CHAPTER 13

Particle Accelerators

Contents

In this chapter we are concerned with the sources – accelerators – that can be used to obtain energetic charged particles, and secondarily neutrons and photons, that can induce nuclear reactions or chemical changes. Thus we include various accelerators for producing beams of charged particles as well as neutrons. Electrons can be accelerated by the same principles as positive ions but in the following paragraphs we will focus on the acceleration of positive ions because these are more useful for nuclear reactions. Although accelerators can be used to produce neutrons, a more copious neutron source is the nuclear reactor, see Chapter 19. Small neutron sources, consisting of the spontaneous fissioning nuclide ^{252}Cf or of mixtures of elements like radium and beryllium in which nuclear transmutations (mostly (α,n)-reactions) produce neutrons, are discussed in §12.5.

13.1. Charged particle accelerators

In order to induce nuclear reactions with positively charged projectiles such as protons, deuterons, α-particles, oxygen ions, or uranium ions, it is necessary that the projectile particles have sufficient kinetic energy to overcome the Coulomb barrier created by the repulsion between the positive charges of the projectile and the nucleus. While there is some probability that a positive projectile can tunnel through the Coulomb barrier at kinetic energies lower than the maximum value of the barrier, this probability is quite small until the kinetic energy is close to the barrier maximum.

As discussed in Chapter 12, in 1919 Rutherford caused artificial transmutation of one element into another by using as projectiles the α-particles emitted in the radioactive decay

of ^{214}Po. These α-particles had sufficient kinetic energy (7.7 MeV) upon emission from the polonium nucleus to overcome the Coulomb barrier and react with nitrogen nuclei. However, the kinetic energy of α-particles emitted in radioactive decay is insufficient to overcome the Coulomb barrier to react with nuclei of higher atomic numbers. Consequently, means had to be devised for acceleration of the charged projectiles to kinetic energies sufficient to achieve reaction.

The principle to be used to achieve the higher kinetic energies was obvious. The projectile particles would have to be ionized to obtain positively charged ions. If these ions could be accelerated through a potential difference of 1000 V, they would acquire 1000 eV additional kinetic energy, per unit of charge. If an α-particle of a + 2 charge was to be accelerated through a potential difference of 10^6 V, it would acquire an additional kinetic energy or 2 MeV (eqn. (2.5)). The problem of obtaining the desired kinetic energy involved two aspects: first, the production of the charged particles: second, the acceleration through the necessary potential difference.

13.2. Ion source

The problem of producing the positive ions is in principle relatively simple. If a gas is bombarded by energetic electrons, the atoms of the gas are ionized and positive ions produced. Figure 13.1 shows a simple ion source.

As hydrogen gas flows into the region above the filament, the electrons being emitted by the filament are accelerated to an anode (a typical voltage drop over the electrodes B_1 - B_2 may be
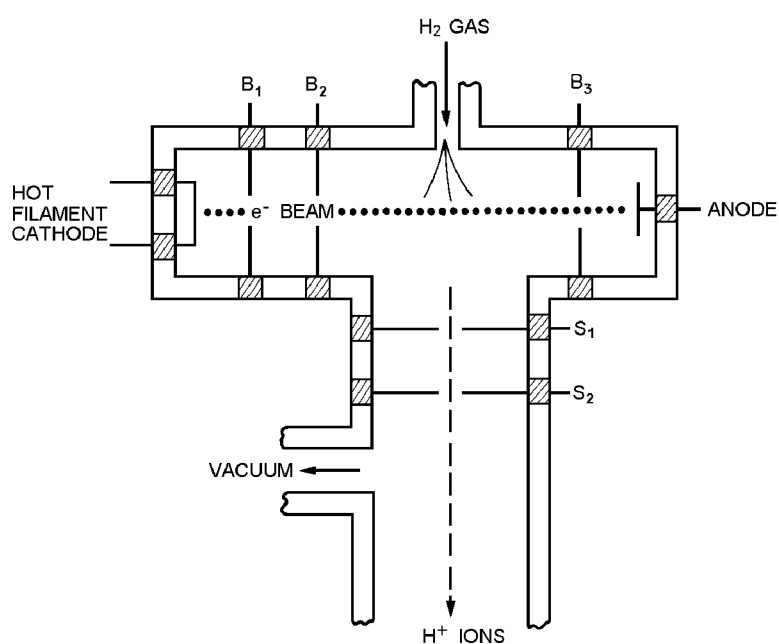

FIG. 13.1. A schematic drawing of an ion source producing protons by electron bombardment of hydrogen gas.

100 V) and in their passage through the gas cause ionization. The positive ions are extracted by attraction to a negative electrode (the voltage drop over S_1 - S_2 may be 1 - 10 kV) into the accelerator region. The vacuum at the beam extraction is of the order 10^{-4} Pa but in the ionization compartment it is normally 10^{-2} Pa. The basic principle, bombardment with electrons, is similar in the different types of ion sources that have been developed to meet the demands of the variety of ions and accelerator types in use. High ion currents of all elements in a variety of charge states can now be produced.

13.3. Single-stage accelerators

The first successful accelerator for causing nuclear transmutations was developed by Cockcroft and Walton in 1932 and used a high voltage across an acceleration space. Gamow's development of the tunneling theory for α-decay led Houtermans to suggest an opposite reaction, a high energy proton tunneling through the Coulomb barrier into a target nucleus. Calculations showed that such tunneling could occur even at about 100 keV. Cockcroft, who was an electrical engineer, realized that it would be possible to build a high tension generator capable of accelerating protons to such energies (although even Rutherford first thought it technically impossible).

Cockcroft-Walton accelerators are still used for obtaining "low" kinetic energies, up to 4 MeV for protons. Presently, such accelerators are used in many installations as the first stage of acceleration, *injector*, in a more complex machine designed to produce high energy beams (see Figures 13.8 and 13.9).

In a single-stage accelerator, such as a Cockcroft-Walton type, the total potential produced from a high voltage generator is imposed across the accelerator, i.e. between the ion source and the target. The kinetic energy, E_{kin}, of the projectile is:

$$E_{kin} = nqV \tag{13.1}$$

where q is the charge of the accelerated ions (Coulomb) and V is the imposed potential across the acceleration gap. This equation is identical to (2.5) except that n is the number of accelerating stages ($n = 1$ for the Cockcroft-Walton machine).

