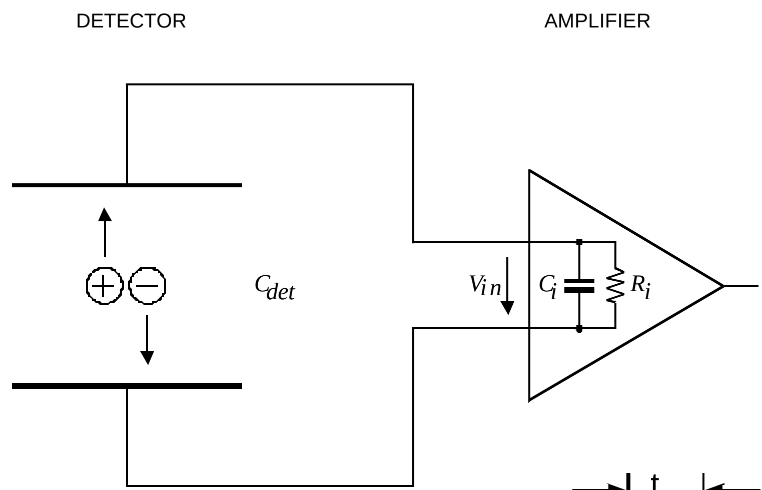
Ionization Chamber

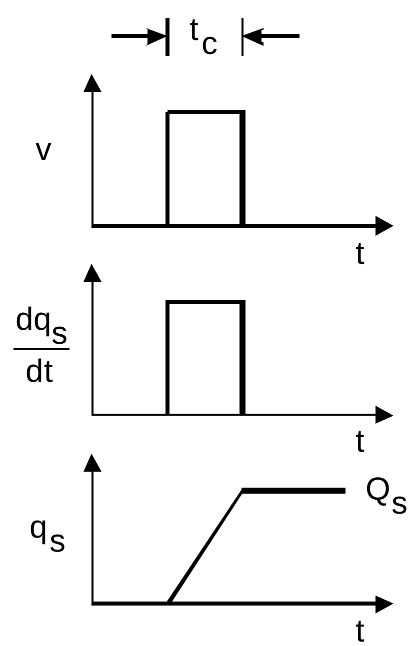
All ionization chambers utilize the same principle:

1. Particles deposit energy in an absorber and create mobile charge carriers (positive and negative charge pairs).

   in solids, liquids: electrons and holes
   in gases: electrons and ions

2. Electric field applied to detector volume sweeps charge carriers towards electrodes and induces a signal current





velocity of charge carriers

rate of induced charge on detector electrodes

signal charge

if R_i x $(C_{det} + C_i)$ >> collection time t_c:

peak voltage at amplifier input

$$V_s = \frac{Q_s}{C_{\det} + C_i}$$

The Signal

Any form of elementary excitation can be used to detect the radiation signal.

$$\text{Magnitude of signal} = \frac{\text{absorbed energy}}{\text{excitation energy}}$$

An electrical signal can be formed directly by ionization.

Incident radiation quanta impart sufficient energy to individual atomic electrons to form electron-ion pairs (in gases) or electron-hole pairs (in semiconductors and metals).

Other detection mechanisms are

Excitation of optical states (scintillators)

Excitation of lattice vibrations (phonons)

Breakup of Cooper pairs in superconductors

Formation of superheated droplets in superfluid He

Typical excitation energies

Ionization in gases	~30 eV
Ionization in semiconductors	1 – 5 eV
Scintillation	~10 eV
Phonons	meV
Breakup of Cooper Pairs	meV

Signal Fluctuations in a Scintillation Detector

Example: a typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

ß

25000 photons in scintillator

ß

15000 photons at photocathode

ß

3000 photoelectrons at first dynode

ß

$3 \cdot 10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = \text{ 2\% r.m.s. } = \text{ 5\% FWHM}$$

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.

