Accelerators and Nobel Laureates

by Sven Kullander
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Why Accelerators

Particle accelerators are devices producing beams of energetic ions and electrons which are employed for many different purposes, one being ultra-precision microscopy. As is well known objects with dimensions down to the size of a living cell are investigated by optical microscopes and those down to atomic dimensions by electron microscopes. The object details that can be seen (resolved) are given by the wavelength of the irradiation. To penetrate the interiors of atoms and molecules, it is necessary to use radiation of a wavelength much smaller than atomic dimensions. Nucleons (protons and neutrons) inside atomic nuclei have a size of around $10^{-15}$ meters and are separated by distances of the same order of magnitude. The electrons orbiting atomic nuclei as well as the quarks inside nucleons have a size, if any, smaller than $10^{-18}$ meters; they appear point-like.

Probing particles such as electrons and protons provided by particle accelerators are required for studies of atomic constituents. The associated de Broglie wavelength of a probing particle rather than the "macroscopic" wavelength defines the minimum object size that can be resolved. The de Broglie wavelength is inversely proportional to the particle momentum. For example if an electron is required to have a de Broglie wavelength comparable to the size of the nucleon, it must have a kinetic energy of 1,200 MeV (for an electron energy above 10 MeV, kinetic energy is proportional to momentum). This energy is several thousands times higher than the typical energy of electrons used in electron microscopes. The unit MeV, Million electron Volt, denotes the kinetic energy which a particle of unit charge acquires after passage in a voltage drop of one million volt.

Besides being required for ultra-precision subatomic microscopy, particles from accelerators colliding with target particles may lead to the creation of new particles, which acquire their mass from the collision energy according to the formula $E=mc^2$. It is thus by conversion to mass of excess kinetic energy in a
collision that particles, antiparticles and exotic nuclei can be created.

Particle accelerators are not only unique as tools for the exploration of the subatomic world, but are also used in many different applications such as material analysis and modification and spectrometry especially in environmental science. About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization. The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose. Accelerators also produce radioactive elements that are used as tracers in medicine, biology and material science. Of increasing importance in material science are ion and electron accelerators that produce abundant numbers of neutrons and photons over a wide range of energies. Well-defined beams of photons are for example increasingly used for lithography in order to fabricate the very small structures required in electronics.

The living cell is commonly studied by means of an optical microscope which receives scattered photons of visible light. Illustration: Fredrik Stendahl

Sub-micron objects such as the constituents of a living cell are often investigated in electron microscopes where electrons, accelerated typically to a few hundred kilovolts, are used to hit the objects and scatter from them. Illustration: Fredrik Stendahl

Quarks and leptons can be sensed down to distances of $10^{-18}$ meters by means of particles from giant accelerators. Illustration: Fredrik Stendahl

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)

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<td>Synchrotron radiation sources</td>
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History

In the first accelerators, particles were accelerated by a high voltage applied over the gap between a cathode and an anode (the electrodes). These were called cathode ray tubes and were conceived in the end of the 19th century. Using cathode ray tubes, X-rays were discovered in 1895 by Wilhelm Conrad Röntgen who obtained the first Nobel Prize in Physics (1901) for this discovery. In 1896 Joseph John Thomson investigated the nature of the cathode rays which were found to be charged and to have a precise charge-to-mass ratio. This discovery of the first elementary particle, the electron, marks the start of a new era, the electronic age which thus dates back to 1896. Thomson was awarded the 1906 Nobel Prize for work related to this discovery. The most common accelerator today is the cathode ray tube which is used in TV sets and in computer displays. In the tube, a beam of electrons, after having been accelerated to a maximum energy of up to 30,000 electron volts, is swept across a screen which emits light when hit by the electrons. In the following these single-gap devices as well as electron microscopes are disregarded.

The existing different types of accelerators were invented during a time span of nearly four decades. Around 1920, the first high-voltage particle accelerator consisting of two electrodes placed inside a vacuum vessel had a potential drop of the order of 100 kilovolts and was conceived by and named after John Douglas Cockcroft and Ernest Thomas Sinton Walton. Later in the 1920s it was suggested to use time-varying potentials across a series of gaps. (See below in the section on Linear accelerators). These suggestions to accelerate particles in a repetitive fashion inspired Ernest Orlando Lawrence to work out a new concept for accelerating particles. In the cyclotron invented by him, particles are made to circulate in a magnetic field and pass one and the same accelerating gap several times. Instead of a DC voltage, a high frequency voltage is applied over the gap so that particles are accelerated along a spiral trajectory in a repetitive fashion. After the invention of the principle of phase stability in the mid 1940s, two new types of accelerators were conceived: the linear accelerator and the synchrotron. In the linear accelerator, the gaps are placed along a straight line. In the synchrotron, the magnetic field is increased during the acceleration so that particles move in rings of essentially constant orbit. In these accelerators, particles are accelerated in a repetitive way and the energy is limited by the size of the accelerator and not by the maximum voltage that can be reached.

The inventor of the cyclotron, Ernest Orlando Lawrence (left), and his student Edwin Mattison McMillan, one of the two inventors of the principle of phase stability show the accelerating point at the entrance to a screened semi-circular electrode structure. The first cyclotron was built between
Potential-drop Accelerators

The electron vacuum tube, invented at the end of the 19th century, was used for the discovery of electrons and X-rays. The electrons are accelerated in vacuum between the two electrodes, a cathode and an anode. Air of atmospheric pressure would decelerate particles due to the collisions of electrons with air molecules. The vacuum tubes were pre-cursors to subsequent high-voltage accelerators. As mentioned above the first high-voltage particle accelerator had a potential drop of the order of 100 kilovolts and was conceived by and named Cockcroft Walton Accelerator after John Douglas Cockcroft and Ernest Thomas Sinton Walton. In 1951 they obtained the Nobel Prize in Physics for their pioneering work on the transmutation of atomic nuclei by artificially accelerated atomic particles.

The most common potential-drop accelerator in use today is named after its inventor, the American Robert Jemison Van de Graaff. The high-voltage terminal is connected to the low voltage (earthed) electrode by a moving insulating belt. Charge is applied to the belt at low potential and transferred to the terminal by conducting screens sliding on the belt. The potential on the terminal increases until the leakage current from the terminal to the surroundings is equal to the current provided by the belt. Normally, the terminal and tube are placed inside a tank containing SF$_6$ gas at high pressure in order to improve the insulation between the high voltage terminal and earth. The voltage is divided in steps and applied to electrodes placed in succession inside a vacuum tube where electrons or ions are accelerated. Electrons are obtained from a heated wire and ions from a gas discharge placed at the cathode.

Several microamperes of electrons or ions can be accelerated in van de Graaff accelerators. In a modern type for ions, the electrodes at entry and exit of the vacuum tube are at earth potential, and the high-voltage terminal is located at the middle of the tube. Within a small volume at the entry of the tube, a gas is ionized, usually by an electric discharge, and from this volume, negative singly charged ions are extracted. These ions are accelerated within the tube towards the high-voltage terminal, where two or more electrons are removed from each ion as it passes through a very thin foil or gas-filled region. The charge of the ion is hence changed from negative to positive, and the ion is repelled from the terminal and accelerated towards the exit of the tube which is earthed. Compared with van
de Graaff accelerators of the ordinary type, with one accelerating "gap", higher particle energies can be obtained since the potential drop is utilized in two gaps. An accelerator of this type is therefore called "tandem accelerator".

