1 Accelerators – an Introduction

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1.1 Introduction

One of the first uses of energetic charged particles – a "beam" of ions – was when the inner structure of atoms was investigated to verify predictions by Ernest Rutherford in 1911. α-particles obtained from Ra and Th natural sources were used, and in this famous experiment the existence of a positively charged nucleus having a diameter of less than 10^{-13} m was demonstrated. Today, the same well-known technique is used in trace element analysis, surface science, solid state physics, etc. However, now well-defined beams of light ions (such as p, d and He) of a few MeV from an accelerator are used. The technique is named RBS, which is an abbreviation for "Rutherford backscattering."

The next remarkable step took place in 1919 when Rutherford achieved the disintegration of the nitrogen nucleus by α-particle bombardment [1]. The α-particles – again obtained from a natural α-source – hit a target containing nitrogen and produced the first artificially created nuclear reaction. In the reaction, an α-particle enters a nitrogen nucleus, forming a compound nucleus, which quickly splits up into an oxygen and a hydrogen nucleus, according to the following scheme:

$$\alpha + \mathrm{N} \rightarrow \mathrm{O} + \mathrm{H} \tag{1.1}$$

The intensity of the α-radiation from a natural source is of course very weak, and the beam is not collimated at all. As an example, an α-source with an activity of 1 GBq (10^9 disintegrations per second, or 27 mCi in older units) emits the particles into a solid angle of 4π and therefore provides a flux density at a distance of 100 mm from the point source of 8×10^5 particles $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. A beam of 1 µA from an accelerator, which may easily be collimated to a cross-sectional area of 1 cm^2, delivers 6×10^{12} singly charged particles per second.

These two famous experiments conceived by Rutherford demonstrated the demand for beams of particles with much higher intensities, a well-defined energy and the possibility to freely choose the particle species and their energy, i.e. the demand for accelerators. The goal was to continue the investigations of Rutherford and collaborators of nuclear reactions induced by well-defined beams and to obtain particle energies high enough to penetrate the Coloumb barrier which surrounds all nuclei.

During the 1920s the X-ray technique developed rapidly, and DC equipment for producing voltages of a few hundred kV became available. Unfortunately, higher voltages were limited by corona discharging and insulation problems. The MV range seemed at that time to be impossible to reach. At the end of the 1920s, the development of quantum mechanics showed that charged particles could penetrate through the potential wall around an atom and therefore that particle energies of 0.5 MeV or less could be enough for splitting light atoms. This was a more moderate goal, and accelerator development started in different laboratories.

The first persons to reach the goal of initiating a nuclear reaction by use of a beam from an accelerator were J.D. Cockcroft and E.T.S. Walton at the Cavendish Laboratory in Cambridge [2]. In 1932 they had a working proton accelerator, and with a beam of 400 keV they induced the reaction

$$\mathrm{Li} + \mathrm{p} \rightarrow 2\mathrm{He} \tag{1.2}$$

In 1951, Cockcroft and Walton obtained the Nobel Prize; see Table 1.1.

The years around 1930 can be taken as the starting point of the accelerator era, and people at different laboratories did development work following

Table 1.1. Nobel Prizes in Physics awarded to accelerator pioneers

Laureate(s)	Year	Awarded for
E.O. Lawrence	1939	*the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements*
J.D. Cockroft and E.T.S. Walton	1951	*their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles*
E.M. McMillan (in chemistry) (shared with G.T. Seaborg)	1951	*their discoveries in the chemistry of the transuranium elements*
J. Schwinger (shared with S. Tomonaga and R.P. Feynman)	1965	*their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles*
L.W. Alvarez	1968	*his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis*
C. Rubbia and S. Van der Meer	1984	*their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction*

different principles. Ernest Lawrence and colleagues developed the cyclotron; Robert Van de Graaff, Ray Herb and others the electrostatic accelerator; and Cockcroft and Walton the cascade accelerator. Gustaf Ising outlined and Rolf Widerøe built the linear accelerator. During the 1930s and 1940s the development of accelerators was based on the need of nuclear physicists to obtain higher projectile energies to exceed the Coulomb barrier of heavier and heavier elements for nuclear-structure studies, for the production of radioactive isotopes etc. Already in 1937, the first electrostatic accelerator was constructed for clinical use [3]. This machine – an electron accelerator built for the Harvard Medical School – could, in the energy range 0.5–1.2 MeV, produce X-ray intensities up to 40 R/min (or, in modern units, 0.01 C/kg_{air}) per mA electron beam current. The maximum obtainable electron beam current was 3 mA. This was a unique machine at the time and marked the first use of an electrostatic accelerator in clinical work. A schematic drawing of this machine can be seen in Fig. 2.1 in Chap. 2. Beginning in the early 1950s, the community of particle physicists also took part in formulating the goal of accelerator development. The first accelerators were built for protons and electrons. Today, ions from all elements in the periodic table can be accelerated. Furthermore, it is now also possible to handle artificially produced isotopes, i.e. short-lived isotopes far from the stability line, and antiparticles such as positrons and antiprotons. Today accelerators are applied in very diverse fields, such as radiotherapy, isotope production, ion implantation, synchrotron light production, spallation, neutron production, radiography, sterilization and inertial fusion, besides, of course, basic research in nuclear and particle physics. Of the more than 15 000 accelerators in operation around the world, only a handful are used in elementary-particle-physics research, a few hundred are used in physics and applied-physics research, and one-third are involved in medical applications, such as therapy, imaging and the production of short-lived isotopes. The other two-thirds are used for industrial applications, ranging from electron beam processing and micromachining, to food sterilization, and for national-security applications, which include X-ray inspection of cargo containers and nuclear-stockpile stewardship.

