article accelerator, a device that use electric and magnetic fields to raise the energy of electrons, protons and ions to energies far above thermal levels. In the acceleration process the particle velocities are increased (particles are accelerated), often to levels extremely close to the speed of light. The most important types of accelerators are electrostatic accelerators, cyclotron, synchrotrons, and linear accelerators. The technologies that constitute modern accelerators are numerous and varied. They include generators of radio-frequency power, fast electronics and feedback systems, complex diagnostic instrumentation and controls, ultra-high vacuum components, powerful, high precision magnets - both room temperature and cryogenic and sophisticated alignment and support systems. Accelerators were once referred to as "atom smashers" because a primary impetus for their development was as a tool for the investigation of the properties of atomic nuclei and "elementary" particles. Although many small accelerators are made as medical tools (such as for radiation therapy) and for industrial applications (such as ion implantation in semi-conductors), the major use of large accelerators is as an instrument for research.

The accelerator is sometimes called the "physicists microscope". Physicists use many forms of ionizing radiation as the microprobes to study the structure of matter on an ever smaller scale. To study nuclear and sub-nuclear processes, the probe radiation may be protons, electrons or ions. Quantum mechanics tells us that a beam of particles has an associated wavelength, just as a beam of light does. That wavelength decreases as the energy of the beam increases. The smaller the wavelength of the radiation, the smaller the objects that can be "seem" or probed but the larger and more complex the size of the accelerator. The advance of microscopy has demanded ever higher energy probes. The earliest sources of energetic radiation were naturally occurring radioactive materials. Unfortunately the utility of radioactive materials is limited, because the investigator has only a limited variety of particles, intensities and probe energies available. In the 1930's scientists began to build a variety of machines to provide a more comprehensive variety of beam sources. Accelerators now produce all the desired radiation probes at high energy. If the desired probes are X-rays or gamma rays, the starting particles in the accelerator are electrons that produce photons via the bremsstrahlung or synchrotron radiation process. Neutrons are produced by bombarding a suitable target with a concentrated beam of high energy protons or deuterons.

The energy of nuclear particles is measured in measured in units of electron-volts (eV). This unit is based on the fundamental principle that a charged particle, when subjected to an electric force, is accelerated in the direction of the force. If an electron is travels from the negative electrode to positive electrode at a voltage difference V, it gains an energy of V electron-volts. The energies available from accelerators range from thousands of electron volts to that available at the world's largest machine, nearly one trillion electron volts The generally used abbreviations are as follows:

$$1{,}000 \text{ eV} = 10^3 \text{ eV} = 1 \text{ keV}$$

$$1{,}000{,}000 \text{ eV} = 10^3 \text{ eV} = 1 \text{ MeV}$$

$$10^9 \text{ eV} = 1 \text{ GeV}$$

$$10^{12} \text{ eV} = 1 \text{ TeV}$$

To improve the signal–to–noise ratio in experiments and to uncover rare processes, the advance of accelerator based microscopy also demands ever brighter sources of radiation. These two characteristics, probe energy and probe brightness (or intensity), define the technical frontiers that continue to challenge accelerator builders.

Basic Principles:

The basic scheme of a particle accelerator consists of three stages: 1) beam formation and injection, 2) beam acceleration, and 3) beam extraction to a target or beam collisions within the accelerator itself. Every accelerator begins with an injector consisting of a directional source of low energy charged particles (electrons, protons or other ions) plus the associated high voltage electrodes and magnets that extract and form the beam .The first accelerators used hydrogen gas passing through a discharge or passing by a hot filament as a source of protons. In this procedure the discharge strips the electron from the atoms leaving a bare proton. Refinements of this technique (or analogous ones with other gases) are still used to produce beams of protons (heavy ions). The source generates the particle beam, which is characterized by an average initial energy, beam current, cross-sectional area and mean angular divergence. The quality of the injected beam is characterized by the product of the beam radius and divergence; this product is called the beam emittance. Smaller emittance implies better quality of the final, high energy beam of particles. In analogy with optics the particle current divided by the emittance (which is equal to the particle density divided by the divergence) is called the brightness. Many applications of modern accelerators require beams of the highest possible brightness. The beam is produced in or injected into one or more acceleration chambers where electrical forces increase the velocity (and therefore the energy) of the particles.

