

# DC ACCELERATORS

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## **Abstract**

A brief history of the different DC accelerators is given. The main types of generators are presented including the cascade generators, the insulating core transformer and the Van de Graaff accelerators. Some specific features of these machines such as the accelerator tube, the insulating gas, the voltage distribution and regulation are described. Finally, some ion sources commonly found on these machines are presented.

## **1. INTRODUCTION**

By the late 20's, it became clear that natural radioactive sources were no longer sufficient and that accelerators were necessary for the development of Nuclear Physics research . The early 30's saw the development of different types of accelerators almost simultaneously : linear high-frequency, circular and DC accelerators. Cockroft and Walton built their first 600 kV cascade generator in 1932 [1]. Practically at the same time, Robert Van de Graaff built his 1.5 MV machine [2]. It consisted of positive and negative 61 cm hollow copper spheres mounted upon 2.13 m upright pyrex rods. Each sphere was charged by a 5.6 cm silk ribbon belt running from a grounded motor pulley at the base of the rod to a pulley in the interior of the sphere at a linear speed of 89 m/mn. The ascending silk belt surface was charged near the motor pulley by a 10 kV brush discharge powered with a standard transformer rectifier system and the belt was subsequently discharged by a system of points within the copper spheres. The machines operated in air and became gigantic as the terminal voltage rose. The biggest cascade generator reached 2 MV and the biggest Van de Graaff generator reached 2.75 MV on the positive sphere [3]. Raymond Herb at the University of Wisconsin initiated the construction of the first air-insulated generator in 1933 [4]. As the terminal voltage rose, different gases were used as insulating atmosphere instead of air. The maximum voltages reached with electrostatic accelerators lie around 25 MV.

## **2. GENERAL STRUCTURE OF DC ACCELERATORS**

### **2.1 Single ended accelerators**

The general structure of DC accelerators comes down to an insulating column. The ion source lies at one end in a high voltage terminal while the target is at ground potential. The electrical field existing between the two accelerates the particles emitted by the ion source. The final energy  $E$  of the particles will depend on the extraction voltage  $V$  of the ion source, the charge  $q$  of the particle and the acceleration voltage  $V_T$  :

$$E = q(V + V_T) \quad (1)$$

### **2.2 Tandem accelerators**

The earliest report of doubling the energy goes back to the early 1930's. Dempster [5] used a technique involving neutral and positive charges to double the energy of protons. Positive ions from a high positive potential hydrogen discharge were passed through a hydrogen cell where some were neutralized. These drifted onward into an electrode maintained at the same potential relative to ground. Passing thru this electrode under relatively high ambient pressures, some of the neutral atoms were stripped and then accelerated back to ground potential thus doubling their initial energy. In

principle, this could be continued indefinitely but the loss of intensity at each step became rapidly prohibitive.

In the late 30's, attempts were made to accelerate negative ions to high voltage and stripping them either with a charge exchange chamber [6] or in a thin foil and to develop a negative ion source [7]. Nothing really came through until Luis Alvarez proposed in 1951 [8] a machine with negative ions accelerated to a positive terminal, stripped and reaccelerated back to ground potential.

Figure 1 shows the general outline of a tandem accelerator. Negative ions are extracted from the ion source, analyzed, injected into the accelerator and accelerated under the positive potential of the terminal. In the terminal, they are stripped of one or several electrons through charge exchange processes. The beam is now composed of positive ions with a distribution of different charge states and these ions are accelerated towards ground potential. The acceleration of each ion depends on its charge state  $q$  so that the final energy  $E$  of the ions with charge state  $q$  is given by equation (2) :

