Chapter 11 Accelerators

One of the most important tools of nuclear science is the particle accelerator. Prior to its invention in 1932, the only known sources of particles that could induce nuclear reactions were the natural alpha particle emitters, for example radium. In fact, the only type of nuclear reaction known during that period was that of an alpha particle interacting with a nucleus and producing a proton. Today the use of natural alpha emitters to induce nuclear reactions is largely of historical interest because accelerators produce higher intensities and higher energies of not only alpha particles, but of most elements between hydrogen and uranium.

Cockroft-Walton

Common to all accelerators is the use of electric fields for the acceleration of charged particles; however, the manner in which the fields are applied varies widely. The most straightforward type of accelerator results from the application of a potential difference between two terminals. To obtain more than about 200 kV of accelerating voltage, it is necessary to use one or more stages of voltage-doubling circuits. The first such device was built by J. D. Cockcroft and E. T. S. Walton in 1932 and was used for the

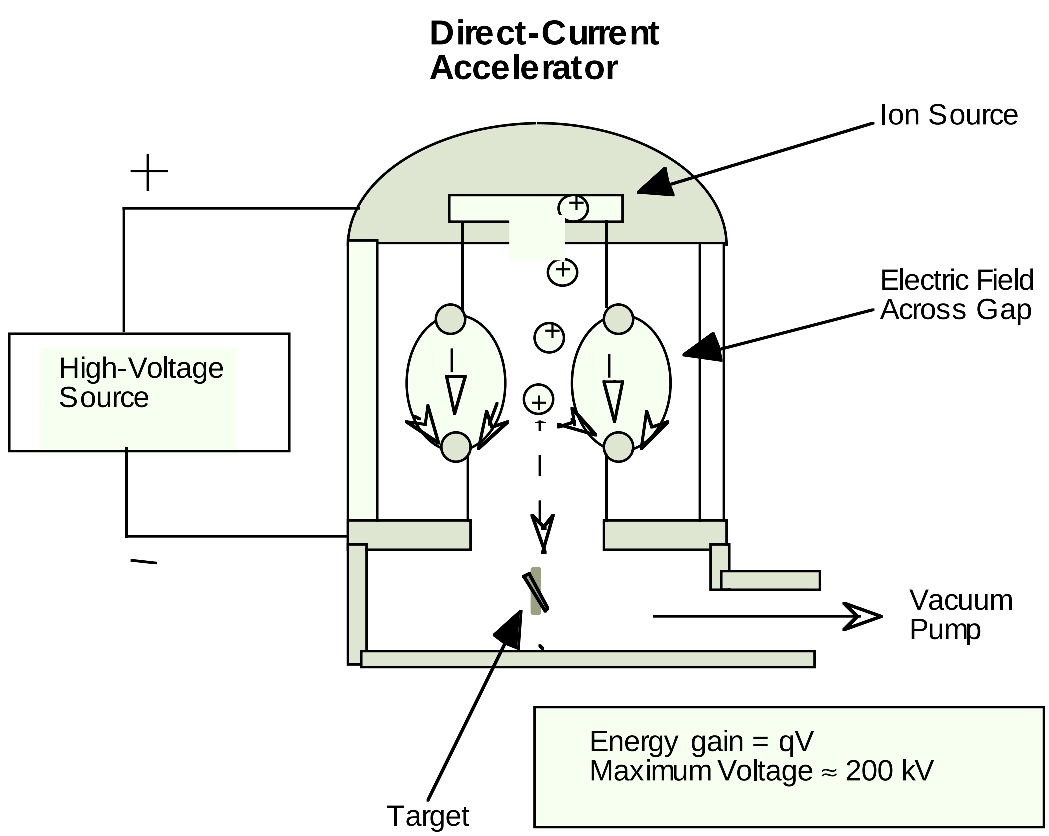

Fig. 11-1. A Cockroft-Walton accelerator. The symbol q in the formula refers to the charge of the particle.

first transmutation experiments with artificially accelerated particles (protons). Cockcroft-Walton accelerators are still widely used today, sometimes as injectors to much larger accelerators.

