Aspects of HEP – Accelerators and Detectors

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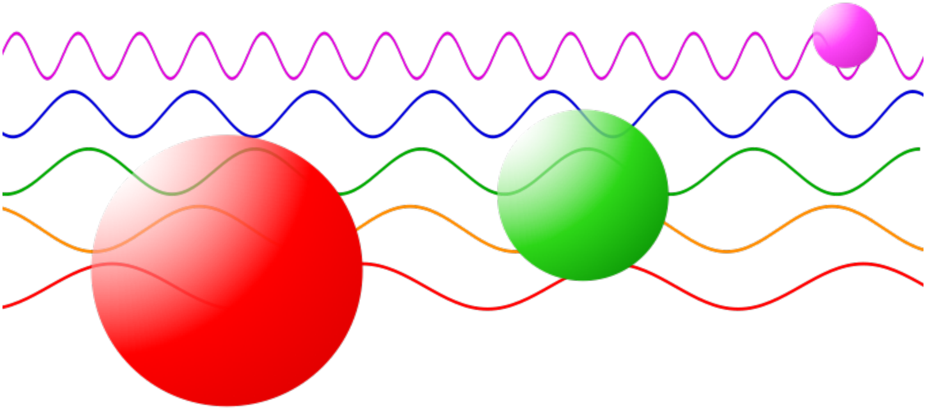
Why Accelerators?

- Larger energy:
  - Smaller distances are explored: $E = h\nu$
  - New massive particles are produced: $E = mc^2$



Collider vs. Fixed Target

- Total (relativistic) energy available E_T:

$$E_T = \left[m_1^2 c^4 + m_2^2 c^4 + 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2 c^2\right)\right]^{1/2}$$

  - Assuming a collision of beam particle B with a fixed target particle A:

$$E_1 = E_B \text{ and } E_2 = m_A c^2$$

$$E_T = \left[2 m_A c^2 E_B\right]^{1/2}$$

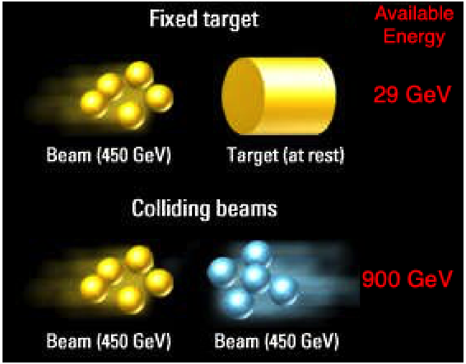
  - Assuming a collision of two beam particles 1 and 2:

$$E_1 = E_B \text{ and } E_2 = E_B$$

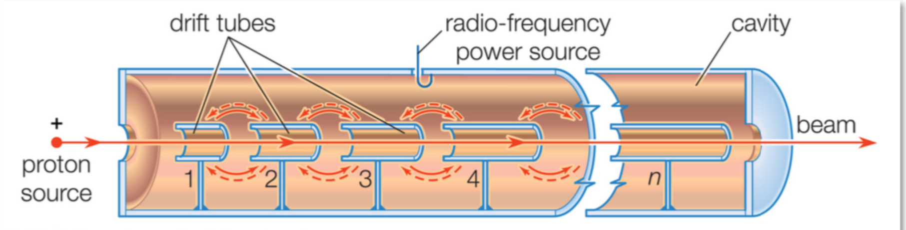
$$|\vec{p}_1| = |-\vec{p}_2| \simeq E_B/c$$

$$E_T = 2E_B$$

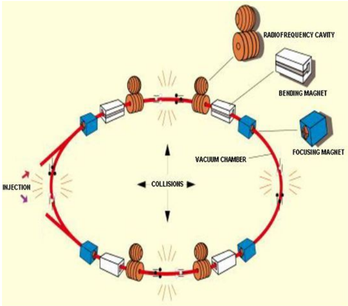
- Target density:
  - Solid iron: $\sim 8.5\times10^{28}$ atoms/m^3
  - LHC beam bunch: $\sim 3\times10^{21}$ protons/m^3



- Charged, stable particles are accelerated
  - Energy is limited only by accelerator length.
  - Beam is lost after collision.
- Acceleration mechanism: drift tubes inside RF cavities
  - Particles are pushed during the “accelerating” half-period of wave.
  - Protected from the “braking” half-period of wave inside the field-free region.



