2 Accelerators and Particle Detectors

All accelerators work by firing charged particles through a region of electric potential difference. For a particle of charge e, the kinetic energy gained is:

$$T = eV \tag{1}$$

The simplest accelerator is just a big source of potential difference like a Van De Graff generator. An excellent example is the Pelletron in the Basement of the Physics building.

The highest energy machine operates up to 25 Million Volts. These devices are limited by the breaked of the insulating gas between the potential source and ground.

2.1 Linear Accelerators

Instead of giving a big voltage difference just once (like a Van de Graff) we can increase the total energy gained by applying a smaller voltage difference many times.

This is the principle of all other accelerating structures. In the case of a linear accelerator a series of accelerating cavity fed by an AC signal of fixed frequency are arranged in a straight line. The lengths of each segment are such that:

$$\frac{L_i}{v_i} = \frac{T}{2} = \frac{1}{2 \times RF frequency} \tag{2}$$

Here T is the period of the RF frequency. Each segment is designed so that the particles receive a boost everytime they cross into a drift region.

The Los Alamos Linear proton accelerator provides up to 800 MeV protons at a beam current of 1 MA.

The Stanford linear accelerator provides 50 GeV electrons at currents of 10 μA.

2.2 Synchrotrons

Synchrotrons are cyclic enclosed accelerators and to date, provide the highest energy particle beams.

Particles are guided along a circular or oval path by a series of electromagnets. The main bending elements are the dipole magnets. These utilize the fact that charged particles travel in circles within a magnetic field.

$$F = qvB = \frac{\gamma m_0 v^2}{\rho} \tag{3}$$

Where v = Particles velocity
B = Magnetic field
ρ = radius of curvature

$$\rho = \frac{\gamma m_0 v}{qB} = \frac{P}{qB} = \frac{P}{0.3B} \tag{4}$$

for P in GeV, B in Tesla and ρ in meters. These magnets do the main job of bend the particle beam.

However they are not sufficient for a particle accelerators since any transverse momentum components of the beam would quickly result in the beam "blowing up" in size auntil it was lost. What is required is some beam focusing elements so that this traverse momentum is reflected back towards the center of the beam pipe.

This focussing is provided by Quadrapole magnets. The are magnetic devices with 4 poles. The field is arranged to be 0 at the center of the device and increases with distance off axis.

All quadrapole magnets focus in one plane and defocus in the other. If you put a series of focus-defocus-focus elements together the net result is beam focussing.

The exact design of magnetic elements to make an accelerator is a high art form known as beam optics. This is a specialized field of Physics known as Accelerator Physics. This field of research has won Nobel Prizes as advances in accelerator design have underpinned many fundamental discoveries.

A synchrotron is a cyclic device. It takes a low energy beam from an injector with magnetic fields. As the particle bunch is accelerated, the magnetic fields are raised and the RF frequency is increased.

Within a synchrotron, the particles in a particular bunch have a range of different energies. Since the device is an enclosed ring, high energy particles (compared to the mean) have a slighter larger radius of curvature and so will takes a longer path around the syncrotron. Conversely low energy particle (compared to the mean) will have a slightly shorter path around the ring.

This is exploited to keep the particle bunch together in energy by arranging the RF accelerating potential to be on a downard gradient such that particles with exactly the mean energy arrive as the accelarting potential has fallen to half its maximum potential. By arranging for this situation, particles arriving early (the low nergy particles which have followed a shorter path) get a larger boost than the mean and are therefore kicked towards the mean. Particles arriving later, (the high energy particles having taken the longer path around the synchrotron) receive a smaller boost and therefore fall towards the mean.

Consequently the beam "surfs" on the accelerating edge. Particles with lower energies get a larger boost and are kicked towards the mean. Particles with higher lower receive a smaller boost and so fall towards the mean.

The beam does "synchrotron" oscillations about the equilibrium position.

