Electrostatic accelerators

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Abstract
The principle of electrostatic accelerators is presented. We consider Cockcroft–Walton, Van de Graaff and Tandem Van de Graaff accelerators. We resume high voltage generators such as cascade generators, Van de Graaff band generators, Pelletron generators, Laddertron generators and Dynamitron generators. The specific features of accelerating tubes, ion optics and methods of voltage stabilization are described. We discuss the characteristic beam properties and the variety of possible beams. We sketch possible applications and the progress in the development of electrostatic accelerators.

1 Cockcroft–Walton accelerator

The Cockcroft–Walton accelerator [1] is the prototype of an electrostatic accelerator. The scheme of the accelerator is shown in Fig. 1. The first accelerator of this type was built in 1932 by J.D. Cockcroft and E.T. Walton. They achieved a high voltage of about 700 kV and they studied the first nuclear reactions with an accelerator. In their experiment a proton beam of about 400 keV kinetic energy was used to investigate the nuclear reactions $^7\mathrm{Li} + \mathrm{p} \rightarrow ^4\mathrm{He} + ^4\mathrm{He}$ and $^7\mathrm{Li} + \mathrm{p} \rightarrow ^7\mathrm{Be} + \mathrm{n}$. Cockcroft and Walton shared the Nobel Prize in physics for 1951.

1.1 High voltage generator

The high voltage generator of the Cockcroft–Walton accelerator is the well known cascade generator or voltage multiplier circuit invented by H. Greinacher [2] in 1921. It consists of a HV transformer, HV capacitors and HV diodes. In Fig. 1 a cascade generator with four stages is shown. The capacitors are stacked in two vertical columns capped by a large rounded terminal electrode. The capacitors in the pushing column P are charged during the negative half-period of the sinusoidal AC voltage, those of the smoothing column S during the positive half-period. In steady state the voltages at the break points of the pushing column P amount to $U_0 + U_0 \sin\omega t$, $U_0 + 3U_0 \sin\omega t$, $U_0 + 5U_0 \sin\omega t$ and $U_0 + 7U_0 \sin\omega t$, those of the smoothing column S to $2U_0$, $4U_0$, $6U_0$ and $8U_0$. Here, U_0 is the amplitude of the AC voltage from the transformer. With n stages a high voltage of $2nU_0$ can be achieved. Extracting a DC current causes a mean voltage drop ΔU and a ripple δU which are proportional to the DC current I,

$$\begin{aligned} U &= 2nU_0 - \Delta U \pm \delta U\,, \\ \Delta U &= \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{3}{4}n^2 + \frac{1}{12}n\right)\,, \\ \delta U &= \frac{I}{fC}\frac{n(n+1)}{2}\,. \end{aligned} \tag{1}$$

Here, f is the frequency of the AC voltage and C the capacitance of the capacitors. In order to keep ΔU and δU small one should choose the frequency f and the capacitance C as large as possible and limit the number n of cascade units. Typical values are $f = 0.5$–10 kHz, $C = 1$–10 nF and $n = 3$–5. The ripple δU can be reduced by an additional RC filter.

The value of the electric field at the surface of the electrodes must kept small in order to avoid excessive corona discharges. Therefore, the intermediate electrodes and the terminal electrodes are formed such that sharp edges and spikes at the outer surface are avoided. Aluminum is commonly used because it can be spun to the desired spherical shape. Polished stainless steel has a higher breakdown limit but is

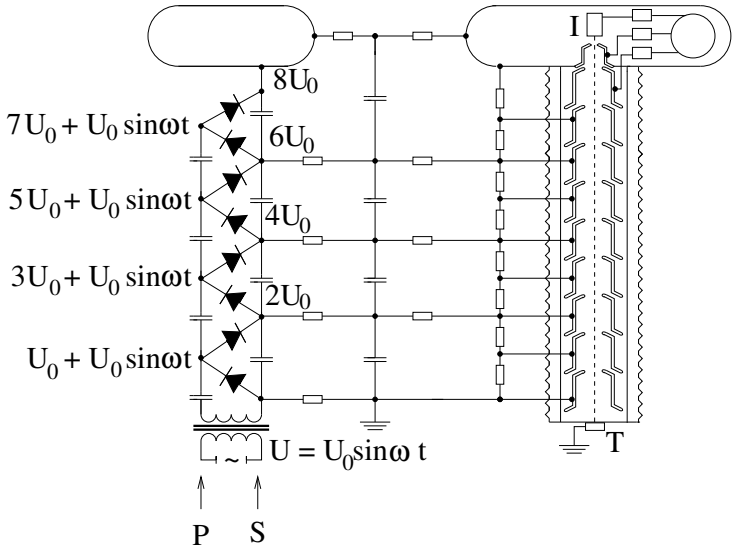

Fig. 1: Scheme of a Cockcroft–Walton accelerator [3]. P: pushing column, S: smoothing column, I: ion source, T: target

more difficult to form. The value of the electric field $|\vec{E}|$ at the surface of rounded electrodes with a local curvature radius r is simply given by

$$|\vec{E}| = \frac{U}{r} \,. \tag{2}$$

For open air accelerators the electric field should not exceed 3 MV/m. The maximum possible voltages of such machines are in the order of 1.5 MV.

1.2 Accelerating tube

The accelerating tubes are installed in an evacuated ceramic isolator, see Fig. 1. The full high voltage is distributed among several tubes yielding a stepwise acceleration of the beam. Thus, the local value of the accelerating field $|\vec{E}|$ is reduced and the voltage stability is increased. For the same reason all inner electrodes are rounded and polished. As a rule of thumb the electric field at the surface of polished stainless steel electrodes in high vacuum must not exceed 100 kV/cm. Higher fields cause violent discharges due to the emission and acceleration of electrons at the electrode surface.

In order to avoid distortions of the ion trajectories by charge islands on the isolator walls the accelerating tubes should be overlapping such that an ion cannot 'see' the isolator walls. This is of great importance in view of the low electric rigidity of low energy ions. Similarly the metal electrodes must be free of oil, hydrocarbon deposits and all kind of insulating deposits.

The ion beam starts at the plasma boundary of the ion source. It is extracted and formed with the aid of an extraction electrode. The acceleration by the rotational symmetric electric fields of the accelerating tube acts like a focusing lens. A proper adjustment of this focusing yields a beam envelope with a beam waist at the target. The electrostatic focusing is discussed in the lecture on electrostatic lenses. The ion source, the electrostatic focusing system at the exit of the ion source, the power supplies and a motor-driven AC voltage generator are housed inside of the HV terminal. The optimum adjustment of the ion source and the extraction system is done by remote control. The high voltage is measured with a voltage divider using Ohm's law.