In recent years small and relatively inexpensive accelerators have come into use based on the Cockcroft-Walton principle. These are known as *transformer-rectifier accelerators* and are primarily used for acceleration of electrons or acceleration of deuterons for production of neutrons through the reaction:

$$^3_1H + {}^2_1H \rightarrow {}^4_2He + n$$
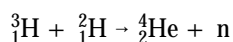
Tritium targets are bombarded by accelerated deuterons. Tunneling of the Coulomb barrier (see Fig. 13.10) results in a good yield for this reaction even for energies of 0.1 MeV.

Figure 13.2 illustrates an inexpensive transformer-rectifier type accelerator. Deuterium molecules leak through a heated palladium foil into the vacuum of the ion source, where a high frequency electric field decomposes the deuterium molecules to form a plasma of D^{+1} ions and electrons. The deuterium ions are extracted from the ion source with a relatively low negative potential to enter the acceleration tube with approximately 2.5 keV
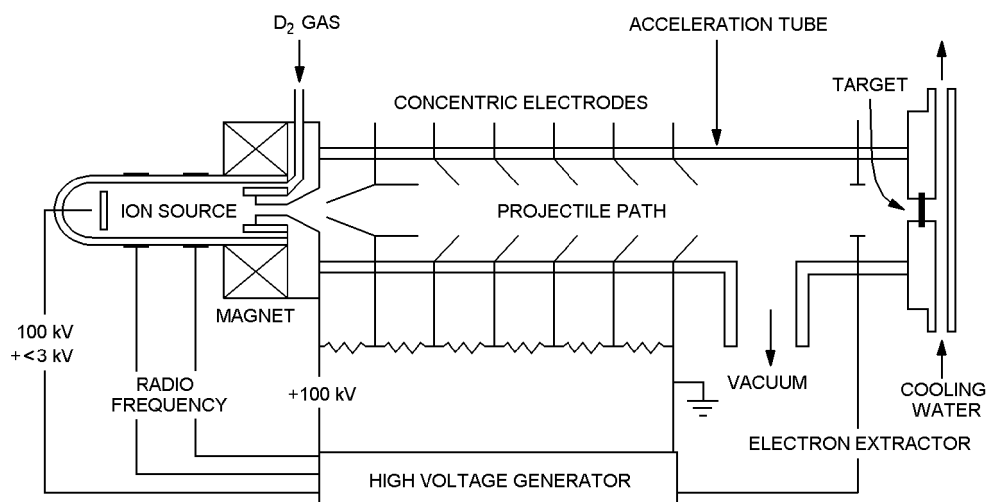
FIG. 13.2. Principle of a single-stage linear accelerator. The D_2 gas enters the vacuum through a palladium membrane.

kinetic energy. The voltage difference of 100 kV across the acceleration space is obtained from a transformer and rectifier unit coupled to a set of cylindrical electrodes connected by a resistor chain.

The cylindrical electrodes serve the purpose both of acceleration and of focusing the ion beam into the proper path. As the beam particles exit from the last electrode they drift through a short tube and strike the target, which consists of a metal foil covered with titanium in which tritium has been absorbed. Approximately 200 GBq of tritium can be absorbed as titanium tritide on an area of 5 cm^2. The target is cooled by water to minimize tritium evaporation. The passage of the beam through the target also results in the emission of electrons which are removed by attraction to an anode to avoid interference with the beam.

With a voltage of 100 kV and an ion current of 0.5 mA, this accelerator can produce approximately 10^{10} n s^{-1} with an energy of 14 MeV. It is often desirable to reduce the kinetic energy of these neutrons to thermal values since thermal neutrons have a much larger probability of interacting with target nuclei. Moderation of the neutrons to thermal energies ($\approx$ 0.025 eV) can be accomplished by placing water or paraffin around the target (see §12.7). The flux of the thermal neutrons is relatively low, on the order of 10^8 n cm^{-2} s^{-1}. However, the production rate of neutrons increases as the beam energy and beam current increases.

Small accelerators of similar design are commercially available with such dimensions that they can be lowered into bore-holes for in situ neutron activation analysis during gas or oil prospecting.

More advanced designs of this type of accelerator use coupling of transformers, rectifiers, and condensers to increase the voltage. With the larger single-stage accelerators it is possible to obtain beams of protons and deuterons which have energies of several MeV and currents of about 10 mA.

13.4. van de Graaff accelerators

A type of electrostatic accelerator that has been of great value to nuclear science since its invention is that designed by van de Graaff in 1931. The van de Graaff accelerator (VdG) can provide beams of higher energy than the single-stage Cockcroft-Walton accelerators with a very precisely defined energy. In a modification known as the tandem-VdG beams of 20 MeV protons and 30 MeV α-particles can be achieved. Positive ions of higher Z and electrons can also be accelerated in VdG machines.

The principle of the VdG accelerator is illustrated in Figure 13.3. A rapidly moving belt of a nonconducting material such as rubberized fabric accumulates positive charge as it passes an array of sharp spray points which transfer electrons from the belt to the spray points. The positive charge on the belt is continuously transferred by the movement of the belt away from ground. At the high-voltage terminal, a hollow metal sphere or nearly cylindrical shape, another set of spray points neutralize the charges on the belt by electrons emitted from the spray points. The result is the transfer of the positive charge to the sphere. By a continuous process of transfer of positive charge to the sphere via movement of the belt a high potential relative to ground can be built up on the sphere. The limit of the voltage that can be accumulated on the hollow electrode is determined by its discharge potential to the surrounding housing. If it is insulated by some pressurized non-conducting
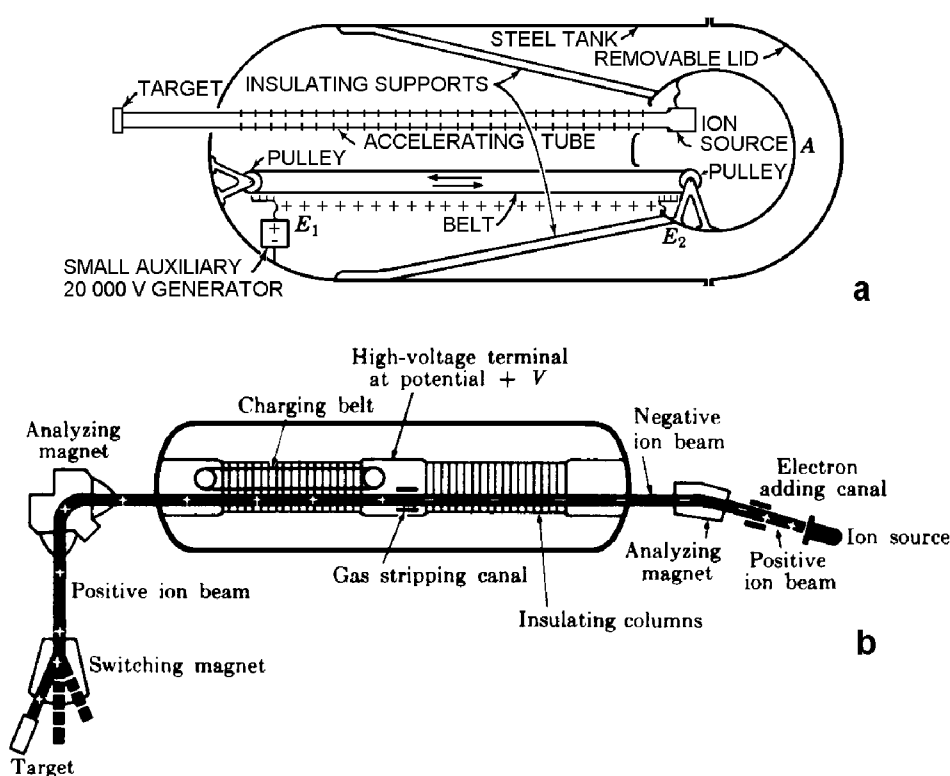

