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DSE2T (Nuclear and Particle Physics)

Topic – Particle Accelerators (Part – 1)

Introduction:

Nature experienced by us here on earth provides us with little opportunity for studying the nucleus. Nuclei are never naturally excited as atoms are when they emit light and nuclear reactions never happen in bulk matter as chemical reactions do in such familiar forms as fire, fermentation, cooking, etc. There is some *radioactive decay* in nature, but this involves only a few nuclei in their lowest-energy states. Our principal information on nuclear structure has therefore come from nuclear reactions, from decay processes initiated by these reactions, and from the *nucleon-nucleon scattering experiments* (discussed in several resources). It is important to note that all nuclear reactions except those induced by neutrons (which are not available in nature) require energies of several MeV (or 10^6 eV) to overcome the Coulomb repulsion between nuclei, and there are similar energy requirements on most scattering experiments. With a few minor exceptions involving natural radio-activity and cosmic rays, particles with MeV energies became available only with the development of the useful devices, called *accelerators* or more specifically, *particle accelerators*.

The purpose of an accelerator of charged particles is to direct against a target a beam of a specific kind of particles of a chosen energy. There are many varieties of methods for accomplishing this task, all using various arrangements of electric and magnetic fields, and in this e-report we will review the general features of some of the most common types of accelerators.

Basic Components of an Accelerator:

As an electronic device, the accelerator shares many features in common with an ordinary television picture tube. Therefore, it requires the following essential components listed below:

(1) A source of charged particles (electrons from a hot filament or ionized atoms from an ion source),

(2) An electric field to accelerate the particles (typically $\sim 10^7$ V in some accelerators),

(3) Focusing elements (or *Lenses*) to counteract the natural tendency of the beam to diverge,

(4) Deflectors to aim the beam in the desired direction,

(5) A target of selected material for the beam to hit and

(6) A vacuum chamber to house all the components in high vacuum to prevent the beam from scattering in collisions with molecules in the air.

Classification of Accelerators:

In terms of energy, accelerators are broadly classified as low, medium or high energy accelerators. *Low-energy accelerators* are used to produce beams in the $10 - 100$ MeV range, often for reaction or scattering studies to elucidate the structure of specific final states, perhaps even individual excited states. Such accelerators should have accurate energy selection and should have reasonably high currents because the ultimate precision of many experiments is limited by counting statistics. The heating of targets by intense beams can be considerable, and often targets must be cooled to prevent the heat from destroying the target.

Medium-energy accelerators operate in the range of roughly $100 - 1000$ MeV. At these energies, collisions of nucleons with nuclei can release π mesons, and so these accelerators are often used to study the role of meson exchange in the nuclear force. In only a few cases are these accelerators able to resolve individual final excited states.

High-energy accelerators produce beams of 1 GeV (1000 MeV) and above. Their purpose is less to investigate nuclear structure than to produce new varieties of particles and study their properties.

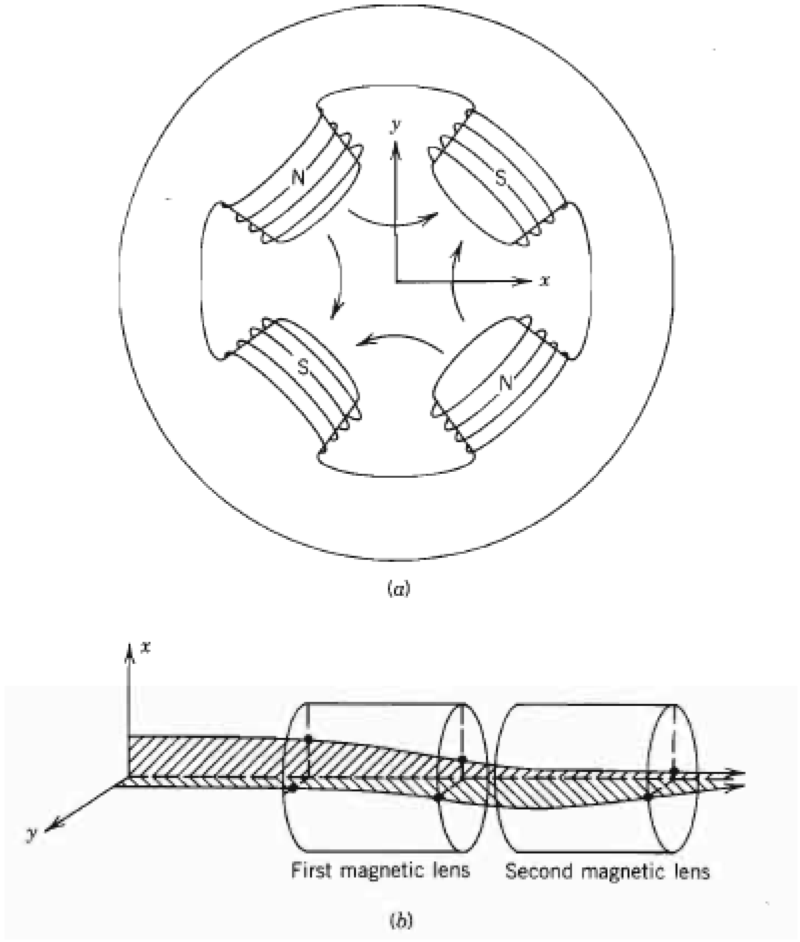

Fig. 1

Beam Optics Arrangement:

The beam transport (or beam optics) system consists of a number of electric or magnetic devices that focus the beam and bend or deflect it along the desired path. In analogy with optics, focusing devices are often called *lenses*, but they consist of magnetic fields, rather than glass. Fig. 1(a) shows an example of a *quadrupole lens*, which creates field components in the x and y directions of the form $B_x = \alpha y$ and $B_y = \alpha x$, with α as a constant. The beam axis is the z direction, along which there is no field. The components of the Lorentz force are given by

$$F_x = -qv\alpha x = -kx$$

$$F_y = qv\alpha y = ky$$

Let’s suppose that $\alpha > 0$. Particles with x displacement feel a restoring force that pushes them toward the x axis and thus focuses the beam along the x direction. In the y direction, the effect is to defocus the beam. It may not appear that we gain anything from such an arrangement, but if we place two quadrupole lenses in series, with the second rotated 90^0 relative to the first, then along each axis (x and y) there is both a focusing and a defocusing effect, and it can be shown that the net effect is to focus the beam. An optical analogy is shown in Fig. 1(b).

Electrostatic Accelerators:

The simplest way to accelerate a charged particle is to put it through a constant potential difference V. If the particle has a charge q, it acquires a kinetic energy of qV. The largest potential difference that can be maintained under accelerating conditions is about 10^7 V (or 10 MV), and thus ions will acquire an energy in the range of 10 MeV per unit of charge. This is just the energy one needs for many studies of nuclear structure, and so this type of accelerator has found wide use in nuclear physics laboratories throughout the world.

Cockcroft-Walton High Voltage Accelerator. The technology of electrostatic accelerators consists entirely in establishing and maintaining a high-voltage terminal to accelerate the charged particles from the ion source. The earliest development of this type for nuclear physics applications was done in 1932 by Cockcroft and Walton, who built a device which could eventually reach a potential upto 800 kV. Fig. 2 illustrates the basic operating principle, in which capacitors are charged in parallel to a common potential, but then discharged in series. The whole operation is done through voltage multiplier circuit.

Let the secondary voltage from the transformer be $V(t) = V_0 \sin \omega t$, where V_0 may be of order 100 kV. The charging of the capacitors is done through a sufficiently large load that the time constants (RC) are large compared with inverse of the frequency (ω^{-1}) of the variation of the transformer voltage. The circuit needs to be examined after a very long time, when the capacitors have become all charged.