2.3 Electron Synchrotrons

All charged particles undergo E/M radiation when accelerated. Under circular acceleration a charged particle loses:

$$\Delta E = \frac{4\pi}{3}\frac{e^2\beta^2\gamma^4}{\rho} = \frac{6.04\times10^{-15}\beta^2\gamma^4}{\rho} MeV/cycle \tag{5}$$

Where:
Δ E = energy loss per particle cycle.
β = $\frac{v}{c}$ fraction of the speed of light.
ρ = Bending radius
γ = Gamma Factor = $\frac{1}{\sqrt{1-\beta^2}} = 1 + \frac{T}{m_0c^2}$

So the ratio of synchrotron radiation loss for electron/proton machines is $(\frac{m_e}{m_p})^4 \approx \; 10^{13}$.

This is a big effect for electron machines. eg A 10 GeV electron loses 1 MeV/cycle in 1 1km radius machines. This synchrotron has incredible value as an intense source of X-rays. It is by far the best source of X-rays available and is widely used for X-ray crystalography. In particular by Pharacetical Companies who investigate sophisticated proteins using protein crystralography.

It is however a big problem for Particle Physicists and limits the useful upper energy of electron synchrotrons.

2.4 Colliding Beam Machines

The CM energy of the collision of a particle m$_a$ with a target of mass m$_b$ is, (units units c=1)

$$E_{CM} = \sqrt{m_A^2 + m_b^2 + 2m_b(m_a + T_a)} \tag{6}$$

Where T$_a$ = lab kinetic energy

For a 100 GeV proton hitting another stationary proton, E$_{CM}$ = 13.8 GeV.

If we can arrange to collide 2 beams of equal momentum then E$_{cm}$ = 2 E$_A$, where E$_A$ = E$_b$ = energy of the beams.

This gives a lot more energy for particle creation.
However you have to use stable particles, (actually there is now an on-going world-wide effort to produce a muon collider).

The reaction rate is given by:

$$R = \sigma L \tag{7}$$

L = luminosity (in units of cm^{2}s^{-1})
R = Reactions rate, (number of reactions/sec)
σ = cross section.

Then L is given by:

$$L = \frac{fnN_1N_2}{A} \tag{8}$$

f = revolution frequency
n = number of bunches in the beam
N$_1$ = Number of particles in beam 1.
N$_2$ = Number of particles in beam 2.
A = cross sectional area of the beams.

Typical luminosities for new state of the art colliders are 10^{34} cm^2/sec. This is the design goal of the KEKB accelerator in Japan. To date we have achieved 2×10^{33} cm^2/sec.

In general colliding beam machines only bring the particle beams together for collisions at one or more positions around the ring. At these points the beams are squeezed as small as possible to achive high luminosity.

The size of the final focus (and hence the luminosity) depends on how nearly parallel the initial beams are.

In this context “Parallelness” is proportional to “lateral momentum spread” which in turn is proportional to the so-called “Temperature” of the beam.

A “cool” beam has a small momentum spread, a “Hot” beam has a large momentum spread.

Proton beams comes from a high quality ion source so they have a low temperature.

Anti-protons on the other hand come from proton-nucleus collisions and have a very high temperature if large numbers are to be collected.

Simon Van der Meer from CERN won the Nobel Prize for the discovery of the W and Z because of his invention of “Stochastic cooling” of anti-protons. This enabled the experiment to achieve the luminosity required to detect the W and Z particles.

2.5 Particle Interactions with Matter

All particles are detected by the transfer of energy from the particle to the medium they are traversing via theprocess of ionization or excitation of the constituant atoms.

Charged particles ionizes or excites the atom as it traverses the material.

The mean rate of energy loss is given by the Bethe-Bloch formula:

$$\frac{dE}{dy} = \frac{4\pi N_0 Z_i^2 e^4}{mv^2}\frac{Z_m}{A}\left[\log_e\left(\frac{2mv^2}{I(1-\beta^2)}\right) - \beta^2\right] \tag{9}$$

Where m is the electron mass
Z_i and v are the charge (in units of e) and velocity of the particle
$\beta = \frac{v}{c}$
N_0 = Avagadro’s Number
Z_m and A are the Atomic Number and mass number of the material (0.5 for most materials)
y is the path length in the medium in units of g/cm^2 = (distance in cm)(desnity in gm/cm^3)
I = Average Ionization Potential ≈ 10 Z eV

Plugging in numerical values give:

$$\frac{dE}{dx} = 0.307 \times \frac{Z_m}{A}\rho_m(\frac{Z_i}{\beta})^2\left[\log_e\left(\frac{1.02\times10^6\gamma^2\beta^2}{I}\right) - \beta\right] \quad MeV/cm \tag{10}$$

ρ = density in gm/cm^3

You can get a quick and dirty estimate for most materials by putting $\frac{Z_m}{A} \approx 0.5$, then all you need is ρ_m.