FIG. 13.3. (a) The main principle of the van de Graaff accelerator. (According to R. S. Shankland.) (b) The principle of the tandem-VdG accelerator. (According to R. V. van de Graaff.)

gas such as N_2, CO_2, or SF_6, potentials of $\sim$ 15 MV can be achieved. This potential can be used to accelerate protons to energies of $\sim$ 15 MeV in a single stage.

The single-stage VdG has only one accelerating tube. In the tandem VdG modification, atoms are first given a negative charge by bombardment with low energy electrons in the ion source, and then accelerated from ground to the positive potential at the center electrode. At this stage, in the center of the accelerator, the negative ions are stripped of electrons by passage through a foil or a gas volume to become positive ions. The average charge, z, of an ion of velocity v (m/s) and nuclear charge Z emerging from a solid material is given by the following empirical relation.

$$z = Z \, [\, 1 + \{v/(3.6 \times 10^6 \ (\text{m/s}) \ Z^{0.45})\}^{-1.67}\,]^{-0.6} \tag{13.2}$$

In the second stage of acceleration, the *post-stripper*, the positive ions are accelerated as they move from the positive potential on the center electrode back to ground. The emergent beam has a total energy of 20 MeV if the accelerating potential is 10 MV. Beams of hydrogen, helium, nitrogen, oxygen, and heavier ions can be accelerated similarly. The highest energy so far achieved in a tandem VdG accelerator is 60 MeV corresponding to M^- ions in the first stage and M^{5+} in the second ($1 \times 10 + 5 \times 10 = 60$ MeV). By using two separate tanks and alternatingly positively and negatively charged ions, three-stage VdG machines with maximum proton energies up to $\sim$ 45 MeV have been built.

The energy of a beam produced by a VdG generator is extremely precise. However, the current intensity, 10 - 100 μA, is somewhat less than that of other accelerators. The beam current i (amperes) is given by the relation

$$i = q I_\text{o} = \mathbf{e} z I_0 \tag{13.3}$$

where q is the projectile charge (C), I_0 the incident particle current (particles s^{-1}), $\mathbf{e}$ 1.6 $\times$ 10^{-19}, and z the net charge (in electron units) of the beam particle (ion).

13.5. Multiple-stage linear accelerators

The potential obtained from a high voltage generator can be used repeatedly in a multiple-stage accelerator process ($n > 1$ in (13.1)). The linear accelerator operates on this principle. The accelerator tube consists of a series of cylindrical electrodes called drift tubes. In the Wideröe linear accelerator, the electrodes are coupled to a radio frequency generator in the manner shown in Figure 13.4. The high voltage generator gives a maximum voltage V which is applied to the electrodes by the radio frequency so that the electrodes alternate in the sign of the voltage at a constant high frequency. If the particles arrive at the gap between electrodes in proper phase with the radio frequency such that the exit electrode has the same charge sign as the particle and the entrance electrode the opposite, the particles are accelerated across the gap. Each time the particles are accelerated at an electrode gap they receive an increase in energy of qV; for n electrode gaps the total energy acquired is nqV (13.1). Inside the drift tubes no acceleration takes place since the particles are in a region of equal potential.
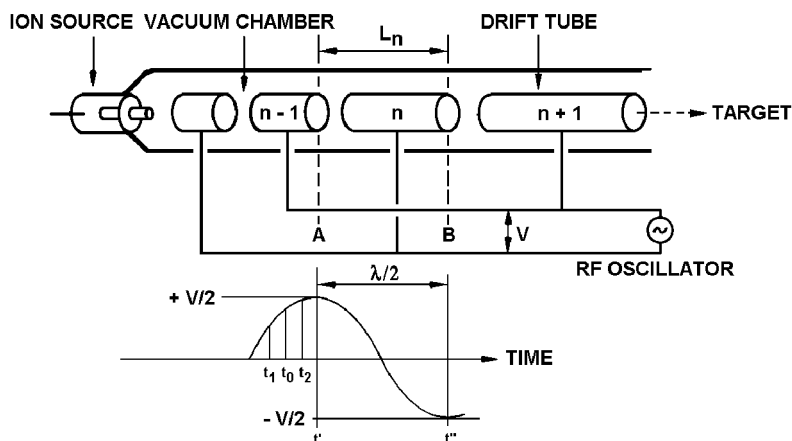
FIG. 13.4. Principle of a multi-stage high voltage linear accelerator of Wideröe type.

Veksler and McMillan independently demonstrated the principle of phase stability, which is based on an effect which tends to keep the particles in phase with the radio frequency oscillation of the potential and allows beams of sufficient intensity for use in research. In the lower part of Figure 13.4 the variation of potential at point A with time is shown. In operation, a particle in proper phase should arrive at the acceleration gap at time t_0. If a particle has less energy, it takes longer time to traverse the drift tube and arrives late at the gap, e.g. at time t_2. Since the potential is now higher, it receives a greater acceleration, thereby becoming more in phase. If a particle is too energetic, it arrives too early at the gap t_1 and receives a smaller acceleration, thereby putting it better in phase. This bunching of the ions not only keeps the ions in phase for acceleration but also reduces the energy spread in the beam. When the velocity approaches **c**, phase stability vanishes gradually because changes in energy now mostly becomes changes in mass and not in velocity.

