PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 56400

Introduction to Elementary Particle Physics I

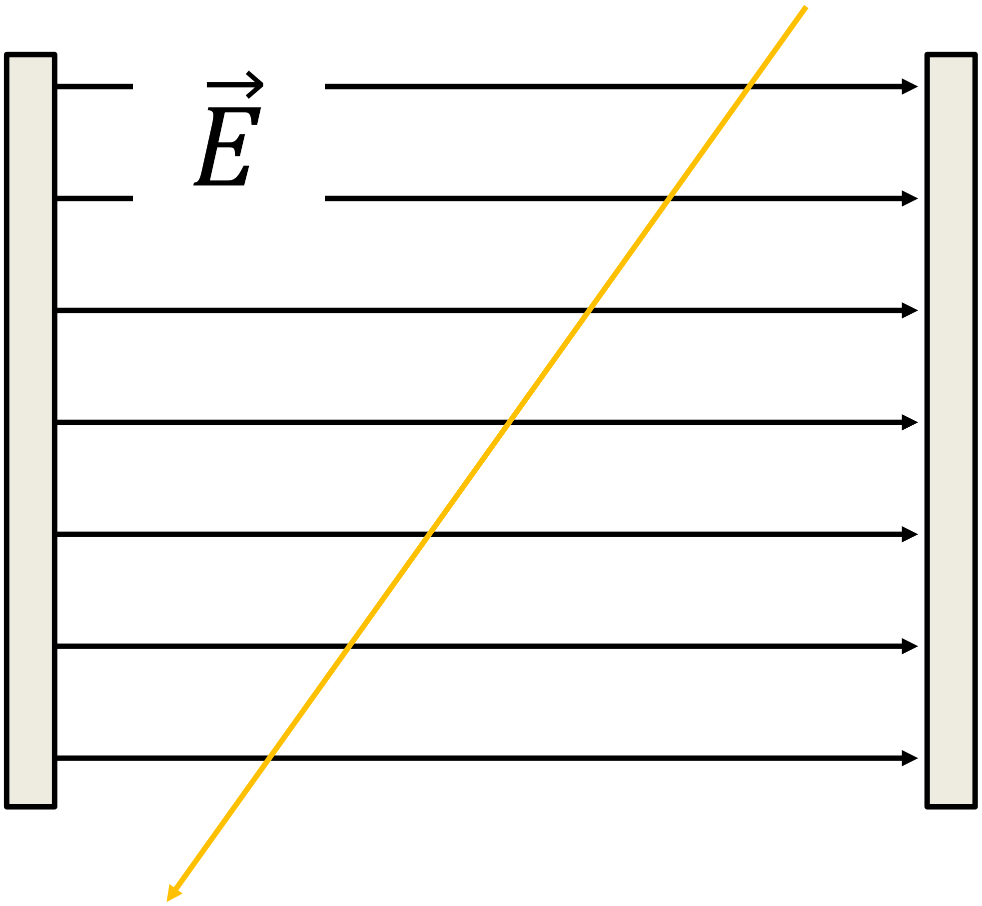
Lecture 8

Fall 2019 Semester

Prof. Matthew Jones

Gas Proportional Counters

- Ion drift in an electric field:



Gas Proportional Counters

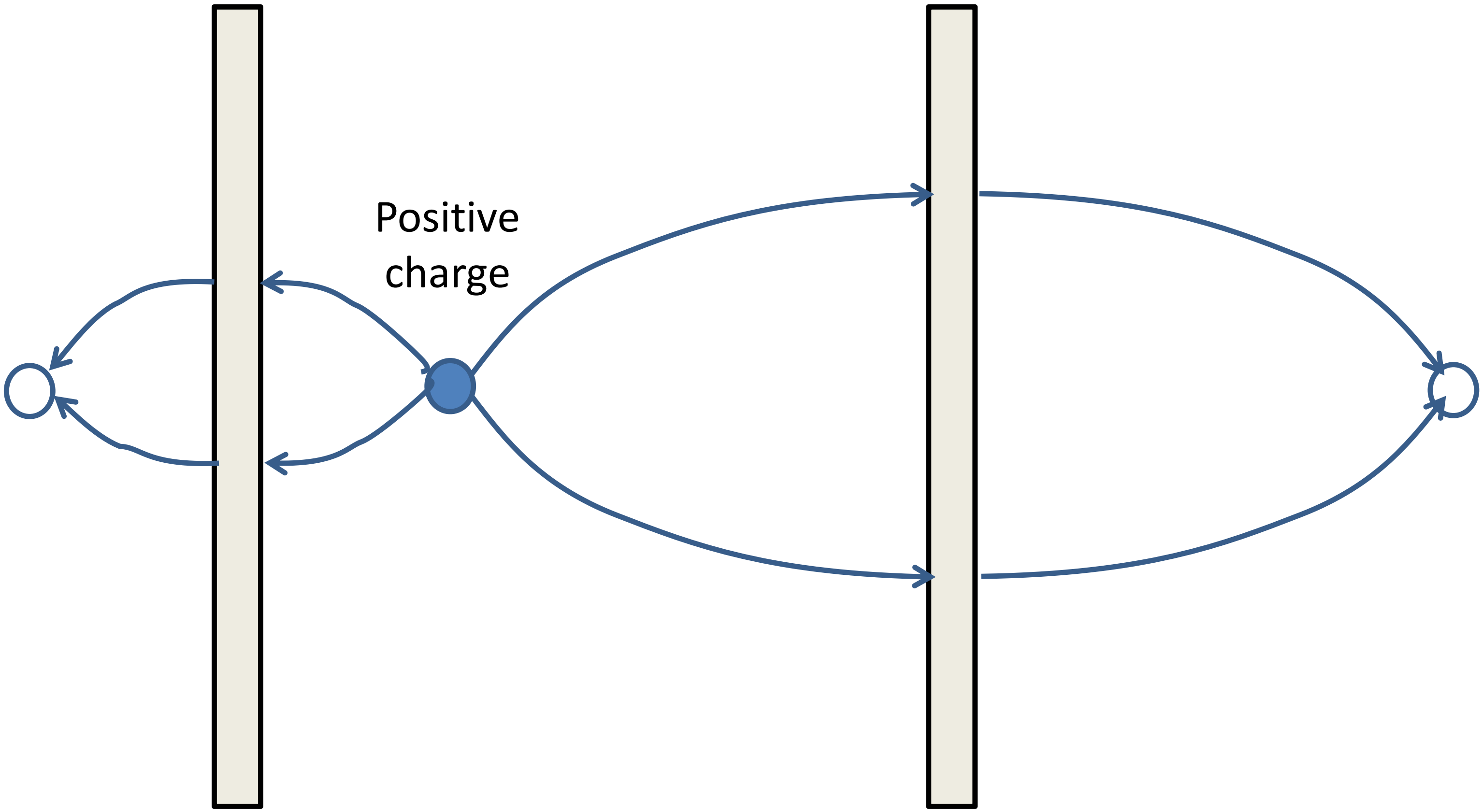
- The electric field in the presence of sources is solution to Poisson's equation:

$$\vec{E} = -\nabla\Phi$$

$$\nabla^2\Phi = -4\pi\rho$$

- When the only charges present are on the plates of the capacitor, the electric field is uniform
- When ions are present, we can use "image charges" to determine the electric field.

Gas Proportional Counters



Remember that the electric field at the surface of a conductor determines the surface charge density. Changing the surface charge requires that a current must flow.

Gas Proportional Counters

- In practice, positive and negative charges are created simultaneously so initially there are no image charges.
- But the ions drift in opposite directions in the electric field.

$$\vec{v}_e = -\mu_e \vec{E}$$
$$\vec{v}_I = \mu_I \vec{E}$$

- A current flows onto each plate in response to the changing surface charge density.
- This current can (in principle) be measured.

