Advances in particle-accelerator technology

9973827

The existence of natural particle accelerators has been predicted by the detection of particles with exceptionally high energies up to 3×10^{20} eV. These particles, known as cosmic rays, are believed to be accelerated by the action of black-holes or explosions of supernovae. When cosmic rays collide with the surface of the atmosphere, they split into showers of particles enabling us to see beyond the scale of the atom. This is how particles like positrons and muons were discovered in 1932 and 1937, respectively. However, those events are hard to study as they are unpredictable and rare as the energy increases [1]. Hence, scientists have been interested in building accelerators to reproduce such events and make their observations easier.
This essay starts with a recall of the basic physics principles behind accelerators followed by the method for accelerating particles. Lastly, it will cover the major technological advances in accelerators throughout the years.

1 Physics principles behind accelerators

There are two major physically-based principles to build accelerators.
First, from the equation $e = mc^2$ uncovered by Einstein, we understand that energy is equivalent to mass. In practice, this means that we can transform energy into massive structures. Thus, the scientific community has been interested in using a large amount of energy to create short-lived, heavy particles.

Second, to observe an object, the wavelength of the light used needs to be smaller than the object itself. The energy of light required is calculated using Equations 1 and 2.

$$\lambda = \frac{h}{p} \tag{1}$$

where λ is the wavelength of the light, h the Planck constant, and p the momentum of the photon. For light, the momentum is equal to the energy e of the radiation over the speed of light c. Therefore Equation 1 can be rewritten as,

$$\lambda = \frac{hc}{e}. \tag{2}$$

Hence, to resolve small objects the wavelength of probe radiation needs to be small and inversely the energy needs to be high. For instance, an atom of size 10^{-10} m needs a radiation energy of the order of 10^{-5} GeV to be resolved. Accelerators aim at reaching energies superior to 1 GeV to resolve smaller particles than the quark [2].

2 Accelerating particles

To increase the energy of charged particles, an electromagnetic field can be used. The interactions between a charged particle and an electromagnetic field are explained by Equation 3 , the Lorentz force of electromagnetism.

$$\Delta e = \int_{\vec{r_1}}^{\vec{r_2}} \vec{F}\vec{dr} = q\int_{\vec{r_1}}^{\vec{r_2}} (\vec{E} + \vec{v} \times \vec{B})\vec{dr} \tag{3}$$

where e is the energy, $\vec{r_1}$ is the initial position vector of the particle, $\vec{r_2}$ is the final position vectors of the particle, $\vec{F}$ is the vector force, q is the charge of the particle, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field and $\vec{v}$ is the velocity vector of the particle.

The electric and magnetic field serve different purposes in an accelerator. From Equation 3, we understand that the force due to the electric field is used to accelerate the particles as it acts in the direction of the velocity. On the other hand, the force due to the magnetic field is used to control the path of the beam as it acts orthogonally to both the velocity of the particle and the magnetic field. A schematic representation of an accelerator is shown in Figure 1 [2,3].

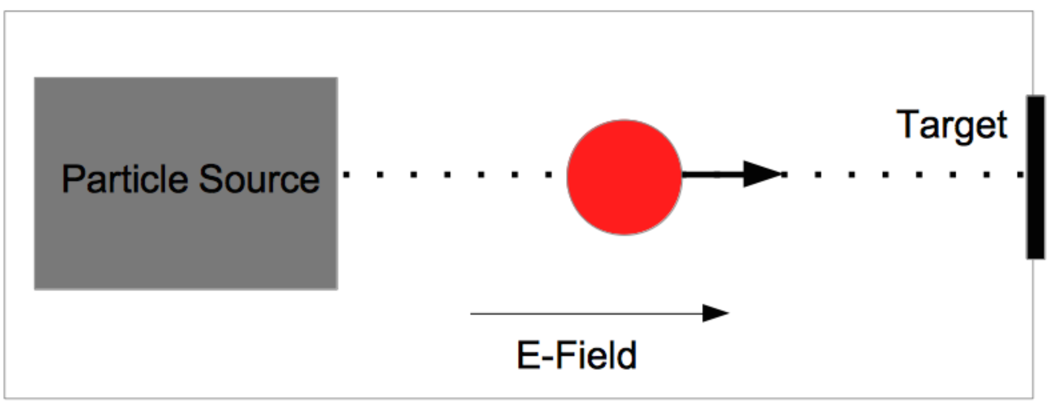

Figure 1: Schematic representation of an accelerator.