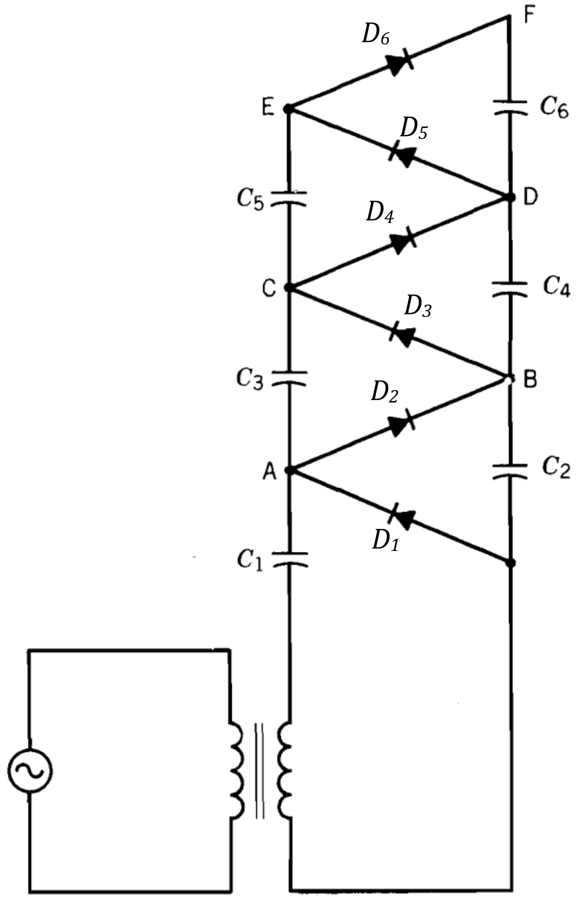

Fig. 2

Capacitor C_1 is charged to voltage V_0, and thus the voltage at point A varies sinusoidally between 0 and $2V_0$ (because the input voltage varies between V_0 to $-V_0$). With the forward conducting of rectifier D_2 point B eventually reaches nearly a constant DC potential of $2V_0$. This same DC potential of $2V_0$ is imposed on point C by rectifier D_3, and thus the AC voltage at point C varies between $2V_0$ and $4V_0$. The rectifier D_4 then fixes the potential at point D to the constant value of $4V_0$, as capacitor C_4 charges to a voltage of $2V_0$. This chain can be continued to higher potentials, limited only by the ability of the high-voltage terminal to hold its potential without sparking to the surroundings. In practice, there is a loss of voltage due to current carried through the load, and each cycle of the applied voltage $V(t)$ restores the lost charge in the steady state. During the charging cycle of $V(t)$ the rectifiers are all conducting, and the capacitors are effectively in parallel. During the discharging cycle of $V(t)$, the rectifiers are non-conducting and look like open circuits, in which case the capacitors are effectively in series. As a result of this charging and discharging cycle, the terminal voltage is not constant, but has a small ripple that depends directly on the external load resistance and on the period (ω^{-1}) of the charging voltage. The ripple also increases in geometric proportion with the number of steps in the chain.

Because of its simplicity of design, the Cockcroft-Walton Accelerator has retained more than just historical interest, currently it is in use to provide sources of neutrons and also as an injector of particles, especially protons, for higher energy accelerators.

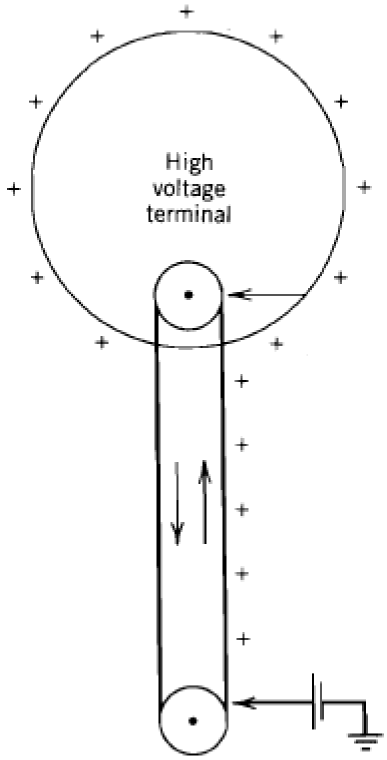

Fig. 3

Van de Graaff Accelerator. The most common type of electrostatic accelerator in use today in nuclear physics laboratories is based on the Van de Graaff generator, shown schematically in Fig. 3. The basic principle of operation is a familiar one from elementary electrostatics. It states, when a charged inner conductor and a hollow outer conducting shell are placed in electrical contact, all of the charge from the inner conductor will flow to the outer one, no matter how much charge resides there already or how high its potential. The resulting potential on the outer conductor is determined by its capacitance (C) with respect to the grounded surroundings, $V = \frac{Q}{C}$, and in principle the potential increases without limit as we add more and more charge Q. In practice, a limit is imposed by the electrical breakdown (or sparking) of the insulating column that supports the outer conductor or of the surrounding atmosphere.

The charge is transferred to the terminal by a continuously moving belt, originally made of insulating material such as silk. Charge is sprayed onto the belt by a sharp comb-like structure at the base of the device illustrated in Fig. 4. A large potential difference (e.g. $+20$ kV) at the sharp points ionizes the air and repels the positive ions, where they are intercepted by the moving belt. A complementary set of comb-like points near the upper pulley extracts the charge and transfers it to the high-voltage terminal. An ion source is located inside the terminal and ions fall to ground potential through the potential difference V. To reduce breakdown and sparking, the generator is enclosed in a pressure tank containing $10 - 20$ atmospheres of an insulating gas which prohibits breakdown. Sulphur hexafluoride (SF_6) is a particularly stable gas that is in common use today. An evacuated accelerating tube guides the ions from the source to the target, which is at ground potential.