Since the velocity of the beam particles are increasing as they progress down the accelerator but the oscillator frequency remains constant, it is necessary to make the drift tubes progressively longer so as to allow the beam particles to arrive at the exit of each tube in phase with the oscillation of the potential. Acceleration to high energies requires relatively long acceleration tubes. The electric field between the tubes which accelerates the particles also spreads the beam. The defocussing effect can be minimized by the use of electrostatic and magnetic lenses, in the drift tubes, which refocus the beam onto the center line of the acceleration tubes.

For protons and deuterons the increase in energy below 10 MeV is directly related to the increase in the velocity of the particles. However, as the kinetic energy exceeds 10 - 20 MeV the relativistic mass becomes important since the velocity is approaching the velocity of light (Fig. 4.2). At projectile energies above 100 MeV, the relativistic mass increase is greater than the increase in velocity and at very high energies, the GeV range, the energy increase is practically all reflected by an increase in the relativistic mass (at 1.9 GeV, the proton mass is double that of the rest mass).

The phase requirement (Fig. 13.4) is that the time from point A to B (i.e. $t''-t'$) must be

$$L_n/v_n = \lambda/(2\mathbf{c}) \tag{13.4}$$

Taking the relativistic mass increase into consideration it can then be shown that the length of the drift tube at the nth stage is

$$L_n = (\lambda/2) [1 - (nk + 1)^{-2}]^{\frac{1}{2}} \tag{13.5a}$$

where

$$k = qV/(m^0\mathbf{c}^2) = z\mathbf{e}V/(m^0\mathbf{c}^2) \tag{13.5b}$$

When $v \rightarrow \mathbf{c}$, nk becomes $\gg 1$ and thus $L_n \rightarrow \lambda/2$. The length of the drift tubes therefore becomes constant at high particle energies.

In the Alvarez linear accelerator the drift tubes are mounted in a tank acting as a micro-wave resonator, see Figure 13.5. By varying the diameter with drift tube length it is possible to achieve resonance for all drift tubes. A powerful high-frequency radio signal is introduced into the tank by a small antenna. The standing electromagnetic wave introduces oscillating potential differences between the drift tubes in a way similar to the Wideröe accelerator. The drift tubes are grounded in the tank wall through their supports and no insulators are required. This permits higher potential differences between the tubes than in the Wideröe design.

A linear accelerator in use at the Gesellschaft für Schwerionenforschung at Darmstadt, Germany, is the UNILAC (for UNIversal Linear ACcelerator), which initially had a Wideröe section (beam energy 1.4 MeV/u) followed by Alvarez accelerators (beam energy 11.4 MeV/u) and 17 single step linear accelerator cavities. To increase the achievable energy, the partly accelerated ions are further stripped of electrons by passage through gas or nickel foil strippers located after the Wideröe section and after the Alvarez tanks, cf. (13.2). The machine was originally designed for synthesis of transuranium and super-heavy elements through bombardment of targets of high atomic number elements with heavy ions. The maximum beam current is $\sim 10^{12}$ particles s^{-1} and the energy ≤ 20 MeV/u, which corresponds to ≤ 5 GeV for accelerated uranium ions. The UNILAC has been used to produce a number of transactinide elements (Ns, Hs, Mt). At present the Wideröe section has been replaced by a radio-frequency quadrupole accelerator (see below) followed by two drift tube linear accelerators. This has resulted in a higher ion current than before.

The world's largest linear accelerator is located at Stanford University in California. In this accelerator electrons and positrons are raised to energies of 20 GeV and used to study
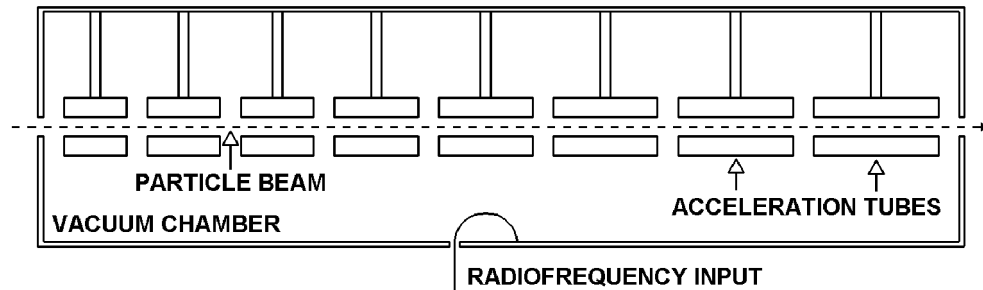

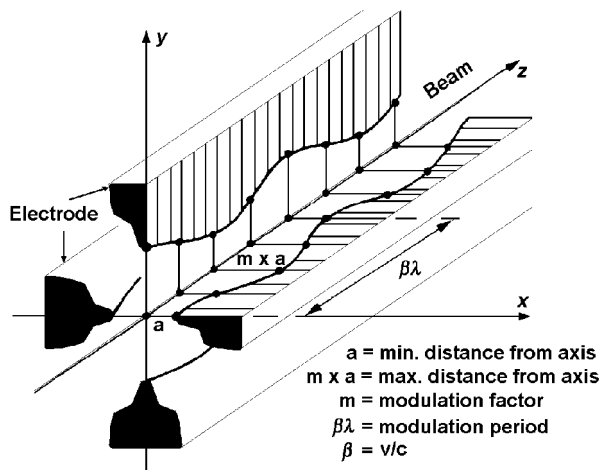FIG. 13.5. Alvarez type of linear accelerator.

FIG. 13.6. RFQ accelerator showing the four shaped electrodes (vanes) of the RF cavity.

elementary particles, the distribution of charges within nuclei, etc. The accelerator tube is 3000 m long; the diameter is about 0.1 m. The maximum beam intensity is 8 pA. At 20 GeV the electrons have a velocity 0.999 999 999 7**c** and the electron mass is 40,000 times greater than rest mass (approximately equivalent to that of a sodium atom).