In its simplest and earliest form, the accelerator increases the energy of the particles by subjecting the beam to a static high voltage electric field within a highly evacuated structure. The energy achievable using electrostatic fields to accelerate charged particles is restricted by the ability of insulators (and the vacuum) in the accelerator to sustain high electric fields without electrical breakdown. Electrostatic injectors of electrons and ions (with mass up to uranium) to energies of 30 keV to 1 MeV are still used as the "front end" of many modern accelerators.

Generating the high voltage is a technical challenge. The high voltage itself maybe be generated by charging a series of capacitors in parallel and then applying the voltage across a series of acceleration tubes in series. In this way Sir John Cockcroft and Ernest Walton achieved voltages as high as 1 MV in 1931. An important practical disadvantage of this approach is that the high voltage also appears on the outside of the structure constituting a high voltage hazard to experimenters. The next year invented an alternative approach. In the Van de Graff generator (see Figure 1) an insulated belt carries electric charges from a source at ground potential up to a metal dome that accepts the charges and thereby increases its potential above ground. Single stage Van de Graff generators can provide voltages as high as 10 MV. Multi-stage machines have produced protons with energies as high as 30 MeV.

If short burst of energy particles is needed rather than a continuous beam, one can exploit the fact that insulators can withstand much higher fields for very short (<1μs) periods. Pulsed diodes can achieve single stage voltages of up to 15 MV in very low impedance structures. Consequently pulsed diodes can deliver several tens of kiloamperes of beam current; in contrast with the tens of milliampere currents accelerated in electrostatic accelerator. A common means of generating the high voltage is the Marx generator. Similar to the Cockcroft-Walton, one charges a collection of capacitors in parallel and discharges them in series across a single gap. The discharge form the Marx launches a high voltage pulse along a transmission line or pulse forming network to shape the temporal characteristics (such as the rise time) of the pulse. The beam electrodes terminate the line and deliver the beam. Large, pulsed, electron diodes are used in for flash radiography and for generating extremely large electromagnetic pulses to test military components. Researchers at Sandia Laboratories in the US and at the Khurchatov institute in Russia have built ion diodes generating hundreds of kiloamperes of light ions for tens of nanoseconds to investigate inertial confinement fusion.

One may also exploit the principle of magnetic induction; that is, the principle of the transformer. If one changes the flux through a torroid of ferromagnetic material by driving a time-changing current through a conductor (primary winding) that loops around the torroid, one will induce a voltage along the axis of the torroid. The beam passing along the axis acts as the "secondary winding" of the transformer; and receives a voltage boost as it traverses the core. The voltage in a single stage of an induction accelerator may be as high as a few hundred kV for periods of a few hundred nanoseconds. By stacking many such cores in series, Nicholas Christofilos was able to produce a beam of > 100 A of 5 MeV electrons in 1962. Accelerators based on this induction principle are now thought to be excellent means of delivering energy to a capsule of deuterium-tritium for inertial confinement fusion.

If the accelerating voltage oscillates at radio frequencies (rf), the accelerator structure can also sustain much higher electric fields without electric breakdown than in the case of static voltages. Using rf-fields to accelerate particles presents a potential conceptual difficulty: the sign of the field rapidly alternates between accelerating and decelerating. Were the particle to traverse the gap between two plates with an rf-voltage applied the direction of the force on a particle would also oscillate; the net effect might be no acceleration at all. The two principal conceptual approaches to overcoming this difficulty that were discovered in the late 1920's are the basis of most modern accelerators.

Linear Accelerators (linacs)

The critical feature that allows rf-fields to be used for long, multi-stage accelerators is that the field varies in space as well as in time. At any given time the strength of the varies sinusoidally over a distance characterized by the wavelength of the rf-field. At any given point of space the field strength varies sinusoidally in time. If one notes the position of the field maxima, one sees that these maxima appear to move through space at a velocity which is called the phase velocity of the field. As time progresses the particles in the accelerator change positions. Hence the particles could move in a way such that the local field is always accelerating; that is, the particles continually leave the regions where the accelerating field is decreasing (or even reversing) and enter regions where the field is increasing. Alternatively they could move to a region in which they are shielded by a metallic structure from the field while it is decelerating. The first use of rf-fields in a linear structure was in 1929. Rolf Wideroë accelerated ions in a short, structure composed of coupled, resonant, radio frequency cavities. When the cavities are designed so that the phase velocity of the field matches the velocity of the particles, then as the particles run down the accelerator, the beam will experience continual acceleration like a surfer riding a wave. The velocities of protons or ions can change markedly during the acceleration process. Consequently the phase velocity of the wave, v_{ph}, must likewise increase in synchronism with the beam along the structure. As electrons can be injected into the accelerator structure at nearly the speed of light, c, the structure typically has a constant $v_{ph} = c$.