3 Advances in accelerator technology throughout history

The greatest advances in particle accelerator technologies have been achieved in only the past hundred years. Within that period, accelerators have gone from generating a few KeV to 7

TeV accelerations. In the early twentieth century, two types of accelerators were imagined and developed: the electrostatic accelerator and the electrodynamic accelerator also called the electromagnetic accelerator.

3.1 The electrostatic accelerator

The electrostatic accelerator uses a constant electric field to accelerate particles. Different models of electrostatic accelerators were built. One of them is the Cockcroft-Walton accelerator able to generate voltages up to 1 MV. As shown in Figure 2, this machine is composed of a high voltage sinusoidal source, followed by a special arrangement of series of rectifying diodes and capacitors. The capacitors charge up and at the end of the series, the voltage is equal to the original voltage times the number of cascades [2,4].

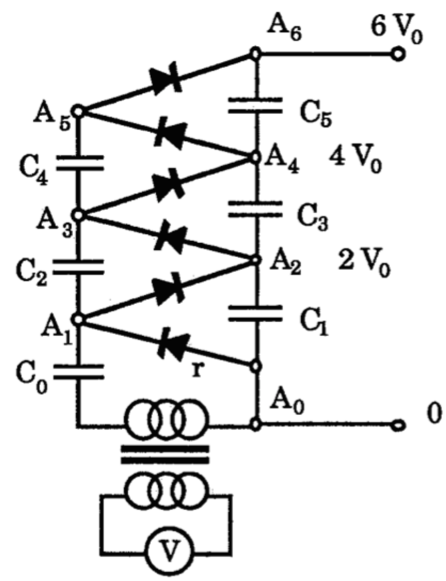

Figure 2: Schematic representation of the Cockcroft-Walton accelerator [2].

A second type of electrostatic accelerator is the Van Der Graaff accelerator, shown in Figure 3. In this machine, the electrodes are under a high-pressure ion gas and charge is accumulated thanks to a charging belt. The ion source is then accelerated by the voltage difference between the top terminal and ground. This apparatus can produce a maximum voltage difference of 10 MV. The breakdown voltage described by Paschen's law is a function of the pressure and the gap between the electrodes [2].

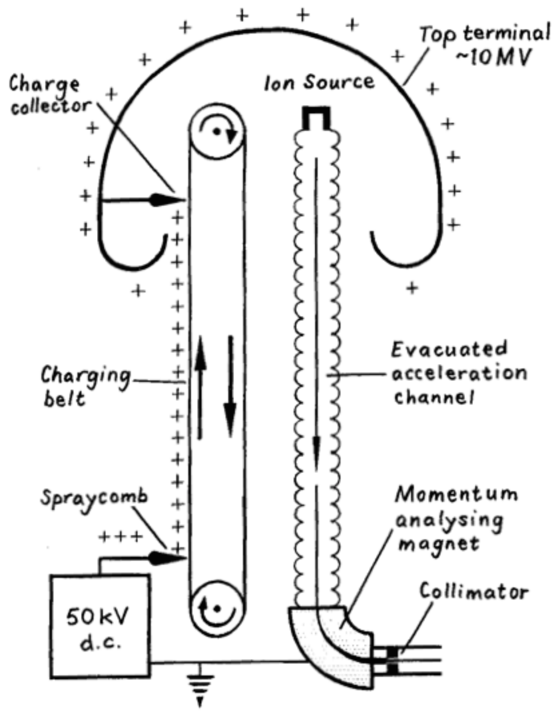

Figure 3: Schematic representation of the Van Der Graaff accelerator [2].

However, in electrostatic accelerators, the particles can only go through the accelerating gap once. Thus, they are limited by the input voltage and are only able to produce up to 10 MV. Therefore, their development for accelerating particles at higher energies has been stopped. Nevertheless, they are still in use for many purposes, such as nuclear physics.