The tremendous progress in the construction of accelerators since the 1930s is illustrated in Fig. 1.1, showing an exponential increase of about an order of magnitude in beam energy per seven years! This graph is called a "Livingston plot" after Stanley Livingston, the accelerator physicist who first constructed such a plot in the 1960s. How can this development have happened? Maybe it can be explained in the following way. The progress of each type of accelerator (electrostatic, cyclotron, synchrocyclotron etc.) has saturated fairly quickly, whereas new ideas have been proposed regularly and have been the main contributors to the rapid advance. The development has been made possible by repeated use of the cycle

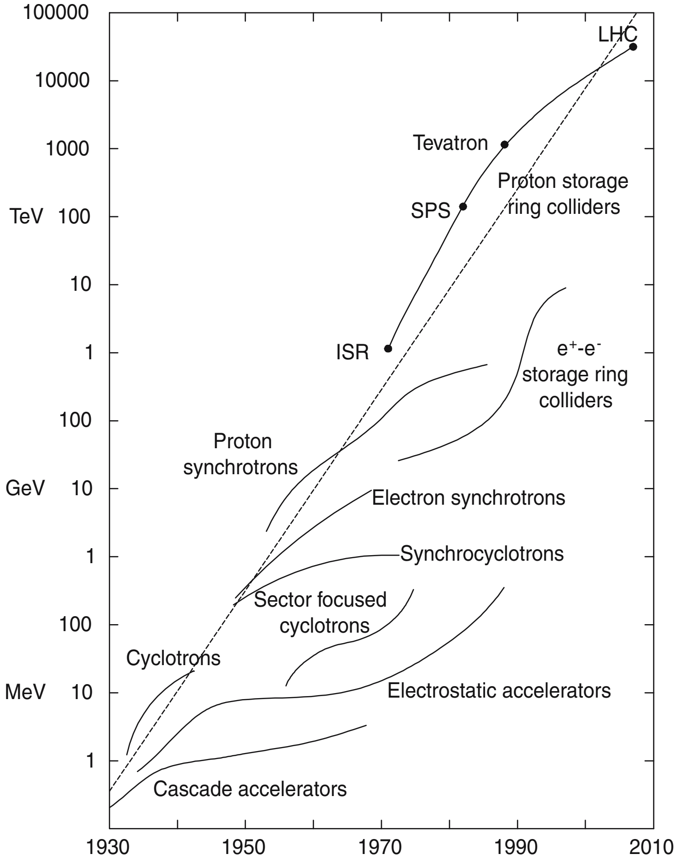


Fig. 1.1. A modified Livingston diagram showing the exponential growth of accelerator beam energy. The extrapolation to 2007–08 ends with the LHC at CERN. The energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center-of-mass energy (This is described in more detail in Sect. 1.6)

New idea → Improved technology → Until saturation → New idea etc.

In the same time period, the cost per eV beam energy has been drastically reduced, roughly by a factor of one thousand. A few startling examples seen in Fig. 1.1 can be pointed out: the development of the cyclotron and the electrostatic accelerator during the 1930s, the development of the synchrocyclotron during the 1940s and 1950s, the invention of alternating-gradient focusing in the 1950s and the application of the colliding beams in the 1960s and 1970s. The question to be asked is whether there is a different paradigm for building particle accelerators at the energy frontier which will dramatically reduce their size and cost. One approach discussed in the literature in recent years is to accelerate particles by collective fields in plasmas, by laser-induced acceleration and by using the field from a low-energy beam to accelerate a high-energy beam. A few words about this can be found at the end of this chapter.

As is shown in Fig. 1.1, accelerators can be classified into different principal designs, but all of these designs are of course based on the only known method to accelerate a particle: to charge it and then apply an electrical field. This occurs either in one big step or in several smaller gaps. Below, a very brief overview of the different design principles is given. The details of accelerator technology are not discussed in this chapter; instead, the general categories are presented, and the strengths and weaknesses of each category are discussed.

1.2 Direct Voltage Technique

In accelerators based on this principle (other names are "potential-drop accelerators" and "high-voltage DC accelerators" because the current is DC, contrary to all other accelerator types), the particle (after ionization) is accelerated through an accelerator tube, in one step. The tube is constructed as a long rectilinear drift tube, with a number of electrodes along the axis with a controlled voltage for each electrode, partly to aid in focusing the beam and partly to distribute the voltage gradient uniformly along the insulation surfaces. The positive ions (or electrons) to be accelerated are generated in an ion source located at high voltage (except for tandem accelerators – see below – in which negative ions are generated at ground potential). Direct voltage accelerators are often identified with the type of high-voltage generator used. The high voltage can be generated by rectifying an AC voltage (such a generator is often called a cascade generator) or by using electrostatic charging, in which a mechanical system carries the charge to the high-voltage terminal (these accelerators are called electrostatic accelerators). An open-air accelerator fails above a few MV, mainly because of the moisture in the air, which causes sparks. The voltage available today, if the accelerator is enclosed in a tank with a suitable gas under high pressure, is up to a few tens of MV.

Cascade accelerators. The high-voltage unit consists of a multiplying rectifier–condenser system (first used by Cockcroft and Walton [2]). Accelerators of this type, enclosed in a tank, are today designed for use up to 5 MV. The main advantage is that a cascade accelerator has a large output current of up to several hundred mA. This type of generator has for several years been used as an injector for high-voltage accelerators owing to the high beam current that such an accelerator can handle. In Box 3, more details about the various design principles of cascade generators will be found, as well as schematic drawings of the various principles. In Chap. 5, a photo of Cockcroft and Walton's first machine is shown.