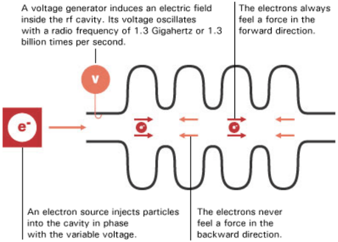
- B-field (bending) and E-field (accelerating cavity)
  - Synchronised with particle velocity.
- pp, ep collider – need different magnets!
- $p\bar{p}$, or e^+e^- – one set of magnets, one vacuum tube.
  - Need to produce antiparticles.
    - Positron – OK, get them from light on material: $e^-\gamma \to e^-e^+e^-$
    - Anti-protons – difficult, get them from proton-nucleus collisions.



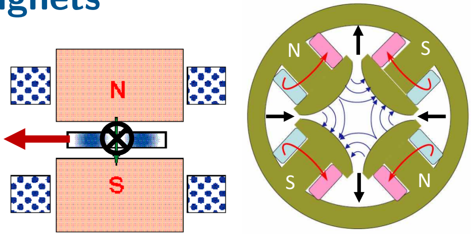
Accelerator Components

RF Cavities

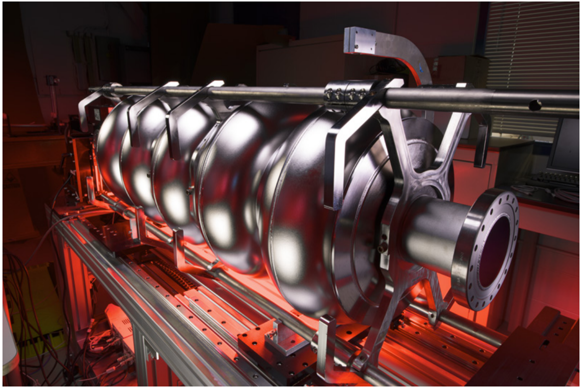
- ☐ Usually made from niobium ☺
- ☐ International Linear Collider plans for 35 MV/m.
- ☐ Length for 500 GeV beams?



Magnets



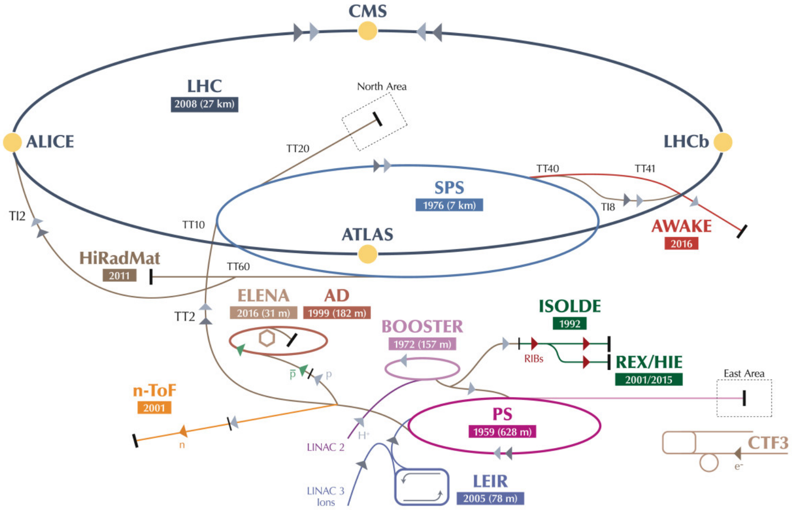
- ☐ Dipoles: bending
  - LHC: Superconducting (1.9K), 14.3 m long, 8.35 T.
  - Proton energy 7 TeV $\Rightarrow$ minimum ring circumference?
- ☐ Quadrupoles: focusing
  - Alternate focusing and defocusing – FODO cell



Synchrotron Radiation

- Energy lost as particles bent to travel in circle: $\Delta E = \frac{4\pi e^2 \beta^2}{3R} \left(\frac{E}{m} \right)^4$.
- Limits energy for a electron/positron machine $\leq$ 100 GeV/beam.
- Hence, higher energy machines (Tevatron, LHC) are hadron colliders.
- Of course, synchrotron radiation is useful on its own right!
  - Useful source of high energy photons for material studies.