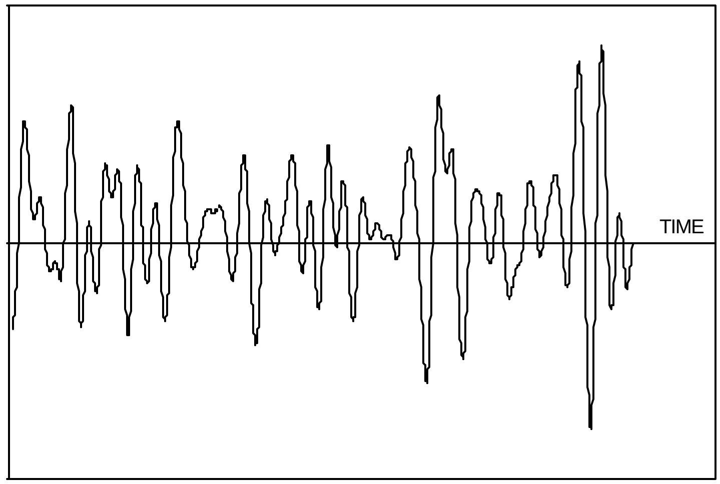
Baseline Fluctuations (Electronic Noise)

Choose a time when no signal is present.

Amplifier's quiescent output level (baseline):

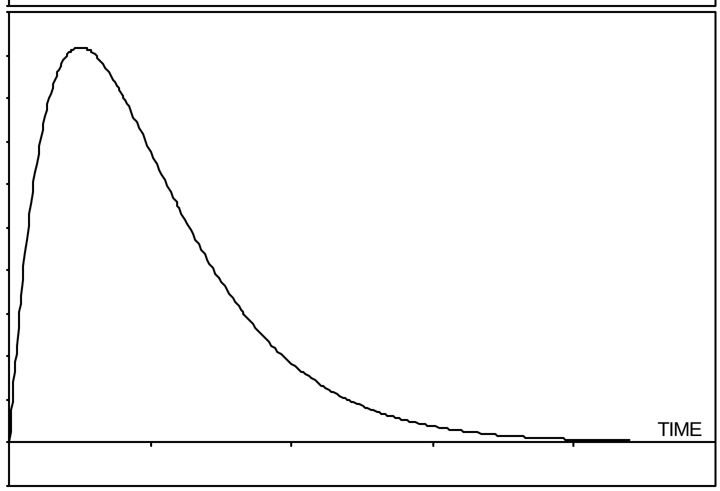
sensitivity x10

These fluctuations are added to any input signal

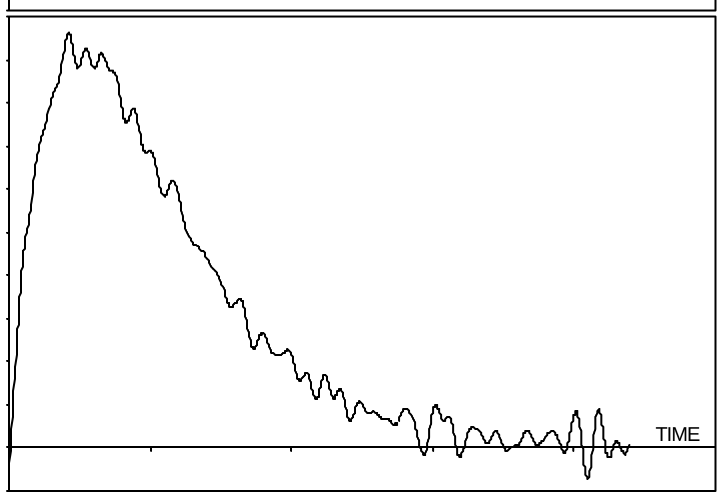


Pulse output of the ideal system

(sensitivity x1)



