CHAPTER 1

Accelerators

Use of Accelerators

Quite simply, accelerators give high energy to subatomic particles, which then collide with targets. Out of this interaction come many other subatomic particles that pass into detectors. From the information gathered in the detectors, physicists can determine properties of the particles and their interactions.

The higher the energy of the accelerated particles, the more closely we can probe the structure of matter. For that reason a major goal of researchers is to produce higher and higher particle energies.

Accelerator: A device (i.e., machine) used to produce high-energy high-speed beams of charged particles, such as electrons, protons, or heavy ions, for research in high-energy and nuclear physics, synchrotron radiation research, medical therapies, and some industrial applications. The accelerator at SLAC is an electron accelerator.

Electron accelerator: Electrons carry electrical charge and successful manipulation of electrons allows electronic devices to function. The picture and text on the video terminal in front of you is caused by electrons being accelerated and focused onto the inside of the screen, where a phosphor absorbs the electrons and light is produced. A television screen is a simple, low-energy example of an electron accelerator. A typical medical electron accelerator used in medical radiation therapy is about 1000 times more powerful than a color television set, while the electron accelerator at SLAC is about 2,000,000 times more powerful than a color TV. One example of an electron accelerator used in radiotherapy is the Clinac, manufactured by Varian Associates in Palo Alto, CA.

Types of Accelerators:

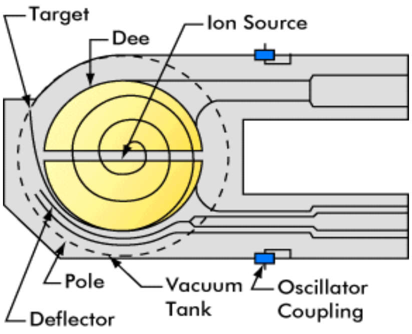
Particle accelerators come in two basic designs, linear (linac) and circular (synchrotron). The accelerator at SLAC is a linac.

The longer a linac is, the higher the energy of the particles it can produce. A synchrotron achieves high energy by circulating particles many times before they hit their targets.

Linacs are used in medicine as well as high energy physics research.

Cyclotron

The cyclotron is a particle accelerator conceived by Ernest O. Lawrence in 1929, and developed, with this colleagues and students at the University of California in the 1930s. (For a short pictorial history, see The Development of the Cyclotron at LBNL.)



A cyclotron consisted of two large dipole magnets designed to produce a semi-circular region of uniform magnetic field, pointing uniformly downward.

These were called Ds because of their D-shape. The two D's were placed back-to-back with their straight sides parallel but slightly separated.

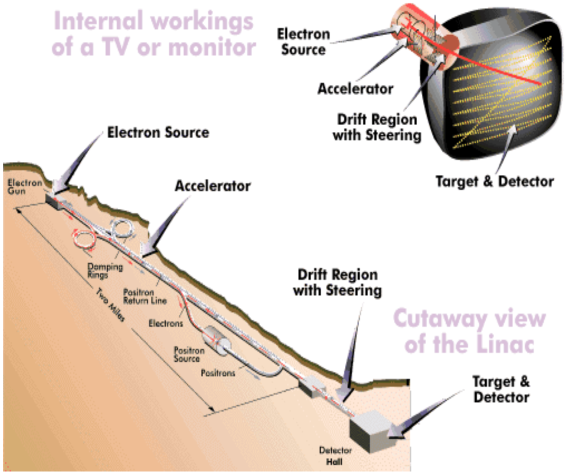
An oscillating voltage was applied to produce an electric field across this gap. Particles injected into the magnetic field region of a D trace out a semicircular path until they reach the gap. The electric field in the gap then accelerates the particles as they pass across it.

The particles now have higher energy so they follow a semi-circular path in the next D with larger radius and so reach the gap again. The electric field frequency must be just right so that the direction of the field has reversed by their time of arrival at the gap. The field in the gap accelerates them and they enter the first D again. Thus the particles gain energy as they spiral around. The trick is that as they speed up, they trace a larger arc and so they always take the same time to reach the gap. This way a constant frequency electric field oscillation continues to always accelerate them across the gap. The limitation on the energy that can be reached in such a device depends on the size of the magnets that form the D's and the strength of their magnetic fields.

Once the synchrotron principle was developed (see below), it was found to be a much cheaper way to achieve high energy particles than the cyclotron and so the original cyclotron method is no longer used.