CERN Accelerator Complex



Particle Detection

- Particles that exist long enough to fly and reach our detector:
  - p, e, γ, ν are stable.
    - But ν hardly interacts...
  - n, μ, K_L^0, π, $K^\pm$ all live for at least 10 ns.
    - 10 ns $\times\ c =$ 3 m
- There are two divisions to be done:
  - Charged (p, e, μ, π, $K^\pm$) vs. neutral (γ, ν, n, K_L^0)
  - Hadrons (p, n, π, $K^\pm$, K_L^0) vs. others (e, γ, μ, ν)
- Other particles have to be **reconstructed** from the particles we detect.
  - $Z \to e^+e^-$, $t \to Wb \to \mu\nu b$
- To detect the particles, we have to make them interact with **bulk matter**.
- After they interact, we have electric / light signals – to **reconstruct** the particles from the data is a different problem, that will be tackled in the next lecture.

Energy Loss of Charged Heavy Particles (1)

- The dominant energy loss is collision with atoms.
  - Mainly excitation and ionisation.

Bethe-Bloch formula:

$$-\left(\frac{dE}{dx}\right)_{coll} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2 W_{\max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z}\right],$$

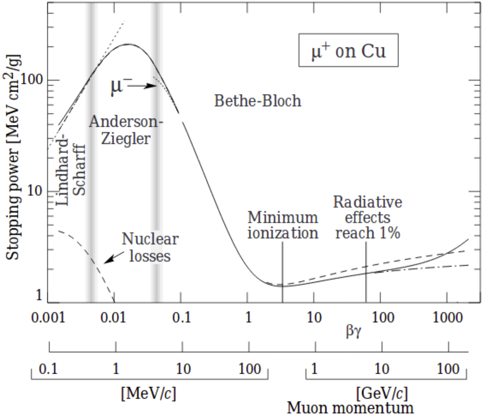
$\gamma = \frac{1}{\sqrt{1-\beta^2}}$: Lorentz factor, and $\beta = v/c$; $r_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{m_e c^2}$;

z: Charge of penetrating particle;
Z and A: Atomic and nuclear numbers of the target;
ρ: Target density;
N_A: Avogadro constant;

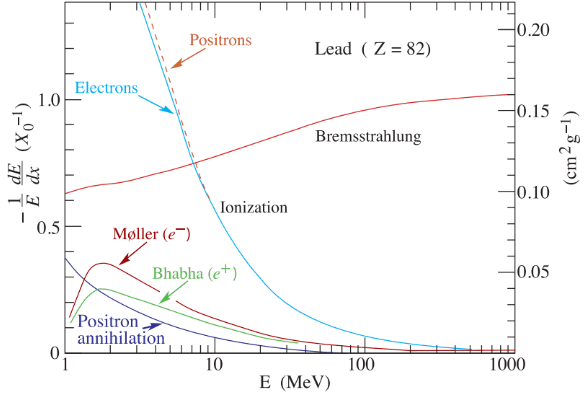
I: mean excitation energy;
W_{max}: Maximal energy transfer in a single collision;
δ: Density correction;
C: Shell correction.

Energy Loss of Charged Heavy Particles (2)

- The $\frac{dE}{dx}$ curve following Bethe-Bloch is a good description for $0.1 < \gamma\beta < 1000$.
- Three regions:
  - At low energies $\frac{dE}{dx}$ drops to a minimum. Particles at this energy are called **minimum ionizing particles** (mip);
  - At higher energies a logarithmic rise follows;
  - At very high energies a plateau is reached...
  - ...but soon a new process comes into play!



Energy Loss of Charged Light Particles: Electrons and Positrons



To the energy loss through collision it is necessary to add effects from **bremsstrahlung**:

$$-\left(\frac{dE}{dx}\right)_{tot} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad}.$$

- Ionisation losses decrease logarithmically with E (and increase linearly with Z);
- Bremsstrahlung increases appr. linear with E (and quadratically with Z);
- **Bremsstrahlung is the dominant process for high energies** (> 1 GeV).
  - Critical energy E_C: electron ionisation losses become equal to bremsstrahlung.

$$E_C \simeq \frac{610(710)\mathrm{MeV}}{Z + 1.24(0.92)} \text{ for solids (gases)}$$

Bremsstrahlung Approximation and Radiation Length

For high energies the energy loss through radiation can be approximated as:

$$-\left(\frac{dE}{dx}\right)_{rad} = 4\alpha\rho N_A \frac{Z(Z+1)}{A} z^2 r_e^2 E \ln\left(183 Z^{\frac{1}{3}}\right)$$