Van de Graaff

Beginning in 1929, R. J. Van de Graaff pioneered the Van de Graaff accelerator, in which a high potential difference is built up and maintained on a smooth conducting surface by the continuous transfer of positive static charges from a moving belt to the surface. When used as a particle accelerator, an ion source is located inside the high-voltage terminal. Ions are accelerated from the source to the target by the electric voltage between the high-voltage supply and ground.

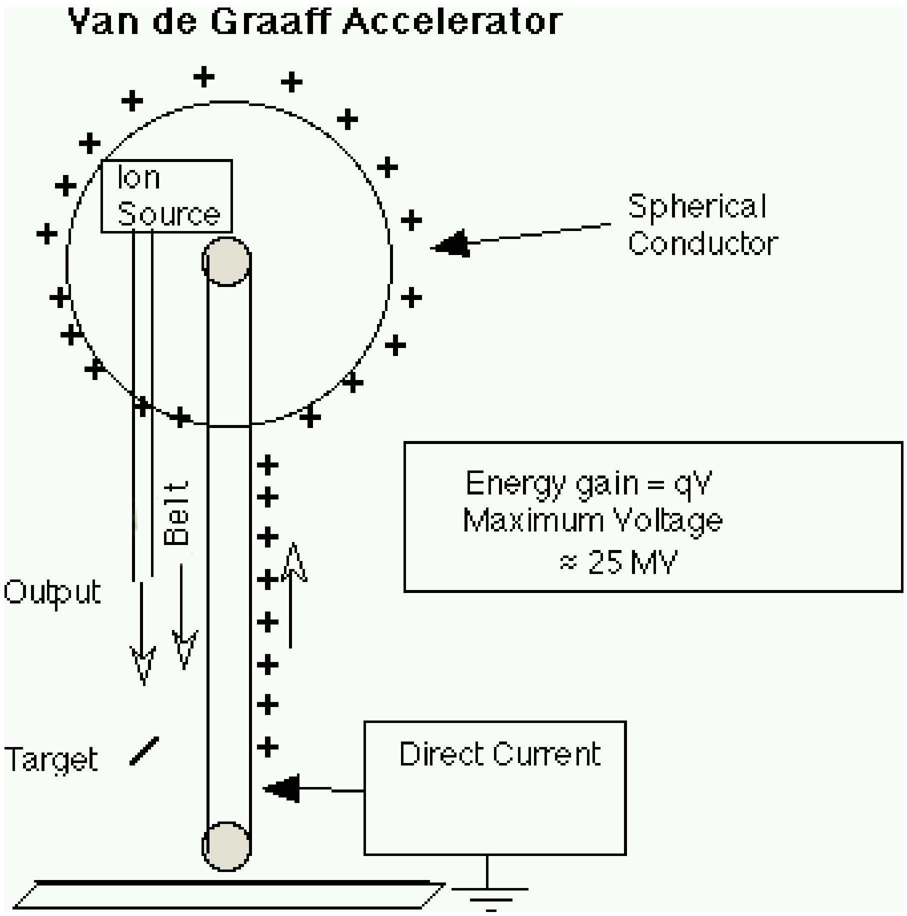

Fig. 11-2. A Van de Graaff accelerator.

The maximum energy obtainable from an electrostatic accelerator such as the Van de Graaff can be greatly increased by the application of the "tandem" principle. In a tandem Van de Graaff accelerator, first built in the 1950s, negative ions are first accelerated towards a positive high-voltage terminal in the center of a pressure tank. Inside the terminal the negative ions, which now have an energy in MeV equal to the terminal potential difference in megavolts (10^6 V) times the charge of the ion, pass through either a foil or gas "stripper" and are stripped of electrons, producing a positive-ion beam. This beam is then accelerated a second time away from the high-voltage terminal. Many tandem Van de Graaff accelerators are in operation throughout the world, including the 25-MV Holifield facility at Oak Ridge National Laboratory in Tennessee.

The limitation of these types of accelerators arises from the maximum practical potential difference that can be held by the charged surfaces. An additional problem in the tandem accelerator is the need to start with negative ions, which can be hard or impossible to obtain for some elements. Positive ion sources are available for a wider variety of elemental species. Positive ion sources can also produce ions of charge higher than one, which is all that is obtainable in negative ion sources.