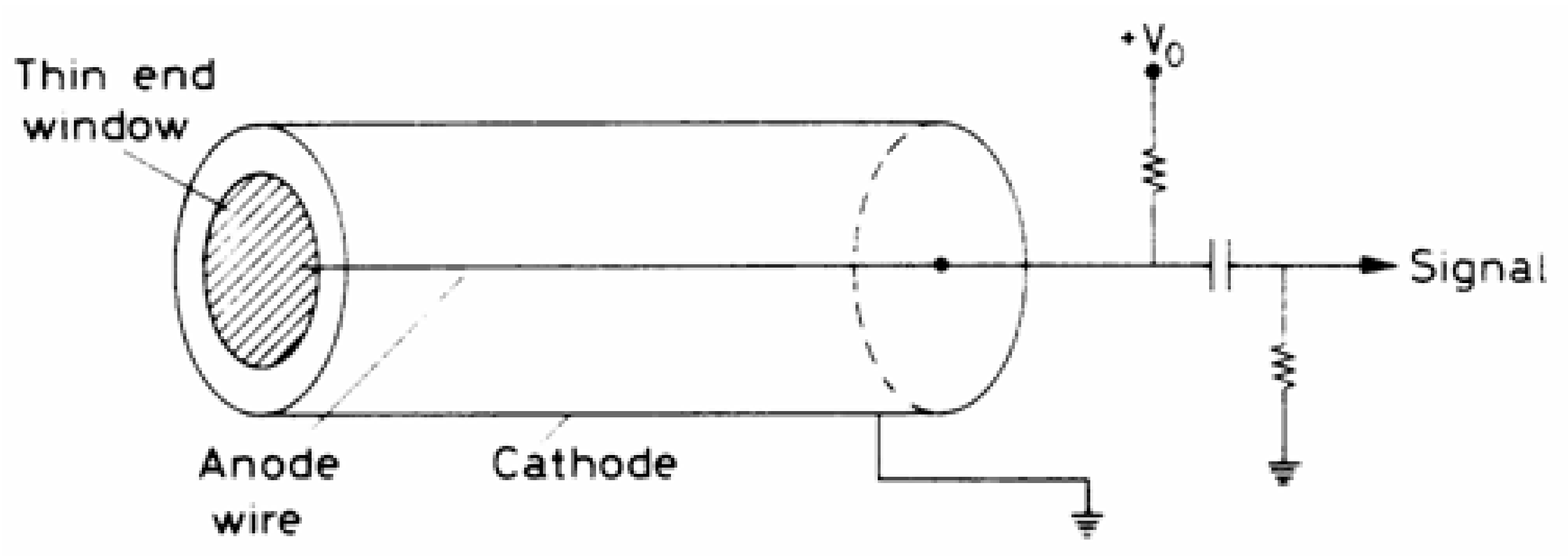
Gas Proportional Counters

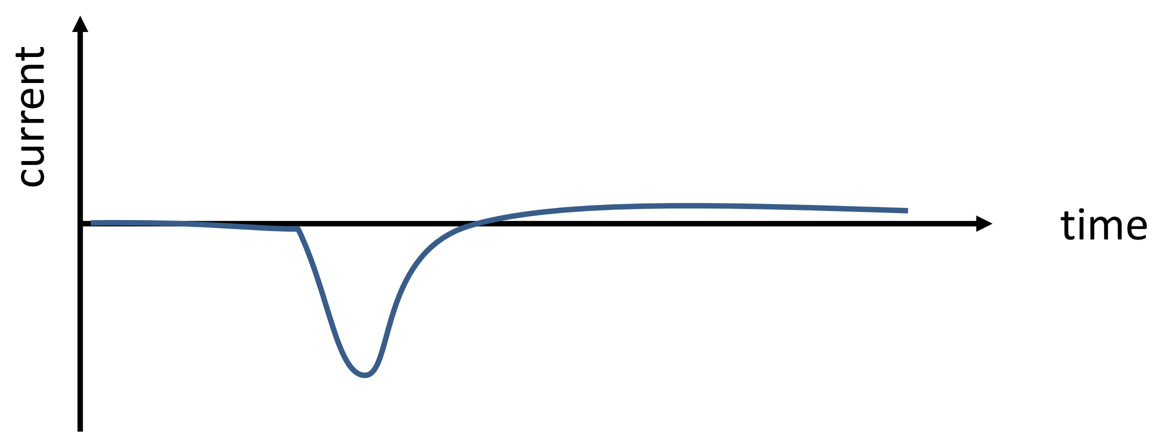
- Clicker question:

  When is the current observed?

  a) *When the electrons or ions arrive at the plate*
  b) *As soon as they start to move*

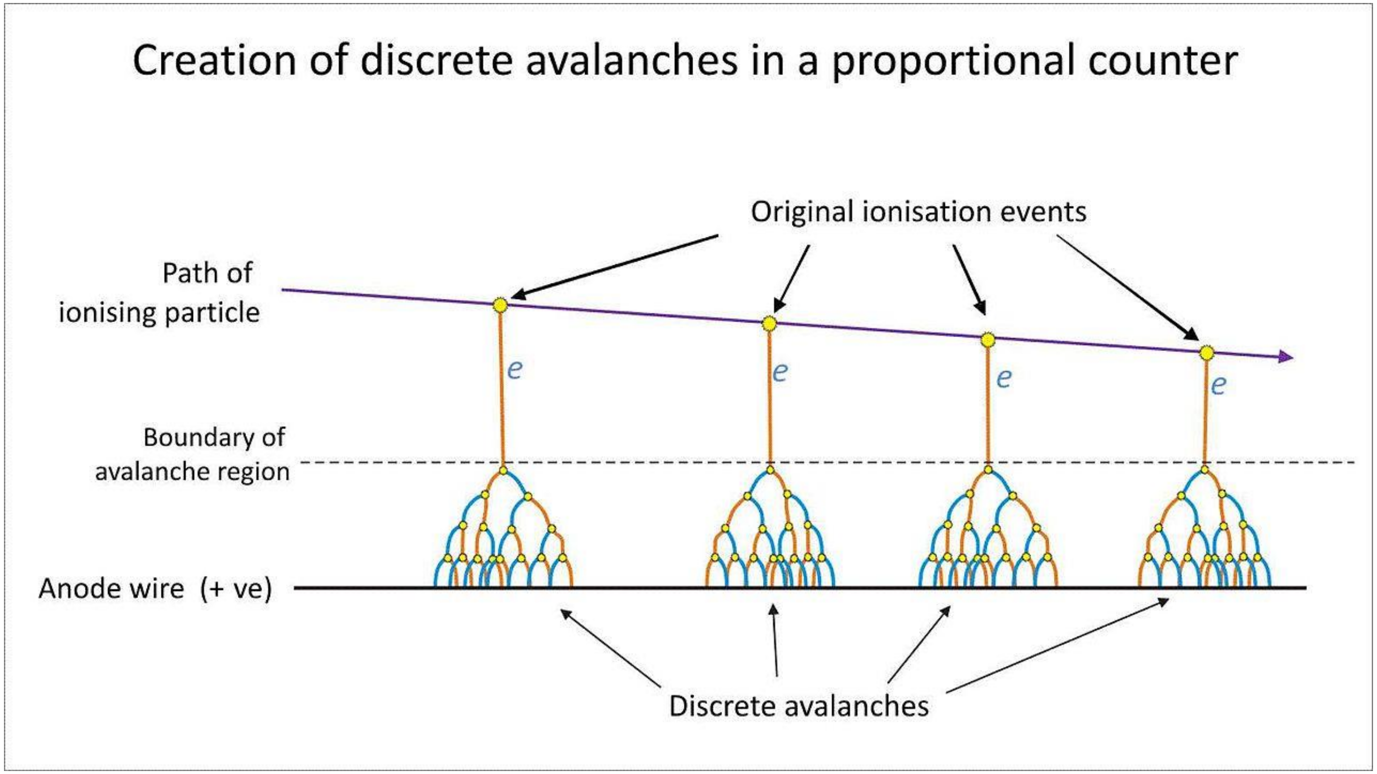
Gas Proportional Counters





Avalanche Multiplication

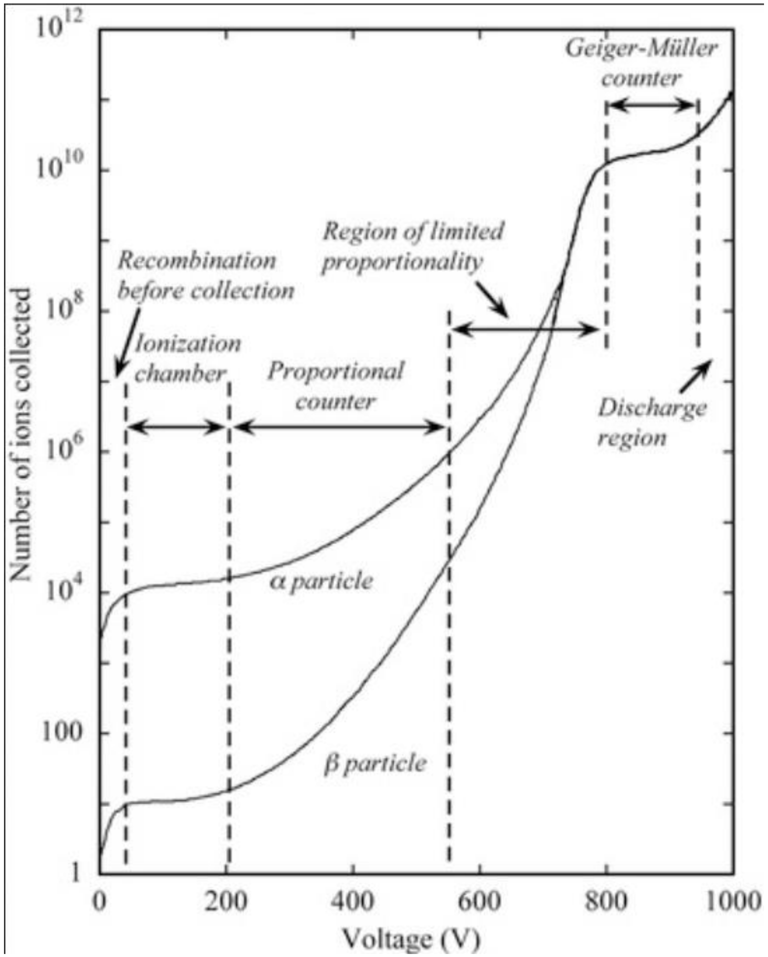
- The electric field surrounding a tiny wire can be large enough to cause avalanche multiplication near the wire.



Avalanche Multiplication

- The positive ions created in the avalanche move away from the positive wire and induce a much larger current than the motion of the primary ionization.
- The pulse height is still proportional to the energy deposited in the gas.
- If the electric field is very large, then the avalanche saturates and is no longer proportional – all pulses are the same size.
- If the electric field gets even larger, then a continuous discharge can occur.

Gas Filled Detectors



Practical issues:

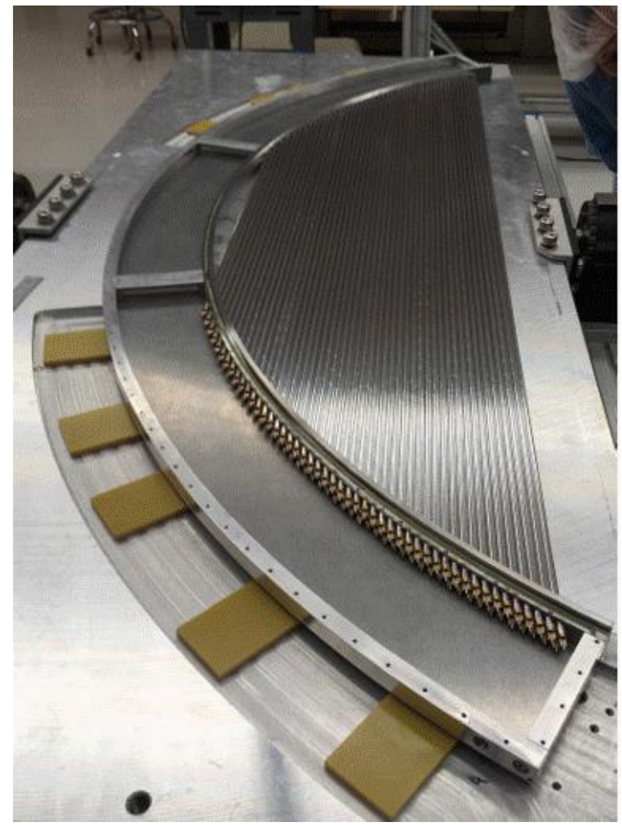
- The gas mixture should have a low recombination rate.
- The drift velocity should be fast.
- The gas should not be ionized by UV light emitted during the avalanche.

Straw Tubes

- Individual chambers can be constructed with very low mass.