Signal + Noise



Measurement of peak amplitude yields
signal amplitude + noise fluctuation

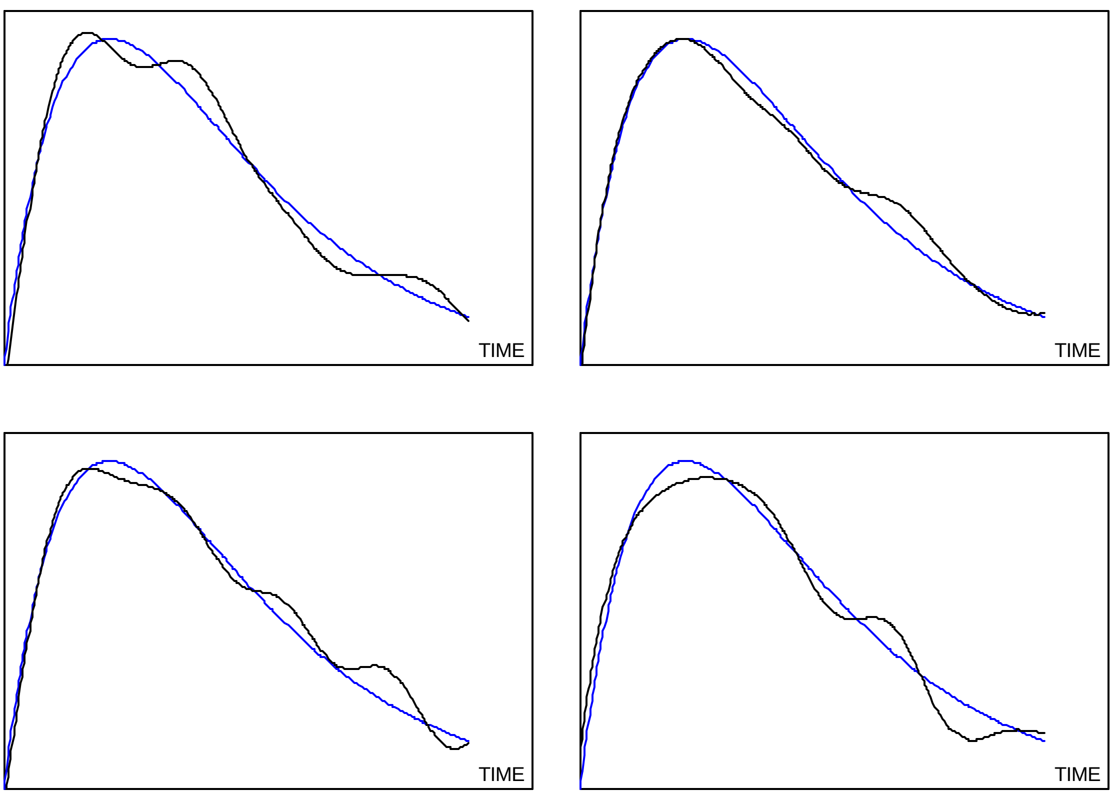
The preceding example could imply that the fluctuations tend to increase the measured amplitude, since the noise fluctuations vary more rapidly than the signal.

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)



Amplitude distribution of noise appears as amplitude distribution of signal.

3. 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

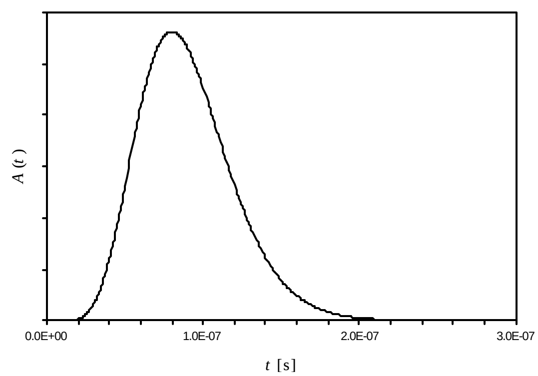
2. For a given sensor and signal: reduce electronic noise

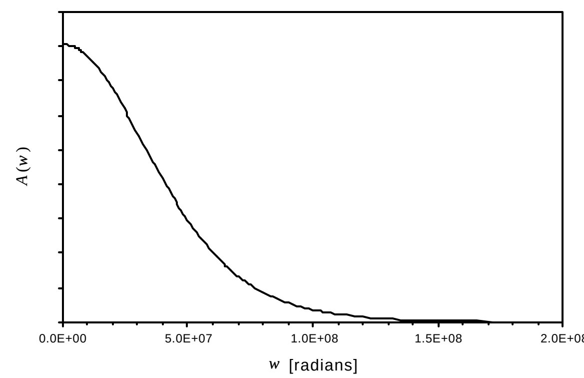
Assume that the signal is a pulse.