A serious problem of positive-ion electrostatic accelerators is caused by electrons which are released by secondary emission processes from the electrodes and walls and by collisions of the ions with the atoms of the residual gas in the accelerating tube. These electrons are accelerated in the opposite

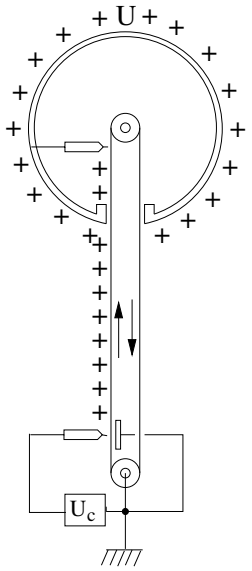

Fig. 2: Scheme of the Van de Graaff generator [3]

direction and generate hard X-rays when hitting the electrodes of the HV terminal. In addition the unwanted electron current makes a substantial contribution to the total current. This electron load can be a limitation on terminal voltage. Therefore, a high vacuum is needed in order to minimize electrons generated from the collisions of ions with the atoms of the residual gas in the accelerating tube. In addition, electron suppression systems are installed in modern electrostatic accelerators. For instance permanent magnets can be installed in the accelerating tube in order to deflect the electrons near the point of origin without causing significant distortions of the ion trajectories.

2 Van de Graaff accelerator

2.1 Van de Graaff generator

The first belt-charged electrostatic generator was developed by R. J. Van de Graaff in 1931. The Van de Graaff generator [4] is made up of a motor-driven belt (made of rubber, vulcanized fabric or another flexible insulating material) stressed between two rollers (pulleys), an insulating column and a spherical or rounded high-voltage terminal electrode which is installed on top of the insulating column as shown in Fig. 2. The belt is electrically charged by a brush or comb of metallic wires which is connected to a DC voltage source. The amount of electric charge sprayed onto the belt is controlled by the voltage U_c. The charge, which can be negative or positive depending on the polarity of the source, is carried by the belt to the terminal electrode. Here, the charge is transferred from the belt to the terminal electrode by a second brush or comb of metallic wires. Electric charges accumulate on the external surface of the terminal electrode. The resulting terminal voltage is a function of the diameter of the terminal electrode. The terminal behaves like a spherical capacitor which has capacitance

$$C = 4\pi\epsilon\epsilon_0 r = (1.11 \cdot 10^{-10}\ \mathrm{F/m})\, r\ , \tag{3}$$

where r is the radius of the terminal electrode. An air insulated electrode with $r = 1$ m yields $C = 111$ pF. If a spherical terminal of radius r_1 is enclosed within a grounded concentric shell of radius r_2, the capacitance C is given by

$$C = 4\pi\epsilon\epsilon_0 \frac{r_1 r_2}{r_2 - r_1} = (1.11 \cdot 10^{-10}\ \mathrm{F/m})\, \frac{r_1 r_2}{r_2 - r_1}\ . \tag{4}$$

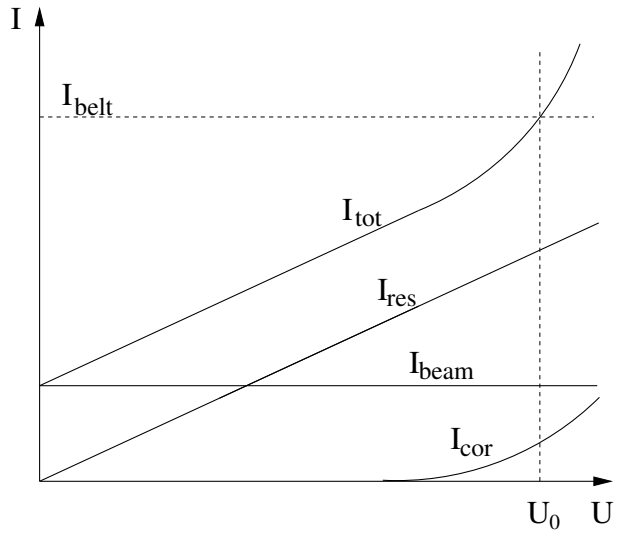

Fig. 3: Typical current-versus-voltage functions for the corona current I_{cor}, beam current I_{beam}, resistive current I_{res} and total current I_{tot} in a Van de Graaff accelerator

The terminal voltage U is proportional to the charge Q accumulated on the terminal electrode,

$$U = \frac{1}{C} Q \, . \tag{5}$$

The achievable equilibrium voltage U_0 depends on the current I_{belt} transported by the belt, the beam current I_{beam} of the accelerating tube, the current I_{res} through the resistor chain including the current due to the residual resistance of the insulating column and the current I_{cor} due to the corona discharge and secondary electrons in the tube. The corona current I_{cor} is highly nonlinear rising rapidly above a threshold value. In Fig. 3 the typical current-versus-voltage functions for those current components is shown.

Assuming a constant charging current I_{belt} the equilibrium voltage U_0 is reached asymptotically. The differential equation reads

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{1}{C}\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{1}{C}(I_{\text{belt}} - I_{\text{beam}} - I_{\text{cor}} - I_{\text{res}}) \, . \tag{6}$$

This equation can be solved analytically at low terminal voltages where the highly nonlinear corona current I_{cor} is negligibly small. Introducing the effective resistance R of the resistor chain and the insulating column, the differential equation may be written

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{1}{C}\left(I_{\text{belt}} - I_{\text{beam}} - \frac{U}{R}\right) \, . \tag{7}$$

We define the time constant $\tau = RC$ and introduce the equilibrium voltage U_0,

$$U_0 = R(I_{\text{belt}} - I_{\text{beam}}) \, . \tag{8}$$

Thus, the solution of the differential equation may be written

$$U(t) = U_0 + [U(0) - U_0]\mathrm{e}^{-t/\tau} \, . \tag{9}$$

This equation holds as long as the currents I_{belt} and I_{beam} and the effective resistance R are constant and the corona currents are negligible. The terminal will reach an equilibrium potential U_0 where the charge

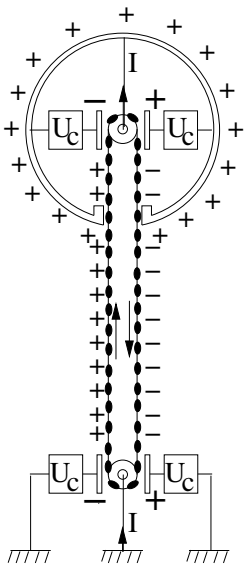

Fig. 4: Scheme of the Pelletron and Laddertron HV generator [3]

delivered by the belt is equal to the charge leaving the the terminal electrode. In modern machines fast closed-loop controls are used in order to achieve a fast adjustment and a high stability of the terminal voltage U. Then, the time dependence of U is determined by the characteristics of the closed loop control. The terminal voltage can be controlled by regulating the charging current I_{belt} and by varying the amount of corona load current with adjustable needles.

The maximum achievable voltage U is strongly limited by the corona discharge from the terminal. Occasionally, a corona streamer will develop into a spark to ground, discharging the terminal completely. The corona discharge is caused by the breakdown of insulation due to excessive electric fields at the surface of the terminal. The breakdown potential of an insulated electrode in gas depends on the radius of curvature, smoothness of the terminal surface, electrode material, surface contaminations, shape and material of the insulating supports, potential distribution along the insulator and last but not least composition and pressure of the surrounding gas. The breakdown electric field in air at atmospheric pressure is about 3 MV/m although limitations on maintaining ideal surface conditions lead to lower electric field limits.