So,

$$-\left(\frac{dE}{dx}\right)_{rad} \propto \frac{E}{m^2}$$

Rewriting the previous expression:

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}.$$

Then,

$$X_0 = \frac{A}{4\alpha\rho N_A Z(Z+1) z^2 r_e^2 \ln\left(183 Z^{-\frac{1}{3}}\right)}.$$

Integrating over it:

$$E(x) = E_0 \cdot \exp\left[-\frac{x}{X_0}\right].$$

The radiation length X_0 is the distance in which the energy of the particle is reduced by $1/e$ due to bremsstrahlung.

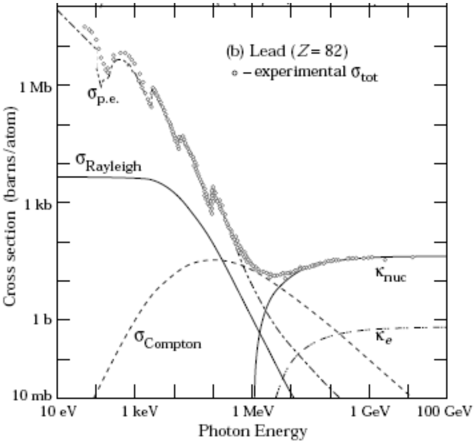
Interactions of Photons – Low Energy

- Photoelectric Effect
  - $\gamma + \text{Atom} \to \text{e}^- + \text{Ion}^+$
  - $E_\text{e} = h\nu - E_\text{binding}$
  - Cross-section (approximation for "high energy" photons):

$$\sigma_\text{photon} = \frac{3}{2}\alpha^4\sigma_0 Z^5 \frac{m_e c^2}{E_\gamma},$$

- Compton Scattering
  - $\gamma + \text{Atom} \to \gamma + \text{e}^- + \text{Ion}^+$
  - $E_\gamma = h\nu_0 - h_\nu = h\nu\left[\frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)}\right]$
  - Cross-section (approximation for "high energy" photons):

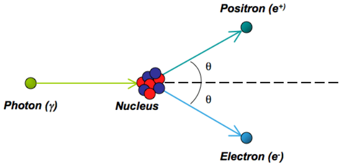
$$\sigma_\text{total} = \frac{2\pi\alpha^2}{s}\log\left(\frac{s}{m_e^2}\right), \quad s = E_\text{CM}^2(e\gamma)$$

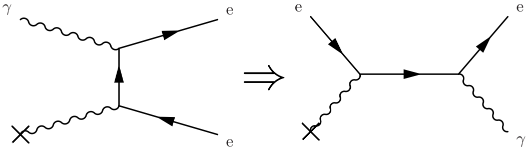


Interactions of Photons – High Energy – Pair Production

- Generation of an electron positron pair by a photon in the field of a nucleus or an electron.

$$\gamma + \text{nucleus} \to e^{+} + e^{-} + \text{nucleus}$$





- The kinetic energy transferred to the target:

$$E_\gamma > 2m_e c^2,$$

$$E_\gamma = h\nu \approx 1.022\ \text{MeV}.$$

- In the high energy approximation the cross section reaches an energy independent value:

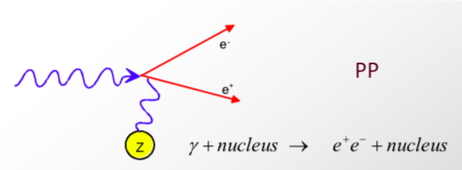
$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right) = \frac{7}{9}\frac{A}{X_0\, N_A}.$$

  - X_0 appears here again because there is a symmetry between the relevant diagrams!