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

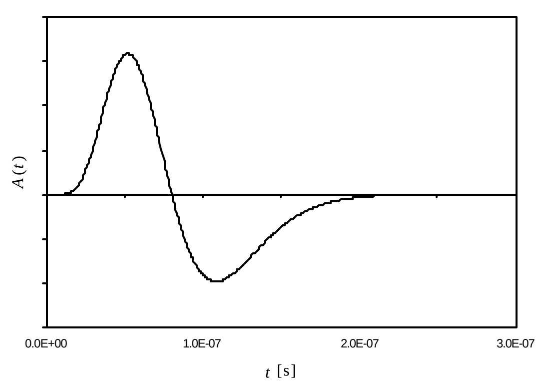
Examples:

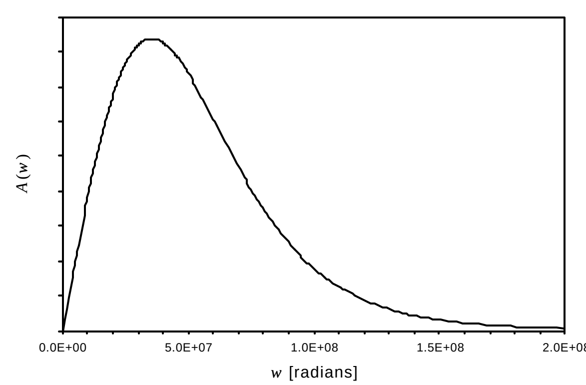
Time Domain | Frequency Domain





The pulse is unipolar, so it has a DC component and the frequency spectrum extends down to 0.

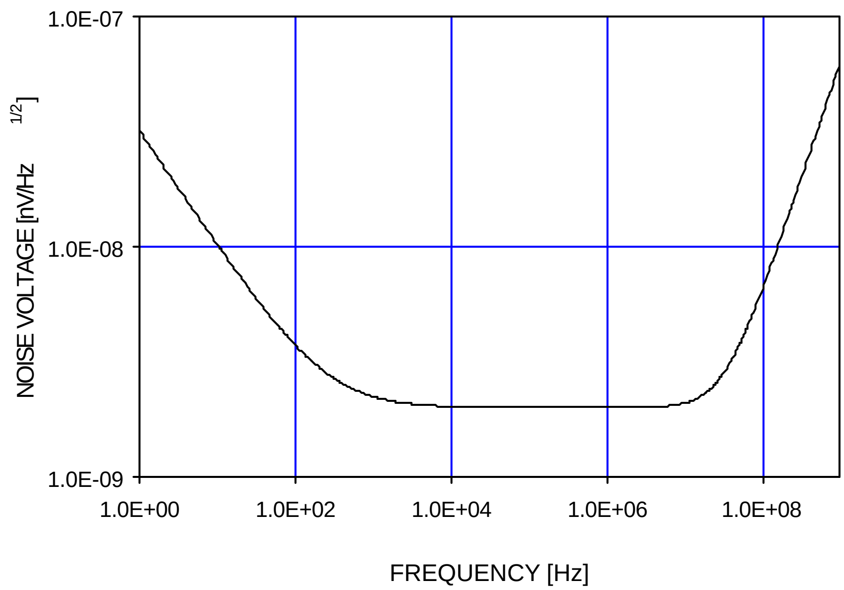




This bipolar pulse carries no net charge, so the frequency spectrum falls to zero at low frequencies.

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

Typical Noise Spectrum:



Þ tailor frequency response of measurement system to optimize signal-to-noise ratio.

Frequency response of measurement system affects both

- signal amplitude and
- noise.

There is a general solution to this problem:

Assume a signal $A_0 \cdot s(t)$ with the Fourier transform $A_0 \cdot S(\omega)$ whose shape is known, but not its amplitude A_0.

Although $s(t)$ is real, generally, $S(\omega)$ will be complex.