Nowadays most van de Graaff accelerators are commercial devices and they are available with terminal voltages ranging between one and 25 million volts (MV). Typically they have voltages below 10 MV. In comparison, the short pulses used in research on lightning reach 10 MV and the potential in clouds just before they are discharged by lightning is about 200 MV. Van de Graaff accelerators are often used in material analysis and modification, and accelerator mass spectrometry especially for environmental science.

The drawing shows the principle of a tandem van de Graaff accelerator. Negatively charged ions from an ion source at ground potential are accelerated towards a terminal at high positive potential in the centre, where gas or a thin foil removes two or more electrons from the ions, which then become positively charged and repelled towards the grounded electrode (V=0). Electric charge is transported on a belt from the ground to the terminal and as a consequence of the charge accumulation, the potential increases. The high voltage (V=5 MV) is insulated from the ground by high pressure gas, normally SF₆.

Illustration: Fredrik Stendahl

One of the biggest tandem accelerators was used for many years at Daresbury in the United Kingdom. Its acceleration tube, placed vertically, was 42 meters long and the centre terminal could hold a potential of up to 20 million volts.

Photo: CCLRC

**Cyclotron**

The principle of repetitive acceleration conceived in the 1920s is an important milestone in the quest for higher and higher energies. According to this principle, acceleration is achieved by means of a time-varying voltage instead of a static voltage as used in e.g. van de Graaff accelerators.
The first accelerator of practical importance based on the principle of repetitive acceleration was the cyclotron, invented by Ernest Orlando Lawrence. In a cyclotron, the charged particles circulate in a strong magnetic field and are accelerated by electric fields in one or more gaps. After having passed a gap, the particles move inside an electrode and are screened from the electric field. When the particles exit from the screened area and enter the next gap, the phase of the time-varying voltage has changed by 180 degrees so that the particles are again accelerated. The process is repetitive. After many turns of acceleration, resulting in an outward spiral trajectory, the particles circulate near the boundaries of the strong magnetic field. Here, the field is shaped so that the beam of circulating particles can emerge and be formed into an external beam. Lawrence was awarded the 1939 Nobel Prize in physics for the invention and development of the cyclotron and for results obtained with it, especially with regard to his research on artificial radioactive elements.

In Europe three Nobel Prize Laureates, Frédéric Joliot, Niels Henrik David Bohr and Karl Manne Georg Siegbahn contributed largely to the first cyclotrons. In 1938 the first European cyclotron at Collège de France in Paris accelerated a deuterium beam up to 4 MeV and by hitting a target, an intense source of neutrons was produced. About at the same time, the Copenhagen cyclotron at the Niels Bohr Institute was ready and in Stockholm, work started on the building of the first Swedish accelerator that was ready around 1940.

A serious problem with the early cyclotrons was the energy limit of about 10 MeV for the acceleration of protons. This limit depends on the slowing down of protons rotating in a constant magnetic field due to their relativistic increase of mass or equivalent total energy. The rest mass of a proton corresponds to an energy of 938 MeV and already after acceleration to a kinetic energy of 10 MeV, the rotation frequency of a proton, which is inversely proportional to its total energy (938 + 10), has decreased by one per cent. When the proton rotation frequency and the electric frequency are equal in the beginning of the acceleration cycle, there is no phase slip and the protons are accelerated with the same accelerating voltage at each gap. However, as the protons gain energy and slow down their rotation frequency, they will arrive later and later at each gap with respect to the maximum of the accelerating voltage of fixed frequency. After a while the phase has slipped so much that there is no longer any energy increment at gap passages.

A cyclotron is not useful for acceleration of electrons since their rotation frequency in a magnetic field slows down quite rapidly even for as low energies as a few MeV due to the small rest mass of an electron. The rest mass of an electron corresponds to a rest energy of 0.511 MeV according to the Einstein formula \( E = mc^2 \).

A variant of the cyclotron is the microtron in which electrons are accelerated at one gap at the periphery of the orbits. The frequency of the accelerating voltage is a multiple of the electron rotation frequency. The expanding circular orbits are tangent and touch each other at the point where the accelerating gap is situated.
The energy increment per turn is designed so that the increased time for a complete revolution of an electron due to its slow-down of the frequency of rotation corresponds to one or more cycles of the electric frequency at the acceleration gap.

Principle of the cyclotron. The ionization of a gas confined in the centre results in ions which are accelerated by a voltage of fixed frequency equal to the ion frequency of rotation in the magnetic field. The magnetic field lines are directed towards the lower magnet pole implying that positively charged ions circulate in the clockwise direction. The ions are accelerated when they move in the gap between the electrodes inside which they move screened from the electric field. When the beam of ions reaches the magnetic field boundary it is extracted from the cyclotron and formed into an external beam.

Illustration: Fredrik Stendahl

In Uppsala, Sweden, a cyclotron accelerates protons to 185 MeV and other ions to comparable energies. The beam of particles is accelerated inside the vacuum vessel seen under the upper coils (brown) for the 600 ton heavy magnet (yellow). The beam is transported to the experimental areas inside the tube that is pointing to the lower left part of the figure.

Photo: Teddy Thörnlund

**Synchrocyclotron**

To overcome the energy limitation of a cyclotron, the principle of phase stability was invented and proved in 1944/45. The inventors were Vladimir Iosifovich Veksler at the Dubna Joint Institute for Nuclear Research, an international research centre 100 km north of Moscow and by Edwin Mattison McMillan, a former student of Lawrence, at the University of California in Berkeley. They showed, independently of each other, that by adjusting the frequency of the applied voltage to the decreasing frequency of the rotating protons, it was possible to accelerate the protons to several hundred MeV. A cyclotron using synchronous acceleration by frequency modulation (FM) has usually been called a synchrocyclotron or FM cyclotron. Edwin Mattison McMillan received the 1951 Nobel Prize in Chemistry together with Glenn Theodore Seaborg for the discovery of the element neptunium.
Another Chemistry Nobel Laureate, Theodor Svedberg, suggested in the mid 1940s an accelerator to be built in Uppsala. Inspired by the Berkeley work it was decided to build a synchrocyclotron. In 1950, protons of 185 MeV were produced and Uppsala had for a while the highest-energy particles in Western Europe. In 1957, the first cancer patient treatment was pioneered. The accelerator has then been rebuilt and operates, since 1986, as a sector-focusing cyclotron-synchrocyclotron hybrid.

The invention of the principle of phase stability implied that there is, in principle, no energy limit for the acceleration of particles. It has paved the way for two new kinds of accelerators, the linear accelerator and the synchrotron.

The largest synchrocyclotron still in use is located in Gatchina outside St Petersburg and it accelerates protons to a kinetic energy of 1,000 MeV. The iron poles are 6 meters in diameter and the whole accelerator weighs 10,000 tons, a weight comparable to that of the Eiffel Tower. The energies attained correspond to that of a proton accelerated in a potential drop of one billion volts. It is used for nuclear physics experiments and medical applications.