3.2 The electrodynamic accelerators

The electrodynamic accelerators use changing electromagnetic fields, which enables particles to pass through the accelerating voltage gap multiple times. Therefore, the beam has to be cut into bunches for the machine to operate. Furthermore, a bunch has to be injected into the accelerating cavity in sync with the electromagnetic field being at its highest amplitude in the direction of the acceleration. The varying electromagnetic field is created by the radio frequency cavity shown in Figure 4. This revolutionary technology is a metallic box that resonates microwaves inside its cavity to generate the electromagnetic field [2,5,6].

The phenomenon of resonance is a fundamental property of matter. When an object is driven at its resonant frequency, it responds with large amplitude oscillations as the energy absorbed is maximised. In our case, from the resonance of the microwaves into the cavity we get a varying electromagnetic field with high amplitudes [7].

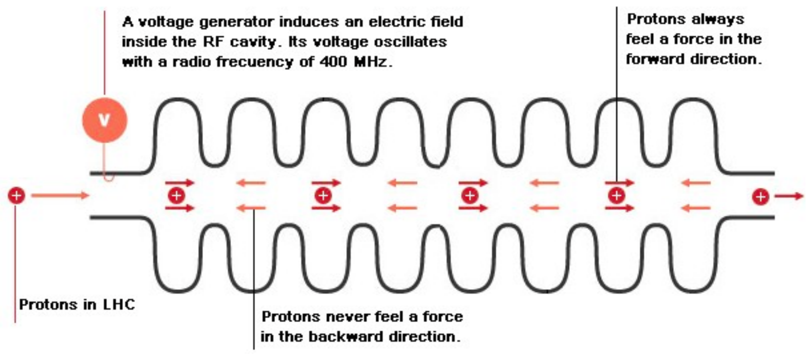

Figure 4: Schematic representation of radio frequency technology [5].

The first electrodynamic accelerators were linear, such as the Ising and Wideroe accelerator built in 1928. However, this geometry was limiting since with the velocity of the particles increasing, the machines were getting longer and costly [2]. Therefore, in 1931, scientists suggested the idea of driving the bunches in a circular path. A magnetic field normal to the plane in which the particles move, changes their direction using the Lorentz force as explained in Equation 3. This new machine represented in Figure 5 is called the cyclotron and generates energies up to 600 MeV. The cyclotron frequency and hence the radius of the paths can be determined by equating the centrifugal force together with the Lorentz force. The radius of the path grows with increasing energy. This limits this setup, as it is technically difficult and costly to build a cyclotron with a large enough radius to contain the path. Another limitation of the cyclotron is due to the relativistic effect which increases the mass of moving particles. Hence, the cyclotron frequency varies, shifting the particle out of phase with the electromagnetic field [8].

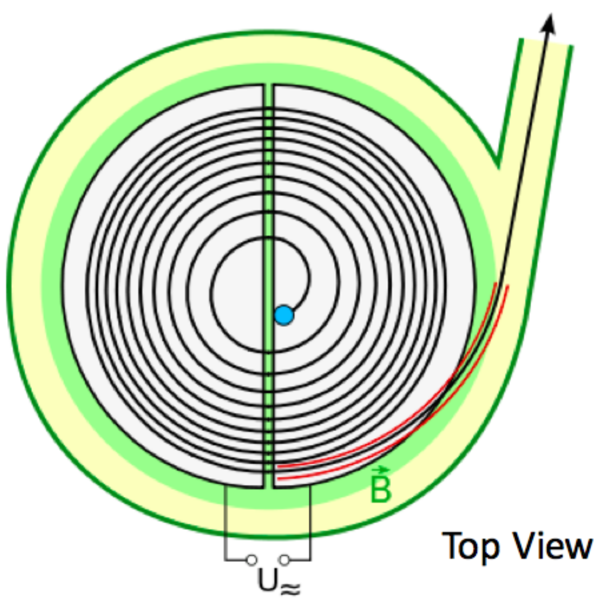

Figure 5: Schematic representation of the path taken by a particle in a cyclotron [2].