In order to achieve higher voltages than about 1.5 MV the Van de Graaff accelerator is enclosed in a high pressure vessel. The use of compressed gas to increase the breakdown potential is based on Paschen's law which predicts a linear increase of sparking potential with pressure. However, the sparking potential curves always deviate from linearity above some value of pressure. In addition, breakdown potentials depend strongly on gas composition. Today, dry and purified sulfur hexafluoride (SF_6) gas or mixtures of nitrogen and carbon dioxide (80% N_2 and 20% CO_2) are used with pressures up to 20 bar.

Another important point is a uniform and smooth voltage distribution along insulator, belt and accelerating tube. This can be achieved by closely spaced equipotential rings connected to resistor voltage divider. The rings are also connected to corresponding accelerating-tube electrodes and to field control bars near the belt.

2.2 Pelletron and Laddertron generator

The Pelletron [5] charging chains (see Fig. 4) were developed by Herb and collaborators from National Electrostatics Corporation (NEC) in the mid 1960s as an improvement over the older Van de Graff charging belts. These belts suffered from a number of operational difficulties including terminal voltage

instability and susceptibility to spark damage. Also, they generated belt dust which necessitated frequent cleaning inside the accelerator tank. The chain rapidly proved to be more durable than the old belts, while producing a greater terminal stability than had been possible before. It eliminated the belt dust problem as well. The chain does not limit ultimate terminal potential, and it is in use in electrostatic accelerators up to and above 25 MV. A different type of charging chain called Laddertron, was developed by High Voltage Engineering Company (HVEC). The name derives from the fact that this chain had originally H shaped metallic carriers, which looked like a ladder.

Pelletron chains are made of metal pellets connected by insulating nylon links. Laddertron charging chains are made of metal plates. The metal pellets or plates are charged using the effect of influence in an electrical field (see Fig. 4). For positive charging, the electric field between the negatively biased inductor electrode and the pulley pushes electrons off the pellets while they are in contact with the grounded drive pulley. Since the pellets are still inside the electric field as they leave the pulley, they retain a net positive charge. The chain then transports this charge to the high-voltage terminal, where the reverse process occurs. When it reaches the terminal, the chain passes a negatively-biased suppressor electrode which prevents sparking as the pellets make contact with the terminal pulley. The positive charge flows smoothly via the terminal pulley to the terminal. Most Pelletrons and Laddertrons employ 'down-charging' as well as 'up-charging'. Down-charging works identically to up-charging, except the inductor/suppressor polarities are reversed, and it effectively doubles the charging capacity of the chain. The typical charging currents are in the order of 100–300 μA. High voltages up to 30 MV have been reached. The terminal voltages can be regulated and controlled by varying the charging voltage U_{c} between inductor/suppressor electrodes and pulleys. Charging voltages up to 50 kV are used. By reversing the polarities of the charging voltages the Pelletron and Laddertron generators can easily be used to accelerate electrons and negative ions. The charging chain for high voltage generation exhibit an excellent voltage stability, a high reliabilty and a long lifetime (over 50 000 hours).

2.3 Dynamitron generator

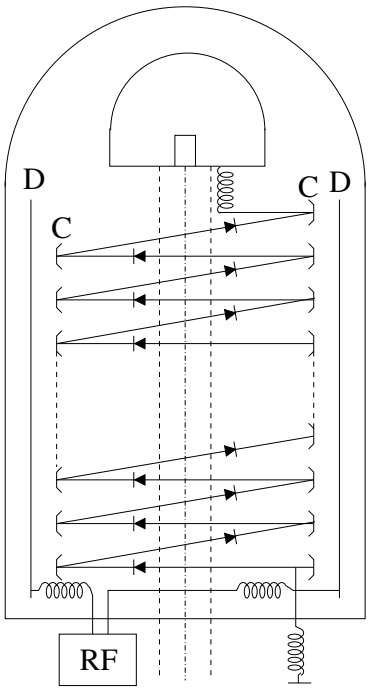

Fig. 5: Scheme of the Dynamitron HV generator. D: Driver electrodes, C: Coupling electrodes, T: Terminal, V: High-pressure vessel

The Dynamitron generator [6] has been developed by Radiation Dynamics Inc. (RDI), Long Island, since 1958. The Dynamitron generator (see Fig. 5) is based on an rf oscillator operating at frequencies between 30 kHz and 300 kHz. Driver electrodes D in the form of half-cylinders transmit the rf power via capacitive coupling to coupling rings C. A Cockcroft–Walton-like cascade generator generates the DC voltage. In modern machines semiconductor diodes are used. RF chokes provide the connection of the rectifier cascade between ground and high voltage terminal. Like in the classical Cockcroft–Walton generator the achievable high voltage is proportional to the number n of rectifier stages,

$$U = 2nf_cU_0 \ . \tag{10}$$

Here, U_0 is the amplitude of the alternating voltage at the driver electrode D and f_c the coupling factor. A rectifier stage consists of two rectifier diodes. The voltage amplitudes U_0 reach values up to about 100 kV. The advantage of this power supply is a high reliability due to the absence of moving parts inside the pressure vessel. Another advantage compared to the classical Cockcroft–Walton generator are the very low capacitances of the system. Therefore possible spark-overs are rather harmless. The regulation loop of the Dynamitron generator can be modelled like in a standard electronic power supply. Therefore the stabilization of the terminal voltage is substantially faster than the classical Van de Graaff belt generator or the Pelletron generator.

A variant of the Dynamitron power supply was developed at the Budker Institute of Nuclear Physics in Novosibirsk. There, the capacitive coupling is replaced by inductive coupling.

2.4 Acceleration tube

The acceleration tube is one of the most critical components of a Van de Graaff accelerator. The tubes are constructed of insulating material, commonly ceramic or glass cylinders with vacuum tight seals to metal-plate electrodes. The vacuum seals are extremely critical in view of the high external gas pressures of up to 20 bar. The electrodes are connected to equipotential rings in the voltage generator column to maintain a uniform potential distribution along the tube. Often, the electrodes have large diameter holes (25 cm) in order to achieve a high pumping speed with vacuum pumps at the grounded end. The electrodes produce an accelerating and focusing electric field for the charged particles. They are arranged such that the insulating walls of the tube are protected from the particle beam in order to suppress flashover and to shield the beam from isolated surface charges on the insulator walls.