The noise has a spectral power density $S_n(\omega) \equiv \dfrac{dP_n(\omega)}{d\omega}$.

The signal is to be evaluated at a time t_m.

We introduce a filter with the transfer function $H(\omega)$.

The signal at the output of a filter

$$g(t_m) = \frac{A_0}{2\pi} \int_{-\infty}^{\infty} H(\omega) \cdot S(\omega) e^{i\omega t_m} d\omega$$

and the output noise power

$$P_n = \frac{1}{2\pi} \int_{-\infty}^{\infty} |H(\omega)|^2 S_n(\omega) d\omega$$

The signal-to-noise ratio is maximal, when the filter function

$$H(\omega) = k \frac{S^*(\omega)}{S_n(\omega)} \cdot e^{-i\omega t_m}$$

where k is any constant. (see the appendix for a derivation)

If the noise spectrum is "white", i.e. $S_n(w) = S_0$,

$$H(w) = KS^*(w) \cdot e^{-iwt_m}$$

The filter is the conjugate of the signal spectrum with an additional phase (or delay) factor e^{-iwt_m} .

Since $S = |S| e^{iwt}$ and its conjugate $S* = |S| e^{-iwt}$, this corresponds to a mirroring in time and an additional shift by t_m, so its impulse response is

$$h_0(t) = s(t_m - t).$$

The optimum filter has an impulse response that is the

signal pulse *mirrored in time* and

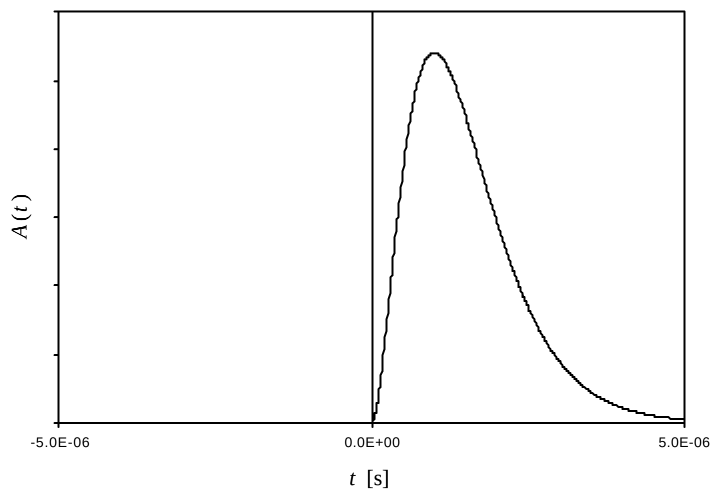
shifted by the measurement time.

With this result it might appear that all we have to do is apply this recipe and all problems are solved.

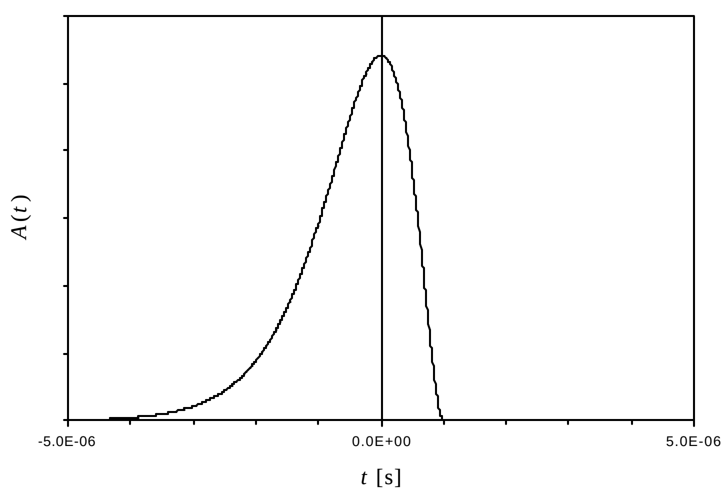
Life is not so simple:

1. 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:



The response of the optimum filter:



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

⇒ only useful if the time of arrival is known in advance.

Not good for random events

– need time delay buffer memory ⇒ complexity!