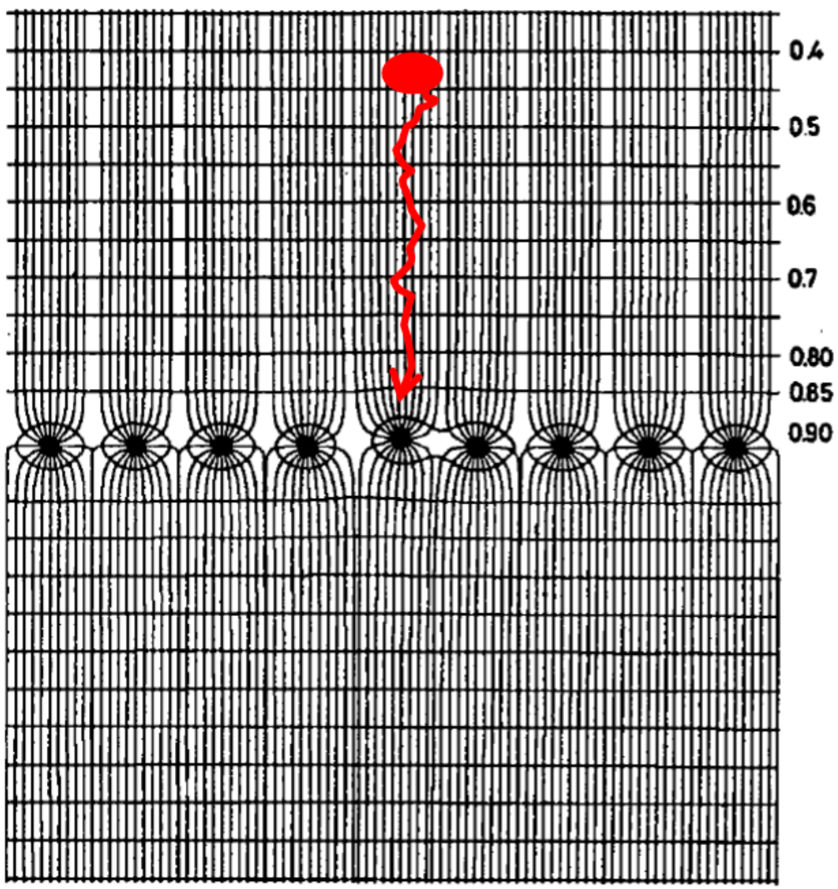
(Mu2e straw tracker – under construction)

The straw is formed from aluminum coated Mylar with a thickness of only 15 μm.



Multi-wire Proportional Counters

- Many wires can occupy the same gas volume



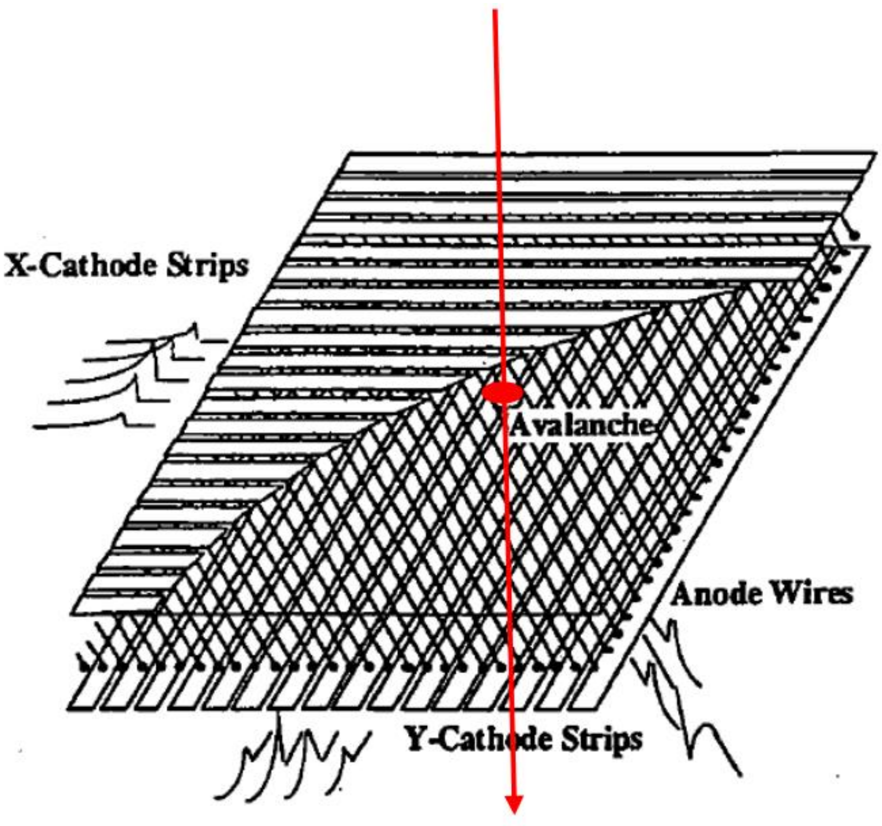
Far from the wires, the electric field is uniform.

The signals induced on the wires determine the location at which ionization was deposited.

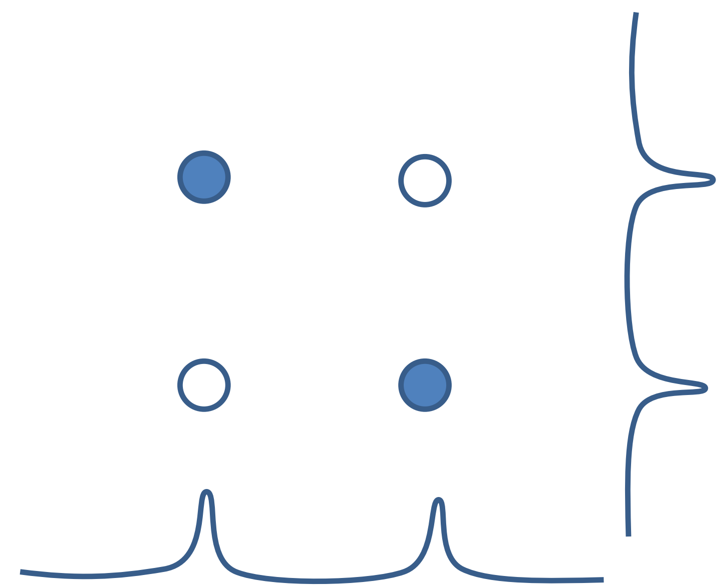
The time at which the pulse is observed depends on the drift distance. Remember that we mostly see the pulse due to the motion of the charges created in the avalanche.

Multi-Wire Proportional Counters

- The cathode can also be segmented to provide (almost) 2d coordinates:

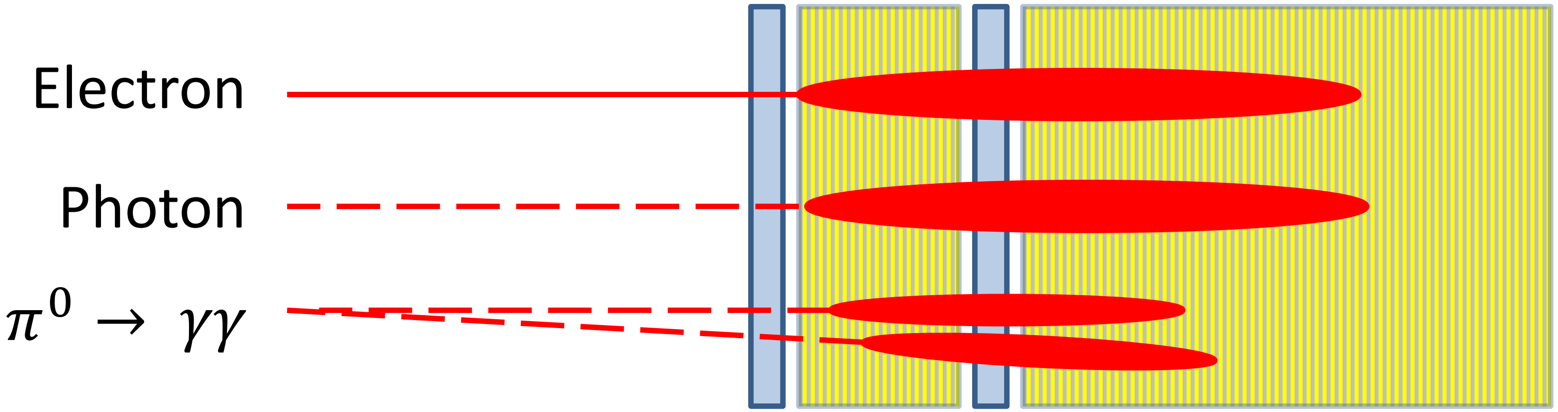


When more than one track passes through the chamber there are ambiguous "ghost" pairings:



Sampling Calorimeters

- Multi-wire proportional counters can be embedded between sheets of lead to sample energy in electromagnetic showers
- The CDF-II electromagnetic calorimeter used a presampler in front and an embedded gas proportional chamber at a depth of t_{max}



Drift Chambers

Drift Chambers

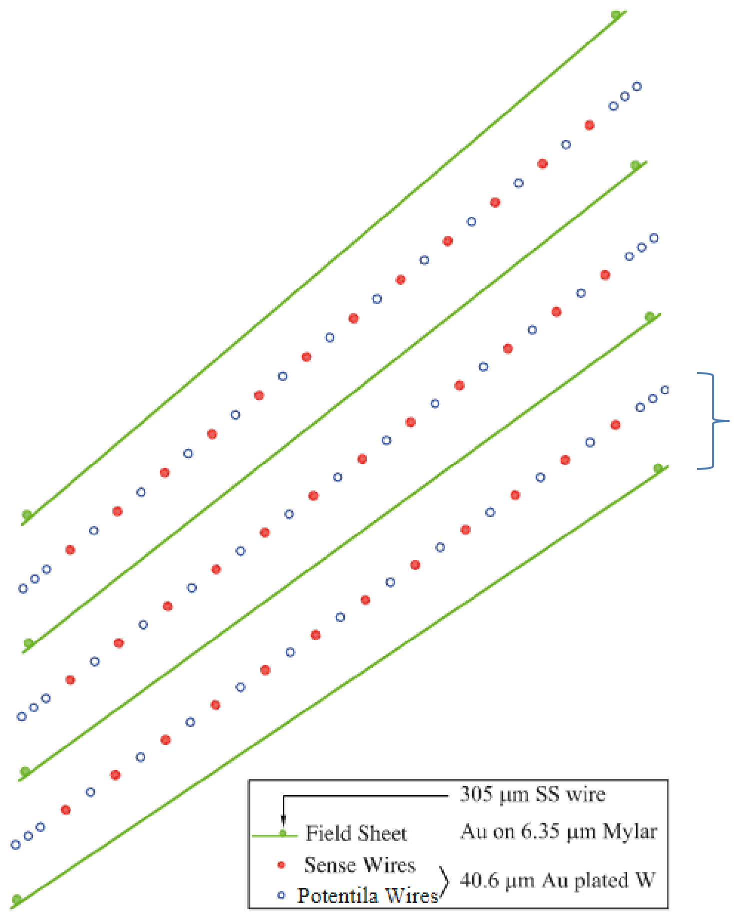


Fig. 3. Three supercells in superlayer 2 looking along the beam (*z*) direction. Some details in this sketch are not precise, such as the position of the shaper wires.