In practice this equation is really only valid for thin layers of materials. As the thickness increases the chance that hadrons will initiate nuclear reactions increases.

The number of interactions dI caused by N particles traversing a small distance dx is:

$$dI = Nn\sigma dx \tag{11}$$

Where σ = total cross section for the interaction of the particles
n = number of nuclei per unit volume

Then dN = -dI (the change in the number of particles N)
so

$$\frac{dN}{dx} = -Nn\sigma \tag{12}$$

$$\Rightarrow \quad N = N_0 e^{\frac{x}{L_0}} \tag{13}$$

and so

$$I = N_0 - N(x) = N_0(1 - e^{-\frac{x}{L_0}}) \tag{14}$$

Where L$_0$ = $\frac{1}{n\sigma}$ = Nuclear Interaction length.

Muons do not undergo nuclear reactions. This is basis of identifying high energy muons. Put a big chunck of matter in a particles path and if any charged particle comes out they are muons.

2.6 Radiation Loss of Electrons

Electrons lose energy via the Bethe-Bloch ionization process and also via Bremstraalung (Breaking Radiation).

The nuclear electric field de-accelerates the electrons so it emits photons.

The Bremsstralung radiation loss is:

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0} \tag{15}$$

Where X_0 = "radiation length", E = energy of the electron.

$$\frac{1}{X_0} = \frac{4Z_m(Z_m+1)r_e^2 N_0}{137 A_m \rho} \log_e \left(\frac{183}{Z_m^{\frac{1}{3}}} \right) \tag{16}$$

Where ρ = density of the material
$r_e = \frac{e^2}{mc^2}$ classical electron radius
Z_m = Z of the material
A_m = Atomic Number
N_0 = Avagro's Number
We therefore get:

$$\frac{1}{X_0} = \frac{1.39 \times 10^{-3} Z(Z+1)}{A\rho} \log_e \left(\frac{183}{Z^{\frac{1}{3}}} \right) cm^{-1} \tag{17}$$

Therefore the average energy after traversing a material x cm thick is

$$E = E_0 \exp \left(\frac{-x}{X_0} \right) \tag{18}$$

So the radiation length is just the length that gives $\frac{1}{e}$ of the original energy.

At high energy or large Z, Bremstraalung dominates over Bethe-Bloch for electrons.

2.7 Particle Detectors

Particle detectors used in Particle Physics are required to give the position, arrival time and identity of charged particles.

Position is needed to determine particle trajectories and with the aid of a magnetic field, the particle momentum.

Time is needed to associate particles from the same interaction (also called event) and to measure particle velocity.

Identity. To distinguish an e, μ , π , K, p, n, γ etc. This is often the hardest part.

In general a detector achieves all these with many components.

2.8 Scintillators

An indispensible part of an experimentalists array of tools.

When a charged particle passes through scintillator material, part of the energy loss it experiences is converted into visible light photons.

These photons are guided to a photomultiplier tube and are converted into an electrical pulse.

Height of the pulse $\propto$ energy loss in the scintillator. Time of the pulse can be determined to $<$ 0.1 nanoseconds.

These give excellent time information and energy loss data.

There are two main sorts of scintillators.

1. Organic "Plastic" scintillators. These are cheap, easy to use, give excellent time and pulse height information.
2. Inorganic Scintillators. NaI, BGO, BaF_2. Give good energy loss information and have large "Z" atomic numbers. These are suitable for Electron and Photon Calorimeters.