Electrostatic accelerators. In 1929, Robert Van de Graaff demonstrated the first generator model of this type [4]. An electrostatic charging belt is used to produce the high voltage. The principal design of the charging system is described in Chap. 6, and a photo of one of Van de Graaff's first open-air machines is shown in Chap. 5. In Fig. 1.2, Van de Graaff is demonstrating one of his first test generators for Karl Compton. Two rollers are provided, one at ground potential driven by a motor and the other located in the high-voltage terminal, well insulated from ground. Over the rollers passes an endless belt of insulating material. Charge is sprayed from sharp corona points onto the moving belt. The belt conveys the charge to the insulated high-voltage terminal, within which the charge is removed by collector points and allowed to flow to the surface of the electrode. After development into a working accelerator, this principle was used in thousands of accelerators

Fig. 1.2. Robert Van de Graaff (*on the left*) and Karl Compton in 1931. This test generator was a double unit consisting of positive and negative hollow spheres mounted upon upright Pyrex rods. Each sphere was charged by a silk ribbon belt, running from a grounded motor pulley at the base of the rod to a pulley in the interior of the sphere. Intersphere voltages of 1.5 MV were reported from this simple machine (Reprinted from [5], copyright 1974, with permission from Elsevier)

around the world. The reasons why this type became so popular are that all types of ions can be accelerated, the ion energy can be changed continuously, the high-voltage stability is extremely good and therefore the ion energy has a very low energy spread. An electrostatic accelerator provides an advantage over a cascade accelerator – the terminal voltage is extremely stable and lacks the AC ripple of the cascade accelerator. A disadvantage is the low current output compared with the cascade accelerator. All modern accelerators of the electrostatic type are enclosed in a tank containing gas under high pressure to reduce the size and to be independent of moisture in the air. The first pressure-insulated machine was initiated by Ray Herb in the autumn of 1933. In Fig. 1.3 Herb is seen working on one of his first accelerators, the "Long Tank" machine.

Fig. 1.3. Ray Herb and the "Long Tank" machine in 1936 (Courtesy of Mrs. Ann Herb)

Tandem electrostatic accelerators. During the 1950s negative-ion sources were developed, i.e. beams of ions with an extra electron added to the ordinary electrons became available. This development made it possible to build two-stage (or tandem) accelerators. In a tandem, the high voltage is utilized twice, as can be seen in Fig. 9.2 in Chap. 9. Negative ions are formed at ground potential and injected into the first stage, where acceleration to the positive high-voltage terminal takes place. The energy gain is eU_T eV, where e is the elementary charge and U_T is the terminal voltage. In a stripper system in the high-voltage terminal, the negative ions lose a few electrons and change charge into positive ions. In the second stage, the positive ions once more gain energy. Now the energy gain is qeU_T eV, where q is the charge state of the ion. Thus a total energy gain of $(q + 1)eU_T$ eV is obtained. For heavy ions and high-voltages, i.e. high-speed ions undergoing stripping, q can be quite high and therefore the final energy of the ions can be hundreds of MeV.

As we shall learn later in this book, the insulating belt for transport of the charge has been replaced in many modern accelerators by a chain of metal cylinders. In this way, a more robust transport system with much more well-defined charge transport and hence a better voltage stability is obtained.

A method similar to the use of a belt or chain has been used by a French company to obtain up to a few hundred kV in a small and compact machine. In this accelerator, often used as a neutron generator to obtain 14 MeV neutrons through the (p + T) reaction, a cylinder rotates and transports charge at a high speed around another fixed cylinder, all enclosed in a tank containing gas at high pressure; see Fig. 1.4.

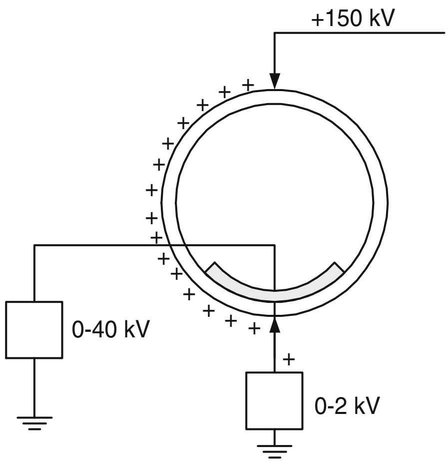
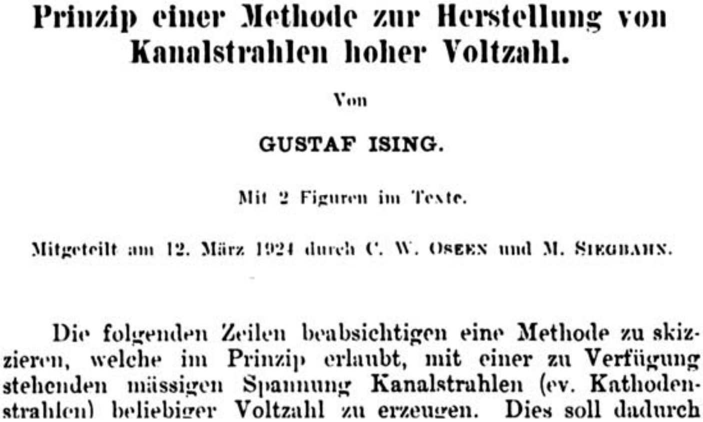


Fig. 1.4. Electrostatic generator using a rotating cylinder to obtain the high voltage

1.3 Resonance Acceleration

The second principle is the use of resonance acceleration by using a radiofrequency field. In the case of this principle, the particle has to pass through a small potential gap several times in resonance with an oscillating electric field. In this way, a much bigger energy gain will be obtained compared with the acceleration voltage. This can be done either in a series of gaps in a straight line called a linear accelerator or with a single gap in a circular machine, i.e. cyclotrons, betatrons, microtrons etc.