- 9 mm drift distance
- Drift time is less than 177 ns

Gas mixture was Ar/Ethane (50:50) + isopropyl alcohol

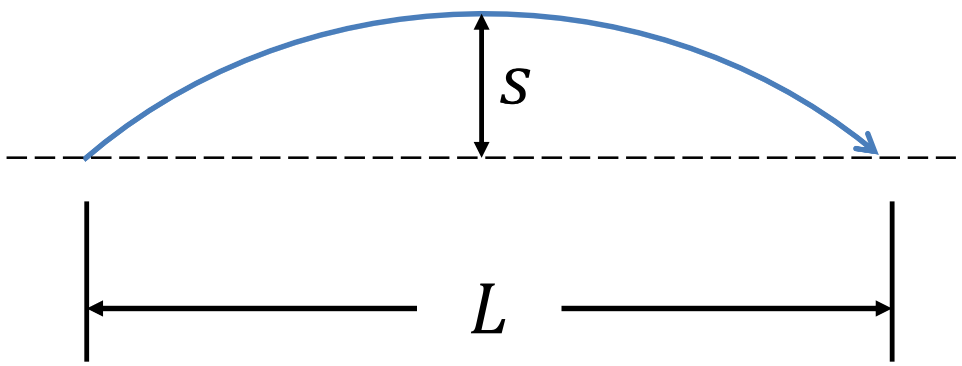
Momentum Measurement

- In a solenoidal magnetic field, charged particles move on helical trajectories.
  - Circular paths in the transverse plane

$$p\ [\mathrm{MeV/c}] = (0.3) \cdot q\ [\mathrm{e}] \cdot\ B\ [\mathrm{kG}]\ \cdot\ R\ [\mathrm{cm}]$$

- The accuracy of the momentum measurement is determined by the accuracy with which R is measured.

$$p = 0.3\,\frac{qBL^2}{8s}$$



Momentum Resolution

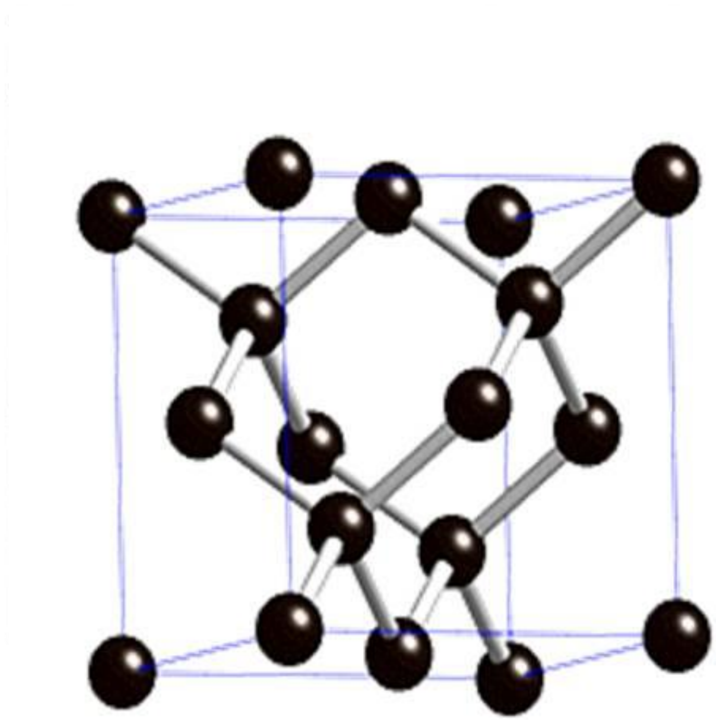
- Gluckstern formula:

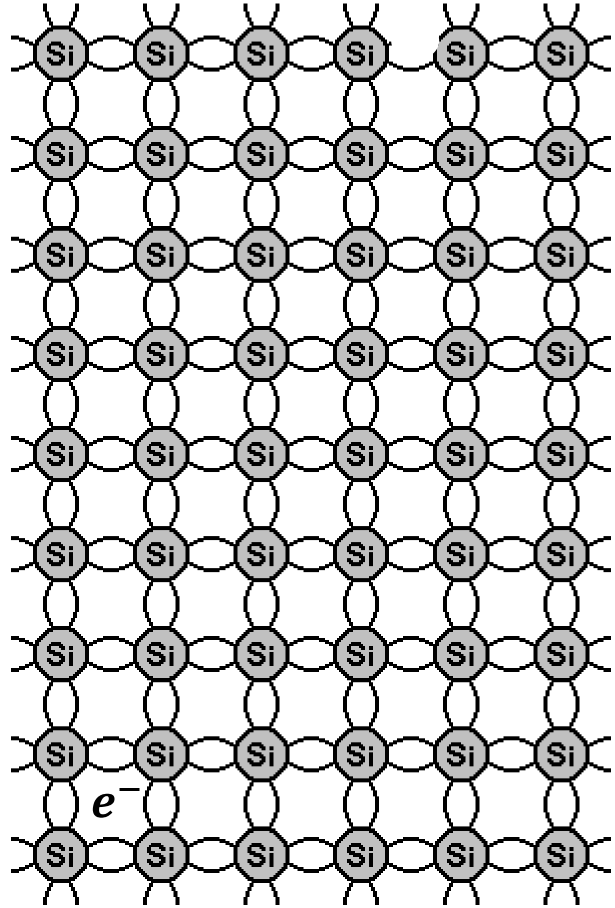
$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 \ \cdot BL^2} \sqrt{\frac{720}{N+4}}$$

  - N equally spaced measurements
  - Single-hit resolution, σ_x
- Momentum resolution:
  - Decreases as p_T increases
  - Improves as B and L increase
  - Improves with more measurements
  - Improves when σ_x gets smaller

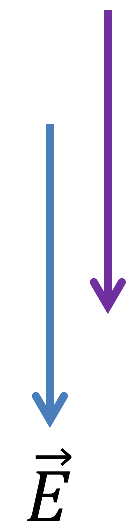
Solid State Detectors

Silicon

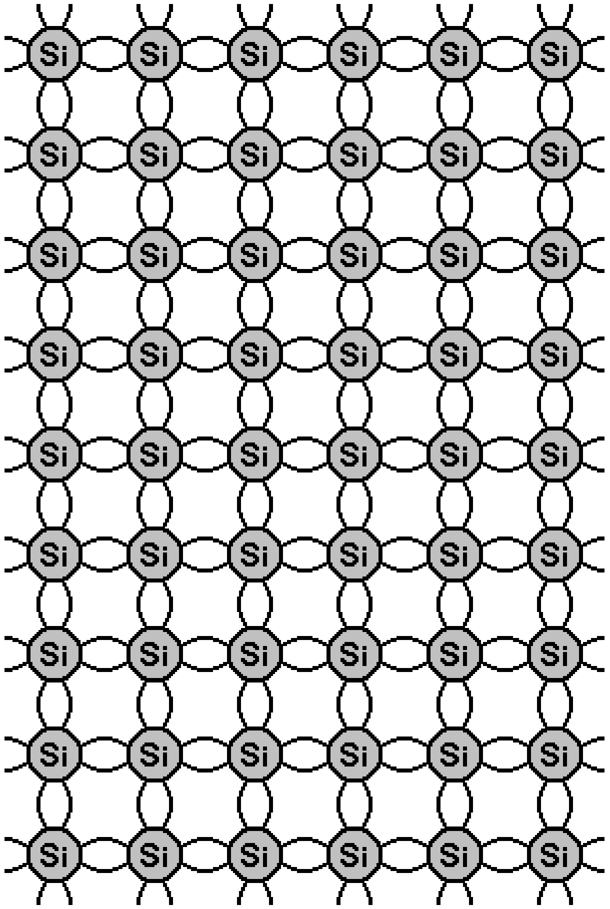




$$\vec{J} = qn\vec{v}$$



Silicon



Mobility, μ: $\vec{v}_e = -\mu_e \vec{E}$

$$\vec{v}_h = \mu_h \vec{E}$$

At 300 K:

$$\mu_e \approx 145\ \mu\mathrm{m}^2/\mathrm{V}\cdot\mathrm{ns}$$

$$\mu_h \approx 45\ \mu\mathrm{m}^2/\mathrm{V}\cdot\mathrm{ns}$$

Example:

$d = 320\ \mu\mathrm{m}$ and $V = 100\ \mathrm{V}$

Electric field: $E = 0.313\ \mathrm{V}/\mu\mathrm{m}$

Carrier speed:

$$v_e = 45\ \mu\mathrm{m/ns}$$

$$v_h = 14\ \mu\mathrm{m/ns}$$

Drift time:

FAST →

$$T_e = d/v_e = 7\ \mathrm{ns}$$

$$T_h = d/v_h = 23\ \mathrm{ns}$$

Doped Silicon

Conductivity of intrinsic silicon, $n_e = n_h = n_i$:

$$\vec{J} = en_i(\mu_h + \mu_h)\vec{E} = \sigma_i \vec{E}$$

Intrinsic conductivity is very low:

$$\sigma_i \sim 10^{10}\ \mathrm{cm}^{-3} \text{ at 300 K}$$

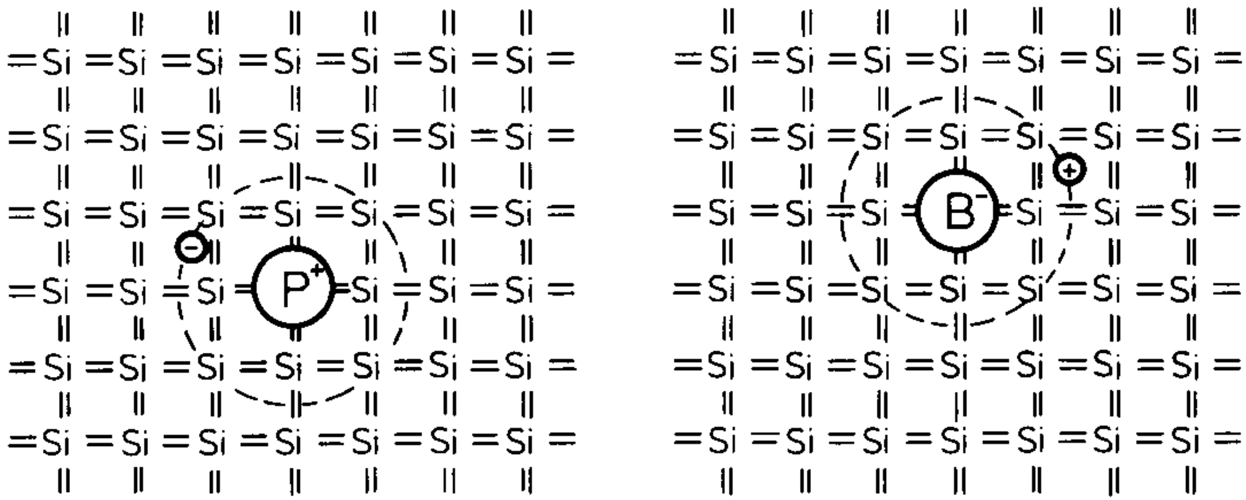
Number density of Si atoms: $n_{Si} = \frac{\rho}{m} N_A = 5 \times 10^{22}\ \mathrm{cm}^{-3}$

