Accelerating devices

The devices used to bring charged particles from rest to a desired kinetic energy are known as particle accelerators. All particle accelerators depend upon a single physical principle, namely the force exerted by an electric field on a charged particle. The simplest form of accelerator, represented electrically in Figure 1, consists of a high voltage generator connected to two high voltage plates (terminals) enclosed in a vacuum chamber. A positively charged particle at the positive high voltage terminal will feel an electrical force proportional to the product of the voltage, V, and the particle charge, q. The force will accelerate particle toward the grounded terminal and the particle then will emerge through the hole in the plate with a kinetic energy qV.

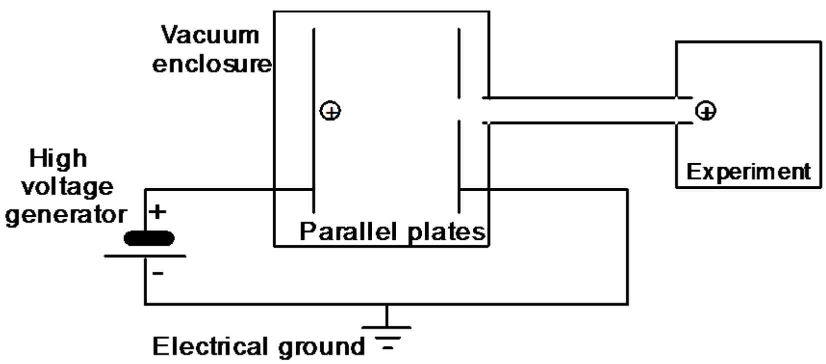

Figure 1. The DC accelerator

This simplest accelerating structure, the dc-accelerator, is the basis for Van de Graaf and Cockroft-Walton accelerators, in which a source of positive ions sits at the high voltage terminal. Such devices which can accelerate singly charged ions to energies of ~10 million electron volts (MeV) have seen wide spread use in university nuclear physics laboratories. In large, modern accelerator complexes the dc-accelerator (or some variant thereof) often serves as the injector or source of particles feeding a much higher energy accelerating device.

The energy attainable with a dc-accelerator is limited by the electrical breakdown of insulators at very high dc voltages. Furthermore, as external components of the dc-accelerator may be at high voltage, requiring stringent access controls are required for safety. To a limited degree both difficulties can be postponed if the vacuum enclosure surrounds the entire accelerating structure, generator and experiment. Even in such an evacuated enclosure dc electric fields exceeding ~12 MV/m cannot be sustained without electrical breakdowns flashing across the surface of the structure.

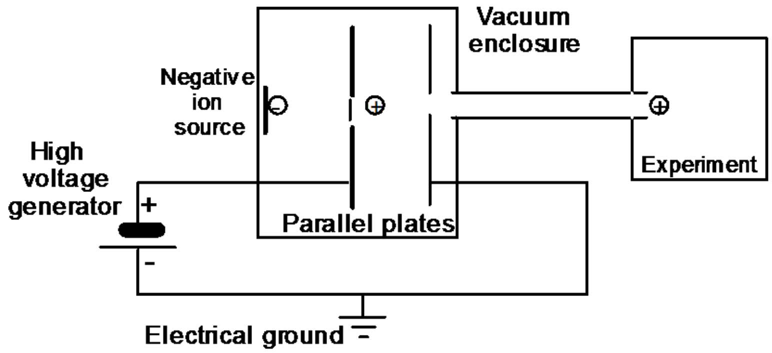

Figure 2. The Tandem accelerator

For atoms capable of attaching an extra electron to form a negative ion, the designer can circumvent this limitation in ultimate energy further. The negative ions will be attracted to the positive, high voltage electrode where they pass through a very thin foil. The foil strips the excess electron plus an additional electron from the ion thereby making a positive ion. The positive ion can now continue on its way toward the ground terminal. Using this "tandem acceleration", one obtains particles with energies of 2qV.

While the change of sign of the charge of the particle can be performed only once the tandem "trick" could be applied many times if we change the sign of the voltage instead of the charge of the particle. Therefore the accelerator designer turns to time-varying electric fields.