Linear accelerators. In 1924, Gustaf Ising from Sweden proposed [6] a method of particle acceleration that would give particles more energy than



Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. OSEEN und M. SIEGBAHN.

Die folgenden Zeilen beabsichtigen eine Methode zu skizzieren, welche im Prinzip erlaubt, mit einer zu Verfügung stehenden mässigen Spannung Kanalstrahlen (ev. Kathodenstrahlen) beliebiger Voltzahl zu erzeugen. Dies soll dadurch

Fig. 1.5. Ising's article from 1924

that provided by the maximum voltage in the system. The first part of his article can be seen in Fig. 1.5. In 1928, Rolf Widerøe from Norway built the first linear accelerator [7] by using a radio-frequency field over two gaps, and accelerated sodium and potassium. The principle of a linear accelerator (or linac as it often is called today) is shown in Fig. 1.6. The beam travels through a series of hollow, tubular electrodes connected alternately to opposite poles of the RF voltage source. Particles are accelerated as they cross the gaps between the electrodes. Upon entering the interior of an electrode, the particle drifts in a field-free region for a time equal to half the period of the RF voltage. In this way, the polarity of the voltage is reversed during the time the particle is within the drift tube, and the particle is then accelerated as it crosses the next gap. The available RF technology has been decisive for the development of linacs. Today, the highest obtainable linac energy is 40 GeV for electrons and 800 MeV for protons. In 1947, Luis Alvarez built

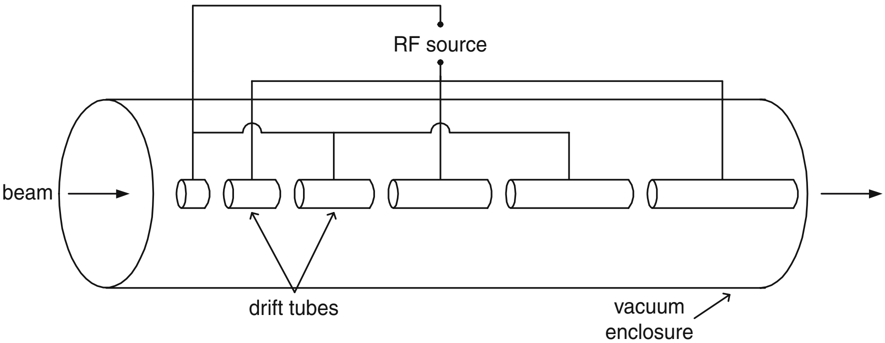


Fig. 1.6. Principle of a linear accelerator

a machine [8] with a structure which differed significantly from the Widerøe structure. The Alvarez structure consists of a set of resonator tubes which have an RF voltage of the same phase applied to them. Inside each resonator tube, a potential distribution exists. Therefore the acceleration takes place in the resonator. A type of standing wave is formed that ensures particle beam acceleration. In 1968 Alvarez obtained the Nobel Prize; see Table 1.1.

Radio-frequency quadrupole (RFQ). A rather new type of low-energy accelerator for very high currents is the RFQ, first proposed by I.M. Kapchinski and V.A. Teplyakov in 1970. The RFQ has a symmetry corresponding to that of an electrostatic quadrupole; see Fig. 1.7. It combines the action of focusing and bunching the beam, in addition to acceleration proper. The acceleration is of a continuous character and therefore it does not occur only in electrode gaps or other structures. The bunching effect is very efficient and close to 100%. Focusing is ensured by a transverse electrical gradient. A 1–2 m long RFQ can accelerate ions from an energy of a few tens of kV up to several MV. RFQs are often used today as part of the injector of big accelerator systems, and in that way are replacing old cascade injectors. The RFQ accelerator is a compact and rather simple accelerator.

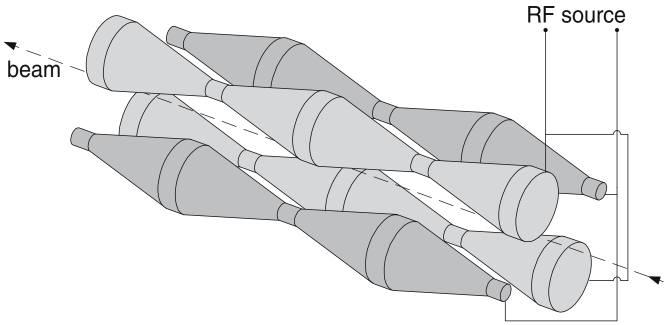


Fig. 1.7. Principle of an RFQ accelerator

Cyclic accelerators. In 1929, Ernest Lawrence at the University of California at Berkeley discovered Widerøe's article [7] and realized – see Fig. 1.8 – that if the ions could somehow be returned to the first gap again, and again, multiple acceleration could take place. In 1930, Lawrence proposed the application of the Widerøe resonance principle, but now inside a homogeneous magnetic field such that the particle would be bent back to the same RF gap twice in each period of the radio-frequency field. The Lawrence type of accelerator is called the cyclotron, and the principle is illustrated in Fig. 1.9. The first demonstration model cyclotron for accelerating particles was built by Lawrence and coworkers (mainly Stanley Livingston) in 1931 [9]. In Fig. 1.10, Lawrence is at the control panel of his 37 inch cyclotron. In 1939, Lawrence was awarded the Nobel Prize; see Table 1.1. Within a flat, cylindrical vacuum