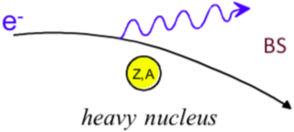
Electromagnetic Shower

Dominant processes at high energies:

- photons: pair production (PP)

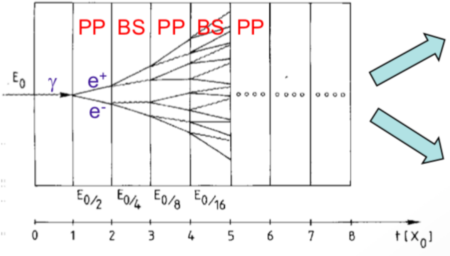


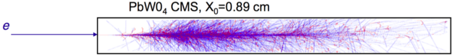
- electrons/positrons: Bremsstrahlung (BS)



Introduce the scale variables

$$t = \frac{x}{X_0} \quad , \quad y = \frac{E}{E_c}$$





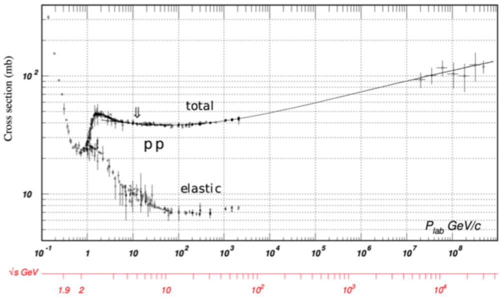
Interaction of Hadrons with Matter (1)

Interaction of a hadron with nucleus

- elastic: $p + N \to p + N$ ($\sigma_{\mathrm{el}} \sim 10$ mb)
- inelastic: $p + N \to X$ (σ_{inel})
  - at high energies also diffractive contribution
- total: $\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{inel}}$
  - dominated by inelastic part: $\sigma_{\mathrm{el}} \sim 10$ mb and $\sigma_{\mathrm{inel}} \propto A^{2/3}$

The total cross section can be approximated:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{tot}}(pA) \approx \sigma_{\mathrm{tot}}(pp) \cdot A^{2/3}$$



Interaction of Hadrons with Matter (2)

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{A}{\sigma_{\text{tot}}(pp) A^{2/3} \cdot \rho N_A} \sim A^{1/3}$$

- Interaction length characterises both longitudinal and transverse profile of hadronic showers
- Similar to the electromagnetic case, but for N particles

$$-\frac{dN}{dx} = \frac{N}{\lambda_{\text{int}}}$$

$$N = N_0 \exp\left(-x/\lambda_{\text{int}}\right)$$

Interaction length x Radiation length:

$$X_0 \sim \frac{A}{Z^2}, \qquad \lambda_{\text{int}} \sim A^{1/3}$$

Dividing one by another

$$\frac{\lambda_{\text{ int}}}{X_0} \sim A^{4/3} \to \lambda_{\text{ int}} \gg X_0$$

Hadronic calorimeter needs to be larger than electromagnetic calorimeter (more layers).

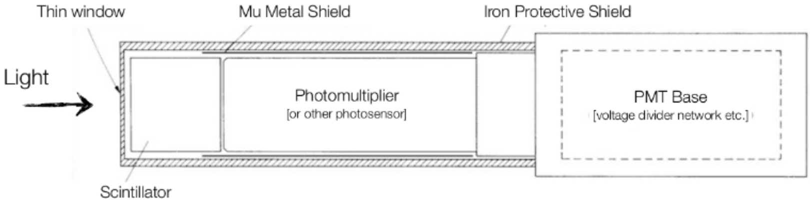
	C	LAr	Fe	U	Scint.
$\lambda_A(\text{cm})$	38.8	85.7	16.8	11.0	79.5
$X_0(\text{cm})$	19.3	14.0	1.76	0.32	42.4

Working principle

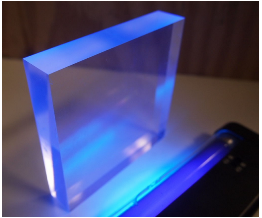
A scintillator is a material that converts the energy of the passage of a particle into light that will be collected by a photosensor.

This process is possible because of fluorescence, an effect that happens when an excited electron moves from a higher energy level, to a lower one.

The scintillator material must be transparent to its own fluorescent light, the conversion must be efficient, and the light needs to be detectable by photosensors.



Types and applications



There are some very important uses for the scintillators:

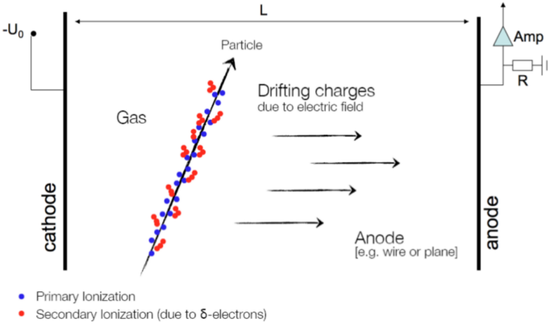
- Particle counters;
- Image displays;
- Energy measurements (at very high rate);
- Trackers (need multiple layers, or can be used as a type of trigger, as will be seen later).