The alternative approach to avoiding the decelerating phase of the radio frequency electric field is to shield the beam from the field during this period. This approach, first exploited by Eanest O. Lawrence in the cyclotron, is the basis of the drift tube or Alvarez linac. Such a linac consists of long evacuated tube which contains a long number of hollow metal drift tubes as shown in Figure 2 (fig. 8 of the present text). Each of the tubes is connected in succession to an rf-transmitter via a transmission line through which the accelerating passes at near the speed of light. Thus each tube is successively charged to a high voltage. If a charged particle leaves the injector at the right time it will be accelerated toward the first tube acquiring a certain amount of energy. Once inside the tube; the particle will drift at a constant velocity through the tube. If the tube is of the appropriate length, the particle will emerge just as the accelerating voltage advances one cycle. In that case the second tube will be at the right voltage to accelerate the ion toward the second tube. Typical voltages are hundreds of thousands of volts. This process is repeated with the particle acquiring an increment of energy in each step. As that velocity of the ion increases, the tubes must be longer and longer to maintain synchronism with the field. Eventually the ion velocity will be very close to the speed of light; at that point the length of the tubes reaches their limiting, constant length.

The spatial variation of the field also introduces a limitation on the temporal structure of the beam; for any bunch of finite length, the actual accelerating field will varies within the bunch. Consequently, the length of the "bunch" of particles must be short with respect to the rf-wavelength of the accelerating field due to the spatial variation of the electric field. Otherwise the particles in the bunch will experience a significantly different degree of acceleration. Excessive energy variation may increase the difficulty of focusing the beam due to chromatic aberrations of the magnetic lenses, it may also decrease the utility of the beam for the specific application desired. The energy variation can also lead to focusing the bunch in the axial direction.

Consider the case of a non-relativistic bunch of ions moving at an initial velocity, v_o. The longitudinal electrical space charge forces act to accelerate the head of the beam and decelerate the tail. By timing the bunch properly with respect to the rf-field as illustrated in Fig. 3, the tail can be accelerated more strongly than the head. This proper phasing of the beam and accelerating field can compensate the defocusing due to space charge and energy spread. For some range of values of the central phase of the bunch, there results a centering and oscillation of the particles about the phase stable point. This phenomenon, known as phase stability, is important to linear ion accelerators, and it is essential to modern circular accelerators of both electrons and ions.. The "price" of phase stability is the limiting of the duty cycle of the accelerator to values well below unity.

During the acceleration process all real beams have a tendency to expand in radius due to two effects: 1) the mutual electrostatic repulsion of the particles and 2) the finite spread in transverse (thermal) velocities. The first tendency is reduced as the beam gets to higher velocities because the magnetic field associated with the beam current tends to pinch the beam together and for relativistic beams nearly cancels the transverse space charge defocusing force. Hence, the first effect is of particle importance to ion accelerators but is nearly negligible for electron accelerators in which the beam is injected at relativistic velocities. The second effect, associated with the emittance of the beam is important for all accelerators.

By surrounding the beam by magnetic fields with a direction perpendicular to the beam axis and with a strength proportional to the distance outward from axis, one can confines the particles near the axis by an harmonic potential. The self-magnetic field of a beam with a uniform charge distribution has such a potential. Unfortunately it is canceled by the space charge repulsion. Thus external fields are required to hold the beam together. Quadrupole magnets also provide such fields. Although a quadrupole will focus the particles in one plane transverse to the average motion, it will defocus the beam in the other transverse plane. The "strong focusing" principle, discovered by Ernest Courant, Stanley Livingston and Nicholas Christofilos, is based on the fact that the combination of two quadrupoles separated by drift spaces and arranged with alternating focusing and defocusing planes leads to net focusing in all planes perpendicular to the beam motion.

Drift tube linacs are still used in proton linacs for those portions which raise the energy of the beam from a few MeV to about 100 MeV. Early electron linacs such as the 1 GeV linac built at Stanford University also used the drift tube approach with the length of the tubes being constant once the beam was injected at an energy of 1 GeV. More modern electron linacs of which the two mile long, 50 GeV machine at the Stanford Linear Accelerator Center (SLAC) is the largest example use the principle of the electrons "surfing" the electromagnetic field to accelerate the beam at almost 20 MeV per meter of accelerating structure. At SLAC large tubes called klystrons supply the radio-frequency power at a nearly 3 GHz. New developments of higher frequency tubes and accelerating structures at roughly 11 GHz will make it possible for future electron linacs to have average energy gains of 50 to 100 MeV per meter.