Photo: Gatchina Nuclear Physics Institute

**Sector-focusing Cyclotron**

In the early 1960s, a new type of cyclotron, the sector-focused cyclotron emerged. Iron sectors were introduced in the pole gap so that an azimuthal variation of the magnetic field was obtained. This azimuthal variation provides a strong vertical focusing on the circulating beam of ions and it is then not necessary to have the azimuthally averaged field to decrease with increasing radius as it has to do in the conventional cyclotron in order to maintain vertical focusing. Hence, the average magnetic field as a function of radius, can be increased so that the rotation frequency of the ion remains constant in spite of the increase of mass of the accelerating ion. The vertical defocusing arising from the increase of the average magnetic field with radius is compensated by the vertical focusing due to the azimuthal variation of the field. The frequency of the accelerating voltage can thus be kept constant while maintaining a steady acceleration at each gap traversal; the energy is limited only by the size of the magnet. The sector-focused cyclotron is sometimes called continuous wave (CW) cyclotron or isochronous cyclotron, to differentiate it from the frequency modulated (FM) cyclotron or the synchrocyclotron. Many sector-focused cyclotrons are now in operation and they
have substituted synchrocyclotrons most of which have been shut down. Not only protons, but any kind of ions can, in principle, be accelerated. Ion sources, which produce ions of practically any element in the periodic table, are nowadays available.

Of special interest for the acceleration of protons in the range 200 to 600 MeV is the separated-sector cyclotron, which consists of a number of iron sectors, instead of a common iron pole with sectors attached to it. Separated sector cyclotrons having 4 sector magnets, are located at the Indiana University Cyclotron Facility in Bloomington, Indiana, USA and at the National Accelerator Centre in Faure in South Africa. Accelerators with 6 sectors operate at the Research Centre for Nuclear Physics in Osaka and at the Paul Scherer Institute in Swiss Villigen. Also should be mentioned in this context, the TRIstate University Meson Facility in Vancouver, having 8 sectors and providing 600 MeV H⁻ ions.

Cyclotrons are important research tools in nuclear physics and are often used for the production of radionuclides in medicine and industry. Cyclotrons also provide beams for radiation surgery and therapy and e.g. the South African cyclotron, is to a great extent used for medical applications. Large cyclotron facilities dedicated to cancer treatments are emerging at many places especially in Japan. Small cyclotrons are needed for the production of radionuclides for different purposes, one being as tracers for positron emission tomography (PET), a technique for mapping the functioning of the human body.

The separated sector cyclotron in Vancouver, provides 600 MeV negative hydrogen ions and it is the largest of all cyclotrons. The picture shows the gap inside which the ions are accelerated.

Photo: TRIUMF

**Synchrotron**

The two other types of accelerators based on the principle of repetitive acceleration, the synchrotron and the linear accelerator, are important in elementary particle physics research, where highest possible particle energies are needed. In synchrotrons, the particles are accelerated along a ring-shaped orbit and the magnetic fields, bending the particles, increase with time so that a constant orbit is maintained during the acceleration. The two largest proton synchrotrons, at CERN, the joint European High Energy Physics laboratory near Geneva, and at Fermilab near Chicago, have been in operation since the mid
In 1952 Ernest D. Courant, Milton Stanley Livingston and Hartland S. Snyder, proposed a scheme for strong focusing of a circulating particle beam so that its size can be made smaller than that in a weak-focusing synchrotron. In this scheme, the bending magnets are made to have alternating magnetic field gradients; after a magnet with an axial field component decreasing with increasing radius follows one with a component increasing with increasing radius and so on. In this way, a magnet defocusing the beam vertically is followed by a magnet focusing the beam vertically. So, like in optics where a defocusing and a focusing lens are combined to provide focusing, a strong net focusing is obtained in an alternating-gradient synchrotron. Thanks to the strong focusing, the magnet apertures can be made smaller and therefore much less iron is needed than for a weak-focusing synchrotron of comparable energy.

The first alternating-gradient synchrotron accelerated electrons to 1.5 GeV. It was
built at Cornell University, Ithaca, N.Y. and was completed in 1954. Pre-acceleration was done in a 2 MeV van de Graaff accelerator and after injection at this energy, the fields of the ring magnets were 0.002 tesla. Acceleration to 1.5 GeV was done in 0.01 second and during this time the magnet field was increased to 1.35 tesla. In 1958 the first European strong focusing electron synchrotron (500 MeV) was started up in Bonn. It was developed and built under the leadership of Wolfgang Paul, Nobel Laureate in Physics 1989 for his development of the ion trap technique. Other electron synchrotrons of the alternating-gradient type in the early sixties were located in Hamburg (6 GeV), Harvard-MIT, Cambridge (6 GeV) and at Tokyo University (1.3 GeV).

Soon after the invention of the principle of alternating-gradient focusing, the construction of two nearly identical very large synchrotrons, which are still in operation, started at the European CERN laboratory in Geneva and the Brookhaven National Laboratory on Long Island in New York. At CERN protons are accelerated to 28 GeV and at Brookhaven to 33 GeV. The CERN proton synchrotron (PS) started operation in 1959 and the Brookhaven PS in 1960.

In the 1960s, the Brookhaven PS was the most powerful of all accelerators and some performance figures may be of interest. It had a linear accelerator as injector and the injection energy was 50 MeV. The protons were accelerated in 12 accelerating stations placed along the circumference of the synchrotron. During an acceleration time of about one second, the fields of the bending magnets were raised from 0.012 to 1.3 tesla. This represents a very big change of stored energy considering that the 800 meter long ring is filled with magnets with a total weight of 4,000 tons. The intensities were typically $10^{11}$ protons per pulse repeated every third second. Nowadays, the intensity is larger by two orders of magnitude. A list of synchrotrons currently in use can be found, for example, via the homepage of CERN.²

Particles produced in collisions between a beam of ions or electrons and a target can be formed into secondary beams which have found many applications in science and technology. We can distinguish beams of short-lived particles such as mesons or muons from beams of long lived particles, such as photons, neutrinos, positrons, neutrons and antiprotons. Some of the short-lived particles can be transported long distances because, according to the theory of relativity, time is slowed down in an object that moves close to the velocity of light. For example, in their own rest frame, π-mesons have a life time of $2.6 \times 10^{-8}$ seconds and during this time they travel a maximum distance of 8 meters if they move with the speed of light. π-mesons, available at the largest proton synchrotrons of today, have an energy exceeding their rest energy, 140 MeV, by a factor of 1,000. Hence their life time is increased by the same factor and they are able to travel, on average, 8 kilometers during their lifetime. This fact is a beautiful proof of the theory of relativity and makes it possible to form beams of high-energy π-mesons, K-mesons and muons and transport them to experimental areas. Together with secondary beams of stable particles like neutrinos, photons, antiprotons and neutrons, secondary beams constituted the basis for extensive fixed-target physics research programs especially at the large synchrotrons at CERN, Brookhaven, Serpukhov.
(Russia) and Fermilab in the 1960s and 1970s.