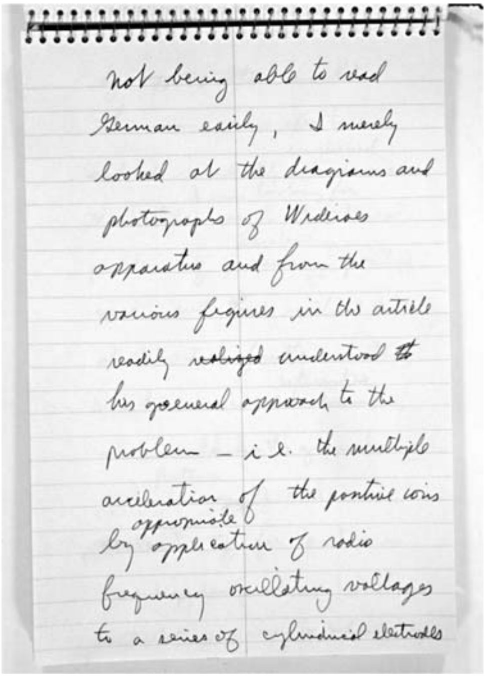

not being able to read
German easily, I merely
looked at the diagrams and
photographs of Wideroe's
apparatus and from the
various figures in the article
readily ~~realized~~ understood ~~the~~
his general approach to the
problem – i.e. the multiple
acceleration of the positive ions
by appropriate application of radio
frequency oscillating voltages
to a series of cylindrical electrodes

Fig. 1.8. Lawrence's handwritten interpretation of Widerøe's diagram (Reprinted with permission from LBL)

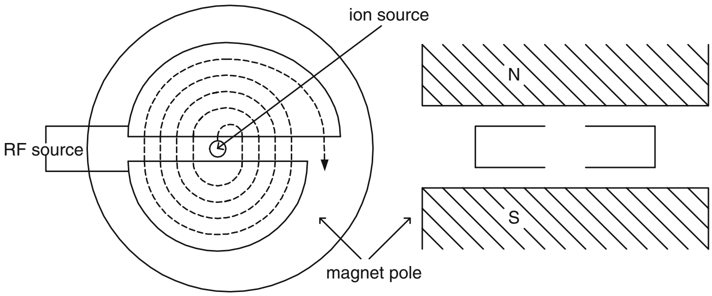


Fig. 1.9. Principle of a cyclotron

chamber placed between the poles of a dipole magnet are two D-shaped electrodes consisting of hollow, flat half-cylinders. In Lawrence and Livingston's first practical cyclotron the "dees" had a radius of 0.125 m, a magnetic field of 1.3 T and frequency of 20 MHz, giving protons of 1.2 MeV. The two dees are connected to the RF source (usually within the range of 10–30 MHz) so that an alternating voltage appears across the gap separating the dees. An ion source, located at the center of the chamber, produces the ions and supplies

Fig. 1.10. Ernest Lawrence at the controls of the 37 inch cyclotron in about 1938 (Reprinted with permission from LBL)

them with a low initial velocity. The path of the ions (with an electric charge q and mass m) is circular in the magnetic field B. The radius R of the circle is given by

$$R = mv/qB \tag{1.3}$$

Since R is proportional to the velocity v, the period of circulation T (and thereby also the frequency f) is constant for all values of R. Once in resonance, the ion will receive an energy gain each time it passes through the acceleration gap between the dees.

The energies possible to obtain with protons are up to 20–30 MeV, corresponding to a magnet diameter of little more than 1 m. As the beam in a cyclotron travels outwards towards the edge of the magnet, the magnetic field lines are diverted somewhat from true straight lines. The curvature of the field lines gives a net force component towards the median plane, which tends to provide focusing and to counteract the tendency of the beam to diverge. At the same time, the field loses its uniformity and the resonance condition can no longer be maintained. The advantage of a cyclotron compared with an electrostatic accelerator is that a much higher beam current (tens of mA) is available from a cyclotron. The disadvantages of the cyclotron are that the beam is pulsed, it is difficult to change the beam energy and, normally, this change cannot be made continuously. The energy resolution of the beam is also much worse compared with the electrostatic accelerator.

It is interesting to notice that subsequent to its initial conception, there has not been a fundamental change in the method of resonance acceleration. Ising's, Widerøe's and Lawrence's approaches can be considered as the beginning of modern RF accelerator development. All later inventions, some of which have been tremendously important as we shall see, have addressed the problems of efficient guiding and collection of the particles rather than the acceleration itself.

The cyclotron cannot accelerate particles as light as electrons, as they will quickly become relativistic and (1.3) is no longer valid. D.W. Kerst invented and constructed in 1940 [10] the first circular electron accelerator, a 2.35 MeV betatron. Widerøe had formulated the principal design of a betatron already in 1928, but he was unable to make the device work. Kerst realized that the magnetic field must be shaped to provide focusing and prevent the electrons from escaping. A betatron consists of a ring-shaped accelerating chamber located between the poles of an electromagnet whose windings are supplied from a 50 or 60 Hz sinusoidal voltage. The magnetic field plays a dual role. First, it causes the trajectories of the electrons – injected at low energy – to curve and keeps the electrons in a circular orbit. Secondly, it accelerates the electrons by means of the electric field induced by the change in the magnetic flux passing through the circular electron orbit. Kerst built first a 2.3 MeV model that worked immediately. He then built a 20 MeV machine, and then a 300 MeV machine. This was the largest betatron ever built. At General Electric, a 100 MeV betatron was built to produce intense X-ray beams. 100 MeV is a high enough energy to make detectable the relativistic radiation emitted by electrons traveling along curved paths. This radiation, now known as "synchrotron radiation", is emitted in a small cone directly ahead of the electron. The importance today of synchrotron radiation is outlined in Chap. 3.