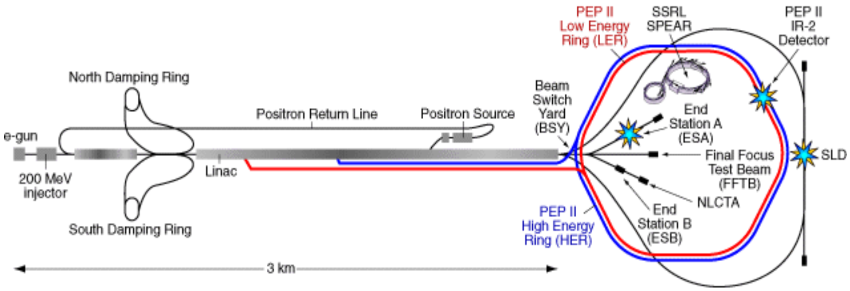
How do they work?

Your TV set or computer monitor contains the components of an accelerator. As you might suspect, operating an accelerator as large as the linac at SLAC is a challenging task. To learn more about the SLAC linear accelerator structural components and experimental facilities, select a link below.

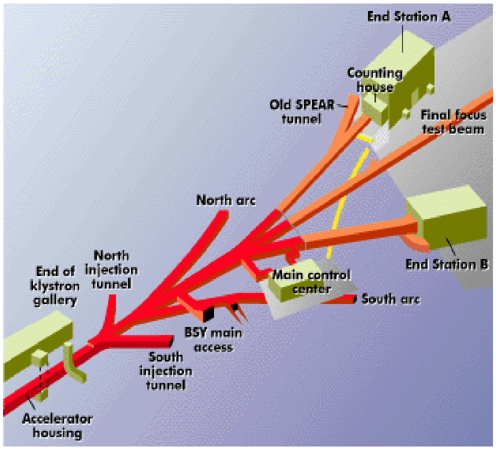


Accelerator Components

- Beam Switch Yard
- Damping Rings
- Electron Gun
- Klystrons
- Linac
- Positron Production



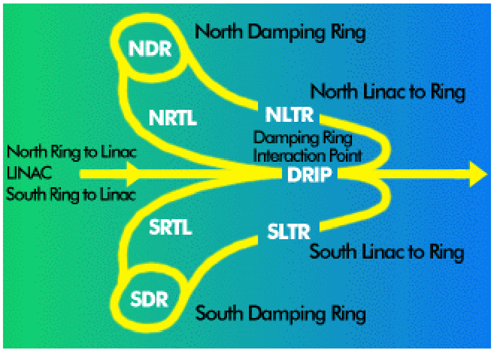
Beam Switch Yard



When the electrons and positrons reach the end of the linac and enter the Beam Switch Yard (BSY), they are diverted in different directions by a powerful dipole magnet and travel into storage rings, such as SPEAR or PEP, or into other experimental facilities, such as Final Focus Test Beam (FFTB) or the arcs of SLC -- the SLAC Linear Collider.

Damping Ring

After the first ten feet of the linac, the electrons are traveling in bunches with an energy of approximately 10 MeV. This means the electrons have reached 99.9% the speed of light. These bunches have a tendency to spread out in the directions perpendicular to their travel.



Because a spread out beam gives fewer collisions than a narrowly focused one, the electron and positron bunches are sent into damping rings (electrons to north, positrons to south).

These are small storage rings located on either side of the main accelerator. As the bunches circulate in the damping ring, they lose energy by synchrotron radiation and are re-accelerated each time they pass through a cavity fed with electric and magnetic fields. The synchrotron radiation decreases the motion in any direction, while the cavity re-accelerates only those in the desired direction. Thus, the bunch of electrons or positrons becomes more and more parallel in motion as the radiation "damps out" motion in the unwanted directions.

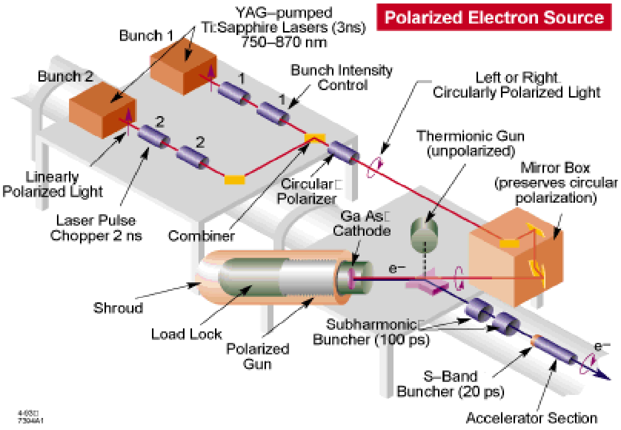
The bunches are then returned to the accelerator to gain more energy as they travel along it.

Electron Gun

At the western end of the two mile tunnel that houses the beam line is the electron gun, which produces the electrons to be accelerated. Any filament that is heated by an electrical current flowing through it releases a few electrons into the space around it. When a strong electric field is applied, more electrons are pulled out of the hot filament. The electric field accelerates the electrons towards the beginning of the accelerator structure. This is the way your TV or computer monitor produces it's electron beams.