The highest energy proton linac is LAMPF at the Los Alamos National laboratory in New Mexico. Using copper resonant cavities with an accelerating field of roughly 2 MeV per meter, it accelerates - for brief periods, a beam of up to 1 milliampere of protons to 800 MeV . Originally built as a "meson factory to produce intense beams of pions and muons, LAMPF will be upgraded to produce a beam of over 100 kW of long-term average power. The beam will then impact a heavy metal target to produce copious neutrons via the nuclear spallation process. This neutron source will be used for fundamental research in the material sciences and biological sciences. New proton linacs operating at average powers up to 50 MW are being designed for applications such as the breeding of tritium and the transmutation of radioactive waste.

Superconducting rf structures have also been developed for the acceleration of heavy-ions as well as protons. The largest superconducting proton linac serves as an injector for the HERA colliding beam accelerator at the German laboratory DESY in Hamburg. Recent advances in the technology of fabrication and preparation of superconducting rf-cavities suggest that accelerating fields of 15 -25 MeV per meter can be achieved at frequencies of 500 MHz. Such low frequency structure are very attractive for the generation of intense beams as the problems of controlling beam losses to ultra-low levels are vastly simplified due to the large apertures of the structure

Circular accelerators

An elegant and economical approach to accelerating a beam by many small kicks is to have the beam pass across the same accelerating gap many times. To do this the particles must be deflected by strong magnetic fields into a roughly circular orbit. This approach was first taken by Ernest O. Lawrence and Stanley Livingston with their invention of the proton cyclotron in 1930. As in the drift tube linac the beam is removed from the region containing the electric fields when the fields are of the wrong phase. If a charged particle of mass m and charge q moves with velocity v in a magnetic field of strength H directed perpendicular to the instantaneous direction of motion, it will move in a circle of radius $R = mv/qH$. In the accelerator as v increases, R increases. Thus the protons (or heavier ions) spiral outward to larger radii. If the two high voltage cavities are shaped like the letter D, then on each turn the beam will cross a gap with time varying electric fields (Fig. 4 -fig 2 of the original text). Lawrence's insight was to note that intervals between crossings is constant (for non-relativistic particles) since the increase in speed just compensates for the increase in radius. During the times in which the fields have the wrong phase, the beam is not in the gap.

$$f = \frac{9}{2\pi}\ \frac{H}{mc^2}\ \sqrt{1-v^2/c^2}$$

where f is the frequency of the alternating voltage in megahertz, H is the field strength in gauss, and mc^2 is the particle mass in MeV. If H is constant over the region of acceleration, then obviously f is independent of radius.

To accelerate the ions to high energy one need only select the magnetic filed and frequency of the voltage to be in resonance; then particles will always cross the gap between the Dee's at the correct time - twice per orbit. Thus a 10 keV voltage source could accelerate the beam to 50 MeV in only 2500 revolutions. For the case of a proton cyclotron a typical operating frequency might be 20 MHz, leading to an acceleration time of roughly 1 millisecond.

As in the case linear accelerators the particles must also be focused transversely during the acceleration process, else all particles except those launched with velocities precisely parallel to the pole pieces of the magnet will be lost. In the cyclotron accepting particles with a finite angular spread is accomplished by shaping the magnetic field so that both above and below the median plane of motion the field has components that bend the particles toward the central plane. Unfortunately in the cyclotron the stability of the bunch requires that this focusing component decrease slowly as the radius increases. This destroys the resonance condition and leads to deleterious effects that limit the intensity of the beam. Another limit on the performance of the simple cyclotron derives from the relativistic increase of mass with the increasing energy of the particles;

$$m = \frac{m_o}{\sqrt{1-v^2/c^2}}\ .$$

For protons, this increase will destroy the synchronism condition at about 10 MeV. One means of restoring the synchronism is to modulate (decrease) the frequency of the accelerating field as the particles spiral outward and their velocity increases. In particular the frequency should vary as

$$f = \frac{9}{2\pi} \frac{H}{mc^2} \sqrt{1 - v^2/c^2} \ .$$

With in such a "synchrocyclotron", protons can reach an energy of several hundred MeV. For example, with a magnetic field of 2 Tesla, the frequency will drop from roughly 32 MHz at injection to less than 19 MHz at 400 MeV. The frequency of the voltage must vary over a few milliseconds. Once the particles have reached the top energy and leave the cyclotron,. the frequency is increased back to its upper value and the cyclotron is ready to accept another bunch.