Specially designed magnets are used to focus beams of particles. A simple focusing element is a quadrupole magnet. It has four iron poles and the magnetic field is excited by currents in surrounding coils. There are two north poles opposite to each other and each of them has neighbouring south poles. The magnetic field is zero at the centre axis and it increases linearly with increasing distance from the centre axis. A quadrupole magnet provides focusing in one plane e.g. the \( x,z \)-plane and defocusing in the other plane, the \( y,z \)-plane. The \( z \)-direction is assumed to be aligned with the beam direction. As in optics where the combination of a focusing and defocusing lens can result in a net focusing, a pair of two quadrupole magnets can be designed to give a net focusing in both the \( x,z \)- and the \( y,z \)-planes.

Photo: Teddy Thörnlund

Most common primary particles produced in accelerators. Secondary particles are produced in interactions of the primary particles with matter. The units are MeV for the rest energy and seconds for the life time.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge</th>
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### Principle of the Synchrotron

Particles are accelerated along a ring-shaped path. The magnets, necessary for bending and focusing, are placed around the particle orbit. The magnetic fields are adjusted during acceleration from a low to a high value, matched to the increasing energy of the particles, so that the orbit remains essentially constant. The particles are accelerated by high voltages across one or several gaps along the circumference.

**Illustration:** Fredrik Stendahl

Inside the 6.9 km long tunnel of the CERN 450 GeV super proton synchrotron. The blue magnets focus, and the red magnets bend the particles.

**Photo:** CERN

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### Particle Properties

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<th>Particle</th>
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<td>-1</td>
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</table>

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**Aerial View:**

Aerial view of the CERN laboratory situated between Geneva airport and the Jura mountains. The circles indicate the locations of the SPS and LEP accelerators placed in underground tunnels. After the LEP accelerator has stopped operation at the end of the year 2000, it was dismounted and the Large Hadron Collider (LHC) is currently being installed in the 27 km long tunnel.

**Photo:** CERN

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**Linear Accelerator**
In 1924, the Swede G. Ising suggested that the maximum energy could be increased by replacing the single gap holding a DC voltage by placing along a straight line several hollow cylindrical electrodes holding pulsed voltages. The Norwegian Rolf Wideröe realized that, if the phase of the alternating voltage changed by 180 degrees during a particle's trip between gaps, the particle could gain energy in each gap. Based on this idea he built a three-stage accelerator for sodium ions. The idea of the linear accelerator was born. The particles were accelerated in small gaps and between the gaps they moved inside shielded cylindrical electrodes. An improved version of a linear accelerator was conceived some years later by Luis Walter Alvarez who generated the AC voltage differently; standing radio-frequency waves inside cylindrical cavities. These so called Alvarez structures are still used for ion acceleration. Alvarez was awarded the 1968 Nobel Prize in Physics for his decisive contributions to elementary particle physics.

These early suggestions were not practical for particle acceleration, and it was not until after the second world war that the development of electron accelerators really started. From the development of radar systems, emerged wave-guides that could be used for the traveling-wave linear accelerator. In this accelerator, the electromagnetic waves propagate forward in the accelerator with the speed of light and the electrons, also moving very close to the speed of light, are steadily accelerated in step with the wave in analogy with a surfer on an ocean wave.

For scientific purposes, there exist presently about 130 linear accelerators for electrons and positrons and about 50 for ions including protons. They cover a wide energy range from a few MeV to 52 GeV for the largest electron linear accelerator located at the Stanford Linear Accelerator Centre (SLAC). In Los Alamos, a proton linear accelerator accelerates protons up to 800 MeV over a distance of 800 meters. This accelerator is the heart of the Los Alamos Meson Physics Facility (LAMPF) and it is the largest proton linear accelerator in the world. Many of the linear accelerators are used as injectors for synchrotrons.

In addition to the scientific accelerators there are thousands of small linear accelerators used at hospitals for the treatment of cancer.

Principle of operation of a linear accelerator. A great many electrodes are separated by small gaps and placed along a straight line. There is no magnetic field that changes the direction of the particles being accelerated. When particles move inside the field-free region of a given electrode, the direction of the accelerating electric field is reversed so that particles are always accelerated in the gaps between the electrodes.

Illustration: Fredrik Stendahl
Electrons have been accelerated in single-gaps for more than 100 years. X-ray tubes and electron microscopes are common types of single-gap accelerators used for a variety of applications. An accelerator familiar to us all, is located in the interior of our TV sets, where electrons are accelerated up to a voltage of 30 kilovolts.

Small electron linear accelerators with energies of around ten MeV, are very common in hospitals for producing strong fluxes of X-rays for cancer treatment.

High-energy electrons are accelerated in linear accelerators and in synchrotrons. Pioneering work was done in the early 1960s in Stanford on the development of electron accelerators under the leadership of Burton Richter. At that time, the sizes of atomic nuclei were measured in Stanford by scattering electrons of energies up to 1 GeV from a 100 meter long linear accelerator. With Richter as a leading scientist, construction of a 3 km long linear accelerator began, and in 1967 it accelerated, for the first time, electrons to 20 GeV. Also the collider concept (see section on colliders) was developed at that time. This development led to the construction of electron-positron colliders and Richter, using such a collider, shared the 1976 Nobel Prize in Physics with Samuel Chao Chung Ting for their pioneering work on the discovery of a heavy elementary particle of a new kind. Stanford of today is an important centre for electron accelerators and at present, besides having the largest 3 km long linear accelerator, two electron-positron colliders are powerful tools for elementary particle physics research.

Very early, in the development of electron synchrotrons, interest was focused on synchrotron radiation. In 1977, the Stanford Synchrotron Radiation Laboratory (SSRL) started. Nowadays, many electron synchrotrons are built exclusively for producing secondary beams of synchrotron radiation. The largest of these is the 8 GeV SPring8 in Harima, Hyogo-prefecture, Western Japan.

There are about ten electron accelerators in the range from a few hundred MeV to some thousand MeV primarily used for research in applied physics, nuclear physics...
and the border line between nuclear and particle physics. The most powerful of these is the race-track synchrotron at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia. It provides an intense and continuous beam of 100 microamperes of 6 GeV electrons.

The continuous electron beam facility (CEBAF) at the Jefferson Laboratory, Virginia, USA, accelerates electrons up to 6 GeV in a race-track microtron with a circumference of 1.4 km. Acceleration takes place in 338 hollow shells (cavities) placed in the straight sections inside cryomodules and the beam is bent 180 degrees in five different arcs. During the first revolution, the electrons move in the upper arcs, they descend successively and after five revolutions of acceleration they have reached the bottom arcs. Experiments are situated in three different halls, A, B and C. In the future, a new hall D will be added and the energy will be increased to 12 GeV.

Illustration: DOE/Jefferson Lab.

Heavy Ions

Sector focusing cyclotrons have been very useful for providing low-energy heavy ions. The ions should be highly charged in order to reach a biggest possible energy for a given accelerator. The energy gained by a charged particle passing a gap with voltage V is ZeV where Z is the charge of the ion in units of the electron charge e. Various types of ion sources have been developed, ECR (Electron Cyclotron Resonance) and EBIS (Electron Beam Ion Source), and they provide intense beams of low-energy highly charged ions. These sources are big and placed externally to the accelerator.