Linear

The radio-frequency (RF) linear accelerator avoids these problems by the repeated acceleration of ions through relatively small potential differences. In a linear accelerator, an ion is injected into an accelerating tube containing a number of electrodes. A high-frequency alternating voltage from an oscillator is applied between groups of electrodes. An ion traveling down the tube will be accelerated in the gap between the electrodes if the voltage is in the proper phase. The distance between electrodes increases along the length of the tube so that the particle stays in phase with the voltage.

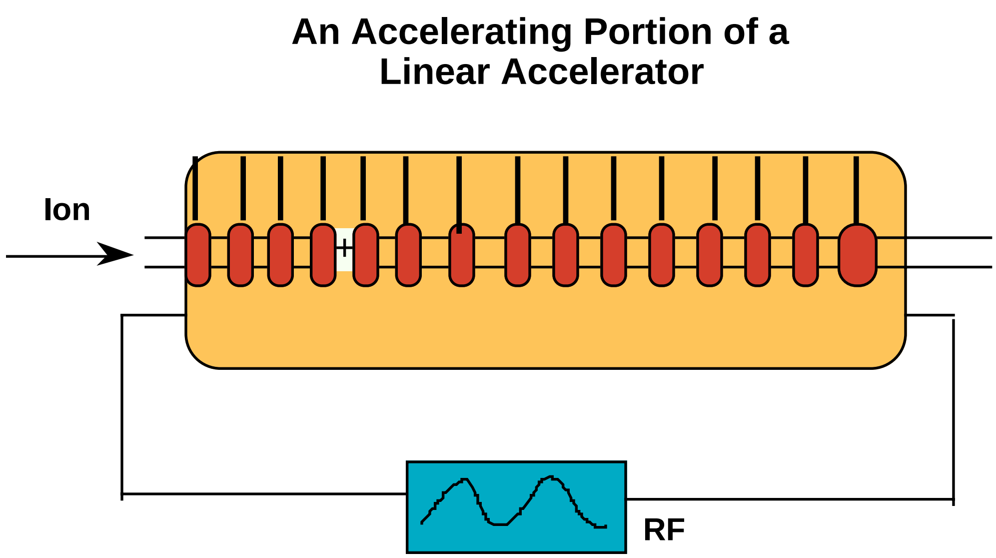

Fig. 11-3. Side view of a linear accelerator. (This figure does not show the increasing spacing between cavities as discussed in the text.)

The first linear accelerator was built in 1928 by R. Wideroe, accelerating positive ions to about 50 keV. Intensive work on linear accelerators was carried out in many laboratories in the early 1930s. The linear accelerator did not receive much further attention until after World War II, when the availability of high-power microwave oscillators made possible acceleration to high energies in relatively small linear accelerators. Since that time, a sizable number of linear accelerators, also called linacs, have come into operation, both for electron and proton acceleration, as well as several heavy-ion linacs. SLAC, a 3-km electron linac at Stanford University, is the longest linac presently operating. It accelerates electrons and positrons to energies of 50 GeV.

Cyclotron

The best known and one of the most successful devices for acceleration of ions to millions of electron volts is the cyclotron, which was invented by E. O. Lawrence in 1929. The first working model produced 80-keV protons in 1930. A cyclotron, as well as a linac, uses multiple acceleration by a radio frequency electrical field. However, the ions in a cyclotron are constrained by a magnetic field to move in a spiral path. The ions are injected at the center of the magnet between two semicircular electrodes called "Dees". As the particle spirals outward it gets accelerated each time it crosses the gap between the Dees. The time it takes a particle to complete an orbit is constant, since the distance it travels increases at the same rate as its velocity, allowing it to stay in phase with the RF. As relativistic energies are approached, this condition breaks down, limiting cyclotrons in energy. However, cyclotrons are still in use all over the world for nuclear science studies, radioisotope production, and medical therapy.

