Lecture 11: Radiation detectors

- Review of radiation detectors
- Silicon Diode Detectors
  - The Fano factor
  - Leakage current
  - Poisson’s Equation
- Applications of Silicon Detectors
  - Particle Physics Highlights

Radiation detector requirements

- We wish to measure the presence of radiation. Therefore we may require knowledge of:
  - **Energy** : Need to know the energy of the incident radiation, type of radiation (E/ΔE).
  - **Time** : Precisely when the radiation interacted.
  - **Position** : Where the incident radiation interacted in our detector.
- The ability of our instrument at measuring the incident radiation is important.
  - **Efficiency** : The detection efficiency of the detector we choose.

Radiation detector solutions

- There are many radiation detectors available. However they can generally be divided into the following categories:
  - **Gas** : Gas filled detectors such as ionisation chambers, proportional counters and Geiger Muller (GM) tubes utilise a gas as the detection medium.
  - **Scintillation detectors** : Utilise either a liquid or solid state scintillator as the detection medium.
  - **Semiconductor detectors** : An elemental or compound semiconductor crystal is used as the detection medium.
- Each approach offers advantages/disadvantages, and a composite approach is often utilised to provide global information about a radiation source.

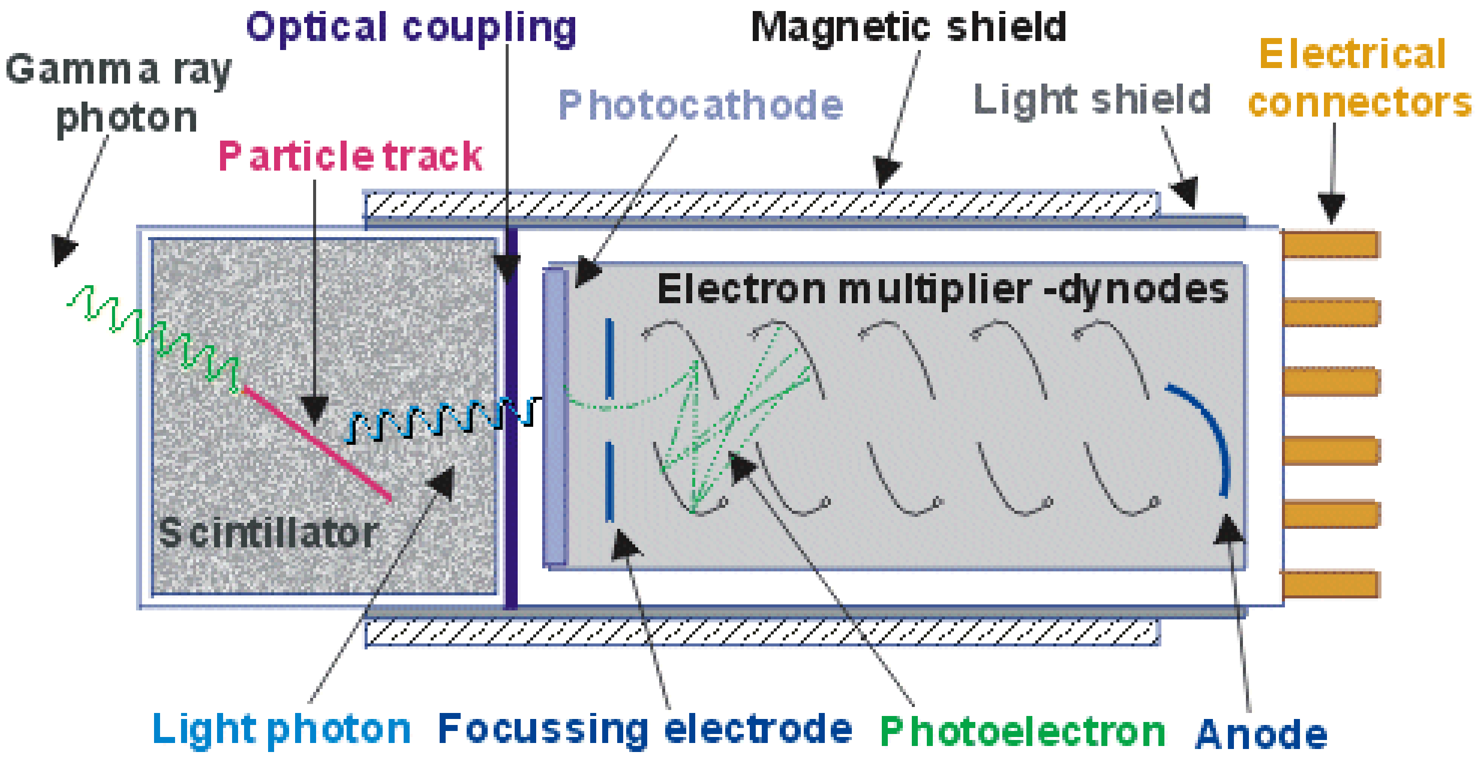
Gas Detectors

- Gas detectors in general offer the following:
  - Poor energy resolution
  - Time resolution
  - Excellent position resolution (MWPC)
  - Low Efficiency:
    - Large volume possible
    - Low density/Z – very low stopping power

Solid state detectors: Scintillators

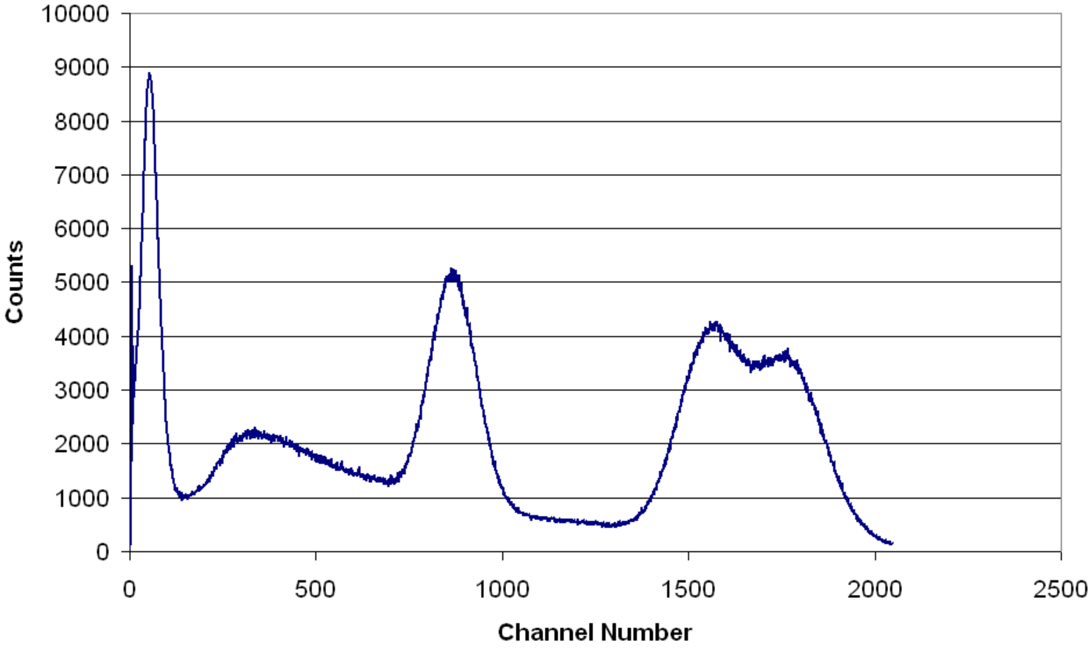
- The use of a solid state detection medium is of great importance in many radiation detection applications.
- For the measurement of high-energy electrons or gamma-rays detection dimensions can be kept much smaller than equivalent gas filled detectors because solid densities are some 1000 times greater than that for a gas.
- **Scintillation detectors** offer one possibility of providing a solid detection medium. They can provide:
  - Poor energy resolution.
  - Good/very good time resolution (sub ns)
  - Reasonable position resolution (~mm)
  - High efficiency

Scintillation detectors



The energy required to produce one information carrier is of the order of 100eV, the number of carriers created in a typical interaction is usually no more than a few thousand → statistical fluctuations → poor energy resolution.