An important advance in linear accelerator technology is the development of radio-frequency quadrupoles (RFQ:s), permitting either simultaneous acceleration and focusing of high currents of particles or the funneling of two or more beams into one which is then fed into a linear accelerator operating at a higher frequency. In principle the RFQ is somewhat similar to the Alvarez design but without separate drift tubes, see Figure 13.6. Its main characteristics can be summarized as: i) it is linear accelerator operating in the low energy range > 20 keV to 2 MeV/u, ii) it bunches, focuses, and accelerates particles with RF fields, iii) typical lengths are 1 to 2 m and operating frequencies 50 to 400 MHz, iv) intervane voltage ~ 100 kV, v) minimum value of a (see Figure 13.6) 3 - 4 mm, Q-factor ~ 10,000, vi) intervane capacity ~ 10^{10} F/m. In order to accept an incoming unbunched beam the a-value has to be rather high at the entrance and then progressively decrease to its final constant value. The undulating vane profiles are normally obtained by using numerically controlled milling machines.

13.6. Cyclotrons

The difficulties inherent in the length of high energy linear accelerators were ingeniously overcome by Lawrence and Livingston in their construction of the first cyclotron in 1931. The basic operating principles of the cyclotron are shown in Figure 13.7. The particles are accelerated in spiral paths inside two semicircular flat metallic cylinders called dees (D's), placed in a flat vacuum chamber. The two dees are connected to a high frequency alternating voltage. The volume within the dees corresponds to an equipotential condition just as does the volume within the drift tubes of linear accelerators. The dees and their vacuum chamber are placed between the two poles of a magnet so that the magnetic field
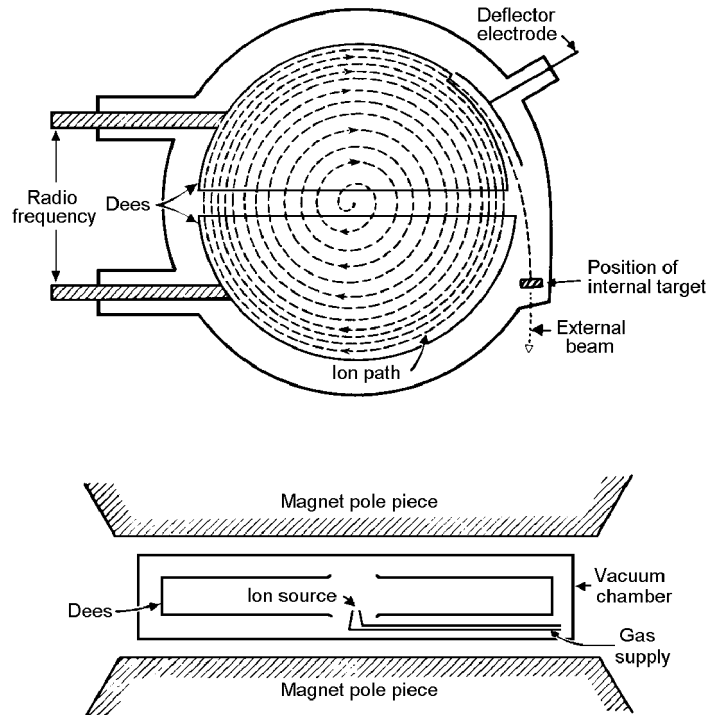
FIG. 13.7. Principle of a cyclotron. (From R.S. Shankland.)

operates upon the ion beam to constrain it to flat circular paths inside the dees. At the gap between the dees the ions experience acceleration due to the potential difference between the dees. The beam particles originate at the ion source at the center of the cyclotron, and as they spiral outward in the dees they acquire a constant increase in energy for each passage across the gap between the dees. The target is located either inside the vacuum chamber (internal beam) or the beam can be taken out through a port into an evacuated tube or through a thin "window" into the ambient air (external beam) after extraction from the circular path by a deflector.

As the projectiles acquire energy, the radius of their path within the dees increases. The longer path-length in the dees is related to the energy of the projectile by the equation (§2.3)

$$E_{kin} = q^2 r^2 B^2 / (2m) \tag{13.6}$$

where r is the radius of the beam path at the energy E_{kin} and B is the value of the magnetic field. This equation is valid for particles of non-relativistic velocities. The successful operation of the cyclotron is based on the principle that the increase in the radius of the path in the dee nearly compensates for the increase in particle velocity. As a result, the particles, as they spiral through the dees, arrive at the gap when the potential difference is of the right polarity to cause acceleration. The principle of phase stability applies also to the cyclotron.

The frequency (in Hz) requirement is

$$\nu = qB/(2\pi m) \qquad (13.7a)$$

or

$$\nu = v/(2\pi r) \qquad (13.7b)$$

where v is the particle velocity at radius r. From (13.7a) it follows at constant ν that B/m must also be constant.

The maximum energies available in conventional cyclotrons of the constant frequency type are about 25 MeV for protons and deuterons, and 50 MeV for α-particles. The shape of the electrostatic field at the gap between the dees as well as the design of the magnetic field to produce a slight non-uniformity at the outer edges of the dees produce a focusing effect on the beam particles. The ion currents are usually ≤ 0.5 mA for the internal beam, and about a factor 10 less for an external beam.

As the energies increase, so does the relativistic mass. From (13.6) we can see that either the frequency or the magnetic field, or both, must be modified to compensate for the increasing mass in order to have the beam particles arrive at the gap in phase. The former is done in synchrocyclotrons (next section) while the magnetic field is varied in sector focused cyclotrons. In the latter, the magnet has ridges (often of spiral form) which provide sufficient modification of the field (retaining azimuthal focussing despite increasing total
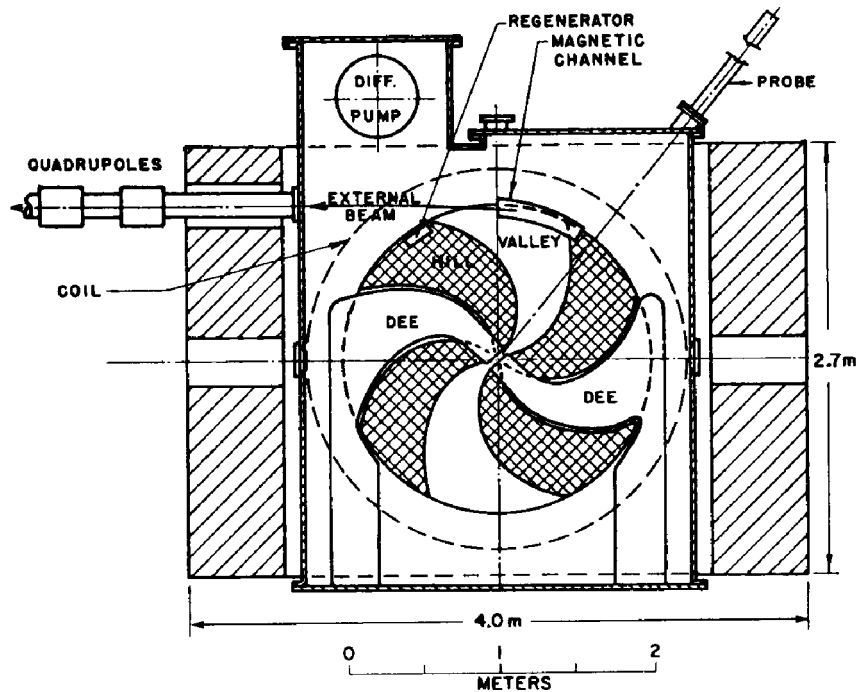