Doped silicon:

A small number of donor or acceptor atoms will completely determine the conductivity:

- $n_{Si} \gg n_D \gg n_i$
- Phosphorus (donates electron – n-type Si): $\sigma_n = en_D\mu_e$
- Boron (makes a hole – p-type Si): $\sigma_p = en_D\mu_h$

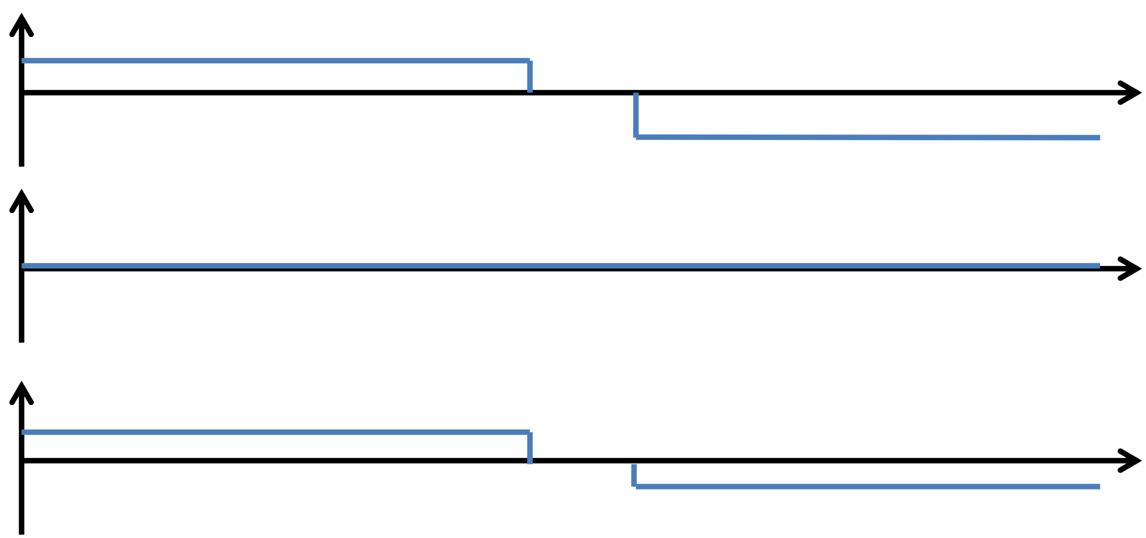
P-N Junction



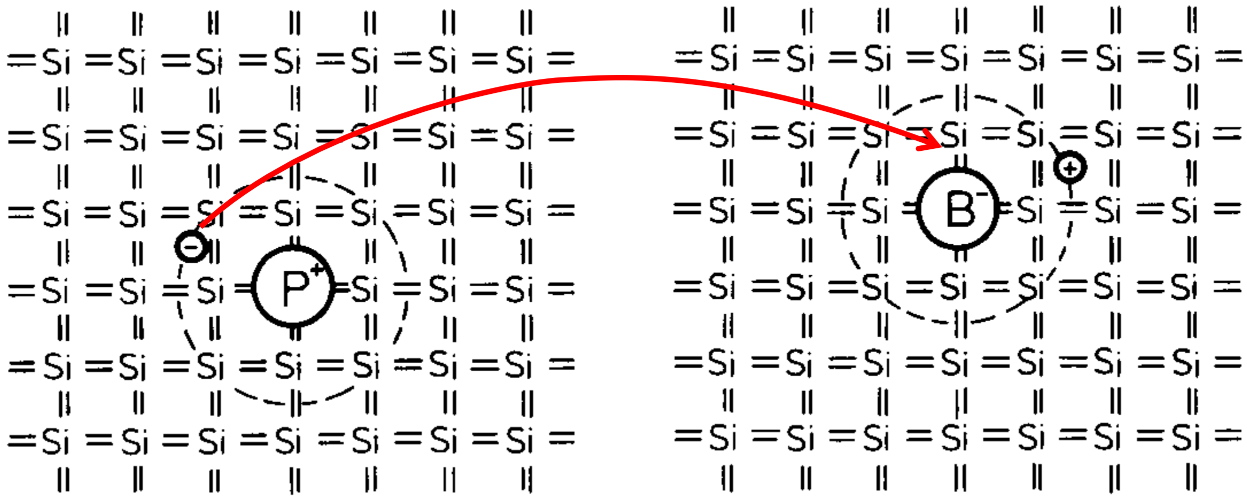
n-type dopant concentration

charge density

carrier density



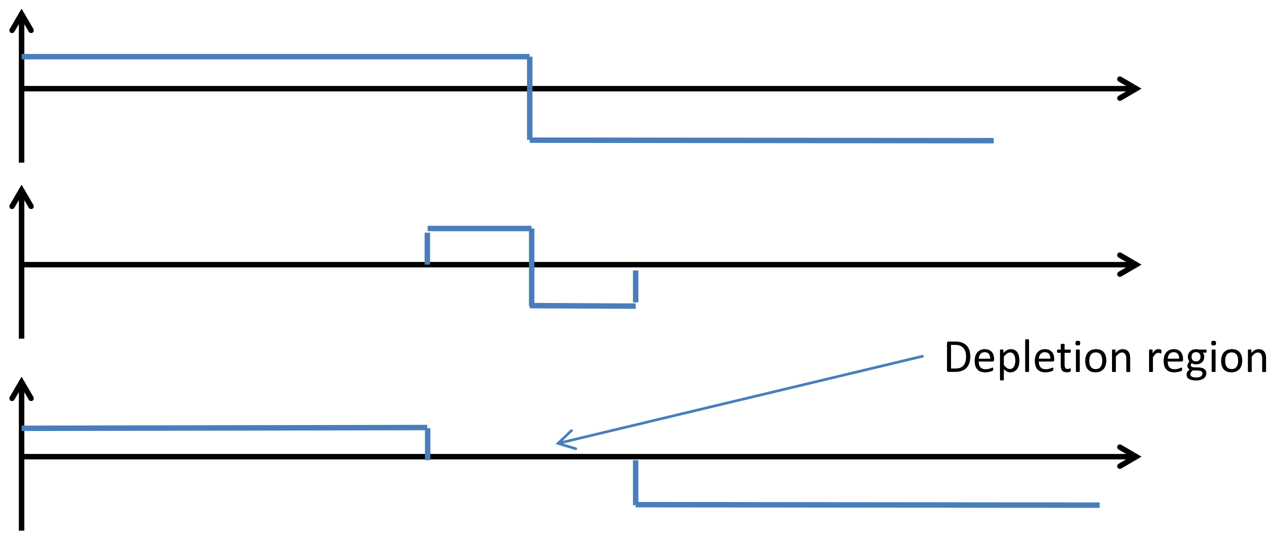
P-N Junction



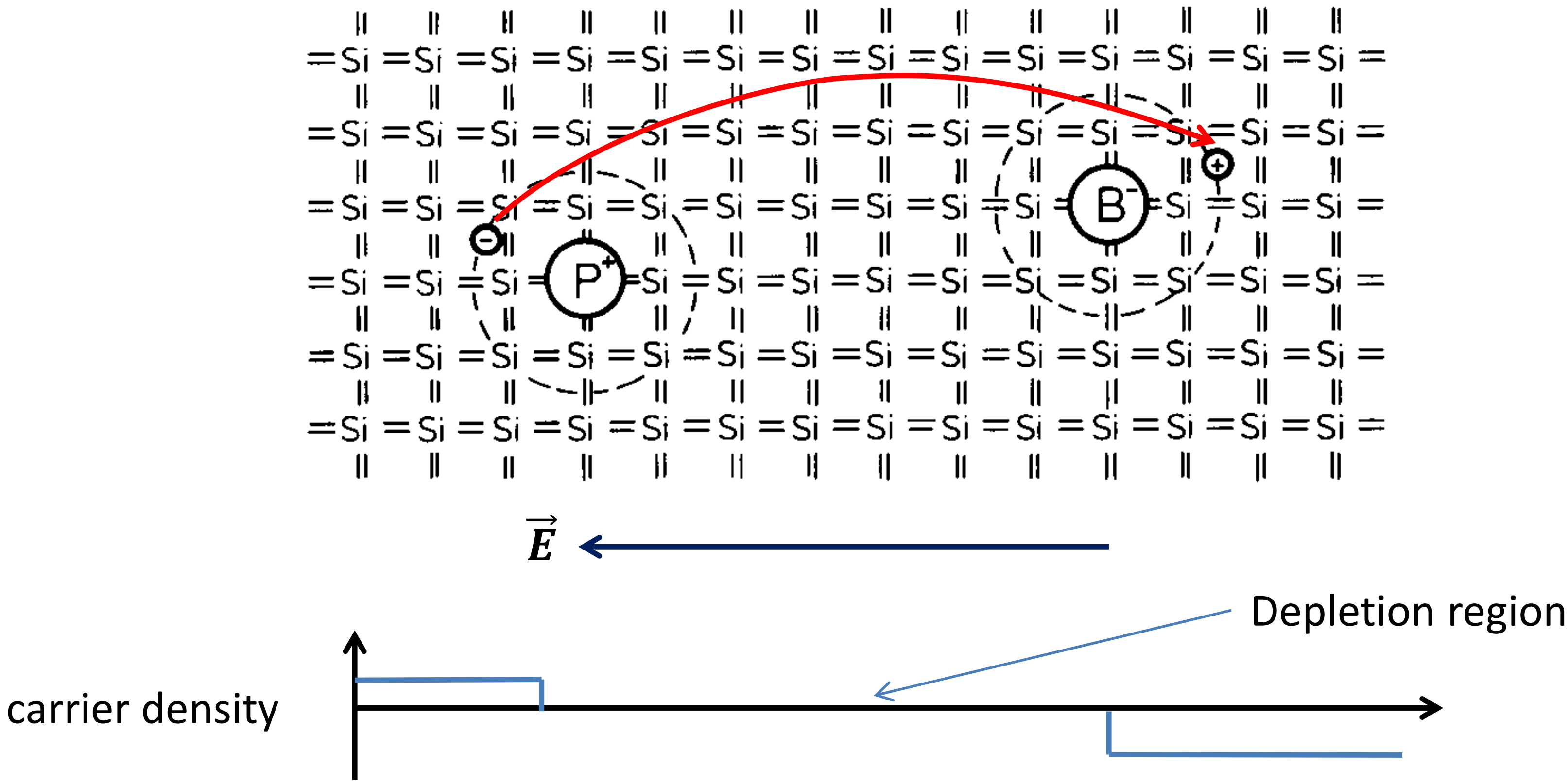
n-type dopant concentration

charge density

carrier density



P-N Junction



Charge carriers in depletion region created by:

- Thermal excitation
- Ionizing radiation

Silicon Strip Sensors

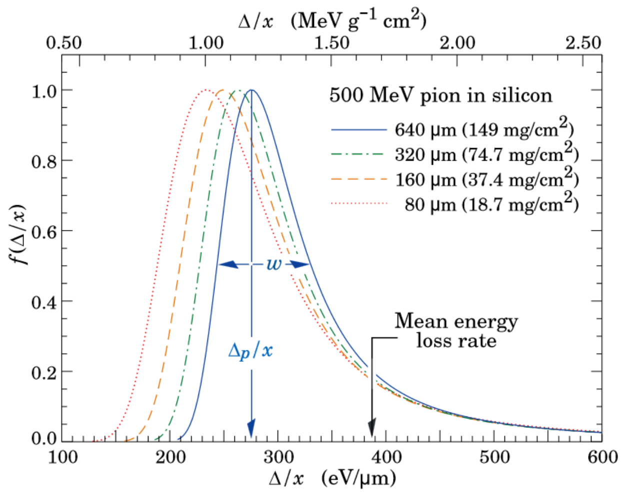


Figure 31.8: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum.

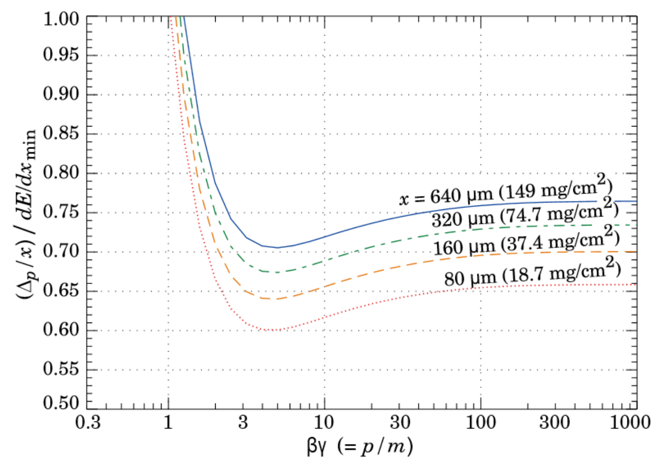


Figure 31.9: Most probable energy loss in silicon, scaled to the mean loss of a minimum ionizing particle, 388 eV/μm (1.66 MeV $g^{-1}cm^2$).

Mean energy loss of a MIP in 320 µm thick sensor:

$$\langle \Delta \rangle = (377\ \mathrm{eV}/\mu\mathrm{m}) \cdot (320\ \mu\mathrm{m}) = 120\ \mathrm{keV}$$

Energy needed to produce electron-hole pair: 3.6 eV

A MIP produces about 33,000 e-h pairs

Energy Resolution

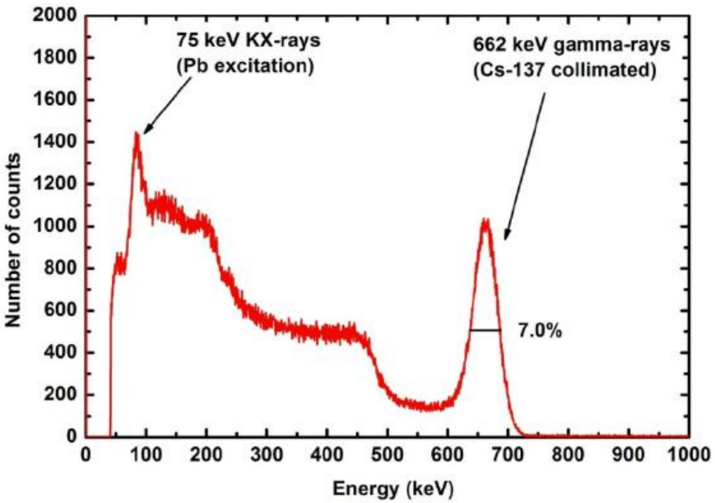
- Electron-hole pairs cannot be created in isolation.
- Energy is also transferred to the crystal lattice.
  - Quantized vibrations are called "phonons"
  - Each electron-hole pair produces n_{ph} phonons
  - The Fano-factor
- The energy resolution can be much better than $\sqrt{E}$

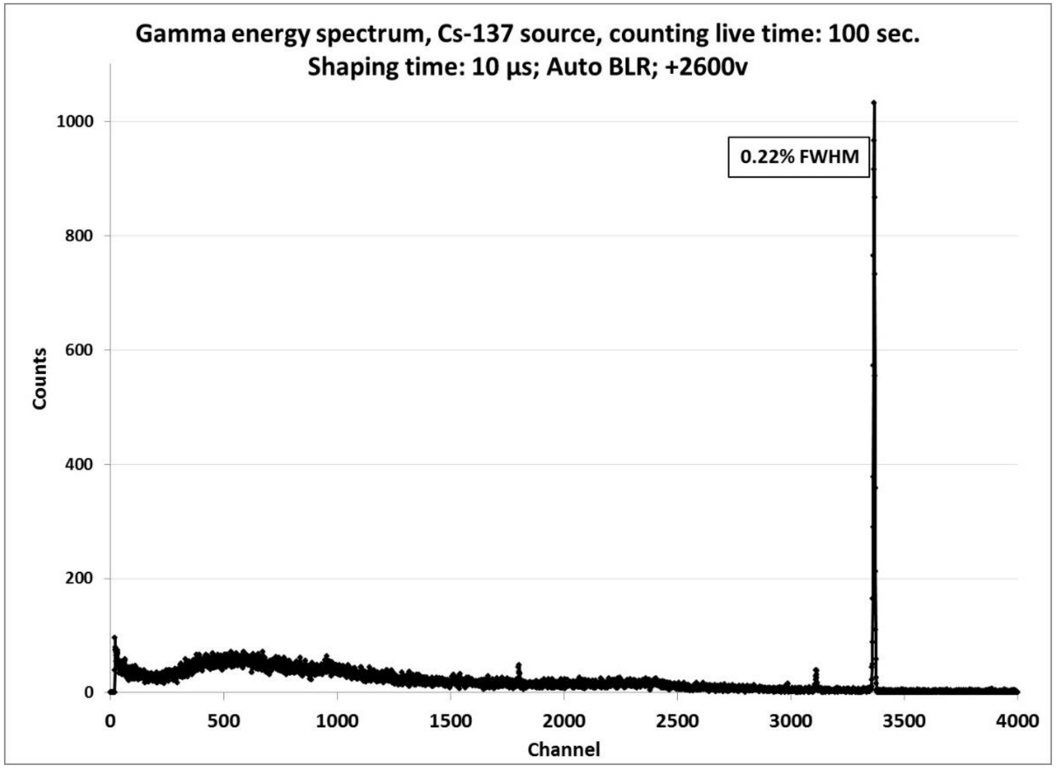
$$\frac{\sigma_E}{E} = \sqrt{F_w/E}$$

Material	F_w
Silicon	0.115
Germanium	0.13
GaAs	0.12
Diamond	0.08

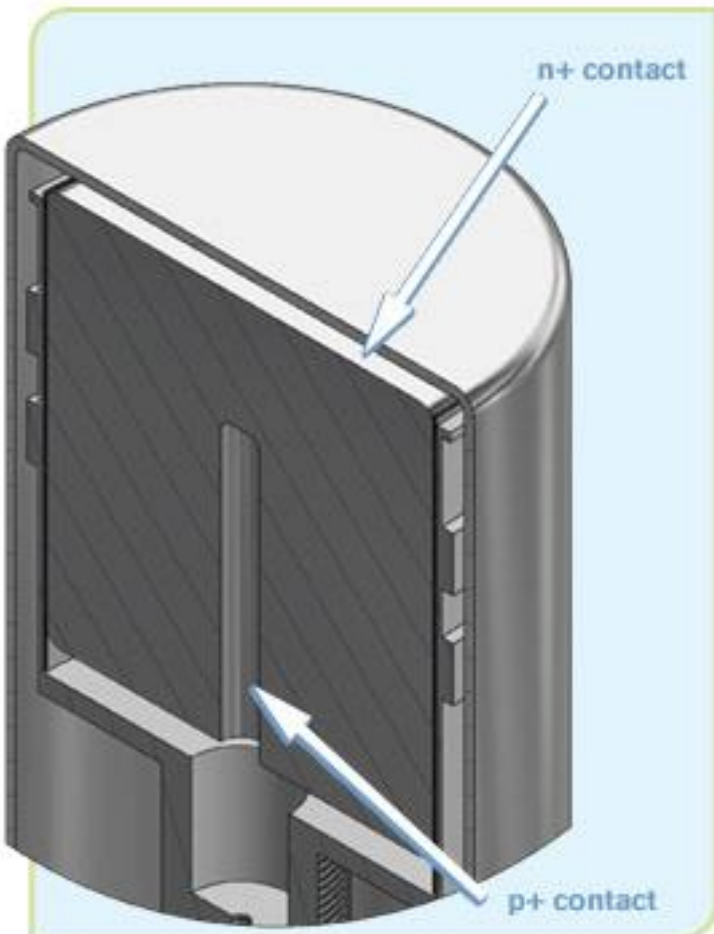
HPGe Counters

- Large crystals of Germanium have excellent energy resolution for low-energy photons