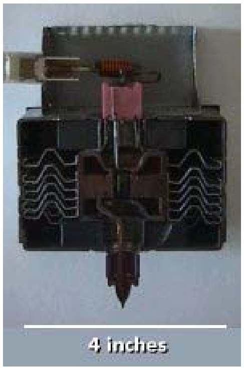
In the polarized electron gun, polarized laser light knocks electrons off the surface of a semiconductor and an electric field accelerates them toward the end of the accelerator pipe.

The polarized electron gun is kept at an even lower level of vacuum than the accelerator, down to 10-12 Torr.



Klystron is a Microwave Generator

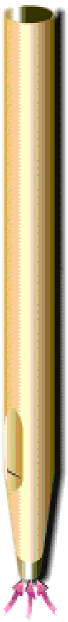
Compare SLAC's large, high-power microwave generator (klystron - below) with this much smaller one (magnetron - right) from a typical microwave oven.



A klystron looks and works something like an organ pipe.

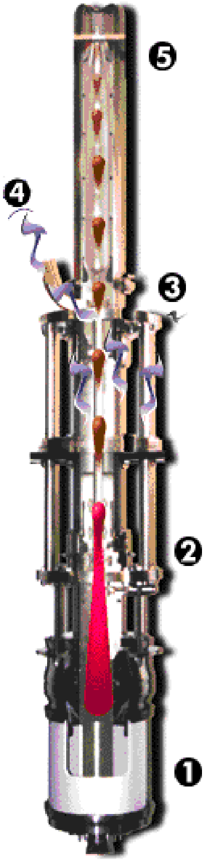
In an organ pipe:

- Blowing into the organ pipe produces a flow of air.
- Flowing air excites vibrations in the cavity of the whistle.
- The vibrations flow into the surrounding air as sound waves.



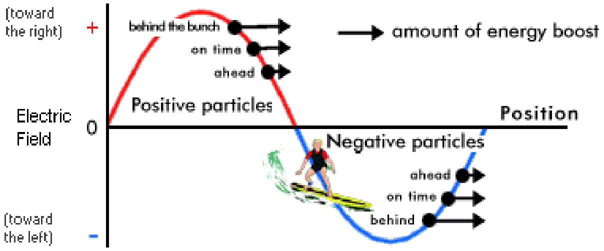
In a klystron:

- The electron gun 1 produces a flow of electrons.
- The bunching cavities 2 regulate the speed of the electrons so that they arrive in bunches at the output cavity.
- The bunches of electrons excite microwaves in the output cavity 3 of the klystron.
- The microwaves flow into the waveguide 4 , which transports them to the accelerator.
- The electrons are absorbed in the beam stop 5.

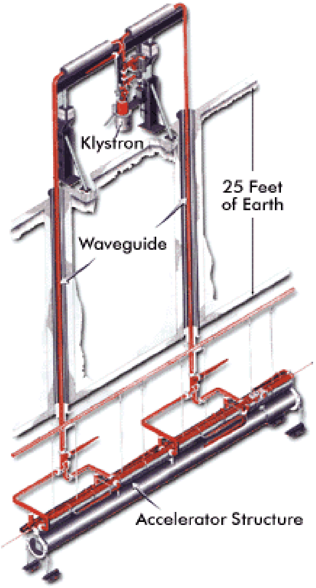


Electrons are Accelerated in a Copper Structure

Bunches of electrons are accelerated in the copper structure of the linac in much the same way as a surfer is pushed along by a wave.



In the linac, the wave is electromagnetic. That means it is made up of changing magnetic and electric fields.



Think of a magnetic field as a region of space where magnetic effects can be detected - one magnet pulling or pushing on another, for example. Similarly, an electric field is a region of space where electric effects can be detected. You can make an electric field by removing electrons from one substance and putting them on another. The region of space between the two substances then contains an electric field. An example is rubbing an inflated balloon on your hair. The effect is to make your hair stand on end.

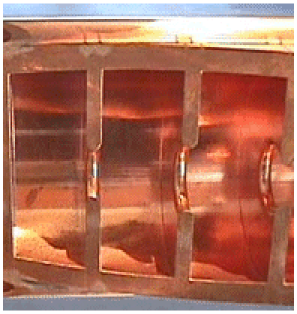
The electromagnetic waves that push the electrons in the linac are created by higher energy versions of the microwaves used in the microwave oven in your kitchen.

The microwaves from the klystrons in the Klystron Gallery are fed into the accelerator structure via the waveguides.

This creates a pattern of electric and magnetic fields, which form an electromagnetic wave traveling down the accelerator.

The 2-mile SLAC linear accelerator (linac) is made from over 80,000 copper discs and cylinders brazed together.