Even with refinements in magnet design and improvements in rf-power supplies, the energy available from cyclotrons is limited by practical considerations: the magnets needed to confine the particles become exceedingly large. In 600 MeV cyclotrons such as that at the laboratory TRIUMF, Vancouver, BC., the magnets have weights exceeding 2000 tonnes and consume megawatts of electrical power. As the cost of synchrocyclotrons scales as the cube of the machine radius, to reach higher energies at practical costs requires new acceleration principles.

Clearly controlling the costs of circular machines implies controlling the radius of the machine; thus one considers keeping the particles in an orbit of constant radius by increasing the magnetic field as the energy increases. The beam is injected at a low energy onto this orbit by a linear accelerator. The fields are needed only over the small region of the beam orbit; thus the magnets need not extend over an entire disk, but are wrapped around the evacuated beam tube. The result is a huge cost savings.

This approach is realized in the proton synchrotron, the first of which was the 3 GeV Cosmotron at the Brookhaven National Laboratory finished in 1952 followed shortly by the 6 GeV Bevatron built at the Lawrence Berkeley National Laboratory. The Bevatron, which was built for the express purpose of discovering the anti-proton, was operated for

39 years and demonstrated the long utility and reliability of particle accelerators. In this early generation of synchrotrons built in the US, Britain France and Russia the focusing forces were weak; thus the size of the radial excursion of particles was large as they speed around the accelerator. The vacuum chamber was therefore roughly 30 cm wide and the magnetic fields had to be carefully controlled in quality over this still large field volume. The breakthrough in 1952 which drastically reduced the size of the beam excursions, and consequently the size of the vacuum chamber, was the strong focusing principle. With superconducting quadrupole magnets arranged in a strong focusing array, the vacuum chamber in modern proton synchrotrons can less than 10 cm across with a correspondingly large decrease in the size, cost and power consumption of the focusing and bending magnets. The first synchrotron built on this principle were the 30 GeV Alternating Gradient Synchrotron at Brookhaven. A similar machine, PS, was built by a consortium of European countries at the laboratory CERN in Geneva. Both machines are still in use. The area of the AGS aperture is nearly 25 times smaller than that of the Cosmotron. The magnet power for the AGS at 30 GeV is about that used by the Cosmotron magnets at 3 GeV. The AGS accelerates 6 x 10^{13} protons per pulse, the highest intensity for a proton synchrotron. In the AGS the focusing is provided by the same magnets that bend the beam by shaping the poles of the magnets as illustrated in Fig. 5 (fig.7 of present text). An alternative approach using separate magnets to bend and focus the beam is typically used in modern accelerators.

Presently the largest proton synchrotron is the Tevatron at the Fermi National Accelerator Laboratory in Batavia, IL. As its name suggests, the Tevatron accelerates bunches of protons to approximately 1 TeV in a ring which is 2 km in diameter. Protons are brought to full energy by a series of accelerators that begin with a Cockcroft-Walton injector (750 keV) which feeds negative hydrogen ions into a 400 MeV linac. The linac injects the beam through a carbon stripping foil into the Booster, a rapid-cycling synchrotron 500 feet in diameter. There the protons travel around about 20,000 times and reach an energy of 8 GeV. Typically the Booster cycles twelve times in rapid succession to load twelve bunches of protons, into the 6.3 km circumference Main Ring, yet another proton synchrotron. Consisting of 1,000 conventional, copper-coiled magnets to bend and focus the protons, the Main Ring accelerates protons to 150 GeV. Directly beneath the Main Ring is the final synchrotron, the Tevatron which contains 1000 superconducting magnets. The beam can also be extracted into multiple external beamlines 1 to 2 miles long for experiments in external experimental areas.

Some of the experiments at Fermilab are performed by colliding the 1 TeV proton beam with a counter-rotating beam of anti-protons also at 1 TeV. For these experiments the anti-protons must be made with a high energy proton beam from the Main Ring that bombard a metal target. The anti-protons produced in the collisions are collected and accumulated in a separate accumulator ring at 8 GeV. When there are sufficient anti - protons they are injected into the Main Ring, accelerated to 150 GeV and injected into the Tevatron. There both the protons and anti-protons are accelerated simultaneously to full energy and then allowed to collide.