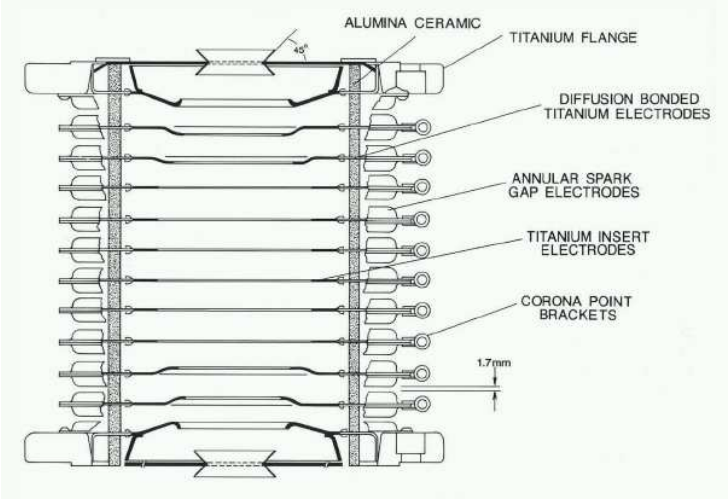

Fig. 6: Acceleration tube segment from NEC. The overall length is 8" and the I.D. of the ceramic is 4". The maximum voltage in SF_6 gas is 330 kV. (Courtesy of G. A. Norton, NEC.)

In modern designs the spacing between electrodes is decreased and the number of gaps is increased resulting in the so-called 'uniform field' tube. This allows to achieve higher voltage gradients along the tube and higher terminal voltages. For illustration, a segment of the accelerating tubes from National Electrostatics Corporation (NEC), Middleton, Wisconsin, USA is shown in Fig. 6. Historically, one of the most serious problems of positive-ion electrostatic accelerators was the limitation on terminal potential due to electron loading. The loading was caused by electrons released by secondary emission processes from the electrodes and walls of the accelerating tube and by collisions of the beam particles with atoms of the residual gas in the vacuum. The electrons traverse the tube in opposite direction and increase the current so as to limit the terminal voltage at constant charging rate. In addition the electrons are focused by the electric fields onto the ion source in the terminal, producing hard X-rays with an energy distribution extending up to the terminal voltage. Such X-rays require expensive shielding of the room in which the accelerator is housed. As a consequence modern accelerator tubes are equipped with electron suppression systems. The suppression is achieved by (i) minimizing secondary-electron emission by applying selected materials, (ii) preventing electrons from entering the accelerator tube, (iii) minimizing ion-atom collisions by improving the high vacuum and (iv) by deflecting the electrons in *statu nascendi* with weak magnetic fields installed within the tube. Another method was to use inclined field tubes where the electric fields between the accelerating sections are inclined yielding a deflection of back-streaming electrons.

3 Tandem accelerator

The concept of the Tandem accelerator was invented in order to achieve higher beam energies than with single ended Van de Graaff machines. It has been specifically proposed by Bennett [7], Kallmann [8] and Alvarez [9]. However, the first practical application was made by the High Voltage Engineering Company in a machine constructed for the Chalk River Laboratory and reported by Van de Graaff [10]. A Tandem accelerator utilises the terminal high voltage twice in sequence in order to obtain output energies of two or more times that available in a single acceleration, see Fig. 7. Negative ions produced by an appropriate ion source I are accelerated from ground to the positively charged terminal. Inside the terminal is a stripper, which uses a gas canal (usually nitrogen or argon) or a very thin carbon foil (areal density about 5 μg/cm^2) to remove electrons from the incoming negative ions. The now positively-charged ions experience a second boost of acceleration (hence the name 'Tandem' accelerator) as they exit the terminal and travel down the acceleration tube to ground at the high-energy end of the machine. The resulting kinetic energies T of the beam depend on the charge q of the positive ions,

$$T = eU + qU = (e + q)U. \tag{11}$$

Here, e is the absolute value of the singly charged negative ions. The positive charge q of heavy ions can be multiples of e. Thus the maximum possible kinetic energy depends on the ions, e.g.,

$$\begin{aligned} \mathrm{p},\ \mathrm{d} \quad &: \quad T = 2\,eU\,, \\ {}^3\mathrm{He}^{2+},\ {}^4\mathrm{He}^{2+} \quad &: \quad T = 3\,eU\,, \\ {}^{32}\mathrm{S}^{16+} \quad &: \quad T = 17\,eU\,. \end{aligned} \tag{12}$$

In principle, the final kinetic energy is a little bit higher since the negative ions are pre-accelerated to about 50 keV by connecting the negative ion source to a negative potential with respect to ground.

Tandem accelerators are enclosed like single ended Van de Graaff machines in high-pressure vessels. Tandem accelerators, especially the ones used in nuclear physics research, can be very large. The most powerful ones can reach high voltages between 20 and 30 MV. Vertical generators are usually installed in specially built towers. The primary benefits of the Tandem accelerator are much higher beam energies for a given terminal voltage. The charge-exchange process results in a significant reduction of beam intensity. However, for a wide range of applications a few microamperes of accelerated ions are

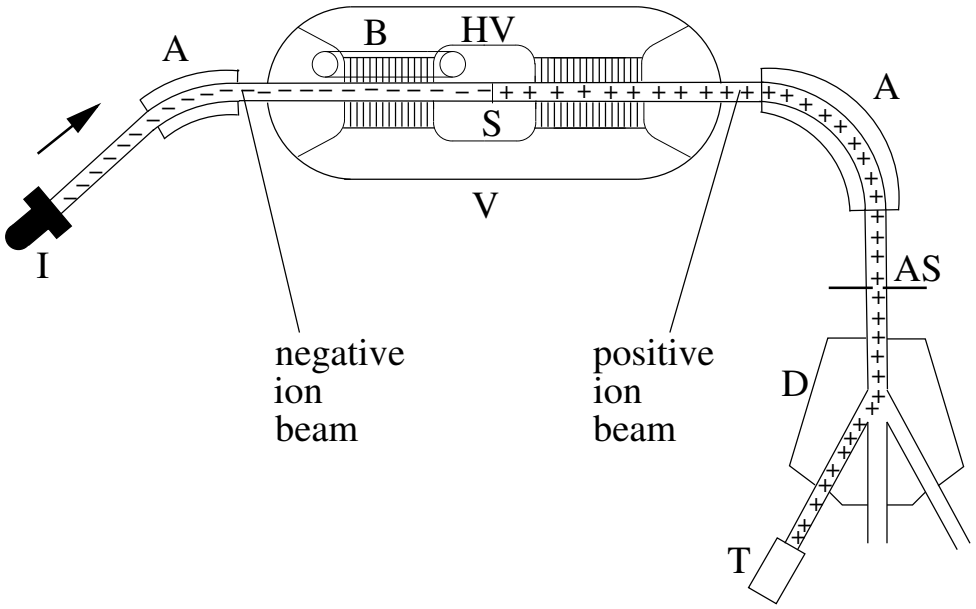

Fig. 7: Scheme of Tandem accelerator with ion source and external beam preparation system [3]. I: negative ion source, V: high-pressure vessel, B: belt generator, HV: high-voltage terminal, S: stripper foil or gas, A; analysing magnet, AS: analysing slit, D: deflecting magnet, T: target.

adequate. In contrast to single ended machines, Tandem accelerators have both ends at ground with the high-voltage terminal in the middle. With the ion source(s) external to the pressure vessel, maintenance requiring entry into the tank and letting the acceleration tubes up to atmosphere is minimized.