Inside the accelerator structure, the microwaves from the klystrons set up currents in the copper that cause oscillating electric fields pointing along the accelerator as well as oscillating magnetic fields in a circle around the interior of the accelerator pipe. The trick is to have the electrons or positrons arrive in each cell or cavity of the accelerator just at the right time to get maximum push from the electric field in the cavity. Of course, since positrons have opposite charge from electrons, they must arrive when the field is pointing the opposite way to be pushed in the same direction.

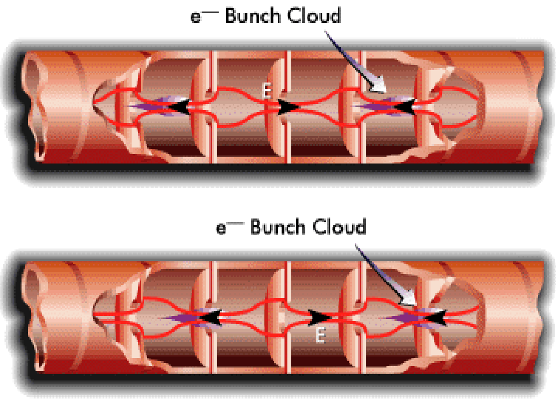


Photograph of accelerator structure, cut open for viewing.

The size of the cavities in the accelerator is matched to the wavelength of the microwaves so that the electric and magnetic field patterns repeat every three cavities along the accelerator.

This means, in principle, there could be electron bunches following one another three cavities apart, and positron bunches half way in between. Usually the spacing between the bunches is kept somewhat larger (though always in multiples of three cavities for the same sign particles).

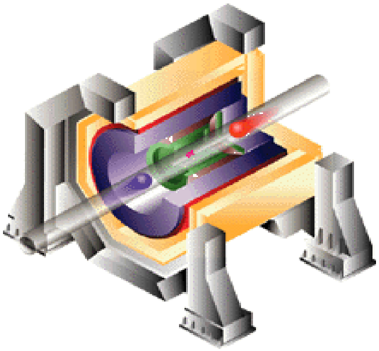
Notice how far the bunches have moved after just 1/20,000,000,000 of a second!



1/20,000,000,000 second later
(notice how far the bunches have moved)

The bunches of electrons are shown in purple. The red lines indicate the resulting electric fields in the cavities.The arrows on the red lines show the direction of the electric fields.

Particle Detectors



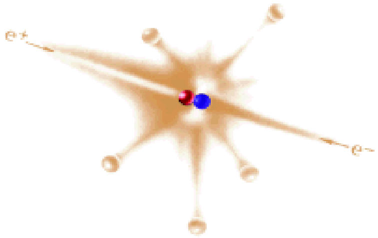
After particles have been produced by colliding electrons and positrons, we need to track and identify them. A particle can be fully identified when we know its charge and its mass.

In principle we can calculate the mass of a particle if we know its momentum and either its speed or its energy. However, for a particle moving close to the speed of light any small uncertainty in momentum or energy makes it difficult to determine its mass from these two, so we need to measure speed too.

A multi-layer detector is used to identify particles. Each layer gives different information about the "event." Computer calculations based on the information from all the layers reconstruct the positions of particle tracks and identify the momentum, energy, and speed of as many as possible of the particles produced in the event.

The Many Layers of the Detector Surround the Collision Point

This cutaway schematic shows all the SLAC Large Detector elements installed inside the massive steel barrel and end caps. The complete detector weights 4,000 tons and stands six stories tall.



If we want to perform an experiment where electrons and positrons collide, how do we produce the positrons? These are antimatter particles. There are none around -- we really have to make them!

Positrons are produced by diverting some of the electrons from the accelerator and colliding them with a large piece of tungsten. This collision produces large numbers of electron-positron pairs. The positrons are collected and sent back along a separate line to the start of the linac.

At the beginning of the linac, magnets turn the positrons around and send then into the linac where they are accelerated in just the same way as electrons.

Waveguide

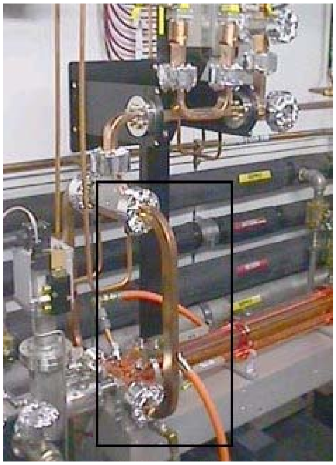
A waveguide is an evacuated rectangular copper pipe. It carries electromagnetic waves from one place to another without significant loss in intensity. This is in contrast to waves broadcast from any antenna, which lose intensity because they spread out over a large volume.

The size of the waveguide must be a multiple of the wavelength of the wave, so waveguides are only practical for electromagnetic waves in the microwave range, with wavelengths on the scale of a few centimeters.