Higher energy beams require stronger bending and the focusing fields to confine the beam. Proton synchrotrons at multi-TeV energies (for sub-nuclear "microscopy") require thousands of superconducting bending and focusing magnets 5 to 15 meters in length with several centimeter apertures and exquisite field precision and temporal stability. Such a machine is presently in the design phase at CERN.

The major llimit to extending the enrgy frontier with proton synchrotrons is the cost and complexity associated with their very large size. Even with the use of powerful superconducting magnets the ill-fated Superconducting SupercColider with 40 TeV beams would have been over 80 km in circumfirence. The coils of present superconducting accelerator magnets are made of a ductile superconductor, niobium-titanium. For economicalmagnet design the conductor should carry ≈ 2000 Amperes per square millimeter . Operating at 4.2 K, even short samples of NbTi will not support fields above 12 T (the critical field value, H_c); this means the current density falls to zero at higher fileds.Thus practical Nb-Ti magnets the fields are limited to < 10 T. If the limits on size of accelerators demands magnets with fields above 12 Tesla, a new technology must be brought to bear. No known ductile materials have H_c above approximately 12 Tesla; therefore, very high field dipole magnets will have to based on brittle superconductors, such as Nb_3Sn or Nb_3Al with H_c above 20 T. A promising alternative are the brittle, mixed oxides that are high temperature superconductors; operating at <20 K these materials may provide current densities of 2000 Amperes per square millimeter even above 15 Telsa. The magnetic pressures associated with such high fields are hundreds of atmospheres. Not surprisingly the challenges of the mechanical design are great.

Colliding beam accelerators

Not all of the energy of an accelerated particle is available to produce reactions. A significant fraction is lost when the target particle recoils to satisfy the law of the conservation of momentum. The useful available energy in such "fixed target" experiments with projectiles of energy E and target particle of mass M is

$$E_{avail} = \sqrt{2EMc^2} .$$

Thus fixed target experiments at the Tevatron have an available energy of limited to only 43 GeV. In contrast in the Tevatron collider mode in which the counter rotating protons and anti-protons can run headlong into each other, the total momentum of the colliding particles is zero and all the energy (2E) is available. In the Tevatron this energy is nearly 2 TeV. This great gain in energy reach comes at the expense of a greatly reduced collision rate between particles as the two tenuous beam pass through each other. This reaction rate is measured by the 'luminosity' defined as the number of collisions per second for a reaction having a given cross section. The luminosity scales linearly with beam energy, with beam current, and inversely with the beam radius; the energy of the beam in the collider is set by the energy scale of the physics to be investigated. In order for maximize the luminosity, the beams must be made as dense as possible at the collision point. Consequently the technical challenge in designing colliders is focusing the beams at the collision point to an exceedingly small spot and increasing the beam current as much as practical; for sufficient luminosity the circulating current may exceed 1 Ampere. Another sophisticated technical challenge is to provide extremely high vacuum in the collider. As the collisions between beam particles is relatively rare, the collisions with residual gas molecules is an important competing process that can deplete the beam faster that the desired the beam-beam collisions themselves. Beam-gas collisions are also a source of unwanted background in the detector that can obfuscate the physics to be studied. Typically the vacuum in colliders must be in the range of 10^{-11} to 10^{-9} Tore (mm of mercury) depending on the collider luminosity.

The desire to explore the energy frontier of high energy physics has lead to the construction of proton colliders at CERN and Fermilab and of many colliding beam electron devices throughout the world. An accelerator (HERA) that collides electrons and protons has been built at the German laboratory DESY in Hamburg. The first proton collider was the Intersecting Storage Rings (ISR) at CERN. There 26 GeV protons and anti-protons were collided in a 1.6 km circumference ring. Beam currents as high as 50 Amps were stored for several days. The highest energy collider is presently the Tevatron with nearly 1 TeV per beam. An even larger (28 km circumference) collider, the Large Hadron Collider (LHC) is presently in design at CERN. The LHC will collide 7 TeV proton beams with an unprecedented luminosity. It will be built in the tunnel that presently houses LEP, the highest energy electron-position collider. There the beams have been colliding at 50 GeV per beam; an upgrade in progress will raise the energy to 100 GeV per beam.