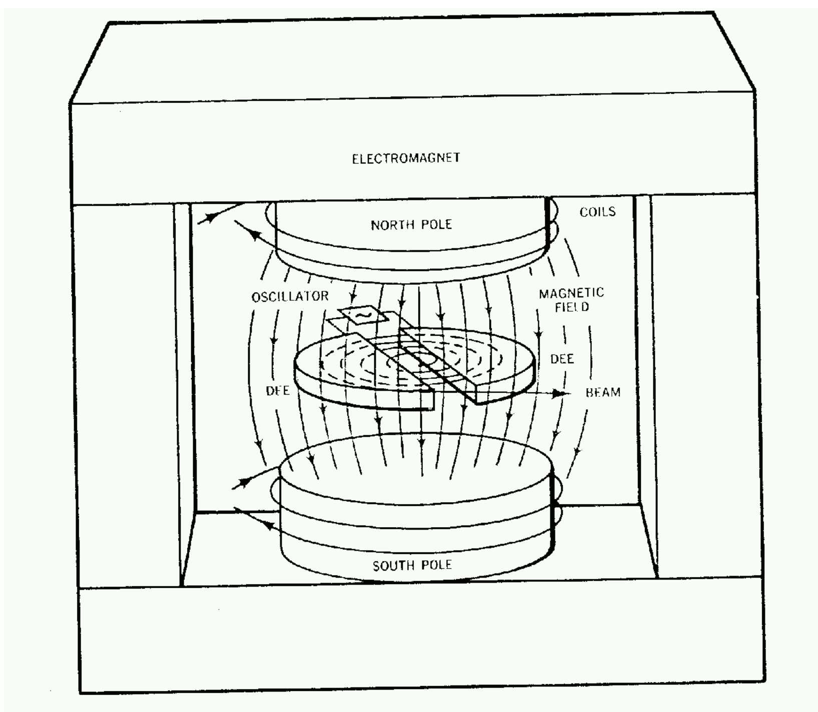

Fig. 11-4. A schematic of a cyclotron.

Synchrotron

The synchrotron was developed to overcome the energy limitations of cyclotrons imposed by special relativity. In a synchrotron, the radius of the orbit is kept constant by a magnetic field that increases with time as the momentum of the particles increases. The acceleration is provided, as in a cyclotron, by a RF oscillator that supplies an energy increment every time the particles cross an accelerating gap. The Relativistic Heavy Ion

Collider (RHIC), presently under construction at Brookhaven National Laboratory in New York, will collide two beams of ions ranging from protons to gold at energies up to 100 GeV per nucleon. Nuclear scientists expect that such collisions will create nuclear temperatures and densities high enough to reach the quark-gluon plasma phase of nuclear matter.

Continuous Electron Beam

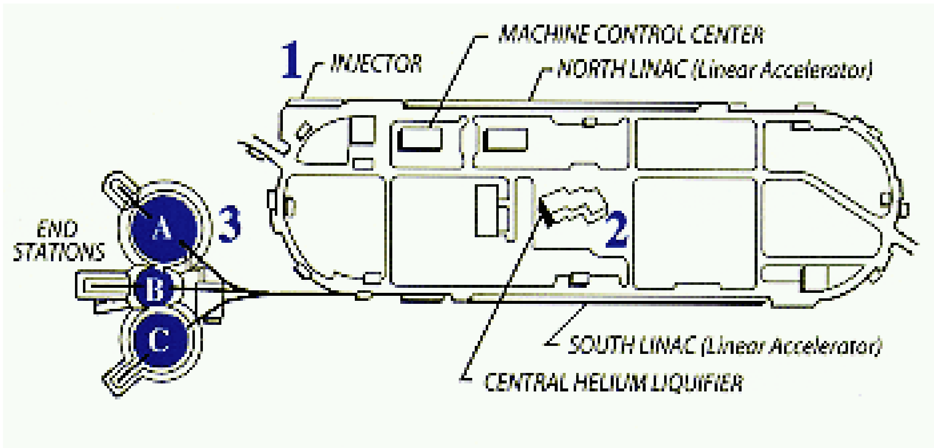

Fig. 11-5. The electron accelerator at Thomas Jefferson Laboratory.

The most recent nuclear physics accelerator to become operational is the Thomas Jefferson National Accelerator Facility in Newport News, Virginia. A diagram of the accelerator is shown in Fig. 11-5. At this accelerator, an electron beam travels through several linacs. The accelerator uses superconducting radio-frequency technology to drive electrons to higher and higher energies with a minimum of electrical power. This accelerator produces a continuous electron beam to ensure that each electron interaction with a nucleus is separated enough in time so that the whole reaction can be measured.