Typical Scintillation detector spectrum



- BGO scintillator, gamma-ray spectrum.
- Energy resolution is defined as FWHM of photopeak.
- For typical 662 keV photon from ^{137}Cs:

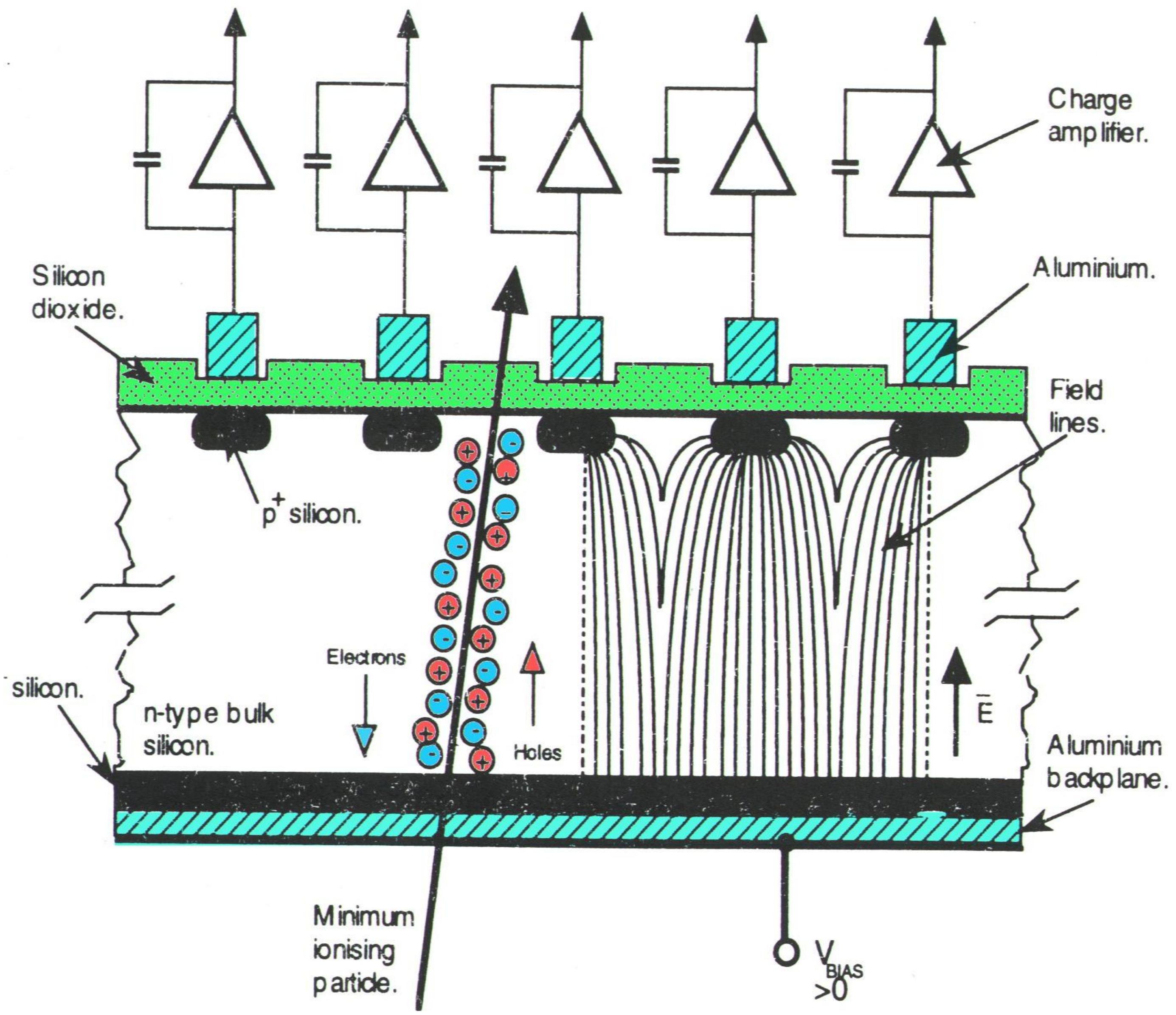
$$\frac{662000}{100} = 6620 \qquad \text{Information carriers}$$

- Typical energy resolution of ~50 keV (@662 keV)

Semiconductor detectors

- The only way to reduce the statistical limit on the energy resolution is to **increase the number of information carriers per pulse**.
- The use of semiconductor materials as radiation detectors can result in a much larger number of carriers for a given incident radiation.
- The best energy resolution achievable today is therefore possible with such detectors.
- The basic information carriers are **electron-hole pairs** created along the path taken by a charged particle (primary radiation or secondary particle) through the detector.
- Their motion in an applied electric field generates the basic electrical signal from the detector.