By having an ion pass a thin medium e.g. a foil, electrons are exchanged between the ion and the medium. The higher the velocity is, the greater the chance is for the ion to lose atomic electrons. For ions of very high energy, all electrons can be removed and the ion fully stripped. A fully stripped uranium ion has a charge of 92 times the charge of a proton and in passing an accelerating voltage, its energy is increased by 92 times as much as a proton. Since it is not possible to produce highly charged ions from ion sources by more than about ten units of the elementary charge, two "cascade" accelerators can be used to increase the charge of the ion by means of "stripping". After acceleration to a high velocity in a first accelerator, the ions are extracted and made to pass a thin foil where electrons are stripped off. The highly-charged ions are then injected into the second
accelerator where they are accelerated to their final energy. One example of such a cascade facility is the GANIL accelerator complex in Caen, where two sector focusing cyclotrons are used for heavy-ion physics. Other facilities are the GSI in Darmstadt, where a linear accelerator, the Universal Linear Accelerator (UNILAC), serves as an injector for the Heavy Ion Synchrotron (SIS) and the CERN PS complex providing ions for the SPS.

Since the maximum energy in a cyclotron is limited by the strength of the magnetic field and its radial extension, superconducting wire coils are used instead of conventional copper coils around the iron poles to provide stronger fields. Hence a higher energy can be attained and the cyclotron can be built more compact. Superconducting cyclotrons were developed first by Henry Blosser and his colleagues in East Lansing, USA, where two "compact" cyclotrons are now coupled together. The magnetic field is 5 tesla and the pole diameters are 1.5 and 2 meters, respectively. In these cyclotrons, heavy ions can be accelerated to energies of 160 MeV per nucleon. For example, argon ions can be accelerated to a total kinetic energy of 6,400 MeV. A new powerful heavy-ion facility is being planned for the Riken Institute of Physical and Chemical Research in Wako, Saitama, Tokyo.

Linear accelerators and synchrotrons for electrons and ions are important research tools also for heavy ion physics when high energies are required. Lawrence Berkeley National Laboratory (LBL), named after the inventor of the cyclotron, adapted an existing linear accelerator and synchrotron in the early 1970s for acceleration of heavy ions up to about 2,000 MeV per nucleon. The Berkeley synchrotron has now been shut down but the SIS synchrotron for heavy ions in Darmstadt provides from 1990 ions with energies up to 1,000 MeV per nucleon and is used for pure and applied physics research.

Using accelerated heavy ions, several new elements have been discovered first in Berkeley and Dubna and later in Darmstadt. The heaviest element so far discovered, element 110, was first found in Darmstadt and the discovery has been confirmed by the groups in Dubna and Berkeley. The research is still intense and element 112 has been claimed in Darmstadt, element 114 in Dubna and elements 116 and 118 in Berkeley. These claims need to be confirmed before a discovery can be clearly established. Information about the Darmstadt accelerators and its research can be found in the GSI homepage.3

At CERN, oxygen and sulphur ions were accelerated initially during 1986/87 in the Super Proton Synchrotron (SPS), to energies of 158 GeV per nucleon. Since then lead ions with energies of 160 GeV per nucleon i.e. 33 TeV total energy have been used to bombard target nuclei of heavy elements. The most interesting objects of study are particles called gluons, the carriers of the strong force that keep the quarks together inside protons and neutrons. An important question is whether a large aggregate of quarks and gluons, a so-called quark-gluon plasma, can be formed when such a high energy ion reacts with a heavy target nucleus. The properties of a quark-gluon plasma will give more insight in the dynamics of interactions of quarks and in the early development of the Universe for the
understanding of the quark era of the Big Bang.

From 1996 ions from the Darmstadt facility are used for the therapeutic irradiation of patients. An interesting diagnosis method has been developed using carbon ions for the irradiation. In order to kill a tumour and at the same time keep the dosage to the normal tissue at a minimum, it is necessary to keep an accurate control on the distribution of the irradiation. By utilizing the small amount of radioactive carbon-11 produced during the irradiation, a map of the dose distribution is obtained. Like in conventional Positron Emission Tomography (PET), the positron annihilates with electrons of the tissue and the produced two photons, recorded in detectors, give information on the origin of the carbon-11 nuclide.

Interesting effects of heavy ions are the peculiar effects astronauts experience with their eyes closed. These light flashes appear like lines or star-like spots. Similar effects could be reproduced in the early 1970s when ions from the Berkeley accelerator were directed on the eye, head on or from the side. Cornelius Tobias, a pioneer of radiation therapy, was one of the first to experience personally the effects of the "light" after penetrating heavy ions from the Berkeley accelerator. The phenomenon of light flashes has been extensively studied on board the Russian space station Mir between 1995 and 1999. The ambient cosmic particle radiation was detected and identified using an array of position sensitive Si strip detectors and the detected signal was correlated with the astronaut's sensation of light flashes via a joy stick. Typically the light flashes are separated by seven minutes and the sensory sensation is clearly correlated with ions passing the eye. It is still an open question whether light is produced in the track of the ionizing particle or if the rods and cones of the eye are directly stimulated by the penetrating particle.

**Colliders**

In the continuous race for higher energies, required in the search for undiscovered heavy particles and for the exploration of smaller distances, particle colliders have been found to be superior to other types of accelerators. A collider consists of one or two storage rings in which bunches of particles are accelerated in opposite directions, clockwise and counter-clockwise. When the particles have attained the required energy they are stored and made to collide at specific points along the circumference of the ring(s), where detectors are placed to register particles scattered and produced in the collisions. Already in the 1960s, pioneering work on how to collide two beams of electrons circulating in two synchrotrons was done in Novosibirsk at the Budker institute, named after the inventor of the electron cooling of particle beams. (See below section on cooler storage rings.)

The first collider to be used for experiments was the intersecting storage rings (ISR), used at CERN from 1971 to 1983. Protons were injected from the proton synchrotron into the two rings which crossed each other at eight intersections where the protons were made to collide. Collision energies up to 62 GeV and proton currents of 30 amperes in each ring could be achieved. Since the velocity of the protons is near the velocity of light, the stored number of protons can be easily...
computed. Knowing that the circumference of ISR was about 1 km, a current of 30 amperes is found to correspond to 600,000 billion stored protons in each of the rings.

Antiprotons, which are negatively charged, can be made to circulate in the same ring as protons but with opposite directions. At CERN, in 1980, it was shown for the first time that antiprotons can be handled and formed into circulating beams. The antiprotons were produced in proton-nucleus collisions and successively accumulated and formed into a narrow beam by a cooling method called stochastic cooling and invented by the Dutchman, Simon van der Meer. Before 1980, antiprotons had been observed for fractions of a second only. The antiprotons could be stored for many hours, circulating inside a tube under exceptionally high vacuum (10^{-12} torr) to prevent them from being destroyed too quickly in encounters with normal matter, i.e. in this case with residual air molecules. It is expected that antiprotons isolated from matter have the same life time as protons i.e. that they are stable particles. The 1984 Nobel Prize in Physics was shared by Carlo Rubbia and van der Meer for their decisive contributions to the discovery of the field particles W and Z, communicators of the weak interaction, which were produced in collisions between protons and antiprotons circulating in opposite directions in one and the same synchrotron ring, the SPS.