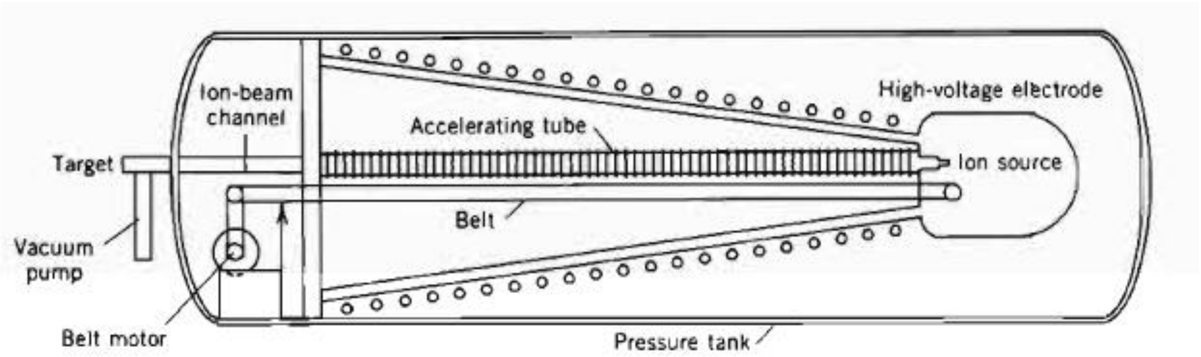

Fig. 4

The Van de Graaff Accelerator provides one enormous advantage over the Cockcroft-Walton Accelerator. The terminal voltage on a Van de Graaff is extremely stable and lacks the AC ripple of the Cockcroft-Walton. Terminal voltages are constant to within ±0.1% which is extremely important when it is desired to measure reaction cross sections leading to specific excited states.

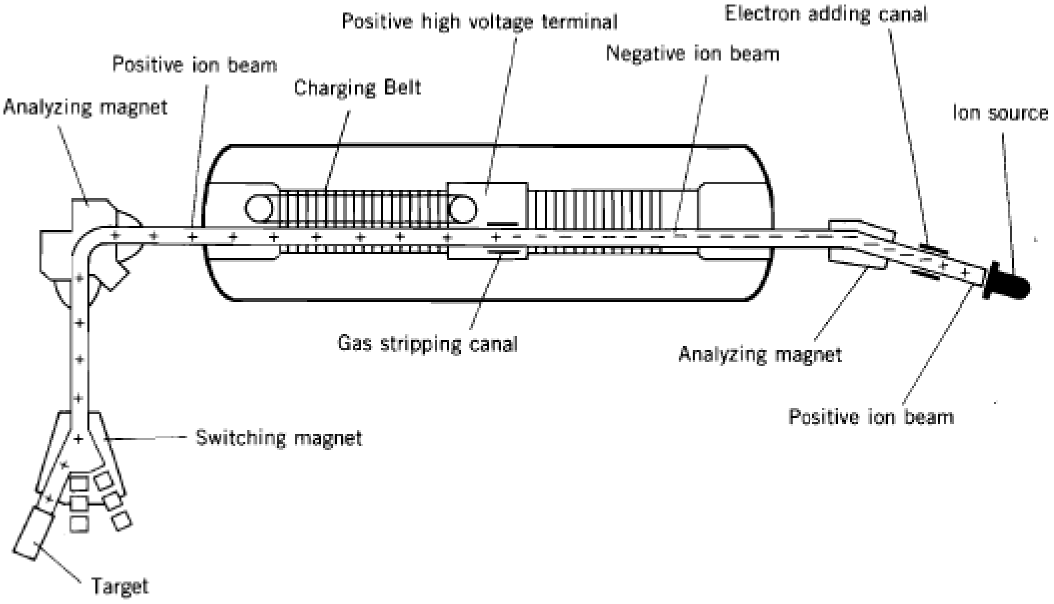

Fig. 5

Tandem Van de Graaff Accelerator (or Tandem Accelerator). Having the ion source located inside the high-voltage terminal creates annoying problems for the experimenter such as gaining access requires discharging the terminal, pumping out and storing the insulating gas, opening the pressure tank and then reversing the procedure to re-assemble the system. The entire process requires the accelerator to be shut down for many hours. An alternative design that eliminates this problem (and gains energy for the beam in the process) is the Tandem Van de Graaff Accelerator (or Tandem Accelerator), shown schematically in Fig. 5. Here negative ions (e.g. hydrogen atoms with two electrons) produced in an ion source at ground potential are accelerated to the terminal, reaching it with energy eV (charges of negative ions are rarely larger than e). In the terminal they pass through a thin foil of material (stripper) which strips off two (or more) electrons, converting them into positive ions of charge ze. After passing through the terminal and out the other side, being positive ions they are again accelerated through the voltage V, whence their final energy is

$(z+1)eV$. The energy of a Van de Graaff accelerator is limited by the voltage that can be held without breakdown occurring. By use of large clearances and a high-pressure insulating gas, terminal voltages as high as 12 MV have been used, giving proton energies up to 24 MeV.

This concludes part 1 of this e-report.

The discussion will be continuing in the part 2 of this e-report.

Reference(s):

Concepts of Nuclear Physics, Bernard L. Cohen, McGraw-Hill

Introductory Nuclear Physics, Kenneth S. Krane, John Wiley & Sons

(All the figures have been collected from the above mentioned references)