4 Ion optics

An important point is the optimum design of the ion optics of an electrostatic accelerator. This can be done with computer programs. If high currents are accelerated the space charge forces must be taken into account. Various requirements have to be considered. Very often the ion beam is mass analysed by a 90° double focusing analysing magnet. With such a system all elements from hydrogen to uranium can be separated. To this end a sharp beam waist at the entrance and exit slits of the analysing magnet system is required.

A technical requirement is a double waist at the terminal stripper of a Tandem Van de Graaff or near the high energy end of a single ended Van de Graff. This can be achieved by preparing a double waist at a well defined distance to the entrance of the accelerator tube. The electric field transition at the accelerator entrance acts like a focusing lens. In nonrelativistic approximation the focal length of this lens is given by

$$f = 4V/|\vec{E}| \tag{13}$$

where V is the total acceleration potential through which the ions have been accelerated before reaching the lens and $\vec{E}$ is the electric field of the acceleration tube. The electric field $|\vec{E}|$ is proportional to the terminal voltage. Therefore the focal length f and the optimum position of the double waist in front of the acceleration tube depends on the final energy of the ions. A possibility to circumvent this problem is to vary the potential V by pre-acceleration such that the ratio $V/|\vec{E}|$ is kept constant. Such a patented injection system for focusing to a waist at the terminal stripper has been developed by High Voltage Engineering Europe (HVEE).

Another important issue is a charge selector in the terminal of a Tandem. Heavy ions passing the terminal stripper exhibit a finite charge distribution. Therefore a charge selection is needed in order to

achieve a well defined beam energy.

At the high energy end of single ended Van de Graaff accelerators and Tandem accelerators a 90° analysing magnet is commonly used in order to prepare ion beams with a well defined energy and to achieve a high energy resolution. To this end a sharp beam waist at the analysing slit of the 90° analyser is needed. Sometimes the analysing system consists of a double focusing magnet with point-to-point imaging between a narrow entrance slit and the analysing slit.

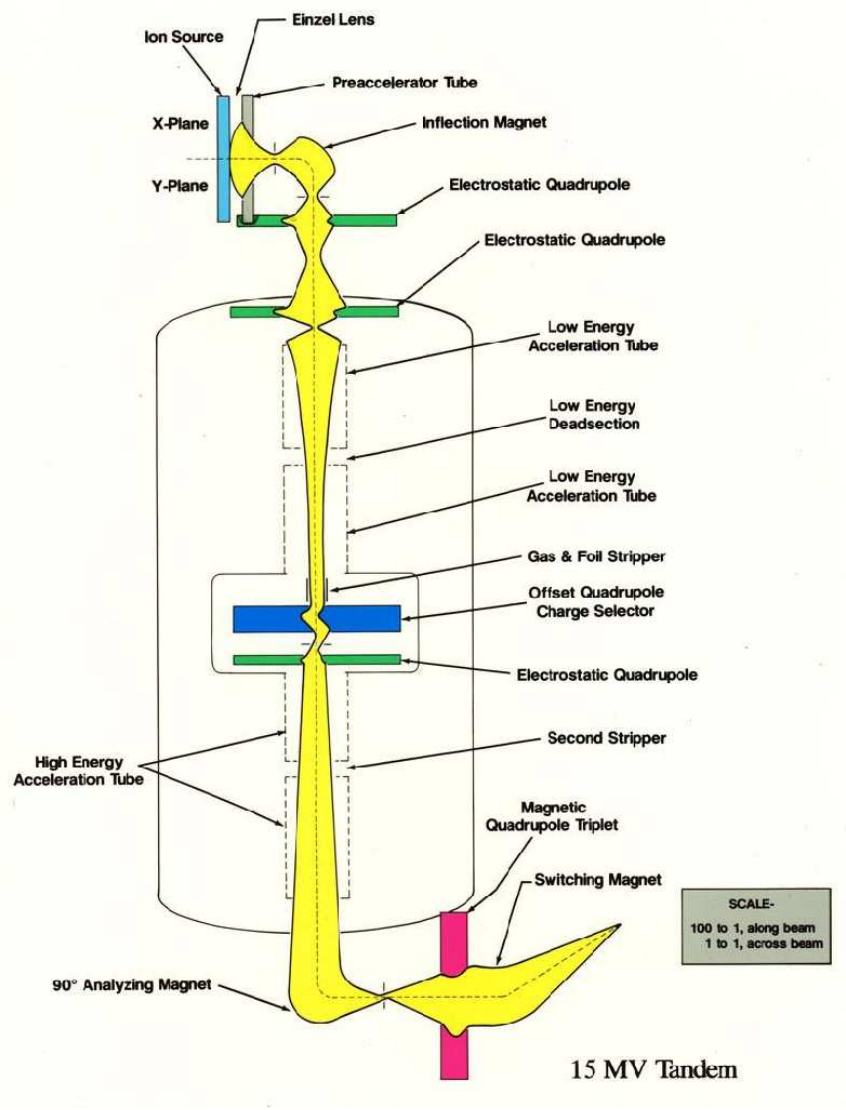

Fig. 8: Beam envelopes in a 15 MV Tandem accelerator from NEC (courtesy of G. A. Norton, NEC)

For illustration the ion optics of a 15 MeV Tandem from National Electrostatics Corporation (NEC) is shown in Fig. 8. The beam from the ion source is first focused with an einzel lens and a pre-acceleration tube to provide a double waist at the entrance slit of the inflection magnet. Another double waist follows at the analysing slit of the double focusing inflection magnet. A system of electrostatic quadrupoles produces a sharp double waist in front of the acceleration tube which is transformed by the focusing effect at the entrance of the acceleration tube into a weak double waist near the terminal stripper. The defocusing effect at the exit of the low energy acceleration tube and the focusing and defocusing effects at the entrance and exit of the high energy acceleration tube are so weak that they cannot be seen. In the terminal an offset quadrupole is used as charge selector followed by another electrostatic

quadrupole. The beam envelopes are diverging to the high energy end of the Tandem. The double focusing analysing magnet produces a sharp double waist at the analysing slit. Then the beam is guided with a switching magnet to the target. The final focusing is done with a magnetic quadrupole triplet.

5 Voltage measurement and control

The problem of voltage measurement is fundamental for many applications of electrostatic accelerators. The most simple method consists in measuring the current in a string of calibrated resistors running from terminal to ground. These resistors must be carefully shielded in order to be free from corona losses. The resistor string can also be utilized to provide a uniform potential distribution between successive equipotential rings. The total resistance is high. A typical value is 10 GΩ per 1 MV yielding a current of 100 μA. A micro-ammeter measures the current at the grounded end of the resistor column. The individual resistors must be calibrated to high precision. If other more precise voltage calibrations are used, the current through the resistor column can still be used as a check of the relative voltage stability.