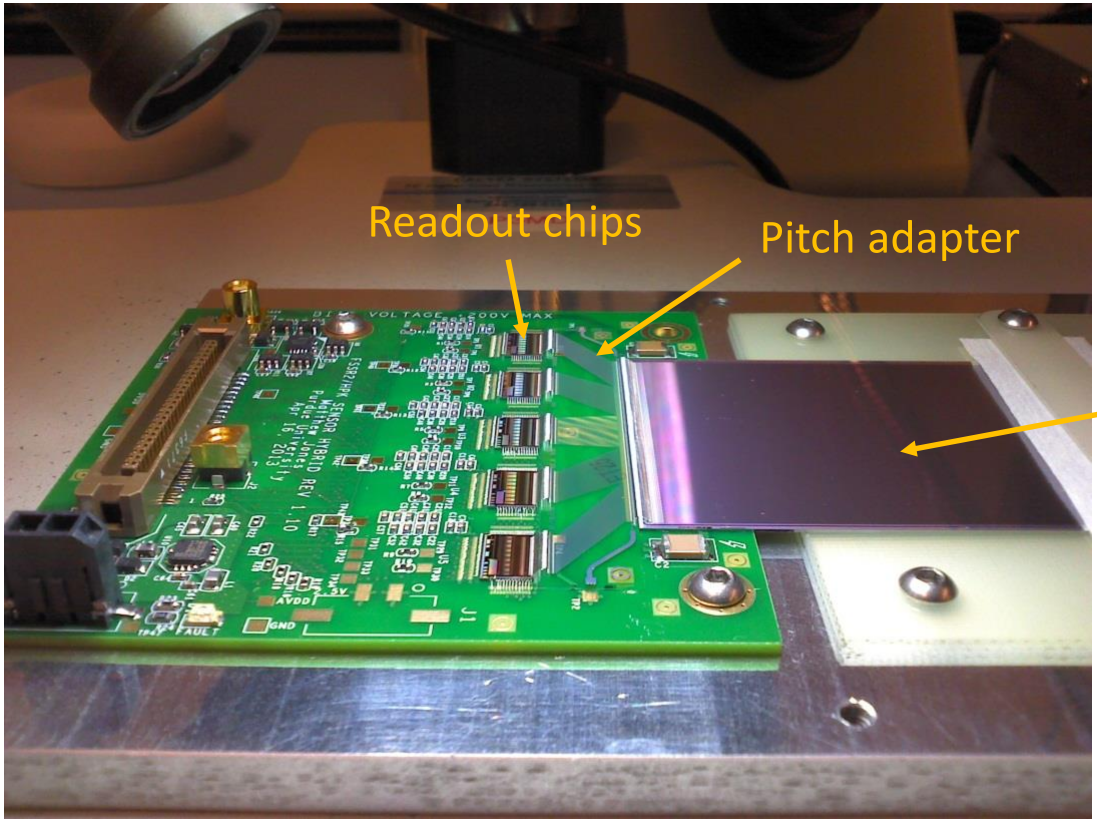
HPGe Counters



LN_2 dewar

Silicon Strip Detectors

Thin (300 µm) thick silicon wafers patterned with finely spaced readout strips, each with its own readout electronics.

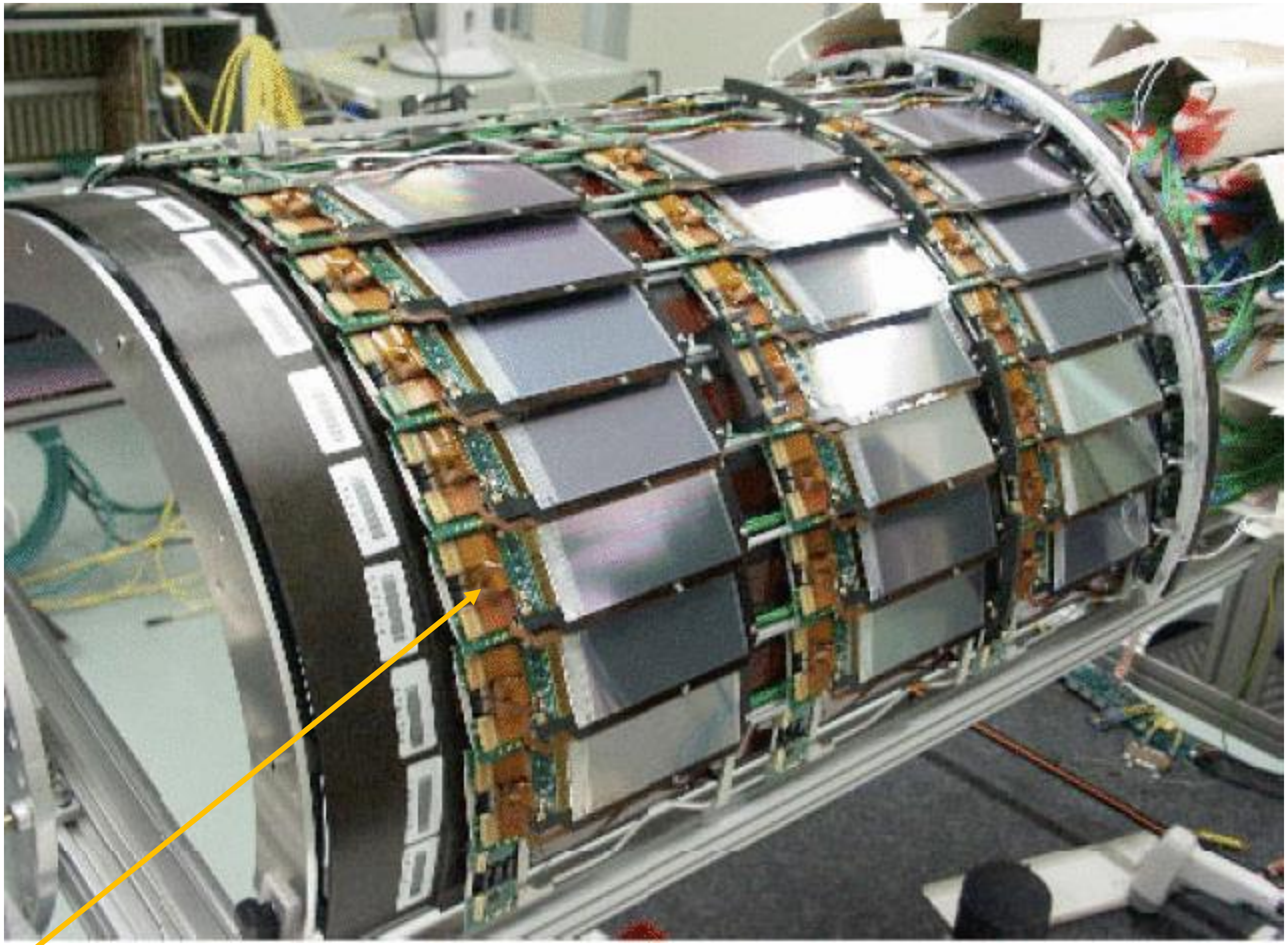


General Features of Readout Electronics

Readout chips are often required to provide:

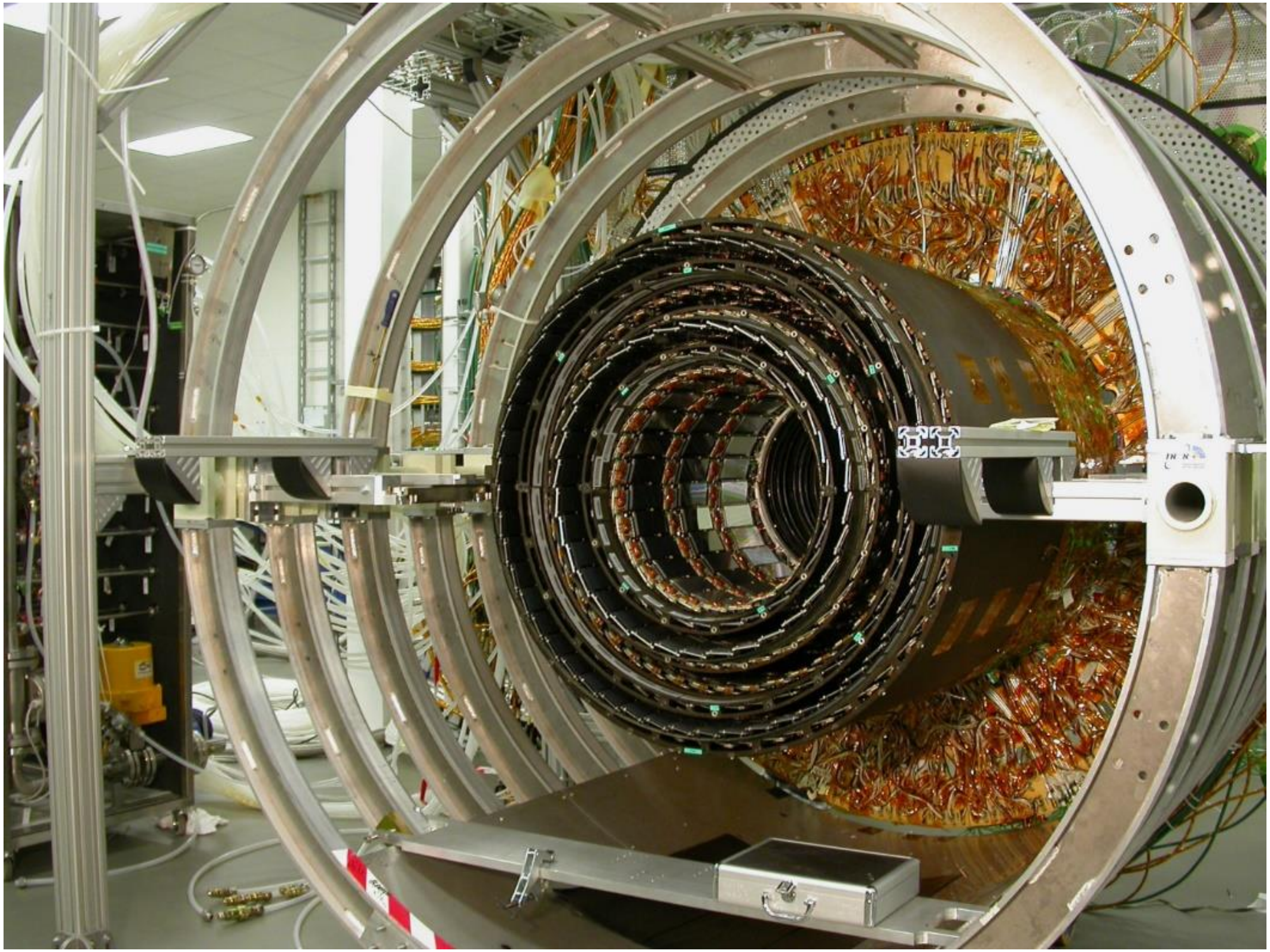
- Low thresholds
- Low noise
- Fast response
- Charge measurement
- Continuous or triggered readout
- Data buffering
- Configuration of internal voltages
- Ability to kill hot channels
- Calibration/trimming of thresholds