Three types of scintillators can be used, each one with its advantages or disadvantages:

- Inorganic scintillators;
- Liquid noble gases scintillators;
- Organic scintillators.

Working principle

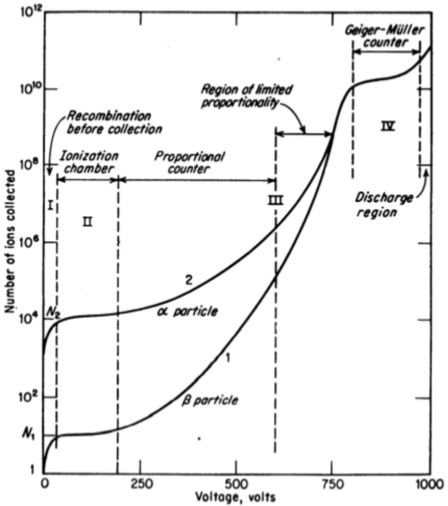
The gas chamber detection principle is based on ionisation. A **charged particle** ionises the gas (gas mixtures are commonly used), the electrons and ions drift through the gas (external $\vec{E}$ applied) and generate an electric signal.



Gas Chambers – Gain and Relevant Effects

The gain of the electric signal is improved by an avalanche of ions and electrons from secondary ionisation (delta electrons).
Some relevant effects are:

- Recombination and electron attachment;
- Delta electrons;
- Diffusion;
- Mobility of charges;
- Avalanche process.

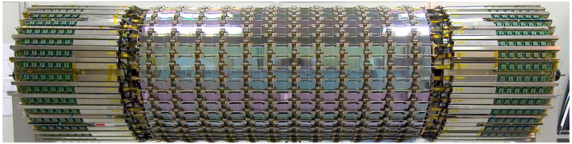


Working principle

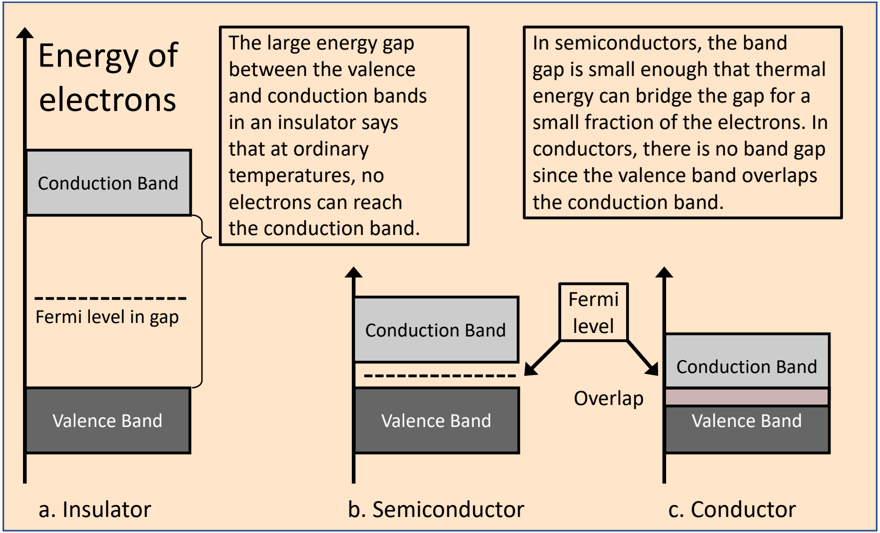
A semiconductor detector is a **radiation damage resistant** type of detector, which can be produced with a few micrometers of precision but at a higher cost.

Its signal is generated by the passage of a **charged particle**, producing electron-hole pairs that will be collected by the readout electronics.

A crystalline material can be modelled by the energy bands, that are separated as conduction band and valence band, and the energy gap of the electrons energy.