How does a waveguide work?

If a microwave oscillation is set up at one end of a waveguide, its electric fields cause electric currents to flow in the copper walls. These currents in turn induce new electric and magnetic fields in the waveguide, oscillating with the same frequency as the original microwave. The net effect is that the microwave travels along the pipe. There is some small loss of energy due to the electrical resistance of the copper, but the microwave intensity that arrives at the far end of the pipe is almost as large as the intensity fed in at the beginning.

***Close-up view of part of a waveguide in the NLC Test Accelerator*.**



For the very high microwave intensities used at SLAC, the waveguide must be evacuated (placed under vacuum) because the intense electric fields would breakdown through lightning-like spark formation if air were present in the pipe. The waveguides at SLAC are kept at about 10-11 times atmospheric pressure. Such low air pressure is also called "high vacuum".

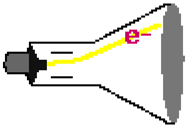
Accelerators - General

Accelerators solve two problems for physicists. First, since all particles behave like waves, physicists use accelerators to increase a particle's momentum, thus decreasing its wavelength enough that physicists can use it to poke inside atoms. Second, the energy of speedy particles is used to create the massive particles that physicists want to study.

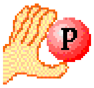
How do accelerators work?

Basically, an accelerator takes a particle, speeds it up using electromagnetic fields, and bashes the particle into a target or other particles. Surrounding the collision point are detectors that record the many pieces of the event.

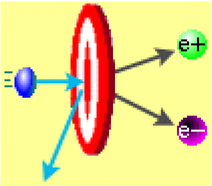
How to obtain particles to accelerate?



Electrons: Heating a metal causes electrons to be ejected. A television, like a cathode ray tube, uses this mechanism.



Protons: They can easily be obtained by ionizing hydrogen.

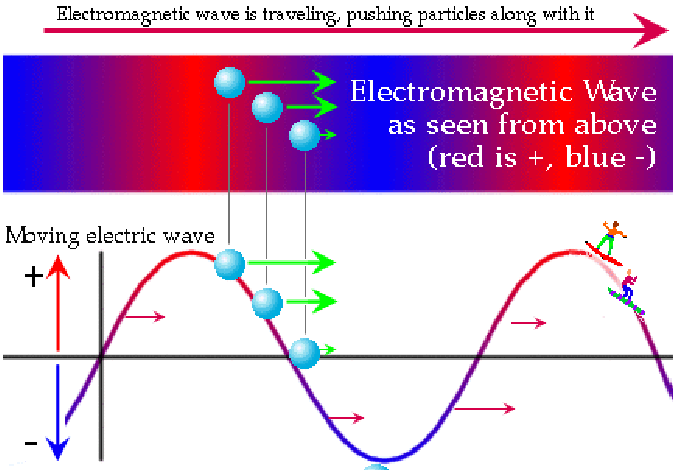


Antiparticles: To get antiparticles, first have energetic particles hit a target. Then pairs of particles and antiparticles will be created via virtual photons or gluons. Magnetic fields can be used to separate them.

Accelerating Particles

It is fairly easy to obtain particles. Physicists get electrons by heating metals; they get protons by robbing hydrogen of its electron; etc.

Accelerators speed up charged particles by creating large electric fields which attract or repel the particles. This field is then moved down the accelerator, "pushing" the particles along.



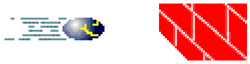
Positively charged particles (●) close to the crest of the E-M wave experience the most force forward; those closer to the center experience less of a force. The result is that the particles tend to move together with the wave.

In a linear accelerator the field is due to traveling electromagnetic (E-M) waves. When an E-M wave hits a bunch of particles, those in the back get the biggest boost, while those in the front get less of a boost. In this fashion, the particles "ride" the front of the E-M wave like a bunch of surfers.

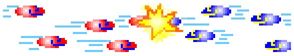
Accelerator Design

There are several different ways to design these accelerators, each with its benefits and drawbacks. Here's a quick list of the major accelerator design choices:

Accelerators can be arranged to provide collisions of two types:



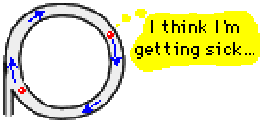
***Fixed targe*t: Shoot a particle at a fixed target.



Colliding beams: Two beams of particles are made to cross each other.

Accelerators are shaped in one of two ways:

Linacs: Linear accelerators, in which the particle starts at one end and comes out the other.

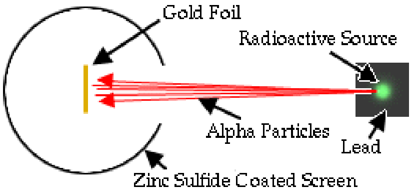


Synchrotrons: Accelerators built in a circle, in which the particle goes around and around and around...