At lower energies in one can accelerate more intense electron beams making it possible to explore rare process associated with the decay of B and K mesons via the electroweak force. A number of such machines sometimes known as "flavor factories" are now being built in the US, Japan, and Italy. Typically these machines are built with two storage rings - one containing electrons, the other, positrons - intersecting in one or two interaction regions. Each ring contains numerous bunches of particles yielding total beam currents exceeding 1 Ampere. The beam energies are chosen so that the available energy corresponds to a resonance that decays into the short lived particles (B mesons or K mesons) to be studied. The basis the design of these machines is the electron synchrotron and the storage ring. The energy limit of circular electron-positiron colliders is the emission of copious radiation by the beam (synchrotron radiation, discussed below).

This limtation can be overcome with linear colliders in which the emission of synchrotron radiation is vastly reduced during the acceleration process. As its name suggests, the linear collider consists of two high energy linear accelerators that direct high intensity beams, one of electrons the other of positrons, at each other. The beams pass through each other a single time beforeand travel on to a beam dump. The first linear colliding beam facility is the Stanford Linear Collider, SLC, which uses the 2 mile long SLAC linac operating at 50 GeV. In the SLC bunches of electrons and positrons are accelerated in the same linac and a separted when the beams reach full energy. The elctron and positron bunches are then transported around separate arcs, in a configuration resemling a stethescope, and focused to a size of 2 μm at the collision point. The next step in linear collider development is expected to be at TeV energies. Such colliders will be limited by cost considerations to 20 or 30 kilometers in length and will require economical means of increasing the accelerating fields, by up to ten times beyond those commonly found in existing accelerators. The search for economical means of acceleration has lead to the design of new accelerator structures and high power sources of radio frequency power operating in the range of 10 to 35 GHz. As the cross sections for processes decrease with the invere square of the beam energy, the luminosity of electron positron colliders must be made extremely large. Consequently the beam densities must be very high. In TeV linear colliders, the beams may have a size of 10 nm, far smaller than the 2 µm size in the SLC. Such small beam sizes imply powerful, very stable magnets controlled by sophisticated feedback electronics to keep the focusing elements in precise alignment. When the electron and positron beams pass through one another the electrical forces within the beams cancel, but the magnetis forces reinforce each other. The resulting fields can be of the order of 10^4 Tesla. These huge fields can severely disrupt the beams and induce large energy spreads due the emission of synchrotron radiation. This effect plus the economics of building ever longer machines will limit the ultimate energy reach of electron-positron colliders:

Electron storage rings

Electron synchrotrons are based upon the same operating principle as proton synchrotrons. They have an important simplifying feature. The small mass of the electron allows the beam to be injected at very nearly the velocity of light. As adding energy cannot change the speed much, the electron synchrotron can operate with a fixed frequency operating voltage as long as the beam is injected at an energy of roughly 10 MeV. This simplification is more than offset by another consequence of the small electron mass. As electron is bend around in a circle, the centripetal acceleration causes the electron to emit photons (radiation) through a process called synchrotron radiation. The power, P, emitted varies as the fourth power of the beam energy, E, linearly with the beam current, I, and inversely with the radius of the machine, R; that is P is proportional to $(E/m)^4 I R^{-1}$. Thus the energy lost in each revolution of the beam around the accelerator must be replaced by the rf-accelerating fields supplied by the accelerating cavities. In high intensity "flavor factories" this emitted power can be tens of megawatts.

Circular accelerators like electron synchrotrons can serve not only to increase the energy of particle beams but also to store large circulating currents of particles at a constant high energy. Storage rings have two major applications: 1) colliding beams for nuclear and elementary particle research. as discussed above and 2) "light sources" for use in atomic physics, material science, chemistry, biological science and medicine.

The average energy of the photons emitted as synchrotron radiation is proportional to $(E/m)^3R^{-1}$. Consequently GeV electrons in a storage ring emit copious synchrotron radiation with energies in the ultra-violet and x-ray range. Most of the photons are emitted within a narrow angle in the vertical (non-bend) plane of m/E. As the electron beam in modern, GeV storage rings can have a radius of tens of microns, the x-ray beam emitted can be extremely bright, bright enough to serve as a powerful probe the structure of materials. The radiation is emitted tangential to the curving trajectory of the electrons. Hence every bending magnet in an electron storage ring provides a sweeping "seaerchlight of radiation as the bunch of electrons passes through the magnet. Radiation escapes down long, evacuated, radiation beamlines tangential to the main vacuum chamber. Aong these beamlines slits and collimators define a narrow bea, and monochrometers provide for the selection of x-ray energy to within a narrow bandwidth.