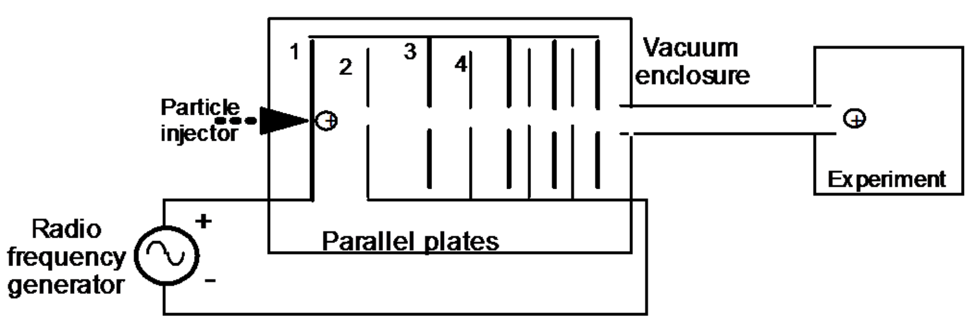

Figure 3. A multi-cavity radio frequency accelerator

The most common way to obtain energies higher than obtainable those with dc devices is to rely on radio frequency (rf) voltage sources. Consider an arrangement of plates attached to a rf-generator as shown in figure 3. When the voltage at plate 1 is near its maximum value +V, positive ions are injected as shown. The particles will accelerate toward plate 2; if the distance between the plates is chosen appropriately the particles will pass through the hole in the plate just as the voltage falls to zero. As the voltage decreases toward -V, the particles will continue to accelerate toward plate 3. If the distance between plates 2 and 3 is just right, the particle will reach the opening in plate 3 just as the voltage once again passes through zero. As long as all the spacings are just right (depending on both the radio frequency and the peak voltage), the acceleration process can now continue indefinitely to ever higher energies without have the peak electric field at any component exceeding the limiting values set by electrical breakdown.

The key challenge in designing rf-accelerators is preventing the particles from “seeing” the electrical fields when they have the “wrong”, decelerating values. Accelerator designers have used various techniques (and combinations thereof) to accomplish this task. Techniques include varying the spacing of accelerating electrodes, varying the frequency of the accelerating fields as the particles gain energy, and providing metal structures to shield the particles from fields of the “wrong” sign. For example, in drift tube accelerators, these structures (drift tubes) provide field-free regions through which the particles travel at constant velocity (drift) during the periods of decelerating voltage.

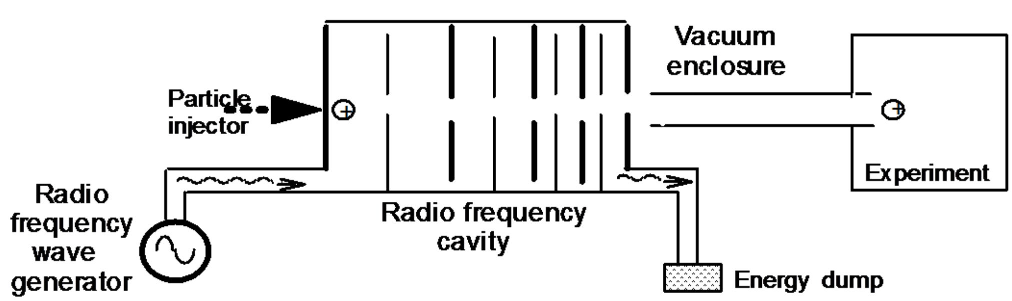

Figure 4. Accelerator with rf-cavities

At radio frequencies exceeding tens of megahertz the accelerating structure can be in the form of resonant rf-cavities. Electromagnetic waves are launched into the structure from a high quality, high power source such as a klystron. Once the energy fills the entire structure, particles can be injected for acceleration. Many such structures arranged end-to-end forms a linear rf-accelerator (linac). Linacs for protons, which operate in the UHF broadcast band, can provide 3 – 10 MeV per meter of structure. Because electrons travel at a nearly constant velocity slightly less than the speed of light at energies > 1 MeV (as compared with > 1 GeV for protons), electron linacs usually employ higher frequencies than the broadcast band. The 2-mile-long Stanford Linear Accelerator (operating at ~3 GHz) now provide electrons at energies of 50 GeV at a rate (accelerating gradient) of 20 MeV/m. Even larger linacs are foreseen to achieve energies of 1000 GeV or more with gradients of 50 – 100 MeV/m.