Energy Bands

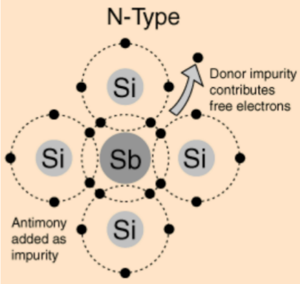


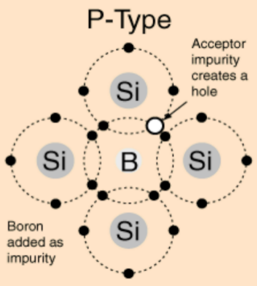
n-type and p-type Semiconductors

Using Si as an example from now on. It's a tetravalent element that will form covalent bonds with the other atoms in a lattice.

It's possible to insert other elements in the lattice to improve its detection capabilities (doping).

Doping the semiconductor is extremely important to increase the resolution of the detector. These materials are called N-type or P-type (increased number of electrons or holes).

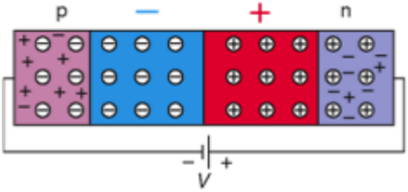


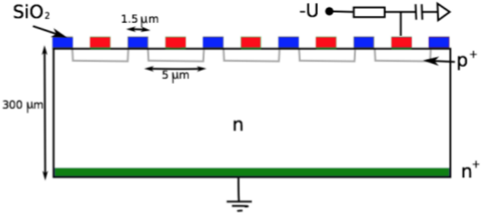


pn Junction and Depletion Region

By putting a n-type material in contact with a p-type material, a depletion region is created, altering the semiconductor conductivity.

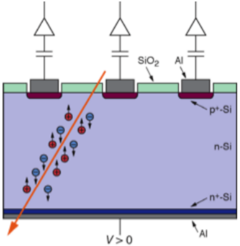
If an external voltage is applied with the cathode connected to the p-type and the anode to the n-type, the depletion zone is enlarged, which makes the current across the junction very small (to improve the resolution). Right figure is an example of a Si detector in the form of microstrips.





Charge Carrier Mobility and Drift Velocity

When a charged particle passes through the detector, it will generate several electron-hole pairs. The drift velocity of those charge carriers in an external electric field is



$$\vec{v}_D = \frac{e\vec{E}}{2M}\tau = \mu\vec{E}, \text{ and } v_D^h \approx \frac{v_D^e}{2} \text{ (distinct from gases);}$$

where the mobility μ was measured as:

$\mu \simeq$ const for $E < 10^3$ V/cm;

$\mu \propto {}^1/\sqrt{E}$ for 10^3 V/cm $< E < 10^4$ V/cm;

$\mu \propto {}^1/E$ for $E > 10^4$ V/cm,

and τ is the mean time between collisions, also defined as $\tau = {}^\lambda/v_{\text{thermal}}$ with λ = mean free path. v_D saturates at approximately 10^7 cm/μs.

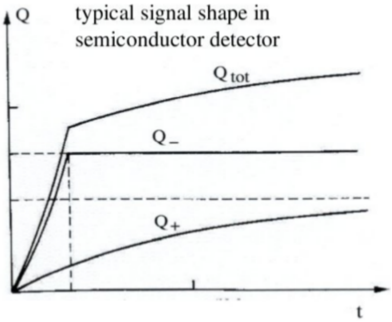
In some detectors, the goal is to achieve constant v_D, to determine the drift time $\Delta t = {}^L/v_D$. For a typical v_D in 100 μm, the drift time is 10 ns.

Signal Rise Time

Another important property that come from v_D is the signal rise time, which will be something of the order of 1 ns for Si detectors, allowing a very high rate.

There are some details:

- $\mu_\pm$ are not constant;
- Loss of charges;
- The charge is distributed over a surface, and some mismeasurements can happen.