Another classical method is to use a *generating voltmeter* for observing the terminal voltage. The operation depends on the electric charge induced by influence on an metal plate or vane in the electric field near the grounded pressure vessel. In the usual form an insulated vane rotates at constant speed behind a grounded shield covering the vane during half its travel. The alternating voltage induced on the vane is amplified and rectified and its magnitude is a measure of the terminal voltage. The voltage scale is usually calibrated against other standards. The most serious limitation is the distortion of electric fields due to corona discharge from terminal. Mostly, the generating voltmeter is used as a relative instrument in tuning the accelerator. With the advent of multiple shields around the terminal its usefulness is reduced since it measures only the voltage of the outer shield.

The most precise method uses electric or magnetic deflection of the ion beams in order to measure the beam energy and to calibrate the terminal voltage. An illustration is the 90° analysing magnet used to measure and stabilize the beam energy of Tandem accelerators as shown in Fig. 7. Such systems yield energy resolutions up to 10 000 corresponding to a relative energy spread (FWHM) of about $1 \cdot 10^{-4}$. The mean energy can be stabilized to a precision of about $2 \cdot 10^{-5}$. In the analysing magnet system the beam passes narrow entrance and exit slits. The magnetic field is highly stabilized to a level of $1 \cdot 10^{-5}$ using NMR probes. A variation of the terminal voltage will cause a deflection of the beam to one side or the other of the exit slit. The slit edges are insulated and the currents to the edges are measured and compared. The detected left-right asymmetry $(I_l - I_r)/(I_l + I_r)$ is used as error signal in order to stabilize the terminal voltage with the aid of a fast control loop.

An important means of cross-calibrating the energy scales is provided by nuclear resonances. Certain reactions have extremely sharp resonances. By measuring excitation functions in the region of those resonances an absolute calibration of the analysing magnets is possible.

An interesting variant of stabilizing the voltage with analyser magnets is offered by High Voltage Engineering Europe (HVEE), Amersfoort, The Netherlands. In order to achieve a very high voltage stability two separate accelerator tubes are installed inside of the Dynamitron-like acceleration column, see Fig. 9. One accelerator tube is used to accelerate and analyse a reference beam. For negative terminal voltages a H^- beam is used, for positive voltages a proton beam. The beam energy is measured using a standard 90° analysing magnet. A stabilization of the terminal voltage up to $1 \cdot 10^{-5}$ can be achieved with such a system.

6 Beam properties and applications

6.1 Beam properties

A great advantage of electrostatic accelerators is the fact that the beam energy can easily be varied over a wide range of energies.

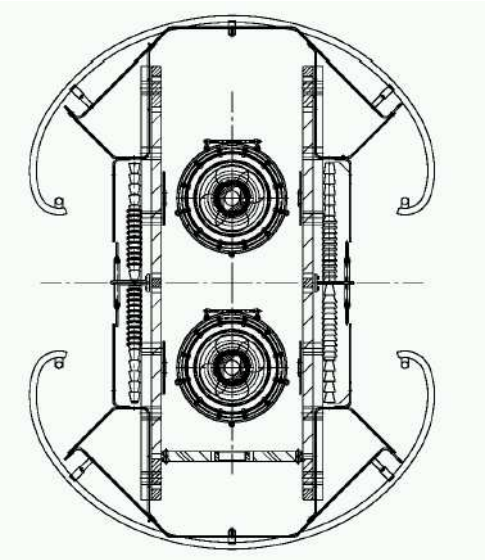

Fig. 9: Cross-section of two acceleration tubes mounted in a coaxial high-voltage power supply (courtesy of H. van Oosterhout, HVEE)

The maximum terminal voltages of the Cockcroft–Walton accelerators are typically between 200 and 1000 kV, thus the kinetic energies of the ions are rather low. Depending on the ions and the high voltage generator typical beam currents vary between 1 μA and several 10 mA. Due to the progress in the field of ion sources not only light ions like hydrogen and helium but all kinds of heavy ions up to uranium can be accelerated. Using pulsed ion sources also pulsed beams with a high time-of-flight resolution can be prepared.

The Van de Graaff and the Tandem Van de Graaff accelerator offer a great variety of ion beams from hydrogen up to uranium. Depending on the ion source and the voltage generator the beam currents vary between 10 nA and several 10 mA. Typical kinetic energies of hydrogen beams are in the range 1 MeV up to 40 MeV. With Tandem accelerators heavy ions can be accelerated up to several hundred MeV. A great advantage of Van de Graaff and Tandem Van de Graaff accelerators is the excellent beam quality. Energy resolutions up to $10\,000$ corresponding to a relative energy spread of $1 \cdot 10^{-4}$ can be achieved. Also excellent transverse beam emittances can be achieved corresponding to the theoretical limit given by the extraction system near the ion source. Thus, experiments with a high angle and energy resolution can be performed. The easy energy variation of the beams allows systematic energy scans in fine energy steps.

6.2 Application of electrostatic accelerators

The Cockcroft–Walton accelerator is still used as pre-accelerator for large accelerator facilities. In medicine and industry it is used as a cheap neutron generator. Here, deuterons with a kinetic energy between 400 and 800 keV are bombarded onto a deuterium or tritium target. The nuclear reactions $\mathrm{d} + \mathrm{d} \rightarrow \mathrm{n} + {}^3\mathrm{He}$ and $\mathrm{d} + \mathrm{t} \rightarrow \mathrm{n} + {}^4\mathrm{He}$ yield neutrons with kinetic energies around 2 MeV and 14 MeV, respectively. Cockcroft–Walton accelerators are also used in solid state physics, ion beam modification of materials, atomic physics, ion beam analysis of materials like Rutherford backscattering (RBS), particle induced X-ray emission (PIXE), particle induced gamma emission (PIGE), nuclear reaction analysis (NRA) and elastic recoil detection (ERD), astrophysics and ecological research.

Van de Graaff and Tandem Van de Graaff accelerators are still in use for basic research in nuclear physics. Besides that they are used in many applications. The capability of producing a large variety of

ion beams with an energy of 100 keV up to several 100 MeV make the Van de Graaff and Tandem Van de Graaff accelerators suitable for:

- Materials modification
  - Ion implantation and ion beam mixing
- Materials analysis
  - Rutherford backscattering spectroscopy (RBS),
  - particle induced X-ray emission (PIXE),
  - particle induced gamma ray emission (PIGE),
  - nuclear reaction analysis (NRA),
  - elastic recoil detection (ERD),
  - resonance scattering analysis (RSA),
  - accelerator mass spectrometry (AMS) and
  - ion micro beam applications (μ-beam).
- Particle production
  - Medical, security
- Radiation production
  - X-ray imaging

The ion micro beam application makes full use of the high beam quality of Van de Graaff and Tandem Van de Graaff beams. A famous application of AMS is the carbon dating of ancient probes by measuring the ^{14}C concentration, see Fig. 10.