2.9 Calorimeters

So called because the total energy of the particle is absorbed in the the device. In the case of electron and Photon Calorimeters the active material is often a large inoganic scintillator crystal with a large effect Z. Typical crystals are NaI and CsI. These are typcially 20 or more radiation lengths thick. Electrons and photons entering the device undergo secondary electron/photon/positron production via pair production and Bremstruung processes. These eletrons, positrons and photons undergo further conversions processes and pretty soon an electromagnetic shower is produced.

The fact that $E = E_0 \exp(\frac{-E}{X_0})$ means that a scintillator crystal 20 X_0 thick will stop <u>all</u> photons and electrons no matter how high their energy.

This energy is eventually converted to light and is detected in the PhotoMultiplier Tube (or other light detection device). The amount of light is proportional to the energy of the incident electron or photon.

2.10 Hadronic Calorimeters

The fact that hadrons undergo nuclear interactions can be exploited to absorb their total energy too. In these devices material with a large nuclear cross section like Fe or Pb is interspersed with scintillators. As the hadrons initiate nuclear interactions they release charged particles which are detected by the scintillator.

Then the total light output is proportional to the incident energy of the hadron.

As mentioned earlier hadronic calorimeters together with charged particle trackers downstream from the Calorimeter can be used to detect muons. Any charged particle that emerges from the calorimeter must be muon since all others will be aborbed via strong or electromagnetic interactions.

2.11 Multiwire Chambers

These devices consist of a (typically) planer chamber filled with gas with embedded wires within the chamber. Charged particles which traverse the chamber ionize the gas which liberate electrons. These electrons are attracted to the wires which are held at a large +ve potential (typically $>$ 1000 Volts). Near the wire the electric field increases as $\frac{1}{r}$ and eventually the electrons gain enough energy to further ionize the gas. These secondary electrons initiate more ionizations causing an avalanch of electrons to fall on the wire.

This process of secondary ionization is called "gas amplification" and in fact the initial few electrons are amplified by a factor of up 10^7. This induced a sizable pulse on the anode wire nearest the position of that the charged particle when through the chamber. In addition information on the position of the interaction in the dimension perpendicular to the anode wires can be obtained by placing cathode strips at right angles to the anaode wires on the walls of the detector.

Thes devices give position resolutions equal to half the wire spacing.

2.12 Drift Chambers

These are like Multiwire chambers but use the drift time between the initial liberation of electrons and when the pulse on the wire occurs to interpolate between the anode wires and achieve an order of magnitude better position resolution.

The idea is that it takes finite time for the electrons to travel from the point where they were liberated by the passage of the charged particle to the anode wire. During that time it is possible to make the electrons travel at almost constant velocity by a cunning arrangement of cathode field shaping strips. Then position of the initial particle interaction within the detector is directly proportional to the time between when the charged particle went through the detector to the time at which the anode wire fires.

For these detectors to work we need the a well defined “start time” or T_0. This is often obtained from scintillators in the detector.

2.13 Cherenkov Detectors

When a charged particle traverses an optically transperent medium at greater than the speed of light in that medium, the particle emits Cherenkov light.

The angle of emission is given by the formula:

$$\cos(\theta) = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n} \tag{19}$$

The minimum β at which cherenkov light is emitted is

$$\beta = \frac{1}{n} \tag{20}$$

So the Cherenkov effect can be used to determine a particle's β.

It is possible to use gas detectors with n $\approx$ 1.0 so that we can determine β very close to 1.0.

Then we can combine information from β and information about the momentum (from the trajectory in a magnetic field) to determine the particles mass and hence do Particle Identification.

2.14 Semiconductor Detectors

These devices are basically reversed biased Diodes. Charged particles create electron-hole pairs by their passage through the detectors. These are collected at the contacts on the device. The size of the pulse from the particle is proportional to the energy loss in the detector.

It ispossible to obtain very precise position information using these devices since the detector contacts can be inscribed with photo-lithographic techniques.

The resoltion of these detectors be made very small, 5 μm has been achieve although better resolutions are possible. These are often placed in arrays to provide high precision tracking near an interaction vertex.

this are widely used to identify the presence and characteristics of B (Beauty) and D (charm) mesons decays. They are vital ingrediant of the BELLE detector which coulkd not do CP violation searches without these devices. The School of Physics has an extensive program to build and operate these semiconductor detectors.