FIG. 13.8. A 150 MeV p$^+$ sector-focused cyclotron showing the magnet with its spiral-ridged pole pieces and ¼-wave D-design.
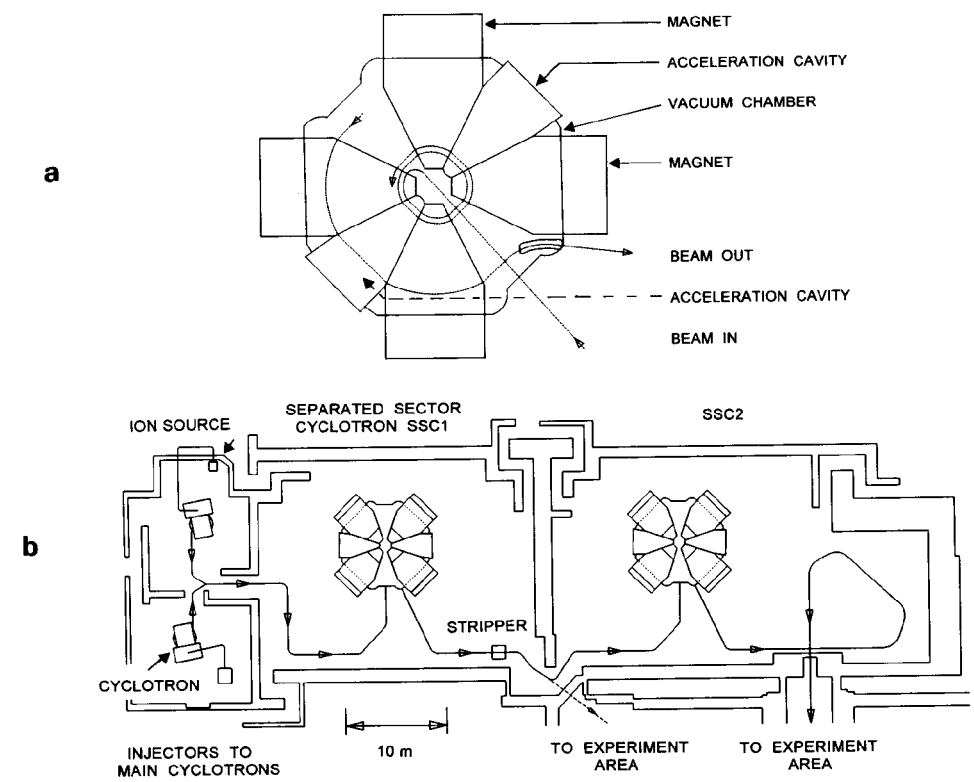
FIG. 13.9. (a) Principle of a sector-separated cyclotron and (b) the GANIL accelerator complex (beam-line bending magnets are not shown).

field strength) to allow the acceleration of particles to much higher energies than is possible with a conventional cyclotron (Fig. 13.8). The energy limit is at about twice the rest mass of the ions. Superconducting magnets are also used to achieve the highest possible magnetic field.

In the *separated-sector cyclotron*, SSC, the magnet is split into two, four, or more, submagnets, each magnet bending the beam only part of the circle. Between the bending magnets the beam follows a linear path. A few (or none) acceleration gaps (corresponding to the dees) are located in each of the linear paths, see Figure 13.8(a). The split of the magnet into several separate sectors permits a larger bending radius to be used, i.e. a higher energy can be achieved with smaller magnet pole pieces although the total magnet weight normally increases compared to a single magnet machine. As an example, in the GANIL accelerator complex (at Caen, France) normal cyclotrons are used as injectors to a SSC with two acceleration cavities, each corresponding to two acceleration steps, and four bending magnets. The beam exiting from the SSC is further stripped by passage through a thin carbon foil and then fed into a second SSC where it achieves its final energy, see Figure 13.9(b). The beam quality from SSC no 2 is increased by a magnetic spectrometer.

Although there is a limit to the energies achievable with cyclotrons of constant frequency and magnetic field, they have the great advantage of high beam currents. For a heavy ion cyclotron, accelerating particles of charge z ($z \leq Z$), the final energy per mass unit, E/A (MeV/u), is given by

$$E/A = K (z/A)^2 \qquad (13.7)$$

and such machines are usually characterized by their K-value. The GANIL SSC:s have e.g. both $K = 400$ but use different z of the ions. The development of ion sources producing higher currents of more highly charged ions is important as it increases the maximum energy achievable at a given K-value.

The magnetic bending of the beam corresponds to a centrifugal acceleration of the charged particles. The acceleration or deceleration of electric charges is always accompanied by the emission of electromagnetic radiation. Although only a small part of the energy input of a cyclotron is lost through this *synchrotron radiation*, it is still sufficient to require considerable radiation shielding (usually concrete walls). Synchrotron radiation is much less of a problem for linear accelerators, except for protons.

13.7. Frequency modulated cyclotrons and synchrotrons

The frequency of a cyclotron can be modulated to take into account the variation in velocity and mass as relativistic effects increase in importance. At very high energies the radius becomes very large. This has led to two somewhat different accelerator designs. The *frequency modulated* (FM) or *synchrocyclotron* maintains the original cyclotron principle with a spiral particle path, while in *synchrotrons* the particle path is fixed in a circular orbit; Figure 13.10 is an example of the latter.

In a synchrotron there is a balance between frequency and the magnetic field, one or both being varied during the acceleration (cf. (13.7a)). From (13.6) and (13.7) one obtains

$$E_{\text{kin}} = \nu \pi r^2 Bq \qquad (13.8)$$

by eliminating the mass from the relation for the kinetic energy of the projectile. In these machines the particles are accelerated in bursts, since the frequency of the accelerating potential must be modulated throughout the traversal of one beam burst in the machine, and only the particles in that burst would be in resonance with the frequency change of the accelerating gap. As a result, average beam currents are much smaller in FM cyclotrons and synchrotrons than in constant frequency cyclotrons.