At Fermilab near Chicago, the world's first synchrotron based on superconducting magnet technology was built and has operated since 1987. In the magnets with superconducting wire coils, protons and antiprotons are accelerated to an energy of 1,000 GeV, stored and brought to collide. The energy can also be expressed as one tera electron volt (1 TeV), from which the name Tevatron has been derived for the Fermilab collider. When the Tevatron collider started in 1987, antiprotons were produced by operating the Main Ring at 120 GeV. The antiprotons were collected in a Debuncher ring before they were transferred to the Accumulator where stochastic cooling was applied. After cooling, the antiprotons were injected into the Main Ring and Tevatron for acceleration to 1 TeV. With the recent extension of the Fermilab complex, the main Ring has been replaced by a new rapid cycling 120 GeV synchrotron, the Main Injector. In the same tunnel, an 8 GeV storage ring, the Recycler, has been constructed using permanent magnets. The Recycler acts as a repository for cooled antiprotons, thus permitting a high rate of cooling in the Accumulator which works best with low currents, to be maintained. The Recycler also receives antiprotons left over and decelerated after completion of a storage in the Tevatron. Stochastic cooling, initially installed in the Recycler, will be enhanced by the addition of electron cooling in the near future.
In a single head-on collision between proton and antiproton in the Tevatron, hundreds of new particles are usually created. According to Einstein’s formula $E=mc^2$, the maximum mass that can be converted from kinetic energy corresponds to the mass of about 2,000 protons, if all the kinetic energy of the proton and antiproton in a single collision were to be converted to mass. If instead an antiproton of the same energy were to collide with a stationary proton in a
A maximum mass corresponding to the mass of about 40 protons can be created. So much less energy is available for mass production in this latter case because, in a collision with a stationary target, the momentum (motion) of the moving antiproton must be conserved. For a similar reason, a collision head-on between two cars in motion is much more violent than if one of them is at rest.

A collider for heavy ions of masses up to gold has been started during the year 2,000 in Brookhaven. The two rings in this Relativistic Heavy Ion Collider (RHIC) employ superconducting magnets for the bending of the ions. It has the potential of colliding any element of the periodic system up to an energy of 100 GeV per nucleon. In June, 2000, the first collisions with gold ions of 56 GeV per nucleon were registered.

At CERN, in a 27 km long tunnel, two superconducting-magnet rings are being constructed for acceleration of protons and ions. This collider, the Large Hadron Collider (LHC), will make it possible to study proton-proton collisions and ion-ion collisions at the highest energy ever in a laboratory. The protons in each ring will be accelerated to an energy of 7 TeV. The superconducting coils providing a magnetic field of 8.3 tesla operate at a temperature of 1.9 kelvin, the coolant being superfluid helium. Cooling more than 31,000 tons of material spread over 27 km represents a milestone in the development of superconductor technology. LHC is expected to be taken into operation around 2006.

Like protons and antiprotons, electrons and positrons can be made to circulate in opposite directions and collide in the same synchrotron ring. Electron-positron colliders with collision energies from one to ten GeV are common tools for producing mesons, whose decays can be studied under clean conditions. Colliders in this category exist in Rome, Ithaca, Novosibirsk, Beijing, Stanford and Tsukuba. The Beijing collider which started in 1989 has been used primarily for studies of the charm quark and the tau lepton. The collision energy varies between 2 and 5.6 GeV. The colliders in Stanford and Tsukuba, called B factories, have been started up a couple of years ago. They produce large numbers of B and anti-B mesons.
whose decays will be studied in order to provide a better understanding of the so
called CP violation i.e. the asymmetry in the decays of matter and anti-matter
particles. The Stanford B factory consists of two separate rings placed in a tunnel
of 2.2 km length. Electrons are accelerated to 9 and positrons to 3.1 GeV before
they are brought to collide.

The Stanford B factory consists of two separate rings placed in a tunnel
of 2.2 km length. Electrons are accelerated to 9 and positrons to 3.1 GeV before
they are brought to collide.

The picture shows the KEKB collider at Tsukuba in Japan. The electrons are
accelerated to 8.5 and the positrons to 3.5 GeV and then they are made to
collide to produce B and anti-B mesons.

Photo: KEK

The largest electron-positron collider ever built, LEP, Large Electron Positron
collider, had a circumference of 27 km and was commissioned in 1989 at CERN. In
the first phase, collisions between positrons and electrons at a collision energy of
91.2 GeV, corresponding to the rest mass of the Z boson, were studied. After the
installation of very powerful superconducting radiofrequency accelerating cavities,
the collision energy was successively increased and reached finally a maximum of
209 GeV. LEP stopped operation by the end of the year 2000 at the same time
installation of the LHC commenced in the LEP tunnel.

An interesting variant of a collider was the Stanford Linear Collider (SLC). Positron
and electron bunches were simultaneously accelerated to about 45 GeV in the 3
km long linear accelerator. At the end of the linear accelerator they were bent
away from the straight directions, to the left and to the right, respectively, and
then bent back and made to collide along a straight line. The particle bunches just
met once whereas in a conventional collider, they meet repetitively in the collision
point. To get a sufficient interaction rate, the two beams, colliding in one pass,
must have extremely small transverse dimensions. The cross sections of the two
beams were only 1 micrometer in diameter. The SLC is now shut down, but the
development at Stanford is of great interest for future high energy electron-
positron colliders which, to avoid excessive synchrotron radiation, have to be
constructed as two oppositely directed linear accelerators accelerating the
electrons and the positrons towards a single collision point.
Refined measurements of the size of the electron using electron-positron colliders have shown that the charge of the electron is confined to dimensions at least 1,000 times smaller than the size of the proton. It is obvious that for probing the inner structure of the proton, an electron is preferred compared with a proton which has itself a structure. Studies of the structure of the proton are the main objectives of the research at the only electron-proton collider, the HERA collider at DESY in Hamburg. In HERA 27 GeV electrons collide with oppositely moving 920 GeV protons. The superconducting proton ring is placed on top of the electron ring, built of conventional magnets, in a tunnel of 6.3 km length.

Future electron accelerators in the TeV range will require very high accelerating gradient per meter in order not to be excessively long. The development of superconducting radiofrequency cavities at DESY in Hamburg has made it possible to reach acceleration gradients of 30 MV per meter. The so called two-beam accelerating method, developed in the CLIC project at CERN, makes use of a very high frequency, 30 GHz, accelerating voltage leading to accelerating cavities of cm dimensions. Instead of exciting the accelerating cavities using klystrons, they are excited, using a low energy, high current electron-drive beam. This drive beam runs parallel with the beam being accelerated and energy is transferred from the drive beam to pick-up cavities which are coupled through short wave guides to the accelerating cavities. With this scheme, an accelerating gradient of 100 MV per meter has been demonstrated. These developments are very important in connection with a future linear electron-positron collider currently considered in

The Stanford Linear Collider (SLC). Electrons were accelerated in the 3 km long linear accelerator together with positrons. After having reached their final energy, the positrons and electrons were separated magnetically and transported along two big arcs at the ends of which they met head-on in a single collision point. The positrons were produced by a fraction of the accelerated electrons which when being stopped in a target generate abundant number of positrons, electrons and photons. The positrons were collected and returned to the upstream end of the linear accelerator where they were formed into a dense beam by damping rings. Subsequently they were accelerated together with the beam of electrons.