Small compact electron accelerators are of great industrial importance. Dynamitron generators are commonly used as high voltage generators in order to accelerate very high beam currents. These systems service a wide range of industrial applications:

- Production of X-rays,
- Sterilization of medical products,
- Wire and cable cross-linking,
- Tyre and rubber pre-cure treatment,
- Shrink wrap sheet products,
- Thin films polymer cross-linking,
- Heat shrinkable tubing and plastics,
- Polymer tube cross-linking,
- Bulk polymer modification,
- Sheet foam materials,
- Silicon wafer processing,
- Specialty automotive wire,
- Food irradiation,
- Purification of gases,
- Treatment of waste water and toxic wastes,
- Advanced composites modification and
- Scissioning of long chain polymers.

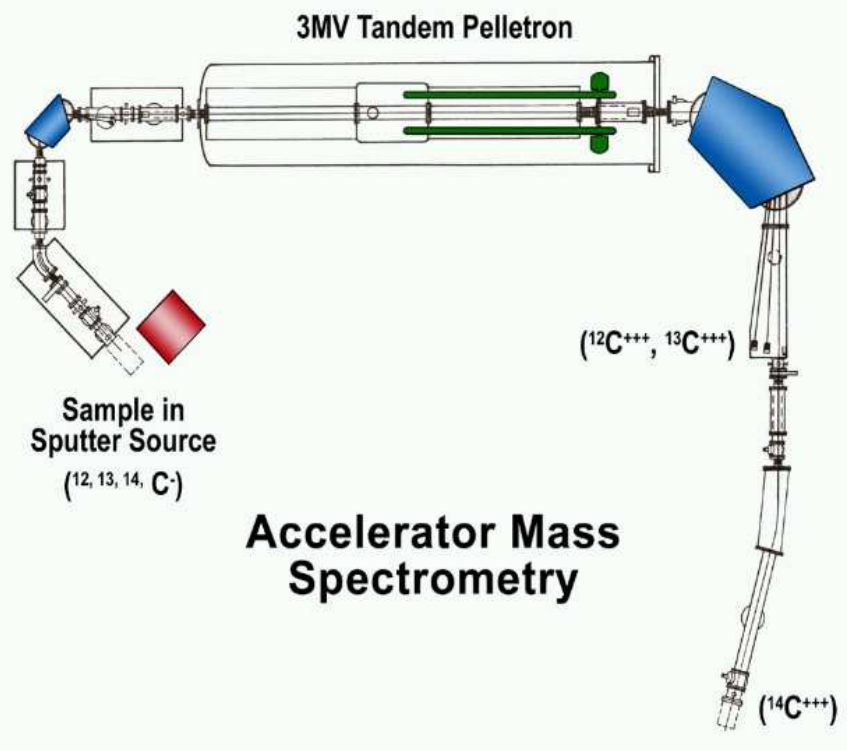

Fig. 10: ^{14}C accelerator mass spectrometry using a 3 MeV Tandem Pelletron from NEC (courtesy of G. A. Norton, NEC)

7 Progress in electrostatic accelerator development

In this section we will sketch the progress in the development of electrostatic accelerators. In the 1960s ad 1970s big Tandem Van de Graaff accelerators were developed and installed worldwide for basic research in nuclear and heavy ion physics. The culmination were Tandem accelerators achieving terminal voltages of more than 20 MV like the facilities in Oak Ridge and Yale, USA, in Daresbury, U. K. and the Vivitron facility in Strasbourg, France. But there was simultaneously a growing demand for small electrostatic accelerators for applications in medicine, biology and industry. This trend continues and goes to compact and customized electrostatic accelerators. In the following, we sketch a few examples.

Beginning in 1971, the Budker Institute of Nuclear Physics in Novosibirsk started the development and manufacturing of high-power electron accelerators of the ELV-type for use in industry (see Fig. 11). The acronym ELV means ELectron Rectifier (Russian: Viprjamitel). The covered energy range is 0.2–2.5 MeV with beam currents 25–800 mA and beam powers 20–500 kW. The high voltage generator is a cascade generator with parallel inductive coupling. The electron beam passes through a thin titanium foil into air. The beam intensity is homogeneously distributed over a large circular area of 1.7 m diameter using two scanning magnets.

Another manufacturer of industrial electron accelerators is Radiation Dynamics Inc. (RDI), Long Island (USA). RDI was founded in 1958, now RDI-IBA is part of the IBA Technology Group, Louvain-la-Neuve, Belgium. During the first ten years RDI primarily supplied accelerators to universities and governmental research facilities, the majority of which are still operating today. Since the late 1960s RDI has supplied over 250 industrial electron beam systems. The Dynamitron generator insures smooth and reliable operation at high voltages. The generator avoids the use of large capacitors, which are particularly vulnerable to spark damage at voltages above 1 MV. Since the Dynamitron has very low stored energy, the chance of spark damage is minimal. Even when sparking does occur, the unit may

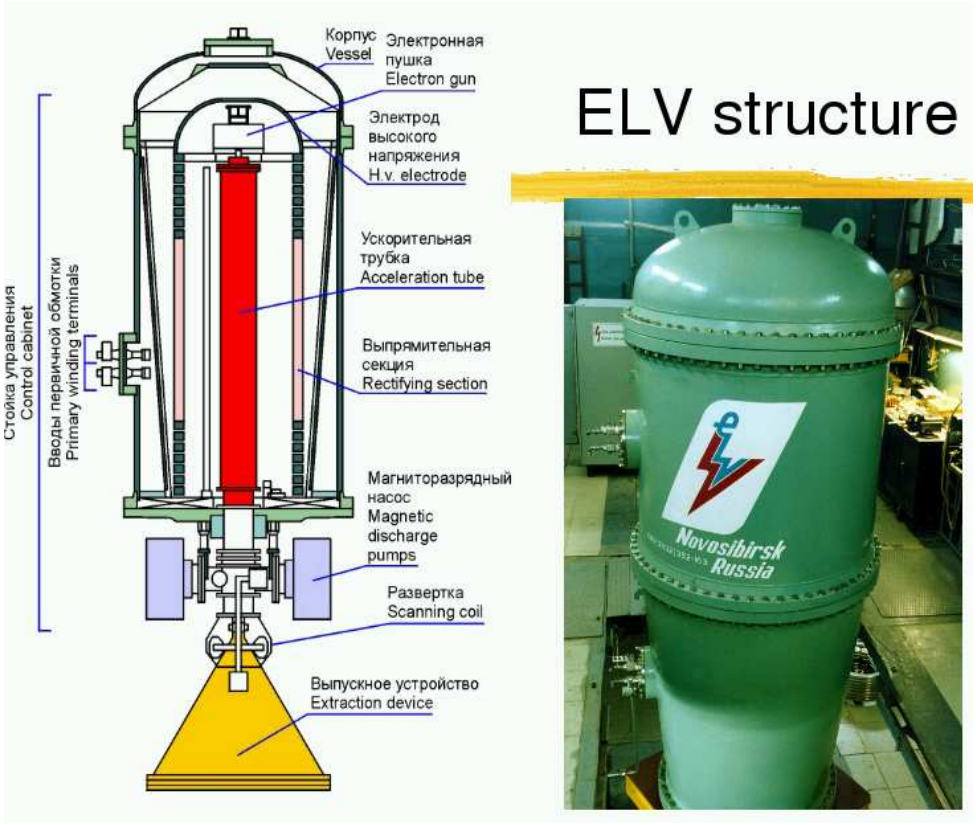

Fig. 11: View of the ELV-4 accelerator from BINP, Novosibirsk (courtesy of V. V. Parkhomchuk, BINP)

be quickly restarted and returned to normal operation. The standard Dynamitron models are designed for high voltages between 0.55 and 5.0 MV. The available beam currents are between 10 and 160 mA, depending on the voltage. The maximum beam power is about 200 kW.