Devices For Charged Particle Detection



Ionising radiation in semiconductors

- The quantity of practical interest for detector applications is the **ionisation energy** (ε), the average energy expended by the primary charged particle to produce one electron-hole pair,
- The ionisation energy is about 3eV for Si or Ge.
- This quantity is experimentally observed to be **independent** of the both the energy and type of radiation.
- **The number of electron-hole pairs produced can now be related to the energy of the incident radiation** – provided that the particle is fully stopped within the volume of the detector.

Semiconductors: Fano factor

- In addition to the mean number of charge carriers, the fluctuation or variance in the number of charge carriers is important.
- The observed statistical fluctuations in semiconductors are smaller than expected if the formation of the charge carriers were a Poisson process.
- The Poisson process would only hold if all the events along the track of the ionising particle were independent and would predict that the variance of the total number of electron-hole pairs as equal to the total number produced or E/ε.
- The **Fano factor** is introduced as an adjustment factor:

$$F = \frac{\text{observed statistical variance}}{E/\varepsilon}$$

Semiconductor detectors

- Two **ohmic** contacts can be fitted on opposite faces of a slab of semiconductor and connected such that the equilibrium charge carrier concentrations are maintained.
- If an electron or hole is collected at one electrode, the same carrier species is injected at the opposite electron to maintain the equilibrium concentrations.
- A steady state **leakage** current will be observed, the variation of which will obscure any signal to be measured.
- Blocking electrodes (based on a *p*-*n* junction) are therefore universally employed to reduce the magnitude of the current through the bulk.
- <u>If blocking electrodes are used, charge carriers initially removed by the application of an E-field are not replaced at the opposite electrode.</u>

Leakage current considerations

- As indicated even in the absence of ionising radiation, all detectors have a steady state leakage current.
- The resistivity of the highest purity silicon currently available is about 50kΩ-cm.
  - If a 1mm slab of silicon with a $1cm^3$ surface area were fitted with Ohmic contacts the electrical resistance between the faces would be 500Ω.
  - An applied voltage of 500V would cause a leakage current of 0.1A.
  - In contrast the peak current generated by a pulse of 10^5 radiation-induced particles would be 10^{-6}A.
  - In critical applications the leakage current should not exceed about 10^{-9}A.
  - At these levels leakage across the surface will be more significant than bulk leakage.

The diode as a detector

- Recall that for a *p-n* junction Poisson's equation allows us to determine the value of the potential $\varphi(r)$ at any point inside the diode.

$$\nabla^2 \varphi(r) = -\frac{\rho(r)}{\varepsilon}$$

- Where $\rho(r)$ is the net charge density:

$$\rho(r) = e \cdot n$$

- *n* is the impurity concentration defined as the difference between the density of donors N_d and the density of acceptors N_a. In one dimension:

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

- Now the shape of the potential across the junction can be obtained by twice integrating the charge distribution profile $\rho(x)$.

The diode as a detector

- Where a difference in the electric field exists, there must be an E-field.

$$E(r) = -\nabla\varphi \text{ or } E(x) = -\frac{d\varphi}{dx}$$

- The electric field extends over the width of the depletion region, in equilibrium the contact (built in) potential ~ 1V.
- Such an unbiased junction will function as a detector but will have very poor performance.
- Induced charges deposited in the depletion region can be lost due to trapping and recombination and **incomplete charge collection** will result.