Illustration: Stanford Linear Accelerator Center

Illustration: Stanford Linear Accelerator Center
USA, Europe and Japan. The goal is to have an acceleration energy of 150 MeV per meter and if this goal can be reached, two linear accelerators each of 10 km length would give a collision energy of 3,000 GeV.

**Cooler Storage Rings**

Cooling a circulating particle beam means reducing the momentum spreads and the transverse dimensions of the beam. Typically uncooled particle beams have dimensions in the mm-cm range and momentum spreads in the permille-percent range. Ideally, a beam should be monochromatic i.e. all the particles should have one and the same velocity and the transverse dimensions should be pencil-like.

A self-cooling mechanism takes place when the particle energies are sufficiently high. Electromagnetic radiation, photons, are emitted by circulating particles due to their continuous radial acceleration, and this emission, "steeling" energy from the circulating particles, combined with the acceleration which keeps their average energy constant, has a cooling effect on them; the circulating particles may be regarded as small antennas. The energy emitted per particle revolution, is proportional to the fourth power of the particle energy, inversely proportional to the fourth power of the mass and inversely proportional to the radius of curvature. This emitted energy, known as synchrotron radiation, becomes significant in electron synchrotrons of a few hundred MeV whereas it is insignificant for all existing proton synchrotrons.

Electron cooling was invented in Novosibirsk in the late 1970s. A beam of electrons of very high quality was then injected into the straight section of a small proton synchrotron and made to move together with the protons over a few meters. The velocity spread of the electrons was extremely small, typically 1/100,000 of the average electron velocity. The average velocity of the electrons was adjusted to be the same as the average velocity of the protons and the electron beam current was significantly larger than the proton beam current. Given these conditions, the velocity spreads of the protons will gradually approach those of the electrons i.e. cooling will take place. In these first tests, the protons were cooled so that their velocity spreads became equal to those of the electrons, an improvement by about a factor thousand.

Electron cooling is useful for improving the quality of beams of protons, antiprotons and ions. However, since it is difficult to accelerate an intense beam of electrons by more than a few hundred kilovolts, in a single gap, electron cooling is not useful for cooling particles with energies in the GeV range. After the Novosibirsk demonstration of electron cooling, research started at CERN on cooling techniques and a new method, stochastic cooling was invented by Simon van der Meer and experimentally demonstrated first in the ISR. In stochastic cooling, an electrode at one point of the periphery senses the average position of the circulating particles with respect to a central orbit. A signal that is proportional to the displacement of the particle with respect to the central orbit, is generated and this signal is sent to another point of the periphery where a correcting pulsed voltage is applied over an electrode, forcing the particles to approach the central orbit.
orbit. Obviously, the scheme works if there is only one circulating particle. However, it was shown that the correction of the fluctuation of the average position of a great many particles was sufficient to produce a cooling effect, hence the name stochastic cooling.

Soon after the successful demonstration of the cooling of protons and antiprotons, two cooler rings were built at CERN, the antiproton Accumulator (AA) and the Low Energy Antiproton Ring (LEAR). The AA received antiprotons produced in a proton-target collision and their quality was gradually improved by stochastic cooling. After many hours of accumulation and cooling, the antiprotons were sufficiently many (hundred billions) and they were then injected into the SPS collider where they were used for experiments between 1981 and 1990, especially producing the intermediate vector bosons, W and Z (see section on colliders).

LEAR operated between 1980 and 1996 and it accelerated and stored antiprotons in the energy range 50 to 1,300 MeV. Both electron cooling and stochastic cooling were employed at LEAR, which was used primarily for studies of the spectroscopy of mesons. One of the spectacular discoveries at the end of LEAR’s operation in 1995 was the discovery of antihydrogen, the first element of the periodic table of antimatter. It was produced in interactions between the circulating beam of antiprotons and a gas jet of xenon. Positrons from positron-electron pairs produced in the antiproton-xenon interactions could be captured into a bound state by the antiproton.

After the successful invention of cooling, scientists in Bloomington, Indiana proposed to build a cooler storage ring for protons with thin targets placed internally in the circulating high-quality proton beam cooled with electrons. The Indiana storage ring in which protons up to an energy of 400 MeV can be stored has been in operation from the mid-eighties. Cooler storage rings providing protons and ions up to energies of a few GeV for research in nuclear and particle physics are presently also in operation in Jülich, Darmstadt and Uppsala. Low-energy ion cooler storage rings for atomic physics experiments are located in Aarhus, Heidelberg and Stockholm. In these low-energy rings, the cooling is provided by electron cooling and by laser cooling, a method that works for cooling ions of low energy. Cooler storage rings have opened up new frontiers of high-precision experiments thanks to the cooling method. Relative momentum spreads down to $10^{-5}$ and transverse dimensions smaller than a mm can be achieved.
Meson Factories

During the 1960s, three accelerators were built to provide intense fluxes of beams of medium-energy, several hundred MeV, charged $\pi$-mesons. They are called meson factories because of the high fluxes, about 1,000 millions of $\pi$-mesons per second. The $\pi$-mesons are produced by an intense beam of protons which is stopped in a target. The primary protons are accelerated in cyclotrons at Villigen, Switzerland and Vancouver, Canada, and in a linear accelerator at Los Alamos, U.S.A. Since the intensity of protons is very high, it is necessary to handle the beam of protons with care during acceleration and transport to the target, where the $\pi$-mesons are produced in reactions between the protons and the target material. The accelerator in Villigen can accelerate a proton current of 1.5 milliamperes to 590 MeV. If the control of such an intense beam containing a power of 900 kilowatt hits the walls of a vacuum tube it can very quickly lead to a melt-down.

Neutron Sources

When a high-energy proton penetrates a target of heavy material such as lead, tungsten or uranium, numerous neutrons are knocked out. For example, one proton of 800 MeV stopped in a target of uranium gives rise to about 30 neutrons on the average. (One uranium nucleus consists of 92 protons and 146 neutrons and each neutron in uranium is bound on average by 8 MeV.) Initially, the neutrons are quite fast having kinetic energies of several MeV but their velocities are reduced, like those from nuclear research reactors, by passage through a moderator material. The kinetic energies of the neutrons are being reduced in their successive collisions with the atoms of the moderator material until the neutrons have the same average energy as these atoms. They are said to be thermal implying kinetic energies around one eV. Accelerator-driven neutron sources, often
called spallation sources, are usually pulsed and they have, compared to research reactor neutron sources, a potential of providing substantially higher neutron fluxes. In a research reactor, the flux is limited by the density of the reactor core.