Fixed Targer Experiment

In a fixed-target experiment, a charged particle such as an electron or a proton is accelerated by an electric field and collides with a target, which can be a solid, liquid, or gas. A detector determines the charge, momentum, mass, etc. of the resulting particles.

An example of this process is Rutherford's gold foil experiment, in which the radioactive source provided high-energy alpha particles, which collided with the fixed target of the gold foil. The detector was the zinc sulfide screen.



Cooliding-beam experiments

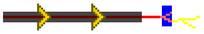
In a colliding-beam experiment two beams of high-energy particles are made to cross each other.

The advantage of this arrangement is that both beams have significant kinetic energy, so a collision between them is more likely to produce a higher mass particle than would a fixed-target collision (with the one beam) at the same energy. Since we are dealing with particles with a lot of momentum, these particles have short wavelengths and make excellent probes.

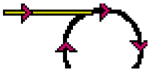
A linear of circular accelerator

All accelerators are either linear or circular, the difference being whether the particle is shot like a bullet from a gun (the linear accelerator) or whether the particle is twirled in a very fast circle, receiving a bunch of little kicks each time around (the circular accelerator). Both types accelerate particles by pushing them with an electric-field wave.

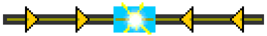
Linear accelerators (linacs) are used for fixed-target experiments, as injectors to circular accelerators, or as linear colliders.



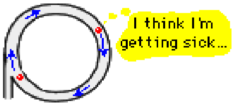
Fixed target:



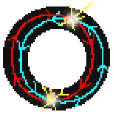
Injector to a circular accelerator:



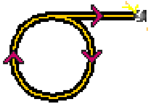
Linear collider:



The beams from a circular accelerator (synchrotron) can be used for colliding-beam experiments or extracted from the ring for fixed-target experiments:

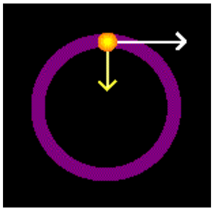


Colliding beams:



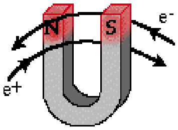
Extracted to hit a fixed target:

The particles in a circular accelerator go around in circles because large magnets tweak the particle's path enough to keep it in the accelerator. How do a circular accelerator's magnets make particles go in a circle.



To keep any object going in a circle, there needs to be a constant force on that object towards the center of the circle. In a circular accelerator, an electric field makes the charged particle accelerate, while large magnets provide the necessary inward force to bend the particle's path in a circle. (In the image to the left, the particle's velocity is represented by the white arrow, while the inward force supplied by the magnet is the yellow arrow.)

The presence of a magnetic field does not add or subtract energy from the particles. The magnetic field only bends the particles' paths along the arc of the accelerator.



Magnets are also used to direct charged particle beams toward targets and to "focus" the beams, just as optical lenses focus light.

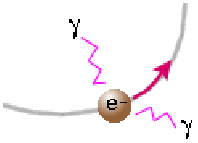
Question: If a magnetic field makes electrons go clockwise, in which direction does it make positrons go?

Answer: Counterclockwise! The same magnetic field makes positrons going in the opposite direction stay in the same circle.

The advantage of a circular accelerator

The advantage of a circular accelerator over a linear accelerator is that the particles in a circular accelerator (synchrotron) go around many times, getting multiple kicks of energy each time around. Therefore, synchrotrons can provide very high-energy particles without having to be of tremendous length. Moreover, the fact that the particles go around many times means that there are many chances for collisions at those places where particle beams are made to cross.

On the other hand, linear accelerators are much easier to build than circular accelerators because they don't need the large magnets required to coerce particles into going in a circle. Circular accelerators also need an enormous radii in order to get particles to high enough energies, so they are expensive to build.



Another thing that physicists need to consider is that when a charged particle is accelerated, it radiates away energy. At high energies the radiation loss is larger for circular acceleration than for linear acceleration. In addition, the radiation loss is much worse for accelerating light electrons than for heavier protons. Electrons and anti-electrons (positrons) can be brought to high energies only in linear accelerators or in circular ones with large radii.

Question: Can an object accelerate while keeping the same speed?

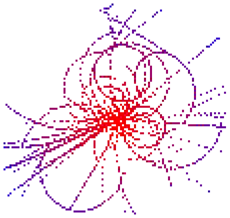
Answer: Yes: Speed is absolute change in position/time. But velocity is speed and direction, and acceleration is change in velocity/time. So, a particle going in a circle maintains the same speed yet changes direction, so it is changing velocity and therefore accelerating.