Synchrotrons which accelerate positive particles use smaller accelerators, often linear, for injecting the beam into the circular synchrotron. Figure 13.10 shows a typical synchrotron design, although it specifically refers to the late Bevatron in Berkeley which provided acceleration of protons to 6.5 GeV (the mass increase of a 6.5 GeV proton is 6.9 u) and heavier ions like carbon or neon to about 2 GeV u^{-1} it illustrates the design of such machines. The Bevatron injectors were a 0.5 MeV Cockcroft-Walton machine followed by a 10 MeV multistage linear accelerator or the Super-HILAC heavy ion linear accelerator. The latter combination was called Bevalac. In the Bevatron, the potential difference over
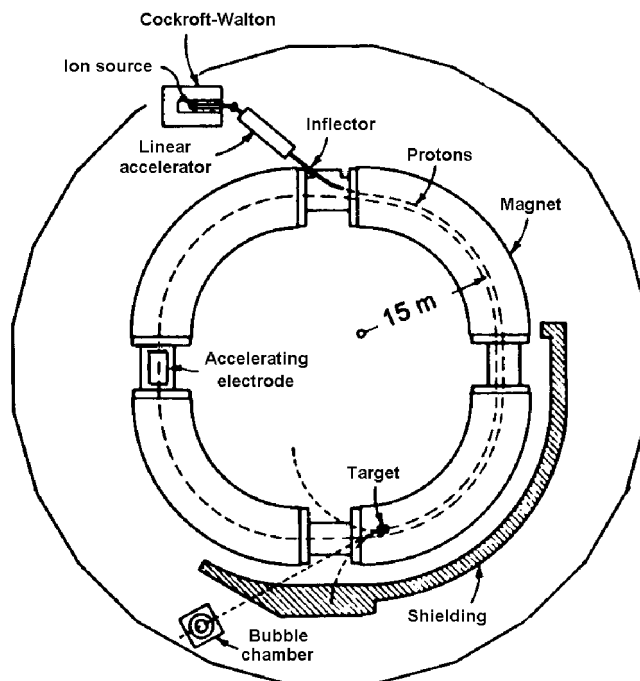
FIG. 13.10. Principle of a modulated multistage circular accelerator.

the accelerating step was only 1500 V. As the particles accelerate, the magnetic field continues to increase in such a way that the radius of the particle orbit remains constant. The frequency of the oscillating voltage applied to the accelerating electrode must also increase, since the time required for a complete circuit becomes shorter and shorter until the velocity of the particles approaches the velocity or light, after which the circuit time remains constant. The whole accelerating cycle requires several seconds, during which time the particles make many millions of orbits. Each burst of particles may contain ~ 10^{12} particles, and in the Berkeley machine there was one burst every 6 s. The successful operation of the synchrotron depends on the existence of phase stability.

The Bevatron (later the Bevalac) operated from 1954 to 1993. Larger and more recent (proton) accelerators are the 28 GeV machine of CERN and the 76 GeV machine of Serpukhov (USSR). The presently largest machine is at Batavia in the USA (500 GeV); it contains 1000 magnets along its 6.3 km orbit, each magnet weighing 10 tons.

At CERN, a machine was built that could produce 10^{13} 400 GeV protons s^{-1}; the acceleration diameter was 2.2 km. The injection time (with 10 GeV protons) was 23 s (to fill the acceleration ring), while the acceleration time was 9 s; for each cycle 2.5 MeV was added in energy. The field strength of the 200 bending magnets was 1.8 T and the power consumption 50 MW.

Still higher energies have been achieved in collisions between particles circulating in two beam trains in opposite direction by using intersecting storage rings (ISR). In this system the energy loss due to momentum conservation in the reaction between high speed
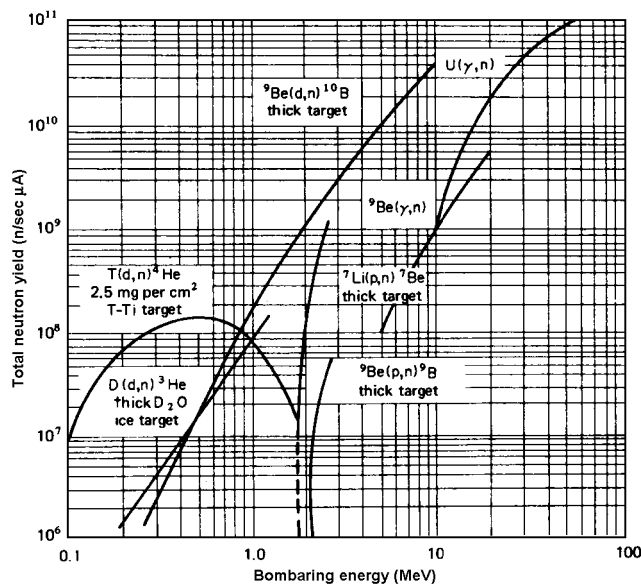
FIG. 13.11. Neutron yield as function of projectile energy.

projectiles and stationary target atoms is eliminated. At CERN proton collision energies of 1700 GeV have been obtained.

Synchrotrons have been built in which electrons are accelerated in a fixed orbit in a strong magnetic field ($\geq$ 1 T) to energies in the GeV range. The intense electromagnetic (synchrotron) radiation has usually a maximum intensity at $\leq$ 1 keV and is used for studies of photon induced reactions (e.g. for meson production), for radiation chemistry, as a strong light source, etc.

13.8. Neutron generators

Many radioactive isotopes are most conveniently produced by irradiation of a target with neutrons. There are three main ways of obtaining useful neutron fluxes:

(a) through accelerator-induced reactions (Table 13.1);
(b) through nuclear reactors (Ch. 19);
(c) through nuclear reactions induced by radioactive isotopes (§12.5).

13.8.1. *Reactions*

Table 13.1 gives the most common accelerator-induced nuclear reactions leading to the production of neutrons. In general, the neutron yield increases with increasing beam energy up to some maximum value of the latter after which competition of other nuclear reactions reduces the probability of the initial neutron producing reaction (Fig. 13.11). The least expensive way to get a neutron flux of sufficient intensity for producing radioactive nuclides

in easily measurable quantities (e.g. for activation analysis) is through the T + D reaction using a Cockcroft-Walton accelerator. The reaction

$$^7\text{Li} + {}^1\text{H} \rightarrow {}^7\text{Be} + {}^1\text{n}$$
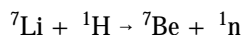
is used for the production of mono-energetic neutrons (cf. §14.3). Higher neutron yields can be obtained by the reaction of ^9Be with deuterons. Neutrons can also be obtained from ^9Be by irradiation in electron accelerators. The passage of the electrons in the target results in the production of high energy Bremsstrahlung γ-rays (§6.4.2) which react with the beryllium to produce neutrons. An even higher neutron flux is obtained for the same reason when uranium is bombarded by electrons.