The diode as a detector

- The effect of reverse bias on the diode accentuates the potential difference across the junction.
- Poisson’s equations demand that the space charge must also increase and extend a greater distance either side of the junction.
- Therefore the thickness of the depletion region increases –extending the volume over which radiation-induced charge carriers will be collected.
- A **partially depleted** detector is a detector in which some portion of the wafer thickness remains undepleted.
- A **fully depleted detector** is a detector operated with sufficient reverse bias so that the depletion extends though the full wafer thickness.

The diode as a detector

- The width of the depletion region for a diode is:

$$d \cong \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$$

- Where *N* is the dopant concentration on the side of the junction that has the lower dopant level.
- The resistivity ρ_d of the doped semiconductor is given by $1/e\mu N$, where μ is the mobility of the majority carrier. Therefore:

$$d \cong (2\varepsilon V \mu \rho_d)^{1/2}$$

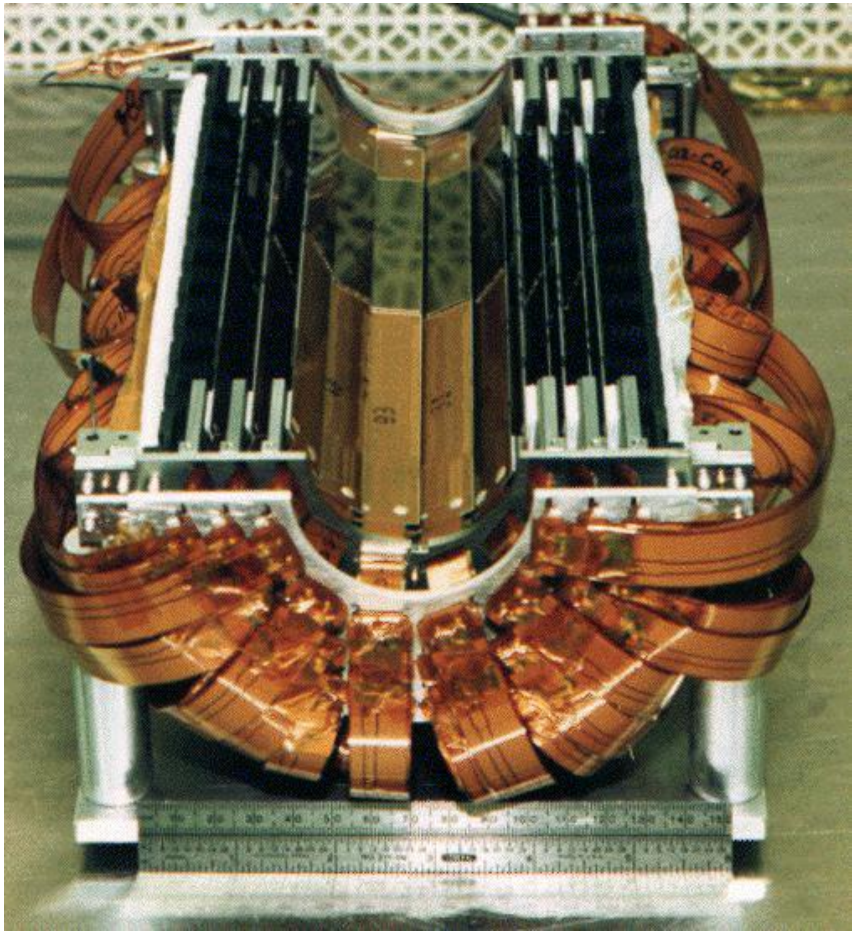
- For the largest depletion region it is advantageous to have the resistivity as high as possible. This is limited by the purity of the semiconductor material before the doping process.
- **Detectors should therefore be formed from the highest purity material possible.**

Applications of Si diode detectors

- Silicon diodes were first developed as practical detectors in the early 1960s.
- Semiconductor detectors have:
  - Good energy resolution.
  - Good stability and freedom from drift.
  - Excellent timing characteristics.
  - Very thin entrance windows and simplicity of operation.
- They are the detector of choice for the majority of applications in which heavy charged particles are involved.
- Silicon diodes at room temperature are ideal detectors for alpha particles.
- With alpha particles the noise contribution of the preamplifier and other electronic components is normally smaller than the energy resolution of the detector itself (10-11keV).