Another principle is used in the microtron, which has a constant field and a fixed frequency. The particle moves in a circular orbit between the pole pieces of a magnet. The orbits share one common point, at which an RF acceleration resonator is located. The relativistic limitation of the cyclotron can be overcome if the increase of mass[1] at each gap transit is so large that the revolution time increases by one radio-frequency period. The increase in energy required at each gap transit can be obtained from the cyclotron equation corresponding to one rest mass. This is impossible to achieve for protons or heavy ions but is practicable for electrons. The principle was suggested by Vladimir Veksler and Julian Schwinger in 1944, and is illustrated in Fig. 1.11. In 1965, Schwinger was awarded the Nobel Prize; see Table 1.1. The beam current in a microtron is of the order of μA and the usual operating energy is in the 5–50 MeV range. Microtrons are mostly used as injectors and for industrial radiography.

1.4 Phase-Stabilized Acceleration

The original cyclotron relied on the fact that the revolution frequency of a charged particle in a homogeneous field is independent of the particle energy

[1] Although the concept of speed-dependent mass is not explicit in modern theory, but is inherent in the definition of the relativistic linear momentum, this concept is useful in accelerator technology.

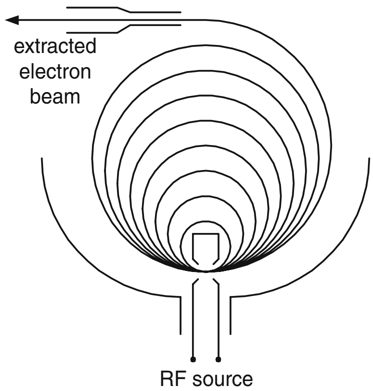


Fig. 1.11. Principle of a microtron

in the nonrelativistic approximation, and the radio frequency used for the acceleration could be kept constant. The increase in particle mass due to relativistic effects limits the energy that can be reached. The remedy is to modulate the applied RF field to keep in step with the cyclotron frequency. In 1945, the third principle, which is to use phase-stabilized acceleration, was proposed independently by Edvin McMillan [11] and Vladimir Veksler [12]. In 1951, McMillan shared (with Glenn Seaborg) the Nobel Prize for chemistry; see Table 1.1. In this type of accelerator, called the *synchrocyclotron*, the frequency f of the applied RF field decreases with increasing particle energy to compensate for the changing mass. This means that the particles travel through the synchrocyclotron in bunches, and the frequency is swept from its maximum value (when the bunch is near the center, the particles are only slightly accelerated and the relativistic increase in mass is slight) to its minimum value (when the bunch is ready to exit the accelerator, the maximum energy has been attained and the mass has its largest value). Technically, the periodic change of f is carried out using a condenser whose capacitance varies when it is rotated. Synchrocyclotrons are sometimes also called frequency-modulated or FM cyclotrons. The limit on synchrocyclotron size is set by magnet cost, which is proportional to $E^{3/2}$, and a maximum energy of up to 1 GeV for protons has been obtained. The disadvantage of a synchrocyclotron compared with a cyclotron is the reduced current. Only one bunch at a time is sent through the synchrocyclotron, compared with lots of pulses through the cyclotron; therefore the beam current is reduced to a mean value of μA or even less. The first synchrocyclotron was built in Berkeley in 1948. It could accelerate protons to 350 MeV and was the first machine used for studies of π-mesons.

Another way of overcoming the problem connected with the lack of resonance due to the increase of the relativistic mass in a homogeneous magnet can be to use an *azimuthally-varying-field* (AVF) cyclotron (also called an isochronous cyclotron) having an increasing magnetic field with increasing radius. Vertical focusing is obtained by use of radial or spiral ridges built on to the poles to create alternate high- and low-field sectors. Focusing forces giving axial stability arise at each sector boundary. The stable orbits in an AVF cyclotron are not circles; the particles perform radial oscillations about the circular orbit. The maximum energy obtainable with an AVF accelerator is about the same as for synchrocyclotrons. An advantage of the AVF cyclotron is the larger possible beam current (of the order of 100 μA), which depends on the fact that not only one bunch per time is possible, but also many pulses at the same time. In this way it is possible to operate the cyclotron at a fixed frequency even up to relativistic energies.

In the *synchrotron* – also invented by McMillan and Veksler – the massive magnet is replaced by a ring of bending magnets. Electrons are injected at relativistic speed and as the electron energy increases, the magnetic field is also increased at a rate that makes the electron orbit the same at all energies. For protons and heavy particles, it is not so easy to inject at relativistic speed. Therefore both the RF field and the magnetic field are varied for protons and heavy particles, in such a way as to keep the orbital radius constant. The principle is shown in Fig. 1.12. Frank Goward and D.E. Barnes in England were the first to make a synchrotron work. They converted a betatron to an 8 MeV electron synchrotron in 1946. The first proton synchrotron was the 3 GeV Cosmotron in Brookhaven National Laboratory, completed in 1952. Its ring of magnets had a diameter of 21 m and a height of 2.4 m. Its injector was a 4 MV electrostatic accelerator from HVEC. In 1954, the Bevatron at Berkeley was completed. Its energy was 6 GeV, enough to demonstrate the existence of the antiproton. Energies up to 100 GeV can be obtained economically with a conventional synchrotron.