Storage rings with the primary purpose of providing synchrotron radiation to users are known by the generic named "light sources". The first generation of light source used storgare rings that were originally built for high energy physics. A notable example of such a source is the 3 GeV SPEAR ring at the Stanford Synhrotron Radiaon Laboratory (SSRL), which was one of th sites for the discovery of "charmed mesons". The first generation sources typically have not had the flexibility to accomodate the hundreds of simultaneous users that a dedicated light source can service. Consequently, as the demand for high flux, high intensity grew, a second generation of light sources was built with the needs of radiation users incorporated from the outset. In particular arrays of magnets were chosen with the express intention os minimizingthe emittance of the electron bean. Low emittance implies smaller beam sizes and thus brighter sources of radiation. The X-ray and vuv rings at the Brookhaven labortory are typical of this generation.

The brightness of the emitted radiation can be increased still more if the beam is wiggled back iand forth in a sinusoidal pattern such that the radiation from each bend is superimposed. Undulators, magnet structures to provide such a motion, are of a series small angle dipole bends placed along a striaght beam line. The brightness of undulator radition can be hundreds of times larger than that from bend magnets. Construction of a third generation of light sources designed to incorporate many such undulators began in the mid-1980's. Notable first examples of third generation sources are the 1.5 GeV Advanced Light Source (ALS) in Berkeley, producing soft x-rays, and the 6 GeV Advanced Photon Source (APS) at the Argonne National Laboratry and the European facility ESRF, in Grenoble, France. APS and ESRF are sources of hard x-rays. Several other light sources have been and are being built throughout the world based on the success of these machines. In innovative design technique for a machine to provide high brightness from the infrared all the way to hard x-rays is have the array of bending magnets be a combination of warm dipoles at ≈ 1.5 Tesla and much shorter superconducting dipoles at □several Telsa. This approach is being explored for a new light source in Switzerland and as a retrofit for the ALS.

The breadth of scientific uses for synchrotron radiation is is already large and still growing. Extremely bright x-ray beams allow for a new generation of x-ray microscopes to study biological systems in their normal aqueous envirmonment. They allows the rapid analysis of the structure of viruses and proteins for the design of new pharmaceuticals with precisely targeted efficacy against their disease-causing targets, and with less effect on other structures in the body. Adverse side-effects of the drugs will be minimized. X-ray beams now provide powerful microprobes for the identification of minute levels of impurities and contaminants. These microprobes can provide a rapid way to "fingerprint" environmental samples to identify routes of pollution and contamination. They can be used to certify the cleaniness of large silicon wafers prior to expensive processing of very highly integrated circuit and they offer the promise of new lithographic techniques to provide feature sizes in integrated circuits smaller than 100 nm.

Accelerators in medicine

The use of accelerators is not confined serving as research tools or as sourcesof process radiation in industry. Accelerators have found an essential, practical role in therapeutic and diagnostic medicine. Many hospitals throughout the world have small electron linacs that produce energetic x-rays for the irradiation of tumors. A much small number use cyclotrons or synchrotrons to generate proton beams to irradiate a wide variety of solid tumors. As the protons have the advantage of depositing their energy more locally than x-rays, proton therapy is especially efficaceous in the treatment of brain and eye tumors where the damage to the surrounding healthy tissue must be kept as small as possible.

The availabilty of small proton accelerators has enabled an exciting diagnostic technique, positron emission tomography (PET). PET is based on the absoption in tissues to be imaged of radio-isotopes that emit a low energy positron when they decay. When the positron anihilates with an electron in the tissue it produces a pair of 511 keV gamma rays; these gamma rays are recorded by two detectors. Possibly the most importtant PET isotope is O^{17}, which is readily incorporated into fructose. As the absortion of fructose is regulated by metabolism, the PET can be used to image functionality rather than merely density variations in the tissue. Thus, imaging of the metabolism of fructose in the brain can provide valuable insight into the loss of brain functionality associated with diseases like Alzheimer's. The half-life of O^{17} is only two minutes; other important PET isotopes also have short half-lives. Hence the spread of this technique beyond laboratory research centers with reactors had to await the commercial availability of small, easy to operate accelerators suitable for isotope production in hospitals.