The Major Accelerators

- SLAC: Stanford Linear Accelerator Center, in California, discovered the charm quark (also discovered at Brookhaven) and tau lepton; now running an accelerator producing huge numbers of B mesons.
- Fermilab: Fermi National Laboratory Accelerator, in Illinois, where the bottom and top quarks and the tau neutrino were discovered.
- CERN: European Laboratory for Particle Physics, crossing the Swiss-French border, where the W and Z particles were discovered.
- BNL: Brookhaven National Lab, in New York, simultaneously with SLAC discovered the charm quark.
- CESR: Cornell Electron-Positron Storage Ring, in New York. CESR performs detailed studies of the bottom quark.
- DESY: Deutsches Elektronen-Synchrotron, in Germany; gluons were discovered here.
- KEK: High Energy Accelerator Research Organization, in Japan, is now running an accelerator producing huge numbers of B mesons.
- IHEP: Institute for High-Energy Physics, in the People's Republic of China, performs detailed studies of the tau lepton and charm quark.

The Event

After an accelerator has pumped enough energy into its particles, they collide either with a target or each other. Each of these collisions is called an event. The physicist's goal is to isolate each event, collect data from it, and check whether the particle processes of that event agree with the theory they are testing.



Each event is very complicated since lots of particles are produced. Most of these particles have lifetimes so short that they go an extremely short distance before decaying into other particles, and therefore leave no detectable tracks.

How can a physicist determine what happened if she can never record the presence of several key particles?

Detectors

Just as Rutherford used zinc sulfide to test for the presence of invisible alpha particles and used this knowledge to determine the path of alpha particles, modern physicists must look at particles' decay products, and from these deduce the particles' existence.

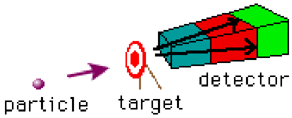
To look for these various particles and decay products, physicists have designed multi-component detectors that test different aspects of an event. Each component of a modern detector is used for measuring particle energies and momenta, and/or distinguishing different particle types. When all these components work together to detect an event, individual particles can be singled out from the multitudes for analysis.

Following each event, computers collect and interpret the vast quantity of data from the detectors and present the extrapolated results to the physicist.

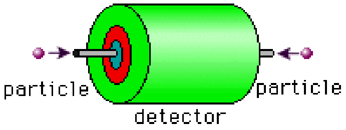
Detector Shapes

Physicists are curious about the events that occur during and after a particle's collision. For this reason, they place detectors in the regions which will be showered with particles following an event. Detectors are built in different ways according to the type of collision they analyize.

Fixed Target: With a fixed-target experiment the particles produced generally fly in the forward direction, so detectors are cone shaped and are placed "downstream."



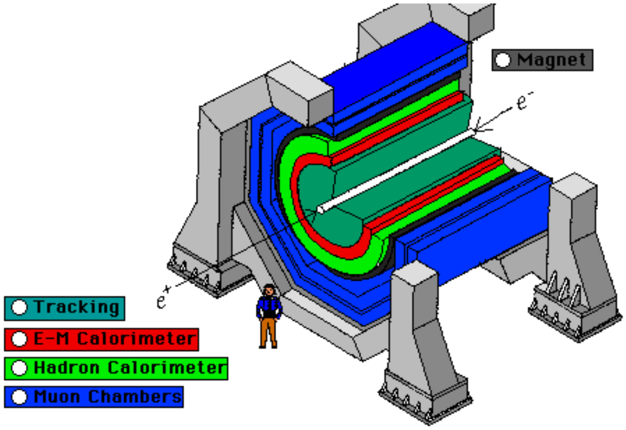
Colliding Beams: During a colliding-beam experiment, the particles radiate in all directions, so the detector is spherical or, more commonly, cylindrical.



Modern Detectors

Modern detectors consist of many different pieces of equipment which test for different aspects of an event. These many components are arranged in such a way that physicists can obtain the most data about the particles spawned by an event.

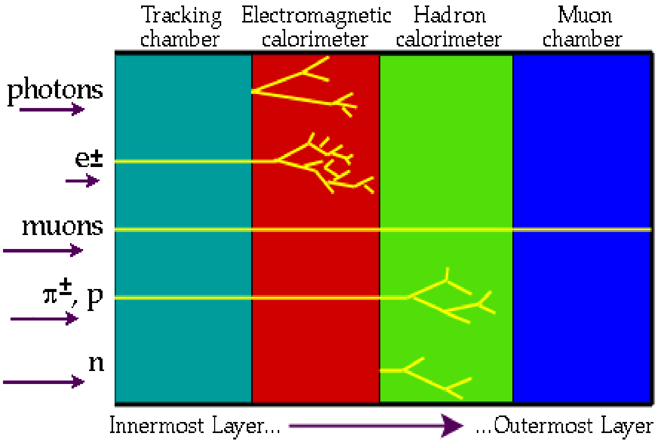
This is a schematic design of a typical modern detector.