 Extremely intense neutron sources can be constructed from a high energy (~ 1 GeV) high current proton linear accelerator and a heavy element (e.g. molten Pb) spallation target. Tentative designs have been described that would be capable of generating ~ 0.1 g of neutrons (0.1 mole) per second. Such intense neutron sources could be used to transmute longlived radioactive nuclides (into inactive or shorter lived ones) or drive a subcritical assembly for production of energy by fission of actinides.

13.9. Areas of application for accelerators

 Let us consider a few uses of accelerators. In §13.8 we have discussed the use of accelerators for neutron production. Electron as well as positive particle beams from these accelerators can be used directly for the study of radiation effects in materials (see Chapter 7), to produce X-rays, or to generate intense light. Accelerators are used in medicine for producing intense γ- or X-ray beams for cancer treatment, or charged particle beams for similar purposes (the "proton-knife"). Accelerators in the 10 MeV range are very useful in producing radionuclides, which either cannot be made through (n,γ)-reactions in nuclear reactors or are very shortlived. Small cyclotrons of a size suitable for use in hospitals are commercially available. The precise definition of energy available in van de Graaff accelerators makes them particularly useful for the study of the energy levels of nucleons in nuclides and for ^{14}C dating. VdG's, cyclotrons, linear accelerators, and synchrotrons have been extensively used for the study of nuclear reactions.

Table 13.1. *Neutron yield for some accelerator produced reactions* (*see also Fig.* 13.10)

Reaction	Q(MeV)	Target	Yield[*] (n s^{-1} μA^{-1})	
$^7\text{Li}(p,n)^7\text{Be}$	-1.64	Li salt	10^7	for 2.3 MeV H$^+$
$^2\text{D}(d,n)^3\text{He}$	3.27	D$_2$O ice	7×10^7	for 1 MeV D$^+$
$^3\text{H}(d,n)^4\text{He}$	17.6	^3H in Ti	2×10^7	for 0.1 MeV D$^+$
$^9\text{Be}(d,n)^{10}\text{B}$	3.76	Be metal	2×10^{10}	for 7 MeV D$^+$
$^9\text{Be}(\gamma,n)^8\text{Be}$	-1.67	Be metal	10^9	for 10 MeV e$^-$
$\text{U}(\gamma,\text{fp})$	-5.1	U metal	10^{11}	for 40 MeV e$^-$

[*] 1 μA = 6.24×10^{12} single-charged ions per second.

Very high energy accelerators are used for the production and study of elementary particles. Once the beam energy exceeds a couple of hundred MeV, mesons and other elementary particles are produced in nuclear reactions and can be studied directly or they can be used to cause various types of nuclear reactions.

High energy electron accelerators are also in use to produce high intensity synchrotron light for basic studies in chemistry, material science and biology. The light is usually obtained by placing multiple bending magnets in the path of a circulating beam of electrons.

13.10. Exercises

13.1. In a small linear accelerator containing 30 stages, He^{2+} ions are accelerated by a 150 kV, 100 MHz RF source. The ions are used to bombard a metal target to induce a specific reaction. (a) What is the proper length of the last drift tube? (b) What is the maximum projectile energy achieved? (c) What is the heaviest target in which a nuclear transformation can be induced (no tunneling)?

13.2. Assume a linear accelerator is built in three sections, each with 30 stages of 100 kV. Between which sections should a thin carbon stripper foil be placed in order to achieve the highest final energy, when accelerating ^{84}Kr ions from an ion source emitting low energy $^{84}Kr^{4+}$ ions? Consider the nearest integer charge after stripping.

13.3. In order to propel a space vehicle to high velocities after its exit from the earth's gravitational pull, "ion rockets" might be used. These can be considered as simple accelerators for charged particles. The electroneutrality of the vehicle is conserved through emission of electrons from a hot filament. The gain in linear velocity Δv is given by the "rocket formula":

$$\Delta v = v_e \ln(m_{Ro}/m_R)$$

where v_e is the exhaust velocity and m_{Ro} and m_R are the initial and final mass of the vehicle respectively. (a) Calculate the propelling power for a rocket, which emits 10 keV protons at a current of 1 A. (b) What is the final velocity gain of such vehicle with 2000 kg initial mass after 1 year's operating time? (c) For the same net available power and operating time, as in (b), calculate the final velocity gain of a 2000 kg vehicle which emits 10 keV Cs^+ ions at a current of 1 A.

13.4. The TD reaction is used to produce 14 MeV neutrons, which are considered to be emitted isotropically from the target. What is the fast neutron "flux" at 5 cm from the target when the ion current is 0.2 mA and the acceleration voltage is 300 kV? Use Figure 13.11.

13.5. Protons are accelerated to 12 GeV in a synchrotron in which the bending magnets have a maximum field strength of 14.3 T. What is the radius of curvature of the proton orbit?

13.6. In a linear accelerator for protons the first drift tube is 1 cm long and the accelerating potential is 25 kV. (a) The speed of light is not approached in the first drift tube. How long should the second and third drift tubes be? (b) What should the full-wave frequency of acceleration be?

13.7. Calculate the maximum energy (a) for protons, deuterons, and helium ions in a cyclotron, whose maximum orbit diameter is 1.25 m and whose frequency is 12 MHz. (b) What magnetic field strength would be required in each case?

13.8. A thin Au target is irradiated with a beam of 800 MeV $^{16}O^{2+}$ ions during 2 hours. After the irradiaten a faraday cup (with current integrator) behind the target shows a total accumulated charge of 92.3 μC. What was the average beam intensity (oxygen ions per second)? Consider the charge-stripping effect of the target.

13.9. In a VdG accelerator a 100 μA beam of He^{2+} ions is accelerated to an energy of 5 MeV before striking a target. How many grams of radium are required to provide the same number of α-particles?

13.10. A cyclotron can accelerate $^4He^{2+}$ -ions to 35 MeV. (a) What is its K-value? To what energy would it accelerate (b) $^{16}O^{6+}$ and (c) $^{18}O^{8+}$ ions?

13.11. Literature

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