Silicon Strip Detectors



Readout electronics at
the ends of the sensors

Silicon Strip Detectors



Pixel Detectors

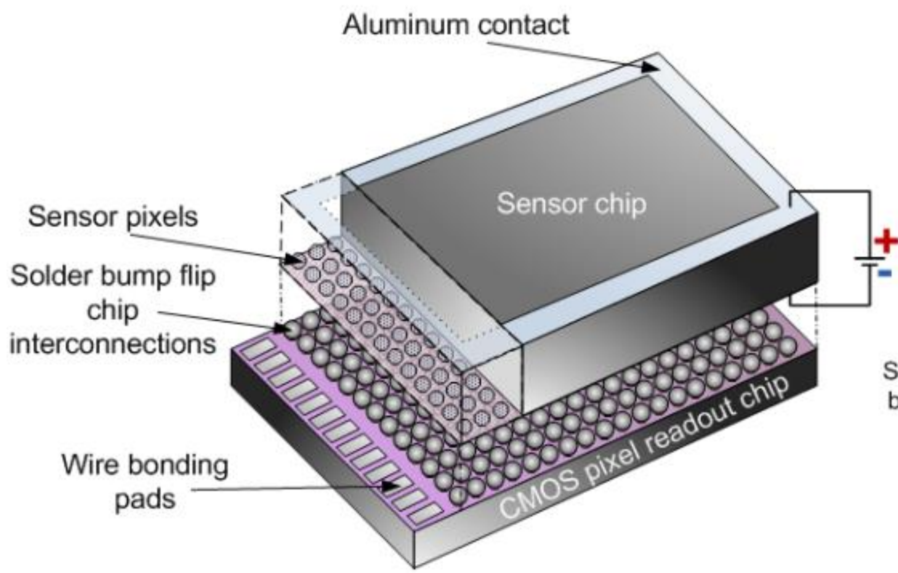
- Silicon strip detectors can have very good position resolution but only in one dimension.
- A pixel detector is segmented in both x and y.
  - Similar to a photographic image sensor

Sensor	Pixel size
ATLAS insertable B-layer	50 x 250 μm^2
CMS pixel detector	100 x 150 μm^2
CMS HL-LHC upgrade	50 x 50 μm^2 (maybe 25 x 100)

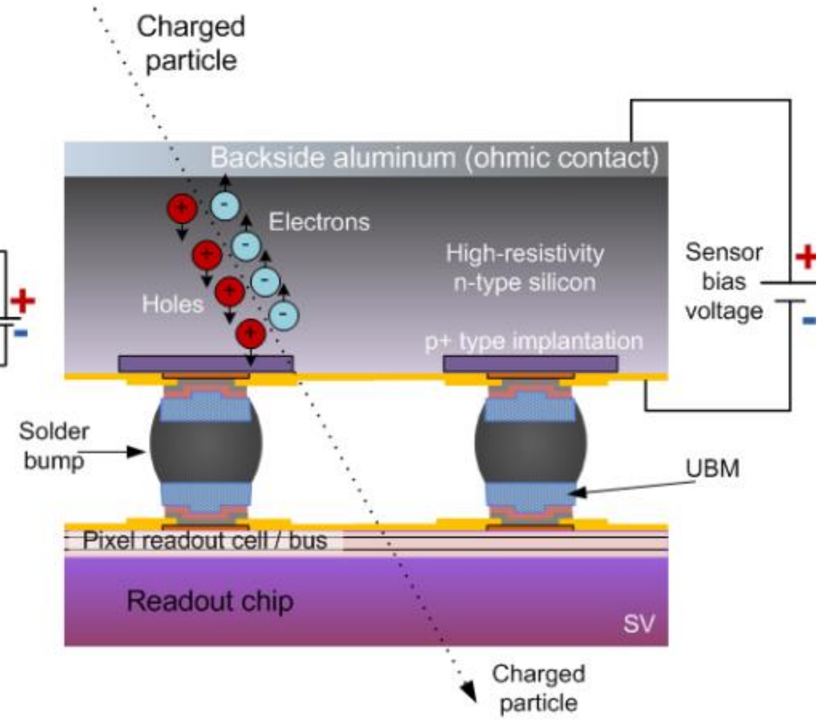
- Connecting the readout electronics to ~20,000 channels per sensor is a challenge

Hybrid Pixel Detectors

- Each pixel is connected to its own readout electronics channel using vertical interconnects

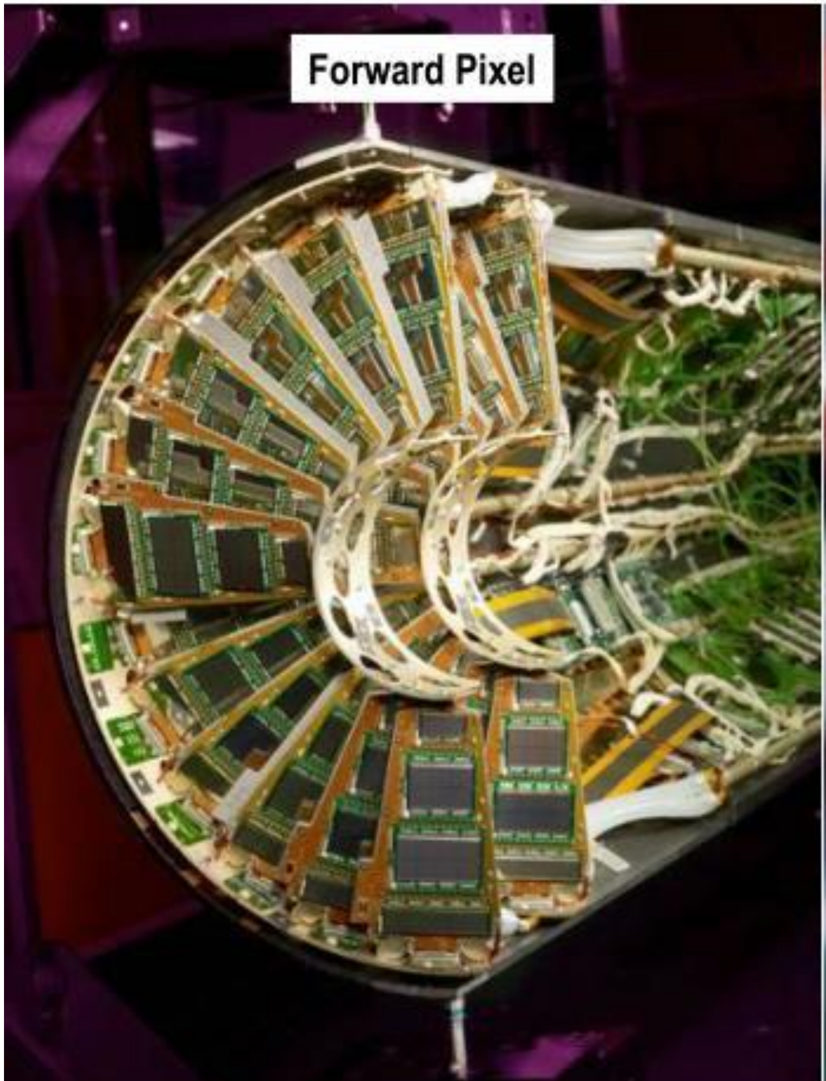


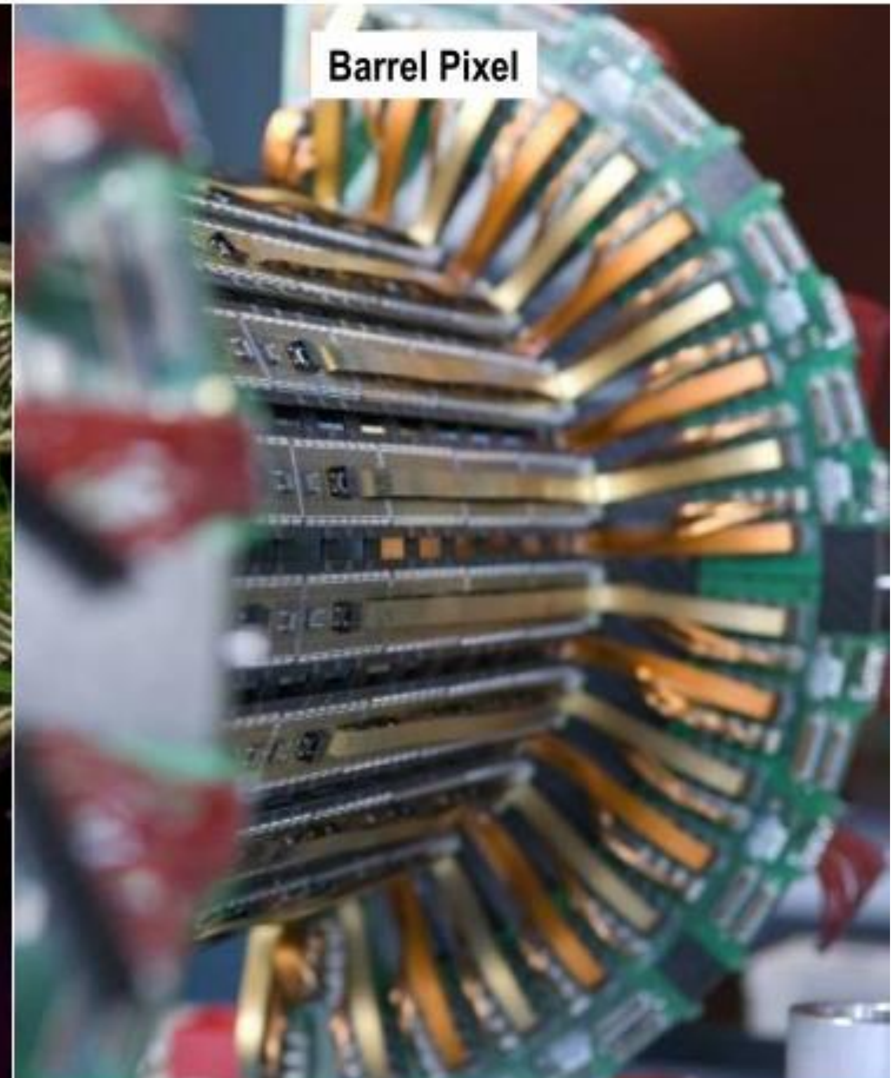
Generic pixel detector



Cross-sectional cut

CMS pixel detector





Particle Detection in CMS