Typical Detector Components

The reason that detectors are divided into many components is that each component tests for a special set of particle properties. These components are stacked so that all particles will go through the different layers sequentially. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.

The interaction of various particles with the different components of a detector:



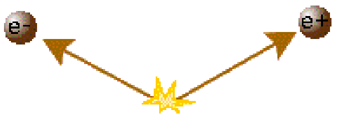
A few important things to note:

Charged particles, like electrons and protons, are detected both in the tracking chamber and the electromagnetic calorimeter.

Neutral particles, like neutrons and photons, are not detectable in the tracking chamber; they are only evident when they interact with the detector. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter.

Each particle type has its own "signature" in the detector. For example, if a physicist detects a particle only in the electromagnetic calorimeter, then he is fairly certain that he observed a photon.

An electron and a positron were produced when a particle and its antiparticle collided head-on, perpendicular to this screen. What conservation law APPEARS to have been broken?



Charge?

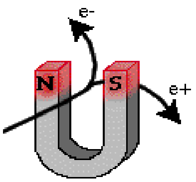
Number of Leptons?

Momentum?

Energy?

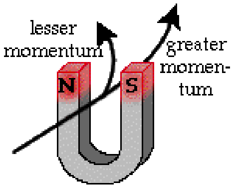
Answer: The conservation of momentum appears to be violated, but there were unseen neutrinos.

Measuring Change in Momentum



One important function of the detector is to measure a particle's charge and momentum. For this reason, the inner parts of the detector, especially the tracking device, are in a strong magnetic field. The signs of the charged particles can easily be read from their paths, since positive and negative particles curve in opposite directions in the same magnetic field.

The momenta of particles can be calculated since the paths of particles with greater momentum bend less than those of lesser momentum. This is because a particle with greater momentum will spend less time in



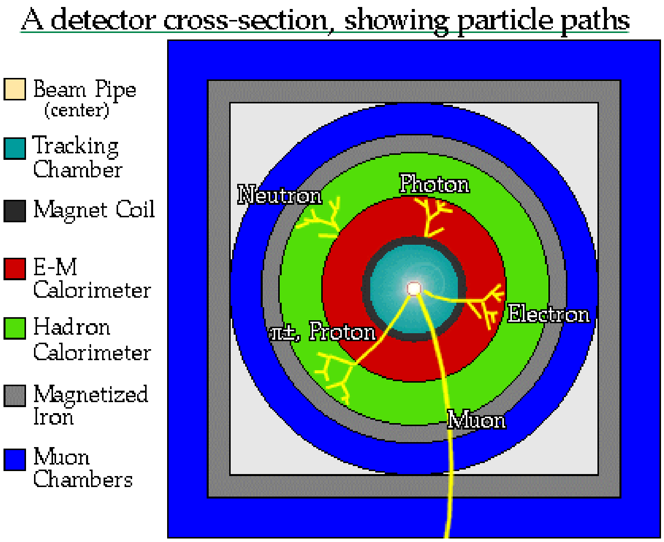
the magnetic field or have greater inertia than the particle with lesser momentum, and thus bends less in a magnetic field.

Question: In what direction does the path of a neutral particle bend in a magnetic field?

Answer: It goes straight, but neutrals don’t leave tracks so they are detected by their decay particles or by the missing momentum and energy.

Detector Cross section

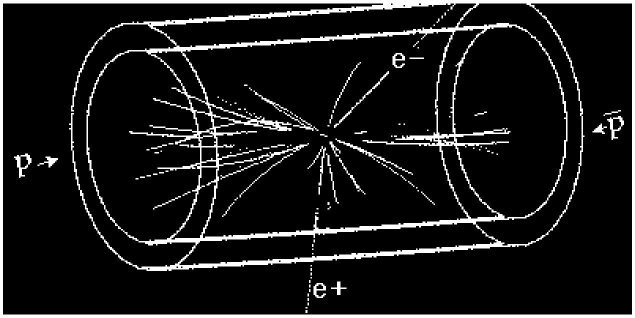
To give you an idea of the paths that particles will take through a detector, here is a cross-section view of a detector, looking down the tube the colliding beams come from. Note the different places where various particles will be detected.



Physicists can figure out the type of particle based on where that particle appeared in the detector.

The Computer Reconstruction

Detectors record millions of points of data during collision events. For this reason, it is necessary to let a computer look at this data, and figure out the most likely particle paths and decays, as well as anomalies from the expected behavior.



This is a computer reconstruction of a proton-antiproton collision event that produced an electron-positron pair as well as many other particles. This particular event, and many other like it, provided evidence for the Z boson, one of the carrier particles for the collision producing top quarks.

It is through analysis of events like these that physicists have found evidence for the Standard Model