In order to keep the radius of the circular path constant, the magnetic field changes with the increasing energy. The first machine to accelerate particles in a circular path was the Betatron in 1940, followed by different types of synchrotron like the Cosmotron in 1952, which accelerated protons to 3 GeV [2]. A diagram of a synchrotron is presented in Figure 6. One of the major problems developing the synchrotron was the faulty focusing of the beam. This was rapidly fixed thanks to the gradient focusing technology, which works in a similar fashion as geometrical optics but using magnets instead of lenses [2]. Synchrotrons are nowadays the most common types of accelerators and can produce energies up to the order of Tera electron volts. Such energies are obtained because of the improvements in vacuum technology and the superconducting magnets which create an intense magnetic field. The coils are cooled down to a few Kelvin to acquire the superconductive properties.

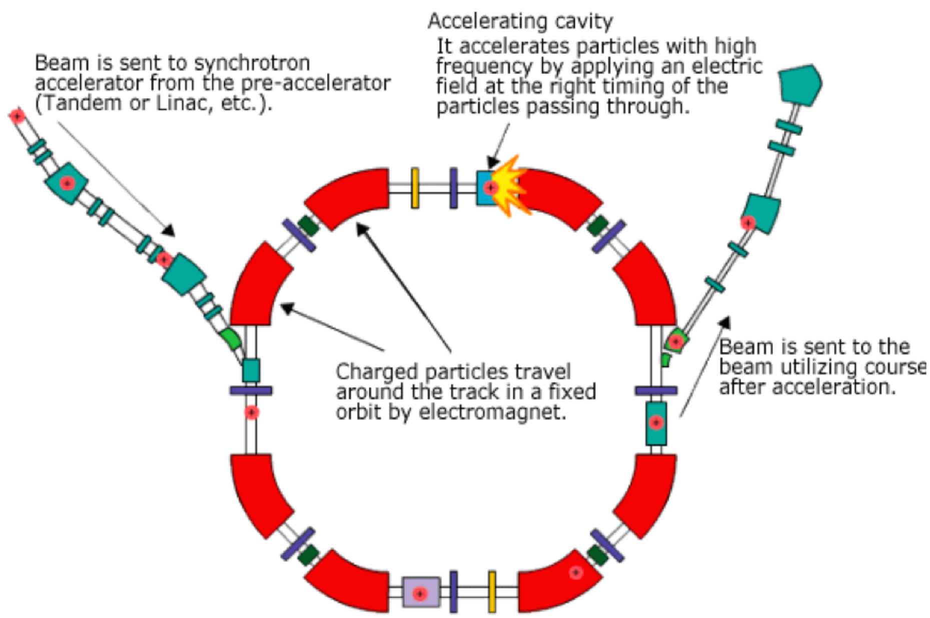

Figure 6: Schematic representation of a synchrotron [2].

In the sixties, the first storage rings were developed. These consisted of a two-beam synchrotron. In these machines, the two beams are accelerated in opposite directions, stored and made to collide in experiments. In these accelerators, the radio frequency cavities are used to compensate the power loss and achieve a higher luminosity by compressing the bunches. Luminosity is a significant value as it is proportional to the number of collisions per time in the accelerator. The High Luminosity Large Hadron Collider (HL-LHC) is the next upgrade of the Large Hadron Collider (LHC) planned for 2025 [9]. This accelerator, built in 2008, with a length of 27 km is the largest synchrotron ever built. It can achieve acceleration of 7 TeV and collisions of up to 14 TeV. The particles get accelerated to almost the speed of light. Thanks to the LHC, the existence of the Higgs boson has been confirmed [10].

4 Conclusion

Thanks to the different technological advances of the last century, we could build reliable accelerators allowing major physics developments like the discovery of the Higgs boson at CERN in 2012 [10]. The next physics advances should lie at energies of at least a thousand times larger than what is achieved today. To reach such energies, it is possible to keep on using the same apparatus and increase the length of the accelerators along with newly developed technologies. However, the lack of a strong physics motivation added to the high costs are slowing the developments. Another promising project is the development of plasma wakefield acceleration at CERN: the AWAKE experiment. The particles are accelerated by a wave in the plasma in the same way as a surfer is accelerated by ocean waves. This new acceleration method would shrink the size of the accelerators by a factor of a thousand [11].

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6 References

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