2. Optimum filter preserves all information in signal, i.e. magnitude, timing, structure.

   Usually, we need only subset of information content, i.e. magnitude or time-of-arrival.

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

   For example, a short rectangular detector pulse would imply a fast filter function. This retains both amplitude and timing information.

   If only amplitude information is required, this is not the optimum filter, as will be shown later.

3. 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.

4. Steps in analyzing a signal processing system:

1. determine the signal magnitude and time dependence

   these will depend on how the measurement system is coupled to the sensor.

   Þ detector models

2. Ascertain the origin and magnitude of fluctuations

   signal fluctuations
   random noise
   external interference

3. design the filter

4. determine digitization and data readout scheme.

Large detector systems may consist of several subsystems especially designed to perform specific functions, for example

- position sensing (tracking)
- energy measurement (spectroscopy, calorimeters)
- timing
- particle identification

Functions

Although these subsystems may look very different and use radically differing technologies, they all tend to comprise the same basic functions:

1. Radiation deposits energy in a detecting medium.

   The medium may be gas, solid or liquid.

   In a tracking detector one wishes to detect the presence of a particle without affecting its trajectory, so the medium will be chosen to minimize energy loss and particle scattering.

   Conversely, if one wishes to measure the total energy (energy spectrometry or calorimetry), the absorber will be chosen to optimize energy loss (high density, high Z).

2. Energy is converted into an electrical signal, either directly or indirectly. Each detected particle will appear as a pulse of electric charge.

   Direct conversion:
   incident radiation ionizes atoms/molecules in absorber, creating mobile charges that are detected.
   (ionization chambers)

   Indirect conversion:
   incident radiation excites atomic/molecular states that decay by emission of light, which in a second step is converted into charge.
   (scintillation detectors)

   The primary signal charge is proportional to the energy absorbed.

   Some typical values of energy required to form a signal charge of 1 electron:

gases	30 eV
semiconductors	1 to 10 eV
scintillators	20 to 500 eV

   In neither of these schemes is the signal charge available instantaneously. In a scintillation detector the pulse duration is determined by the decay time of the optical transitions, in an ionization chamber the charges must move to the electrodes to obtain the full signal.

   Typical pulse durations: 1 ns – 10 μs

3. The electrical signal is amplified.

    a) electronic circuitry

    b) gain by secondary multiplication

        primary charge is accelerated to sufficient energy for it to liberate additional charge carriers by impact ionization.

        Examples: proportional chambers
        avalanche photodiodes
        photomultiplier

Both techniques may introduce significant random fluctuations (noise).

Ideally, a gain stage would increase only the magnitude of the pulse, without affecting its time dependence.

This ideal behavior is never strictly realized in practice, as it would require amplifiers with infinite bandwidth.

However, this is not a severe limitation, as in many applications it is quite acceptable and even desirable to change the pulse shape.

4. Pulse shaping
   (not always necessary, but always present in some form)

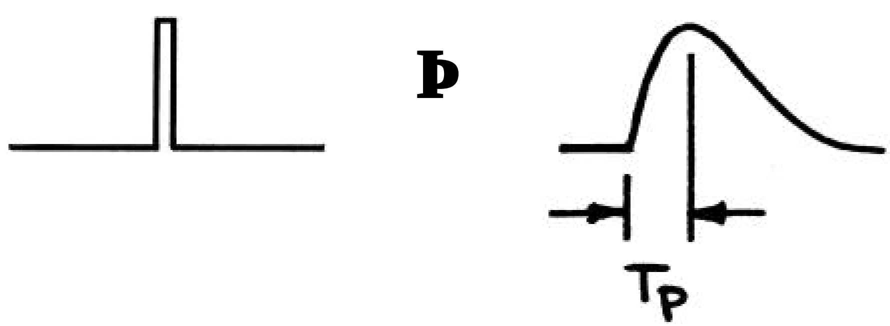
   The time response of the system is tailored to optimize the measurement of signal magnitude or time and the rate of signal detection.

   The output of the signal chain is a pulse (current or voltage) whose area is proportional to the original signal charge, i.e. the energy deposited in the detector.