Concerning positive ion accelerators compact customized electrostatic accelerators are produced by High Voltage Engineering Europe (HVEE), Amersfoort, The Netherlands and by National Electrostatics Corporation (NEC), Middleton, Wisconsin, USA.

HVEE produces air insulated accelerator systems up to 500 kV, single ended accelerator systems 'Singletron' up to 6 MV and Tandem accelerator systems 'Tandetron' up to 6 MV terminal voltage. A modular design allows customized systems from standard components. The acceleration voltage of the air insulated systems is supplied by a free standing generator consisting of a RF driver and a voltage multiplier and rectifier stack. A high voltage stability is achieved using a fast stabilization circuit. The acceleration tube consists of glass insulators and aluminum electrodes. A low voltage gradient makes conditioning of the acceleration tube superfluous. Secondary electrons are suppressed by electron catcher and an internal magnetic suppression system.

The high voltage generator of the Singletron and Tandetron accelerator systems is a SF_6 insulated Dynamitron power supply. It is characterized by a very high voltage stability and a low voltage ripple resulting in an excellent beam energy resolution. The most compact versions are the coaxial Singletron and Tandetron accelerators (see Fig. 12) where the HV power supply is built around the acceleration tube. In the other versions the power supply is a self-supporting unit in a separate section of the pressure vessel. The new generation of single ended Van de Graaff accelerators is equipped with a unique ion source exchange system that allows for ion source exchange without opening the pressure vessel. Complete Singletron and Tandetron systems for ion implantation and ion beam analysis and Tandetron systems for

Fig. 12: Photo of 5 MV Tandetron in service position from HVEE (courtesy of H. van Oosterhout, HVEE)

accelerator mass spectrometry are available.

NEC produces three distinct classes of electrostatic accelerators. The U-series are Pelletron accelerators with terminal voltages from about 4 MV up to about 25 MV. They are mainly used for basic nuclear structure research. The S-series are Pelletron accelerators with terminal voltages from $<$1 MV up to about 5 MV for applications involving MeV ion implantation, surface analysis, micro-beam applications, electron beam and X-ray production up to 5 MeV, neutron generation and advanced research. In addition open-air accelerators up to 250 kV are available. The NEC high gradient acceleration tube used in the Pelletron accelerators is an all metal/ceramic assembly, see Fig. 6. Titanium electrodes are bonded to alumina ceramic using aluminum diffusion bonding. There are no organic compounds in the vacuum. Limiting apertures and an external magnetic field suppress secondary electrons in the tube. In order to provide higher beam currents the Pelletron accelerators can be equipped with up to four charging chain systems. For maximum stability, the control system uses a liner driver in addition to the corona probe to increase terminal voltage stability and decrease ripple. Signals from the capacitive pick off plates are inverted and amplified providing a potential to the liner driver. Stabilities of better than 10^4 are typical. For accelerator mass spectrometry, especially radiocarbon dating, a 3 MV Tandem accelerator system (see Fig. 10) and a new single stage 250 kV accelerator system is available.

The progress in building compact electrostatic accelerators pioneered the development of commercial ion implanters. Semiconductor manufacturer use ion implantation for doping processes in silicon integrated circuits. Doping and modifying silicon and other semiconductor wafers involves generating an ion beam and steering it into the substrate so that the ions come to rest beneath the surface. The most commonly implanted ions are arsenic, phosphorus, boron, boron difluoride, indium, antimony, germanium, silicon, nitrogen, hydrogen, and helium. The scheme of an ion implanter is shown in Fig. 13. The ion energies of ion implanters must be variable over a wide range. High current implanters can produce currents up to about 30 mA with ion energies from 1 keV to about 200 keV. Medium-current implanters are designed for maximum dose uniformity and repeatability. Their beam currents are in the range of 1 μA to 5 mA, at energies from 2 keV to about 900 keV. High-energy implanters provide ion beams in the MeV range with beam currents for singly-charged ions up to about 1 mA and for multiply-charged ions up to about 50 μA. High-energy implanters with a large energy range can also be used for many medium-current applications in the energy range 10–900 keV. Major manufacturers of commercial ion implanters are Axcelis Technologies, Beverly, MA, Varian Semiconductor Equipment Associates, Gloucester, MA, Applied Materials Implant Division, Horsham, U.K., Sumitomo Easton Nova (joint venture with Axcelis), Tokyo, Japan, Nissin Electric, Kyoto, Japan and Ibis Technology, Danvers, MA.

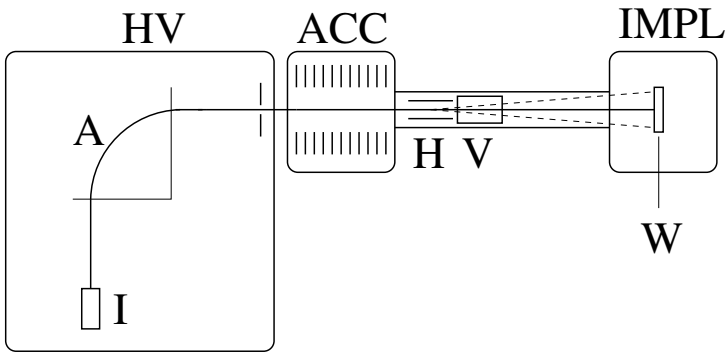

Fig. 13: Scheme of an ion implanter. I: ion source, A: analysing magnet, HV: high voltage terminal, ACC: electrostatic accelerator, H,V: horizontal, vertical electrostatic raster scanning, IMPL: ion implantation chamber, W: silicon wafer.

8 Conclusion

The basic features of electrostatic accelerators are described in this paper. The principles of Cockcroft–Walton, Van de Graaff and Tandem Van de Graaff accelerators are presented. This presentation includes high voltage generators such as the Cockcroft–Walton cascade generator, the Van de Graaff band generator, the Pelletron and Laddertron generator and the Dynamitron generator. The beam properties and the application of electrostatic accelerators in research and industry are sketched. The progress in the development of compact and customized electrostatic accelerators is emphasized. Electrostatic accelerators are very much alive.

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