Charge Coupled Devices (CCDs)

The SLAC (Stanford) Large Detector (SLD) ‘Micro-vertex’ Tracking Array

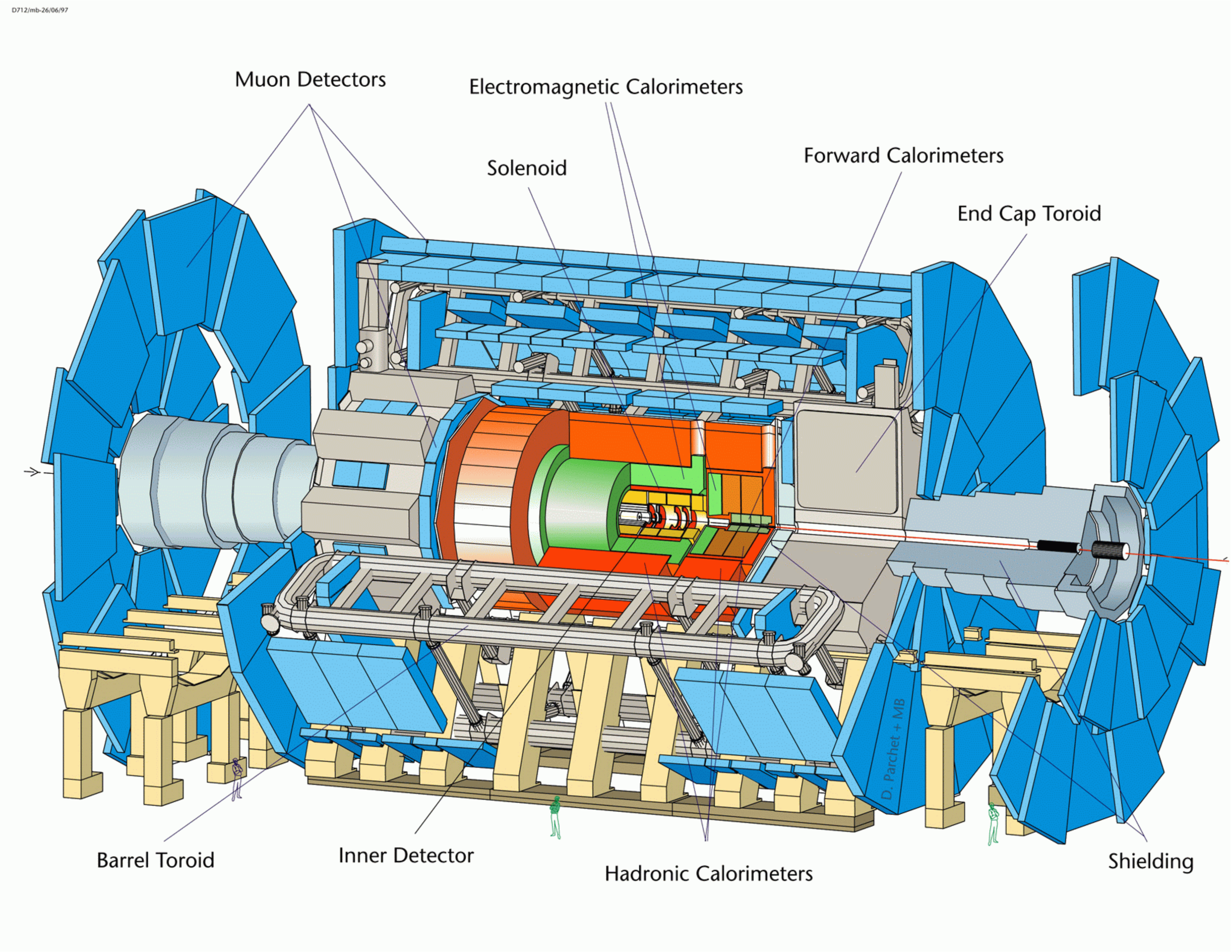


- Large areas of silicon segmented on the μm scale can require instrumentation with millions to billions of channels of electronics
- Digital cameras have millions of sense elements, ‘pixels’, and use the large area CCD technology originally developed for astronomy (imaging) and particle physics (tracking)
- eg SLD 300,000,000 Pixels