At present, the most powerful pulsed neutron source is located at the Rutherford Appleton Laboratory near Oxford, U.K., where a 70 MeV linear accelerator is the injector to a synchrotron that provides protons of 800 MeV with an intensity of 200 microamperes. The beam is pulsed and the repetition frequency is 50 hertz. The target used is tantalum and there are 17 neutrons produced per incident proton. In Villigen, Switzerland, the 590 MeV separated sector cyclotron provides a continuous flux of neutrons. The beam current is a record high, 1.5 milliamperes, and the number of neutrons produced from a zircaloy target is 15 per incident proton. Other pulsed neutron sources are in operation at Argonne, Illinois, at Los Alamos, New Mexico and at Tsukuba, Japan. The energies are 450, 800 and 500 MeV respectively and the targets used are uranium, tungsten and tantalum.

Accelerator-driven neutron sources have turned out to be valuable complements to reactor-produced neutron sources in material science, biology and medicine. In chemistry, the combination of neutron diffraction, which provides information on the location of atomic nuclei in a molecular crystal, together with X-ray diffraction, which is sensitive to the location of the electrons, gives valuable information on molecular structure.

In 1990 Los Alamos scientists proposed to build a linear accelerator with a continuous current of 250 milliamperes of 1,600 MeV protons. These numbers imply a beam power of 400 megawatts, more than two orders of magnitude above what is produced by any existing accelerator. According to the proposal, the interaction of this powerful beam with a lead/bismuth target should provide a very strong neutron flux that could be used to transmute long-lived radioactive waste from weapons and to produce sustainable energy from an under-critical core of uranium-238 or thorium-232.

Continued research in the USA, Europe, Russia and Japan has led to more realistic designs in this field often called Accelerator Driven Transmutation Technologies (ADDT). Presently the design figures for the accelerator part of a prototype facility are 1,000 MeV and 10 milliamperes. An accelerator with such a performance will be only a few times more powerful than existing meson factories in Los Alamos and Villigen and comparable with new spallation neutron sources proposed in USA, Japan and Europe. Thus this new principle for the destruction of nuclear waste and for the production of nuclear energy may be tested according to present plans within 20 years. In Europe, one of the principal driving persons behind the development of accelerator-driven transmutation technologies has been Carlo Rubbia.

**Synchrotron Radiation**

Electrons orbiting in a magnetic field lose energy continually in the form of electromagnetic radiation (photons) emitted tangentially from the orbit. This is
called synchrotron radiation. It was predicted by John Blewett in 1945 when he calculated that a beam of circulating electrons should lose energy by emitting radiation and subsequent reduction of the radius of curvature. Synchrotron radiation was subsequently observed at General Electric's Research Laboratory in 1947 from a 70 MeV electron synchrotron.

Electromagnetic radiation for example from an antenna is caused, according to Maxwell's equations, by electrons moving with a non-uniform velocity. In a synchrotron, the electron trajectories are continually being deflected and due to these continuous changes of direction, electromagnetic radiation (photons) is emitted continually along a straight line tangential to the orbit. Synchrotron radiation is important also in astronomy. Many galaxies emit synchrotron radiation as a result of electrons circulating in the magnetic fields (of the galaxy). The radiation from such radio galaxies is studied using large radio-telescopes.

The large energy loss increasing with the fourth power of the energy of the electrons is the main reason why it is difficult and impractical to use synchrotrons for the acceleration of electrons to the same high energies as protons. The highest energy so far, 104,000 MeV, has been obtained in LEP for electrons having been accelerated in the 27 kilometer long underground tunnel at CERN. The excessive synchrotron radiation about 13 megawatts is the reason why a bigger electron synchrotron than LEP has not been proposed.

Synchrotron radiation, which thus limits the energy attainable in circular electron accelerators, has turned out to be a very interesting alternative to conventional X-ray and UV light sources for research which requires high fluxes of photons. Synchrotron radiation emitted tangentially from the orbit, is pulsed, polarized and occurs with high intensity over a wide spectrum of wavelengths. A desired wavelength is selected by diffraction in a suitable crystal or grating, called a monochromator. The word arises by analogy with how a single colour of light may be selected from white light by means of a prism.

The first experiments using synchrotron radiation were initiated more than 30 years ago at synchrotrons used primarily for research on elementary particles. Now, many synchrotrons are used exclusively as powerful photon sources in laboratories all over the world e.g. at Stanford, Brookhaven (Long Island), Argonne (Illinois), Berkeley (California), Daresbury (UK), Orsay (Paris), Grenoble, Berlin, Hamburg, Lund, Tsukuba (North of Tokyo) and SPring8 in Harima, Hyogo-prefecture, Western Japan to mention some of the big installations. More information on synchrotron radiation facilities can be found on the set up at the European Synchrotron Radiation Facility in Grenoble.4

Stored electrons for synchrotron radiation purposes usually have energies in the range from 500 to 8,000 MeV and provide radiation with wavelengths from infrared light to hard X-rays. Among new applications should be mentioned the measurements of atomic coordinates at solid surfaces, diffraction from quantum dots and stripes and protein crystallography for rational drug design from the measured atomic structure of the protein. Synchrotron radiation of short
wavelength is also of increasing interest in modern microelectronics, where the smallest patterns that can be made are now limited by the wavelength of the radiation used for the etching. Shorter waves than those of visible light are necessary to make sharp boundaries on printed circuit boards with sub-micron technology.

The Free Electron Laser, FEL, is an important research item of electron accelerator laboratories. A FEL consists of a high-energy electron beam passing through periodic transverse magnetic fields with alternating directions. These fields cause the electrons to bend and perform a wavy motion. At each bend, very short pulses of synchrotron radiation are emitted by the electrons as they perform a large number of bends. The emitted synchrotron radiation at each bend is added coherently and in this way, a pulse of short-wave nearly monochromatic radiation builds up successively. The wavelength of the radiation is dependent on the energy of the electron beam and on the periodic magnetic fields causing the wavy motion. By increasing the energy of the electron beam, the wavelength of the radiation can be made shorter. Compared with a conventional laser, a FEL can be tuned continuously to any wavelength, and radiation of short wavelengths can be achieved. There are presently development projects on FEL X-rays at DESY in Hamburg, KEK in Tsukuba and at SLAC in Stanford. The goal is to be able to produce monochromatic radiation down to wavelengths of one tenth of a nanometer (nm).

Experimental hall for synchrotron radiation from the electron storage ring in Hamburg. Photo: DESY

Arial view of the European Synchrotron Radiation Facility, ESRF, in Grenoble. Photo: ESRF

In the beginning of the year 2000, a new record for the shortest wavelength of radiation ever achieved with a free electron laser (FEL) was achieved at DESY, Hamburg. Radiation down to wavelengths of 80 nm was achieved and the radiation was tunable over the range 80 to 180 nm. Continued research at DESY and elsewhere, aim at reducing these wavelengths by an order of magnitude within a few years. Photo: DESY
Some different probe particles and their ability to resolve objects of small dimensions. Typical values for kinetic energies and wavelengths are given in the units electron volt (eV) and pico-meter (pm) respectively. In principle, objects can be resolved if they are larger than one wavelength of the illuminating radiation.

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<td>X</td>
<td>60,000</td>
<td>20</td>
<td>atom</td>
</tr>
<tr>
<td>reactor</td>
<td>n</td>
<td>1</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

More details about accelerators can be found in a recent book, *An Introduction to Particle Accelerators* by Edmund Wilson and published 2001 by Oxford University Press.¹