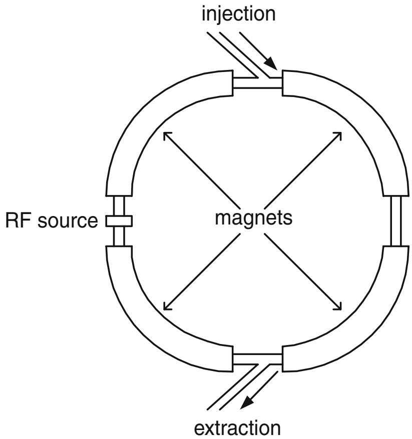


Fig. 1.12. Principle of a synchrotron

1.5 Alternating-Gradient Focusing

The fourth principle uses alternating gradients for magnetic focusing. The use of this principle dramatically reduced the size of the magnets for large accelerators, allowing a much larger energy to become economically achievable. It was Livingston who, at the end of the 1940s, considered the possibility of building a synchrotron with successive magnetic sectors facing inwards toward and outwards from the center in order to compensate for the effects of magnetic leakage. The field at the center of the beam tube has the same value in all sectors, but in one sector it decreases with r and in the neighboring sectors it increases. The variation of the field with r is quite dramatic: $B \sim r^n$ and $B \sim r^{-n}$, with $n \sim 300$, in alternate sectors. This means that in addition to bending the particle trajectories, the magnets have a strong lens effect. The principle is shown in Fig. 1.13. This revolutionized the approach to accelerator design and made it possible to arrive at a compact design; this could also be used for machines with much higher energies than could be envisaged before. The energy range for AG synchrotrons is 100 GeV to 1 TeV. Other than cost of the magnets and the size of the ring, there is no limit on the energy that can be obtained. For synchrotrons from around 1970, a major advance in design has been the separation of the bending and focusing, functions, so that dipole magnets bend the beam and quadrupole magnets do the focusing, as illustrated in Fig. 1.14.

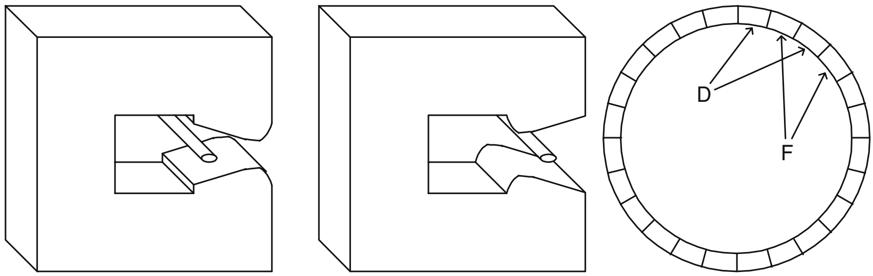


Fig. 1.13. Alternating-gradient (AG) synchrotron having sectors with focusing increasing with r (F) and sectors with focusing decreasing with r (D)

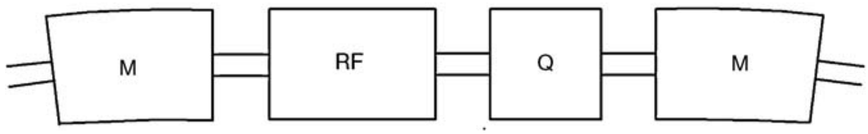


Fig. 1.14. Part of a separate-focusing synchrotron; M = dipole magnet; Q = quadrupole magnet, RF = accelerating gap

1.6 Colliding-Beam System

The next large energy step was taken by a colliding-beam system introduced in the late 1960s. In particle collisions, only the center-of-mass energy is useful. For fixed-target accelerators, this means that the main part of the particle energy will be wasted as kinetic energy of the colliding particles and their reaction products. In contrast, if two particles with the same momentum that move in opposite directions are made to collide, all the available energy can be made use of in the interaction. The first storage rings to operate were the 200 MeV electron ring at Frascati and the 2×500 MeV rings at Stanford. Both started in 1961. Another example of an early proton–proton colliding-beam accelerator is the CERN Intersecting Storage Rings (ISR), in operation during the period 1972–83, with two beams of 28 GeV from the CERN proton synchrotron directed into two interlacing storage rings with opposite directions for the magnetic fields, making collisions at eight positions. The 56 GeV center-of-mass energy is equivalent to a beam energy of 1700 GeV against a fixed target. For the particle density available in a normal accelerator beam, however, the colliding-beam system is unrealistic. The invention of particle stacking changed the picture significantly. From a preaccelerator, a weak current is injected into a storage ring over a long period of time (of the order of a day). At the same time, the beam is focused to occupy a far smaller area than it did upon leaving the preaccelerator. In this way, the particle density is considerably increased, and a circulating current equivalent to several amperes can be obtained. To have beams circulating for long times, an extremely low pressure is needed so as not to lose too much of the intensity by scattering from residual molecules in the vacuum. Storage rings are often equipped with an RF acceleration gap for adjustment of the energy.

In *electron storage rings,* the synchrotron radiation can make the beam shrink in all dimensions, and thus intense electron beams can be accumulated. In *proton storage rings,* the synchrotron radiation is negligible and the required intensity must be obtained by stacking.