Read-out Speed and Electronics

- SLD used 2×48 CCDs each of 3.2 million pixels
- Each pixel signal is clocked out sequentially so each CCD takes 1/5th of a second to read out
- At CERN’s Large Hadron Collider (LHC) proton bunches collide head-on with each other 40,000,000 times per second
- At the LHC each pixel must have its own individual read-out circuit connected to it

Experiments at the LHC



Experiments at the LHC

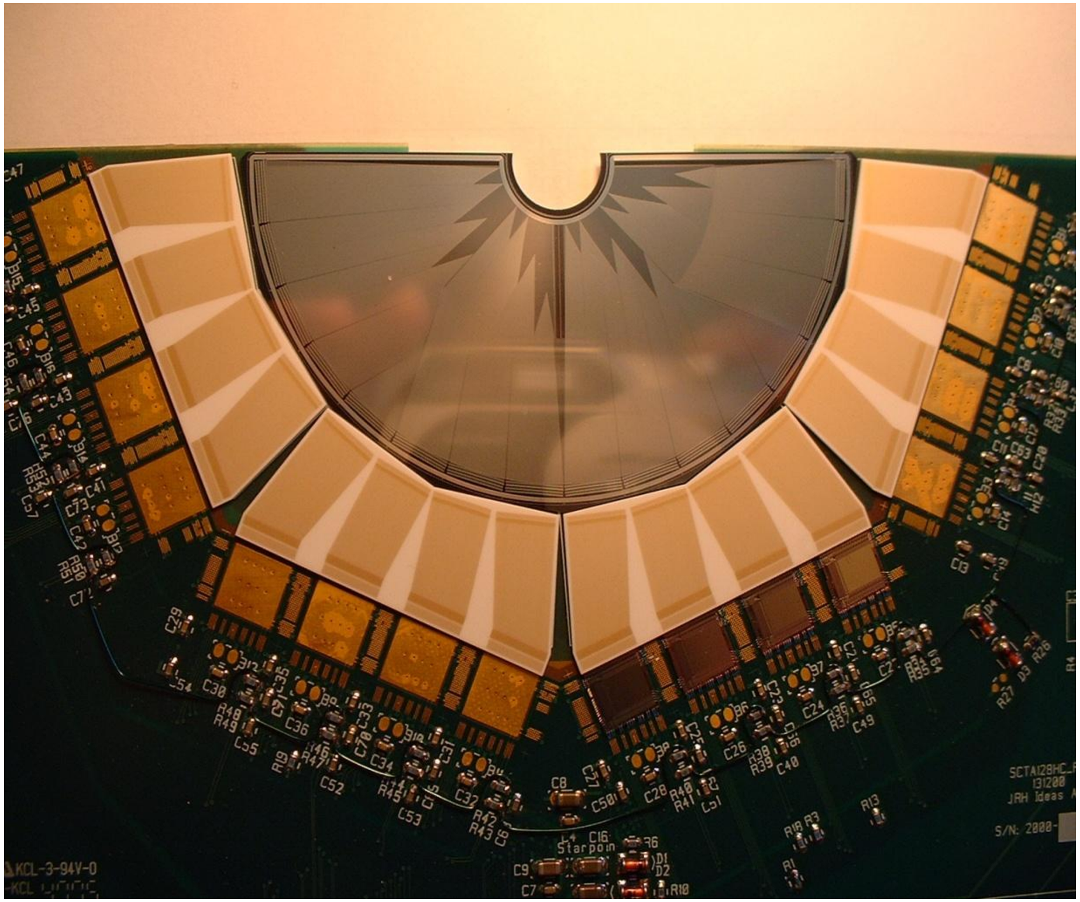
- Liverpool work on two of the four detectors at LHC collision points: ATLAS & LHC-b
- ATLAS is 20m high 26m long with hundreds of millions of read-out channels reading out every 25ns
- Liverpool is assembling a large section of the main silicon tracker array

The LHC-b Vertex Detector Silicon Detectors

- These detectors
- are installed right next to the LHC proton beams

- There are 2048
- read-out channels

- Detectors fabricated with Liverpool masks by Micron Semiconductor (UK) Ltd



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