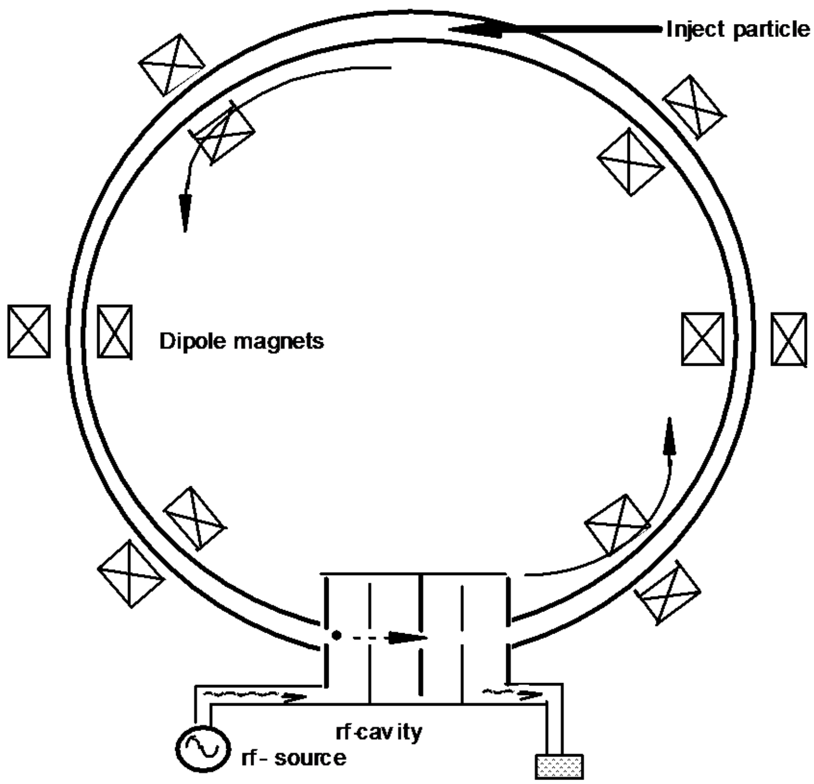

Figure 5. Circular accelerators

The accelerating gradients achievable in linacs increases as the square root of the amount of rf-power fed into the cavities. But even with sufficient rf-power available, the gradient is eventually limited by electrical breakdowns in the rf-cavities. While these breakdown limits may exceed the dc values by more than an order of magnitude, the desire of scientists for ever higher energy beams of particles (particularly ions) from accelerators of manageable sizes using the minimum electrical power necessary leads to a different tactic. If the particles are carried on circular orbits using strong magnets to bend their trajectories, they can pass through the same rf-cavity many times. As long as they always enter the cavities when the fields have the correct sign, the particles will continue to accelerate to higher and higher energies limited only by the strength of the magnets which bend them around through the evacuated beam tube. In circular accelerators such as the synchrotron the field of the magnets is increased (ramped) so that the particles stay on the same circular orbit and stay in synchronism with the rf-field during the acceleration process.

By reusing the same rf-cavities many times, the ion synchrotron attains an "effective" gradient may be increased to hundreds of MeV/m. Electrons in circular accelerators are also limited by their emitting electromagnetic copious radiation (synchrotron radiation). Thus, a power balance between the rf-source feeding energy to the electrons and the energy lost via synchrotron radiation also limits the ultimate energy of electron synchrotrons.

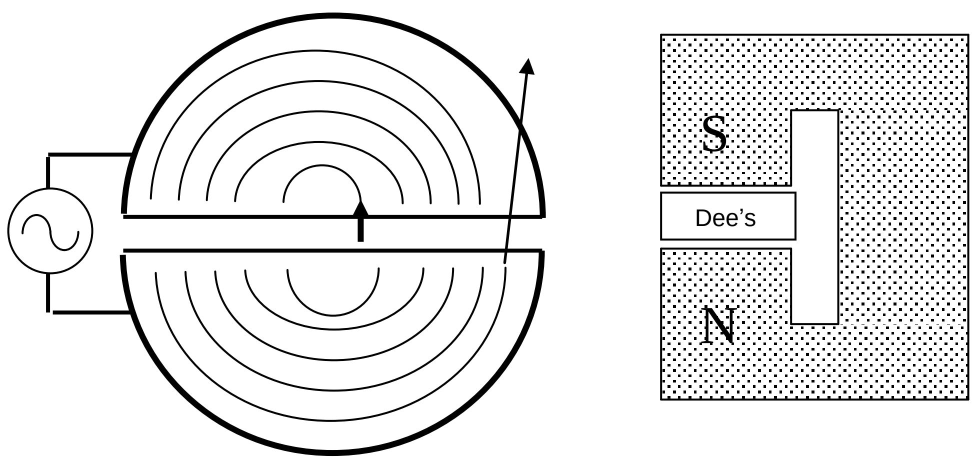

Figure 6 The cyclotron : top view (left) and side view (right)

The first circular accelerator was the cyclotron invented in the 1930's by Earnest Orlando Lawrence. It represents a convenient way to realize the scheme of figure 3 in a compact geometry. In the cyclotron (Figure 6) ions are injected at the center of two hollow, D-shaped electrodes (Dee's). The Dee's are connected to a rf-generator and placed between the poles of a large electromagnet. Each time the particles cross the gap between the Dee's, they experience an electric field which can either accelerate or decelerate the particles. Inside the Dee's, particles are shielded from the electric fields and feel only the static magnetic field, which is perpendicular to their direction of motion. and bends them along a circular orbit until they again reach the gap between the Dee's. The revolution frequency of the particles depends on the ratio of the magnetic field strength and the particle mass. Neglecting the increase of mass with energy due to relativity, this frequency is independent of the particle energy. If the rf-frequency is chosen in resonance with the going around frequency particles injected when the gap voltage is accelerating will continue to be accelerated as they spiral outward on ever larger orbits.

Accelerator designers continue to seek new schemes, structures, and power source to achieve ever higher rates of acceleration. In the twenty-first century, lasers offer to replace rf-sources and plasmas may replace metal structures in the drive to achieve gradients of 10 GeV/m or more. The era of innovation in the design of accelerators is far from over.