The ISR mentioned above was the highest-energy machine in the world until the SPS at CERN started operating as a proton–antiproton collider in 1981 at 2×270 GeV. Antiprotons were produced in a fixed target by irradiation with 26 GeV protons. The beam of $\overline{\mathrm{p}}$ is of very low intensity, and the beam also has an extremely low quality as the $\overline{\mathrm{p}}$ are produced with a spread in direction as well as in energy. However, one of the exciting developments that originated within the ISR project was "cooling" of the beam. This is a method to reduce the beam dimensions (the phase space) and energy spread, and thus increase the beam density. Two methods for improvement of beam quality were developed during the 1970s, namely electron cooling for proton energies less than 1 GeV and stochastic cooling for proton energies above 1 GeV. Cooling is particularly effective for weak beams. Carlo Rubbia and Simon Van der Meer at CERN cooled antiprotons to dimensions and intensities comparable to those of a proton beam and accumulated them over long periods. Then they accelerated them to about 300 GeV in the SPS to make them collide with protons of the same energy. This became a success, and the particles W and Z that mediate the weak interaction were identified in 1982–83. As a result Rubbia and Van der Meer shared the Nobel Prize in 1984; see Table 1.1. Another major discovery made by a colliding-beam accelerator was the top quark, at the Tevatron collider at the Fermi Laboratory using 900 GeV protons and 900 GeV antiprotons [13]. Very large colliders are extremely expensive to build as a double-ring collider. Since a particle and its antiparticle have identical masses but opposite signs of electric charge, they rotate in opposite directions in the same magnetic field. In such a case it is possible to use the less expensive single-ring collider concept.

By the use of superconducting magnets with excitation windings operating at the temperature of liquid helium, the mass of the magnets can be radically reduced by at least one order of magnitude. The reduction in the dimensions, weight, cost and supply power provided by superconducting magnets is very attractive, and a much higher magnetic field is available. In this way, the accelerator will be more compact and cheaper.

The present state of the art for proton accelerators is the Large Hadron Collider (LHC) under construction at CERN (Fig. 1.15). It will consist of

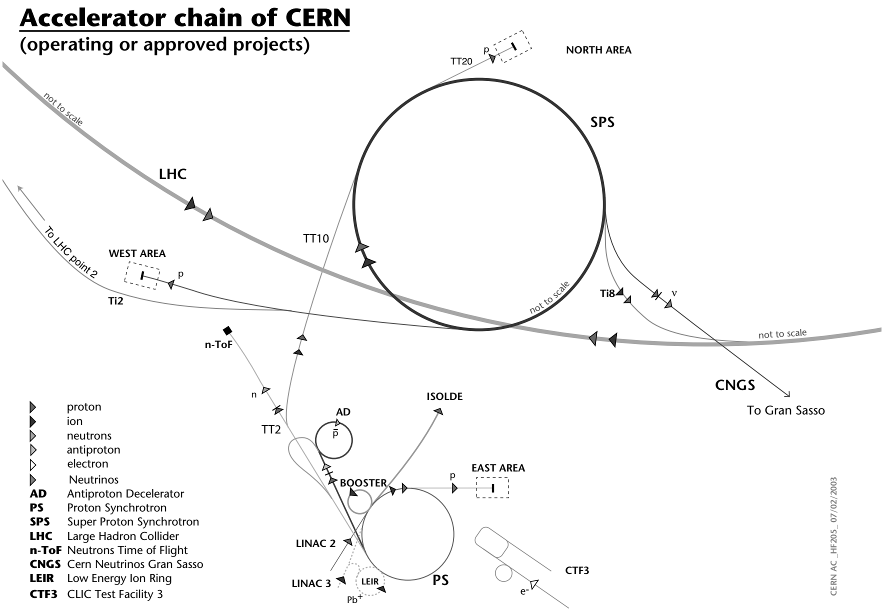


Fig. 1.15. The CERN complex, consisting of various preaccelerators, smaller accelerators, the SPS with a 2.2 km circumference, and the LHC with a 27 km circumference (only part of the LHC is seen in the figure)

more than 1200 superconducting magnets. Two proton beams of 7 TeV each will circulate in the 27 km long circle. The available energy in the LHC is the center-of-mass energy, $2 \times 7\,\text{TeV} = 14\,\text{TeV}$. An equivalent fixed-target accelerator would need to have a beam energy of $E_p = 2 \times 7000^2\,\text{GeV} = 98\,000\,\text{TeV}$, i.e. 14 000 times higher than the 7 Tev of the LHC! The effective constituent collision energy for a hadron collider – i.e. the energy available per quark, which is of most interest as one is looking, primarily, for quark–quark collisions – is 1/6 of the sum of the beam energies, i.e. 1/6 of 14 TeV, or just above 2 TeV.

The development of accelerator technology has been spectacular. However, there is much more to do. The accelerators now in use and under construction are expected to lead the way beyond the present incomplete standard model. They should unearth new classes of particles and enhance our understanding of the asymmetry between matter and antimatter and of the transition to the primordial quark–gluon plasma. With the accelerators of today using RF technology we have come to a limit; they are too big and too expensive. Could it be possible to find a completely different technology, reducing their size and cost? In various articles that have appeared during the last two decades and more, preliminary experiments have been discussed and reported employing different possible approaches. Examples of overview articles are to be found in [14–17]. One approach is to use collective fields in oscillating plasmas. The plasma is excited by lasers or by a driver beam; the accelerating gradients and focusing strengths will be orders of magnitude greater than those achieved thus far by RF accelerators, offering the possibility of smaller, lower-cost accelerators at very high energies in the future. The greater the accelerating gradient, the shorter would be the accelerator to obtain a given energy.

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