   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 amplitude)

Detector Pulse　　　　　Shaper Output

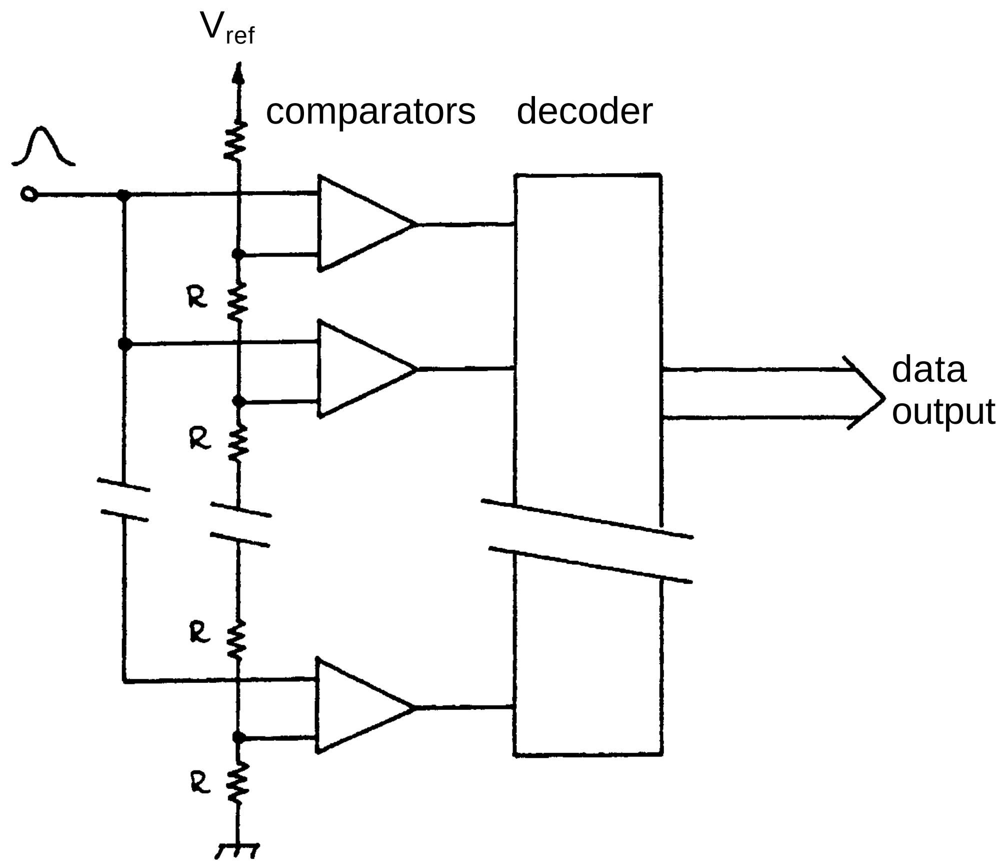


If the shape of the pulse does not change with signal level, the peak amplitude is also a measure of the energy, so one often speaks of pulse-height measurements or pulse height analysis. The pulse height spectrum is the energy spectrum.

5. Digitization of

a) signal magnitude
(analog-to-digital converter, viz. ADC or A/D)

Example:



The input signal is applied to *n* comparators in parallel. The switching thresholds are set by a resistor chain, such that the voltage difference between individual taps is equal to the desired measurement resolution.

In the presence of a signal all comparators with threshold levels less than the signal amplitude will fire. A decoder converts the parallel bit pattern into a more efficient form, for example binary code.

This type of ADC is fast, but requires as many comparators as measurement bins. Other converter types provide higher resolution and simpler circuitry at the expense of speed.

b) time difference between the detected signal and a reference signal
(time-to-digital converter, TDC)

The reference signal can be derived from another detector or from a common system clock, the crossing time of colliding beams, for example.

Circuit implementations include schemes that count “clock ticks” in fully digital circuitry or combine time-to-amplitude and amplitude-to-digital conversion in mixed analog-digital arrangements.

In complex detector systems the individual digitized outputs may require rather complex circuitry to combine the signal associated with a specific event and “package” them for efficient transfer.