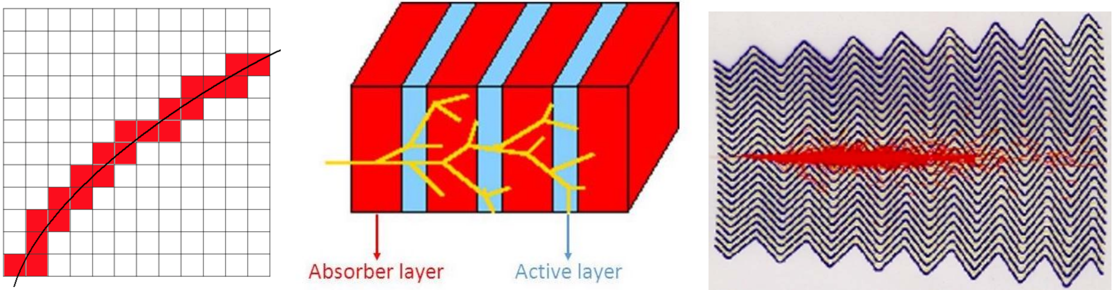
Trackers and Calorimeters

Tracker

- Measures charged particle tracks in a **non-destructive way** and it usually has:
  - a medium that will produce one or more signals as the particles pass through it;
  - a strong surrounding $\vec{B}$ field to determine particles' charges and momenta.
- (At least) two types:
  - Semiconductor tracker: use for high particle rates (closer to interaction point), more expensive.
  - Gas tracker: use for lower particle rates (farther away), cheaper.
  - (Other possibilities also exist, of course. Extensive R&D!)

Calorimeter

- Measures the energy of charged or neutral particles in a **destructive** way, since it totally absorbs the particles after the shower.
  - Made of dense material to produce particles' interaction.
  - Made of active material to produce measurable quantity.
- Two types:
  - Sampling calorimeter: alternated layers of passive absorbers and active detectors.
  - Homogeneous calorimeter: absorber and active detector at same time.

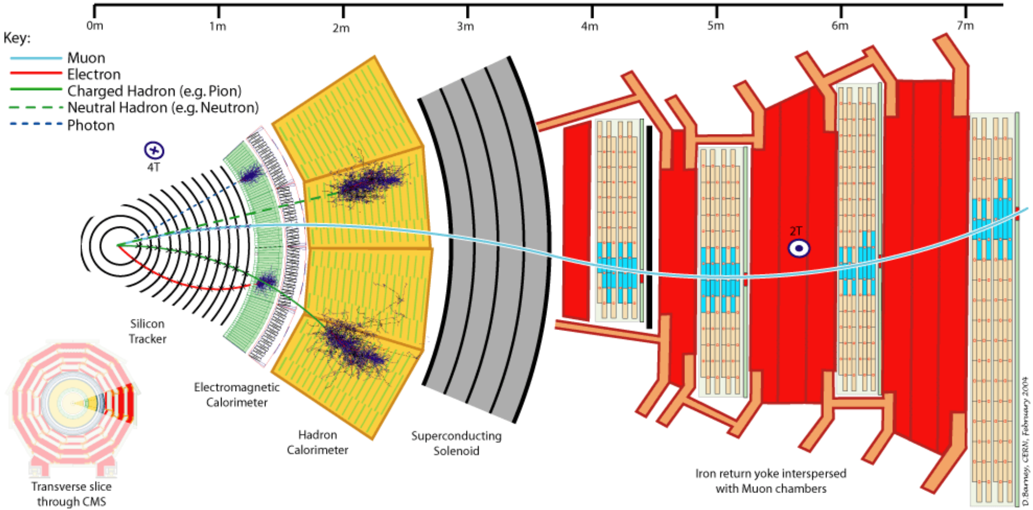


Left: Cartoon of tracker hits. Center: Sampling calorimeter scheme. Right: simulated shower in ATLAS LAr calorimeter.

Integrating All Detectors

- Ideally, we want to measure $(E, \vec{p})$, q, m of all particles produced in the collision.
- Take non-destructive measurements before destructive measurements.
  - Observe the passage of the particle without disturbing it much – small X_0, small λ_{int}.
  - In other words, **track** the particle and measure its momentum.
  - Then, make it undergo a shower in bulk material – in a **calorimeter** – and measure the total deposited energy.
- Special case 1: muons!
  - Muons have very high range – need $\sim$12 meters of pure copper to stop a 20 GeV muon.
  - Alternative: build calorimeters that let the muon pass through, re-track them at the end.
- Special case 2: neutrinos!
  - Interact only through the weak interaction – very small cross-section!
  - Dedicated experiments – Super-Kamiokande, MiniBooNE, DUNE ...

Multipurpose Detectors



Tools of the Trade

GEANT4
A SIMULATION TOOLKIT

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

DELPHES
fast simulation

Delphes is a C++ framework, performing a fast multipurpose detector response simulation. The simulation includes a tracking system, embedded into a magnetic field, calorimeters and a muon system.

We managed to detect the particles. . .

. . . time to reconstruct the data!

Acknowledgements

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