$$E = V_i + (q + 1)V_t \quad (2)$$

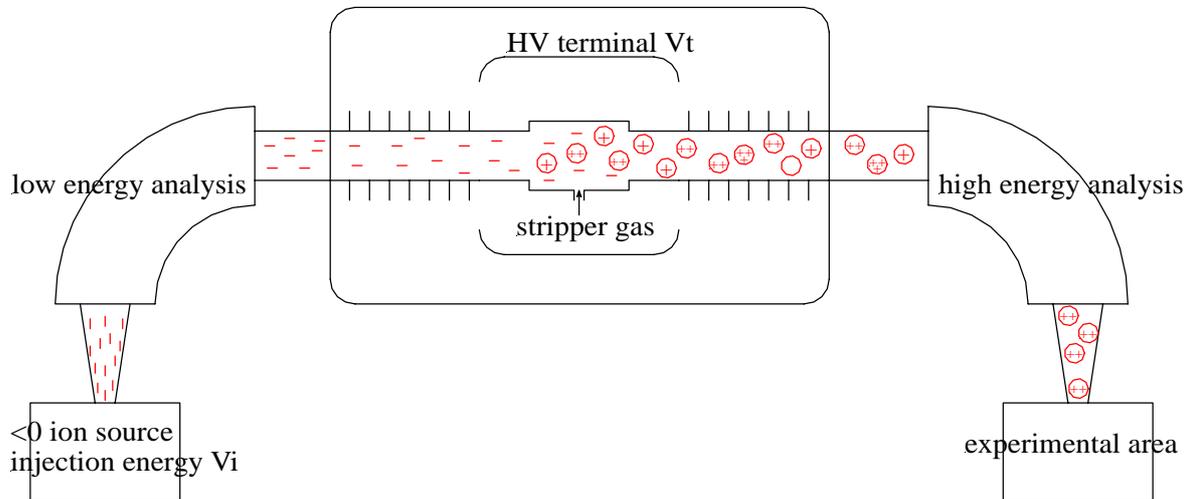


Fig. 1 Outline of a tandem accelerator.

Another great advantage of the tandem apart from increasing the particle energy, is that the ion source is near ground potential and becomes readily accessible. But of course, the double accelerating scheme relies on the availability of adequate negative ion sources.

The stripper can be either a thin carbon foil or a gas depending essentially on the negative ion beam energy and its intensity along with the desired average charge state. At low energy per nucleon, that is  $E/A < 0.5 \text{ MeV/u}$ , electron capture dominates but at higher  $E/A$  values, electron loss becomes the dominant feature. Many factors influence the conversion yield such as the nature of the stripper, its density, the energy per nucleon of the incident particles. Many authors have calculated the cross sections [9, 10] ; these calculations can be rather complicated and one needs to have, from a practical point of view, a reasonable estimate of the average charge state of a heavy ion obtained at a given terminal energy for a particular stripper. A compilation of data and references can be found in Ref. [11]. The thickness of the stripper should be just above the equilibrium thickness that is reached when the cross section out of a charge state is equal to the cross section into it otherwise energy loss effects appear.

### 2.2.1 Gas stripper

In gas strippers, the stripper pressure must be brought to the point where a further increase in pressure will not yield a significant difference in the distribution of charge states of the stripped ion that is to the point where charge-state equilibrium occurs. The important drawback of gas stripper is the fact that they must be windowless and this can cause vacuum problems in the accelerating tubes resulting in bad beam transmission. The solution was to introduce a vacuum pump in the terminal as shown on Fig. 2. Usually, a power shaft running from ground brings power to the terminal. Turbomolecular pumps are now often used [12] but getter pumps have been used. About 90 % of the gas is reinjected into the stripper canal. In the case of turbo pumps, the gas is reinjected through a sorption trap to prevent any migration of oil into the accelerator tubes.

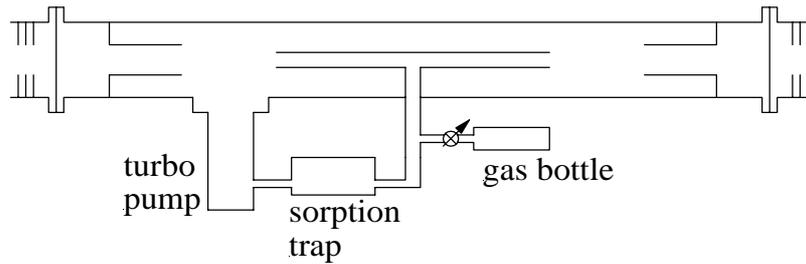


Fig. 2 Recirculating pump at the terminal

### 2.2.2 Foil stripper

Higher charge states are obtained with foil strippers except at low energies. Because of energy straggling and angular dispersion, the emittance of the beam is more deteriorated through a foil stripper than through a gas stripper. The thinnest carbon foil is around  $2 \mu\text{g}/\text{cm}^2$ .

## 3. ELECTROSTATIC GENERATORS

### 3.1 Cascade generators

#### 3.1.1 Cockroft-Walton generators

The first generator Cockroft and Walton built was a cascade generator consisting of identical stages containing capacitors and rectifiers (Fig. 3). The secondary winding of a transformer supplies an alternating voltage to the first stage. Each stage is a voltage doubling circuit. Because of the rectifiers that conduct only if the anode voltage is greater than the cathode voltage, the voltage at point  $P_1$  varies between 0 and  $2V$  and the voltage at  $P_2$  is constant and equal to  $2V$ . If the cascade generator consists of  $n$  identical stages, a constant voltage  $2nV$  is generated at the output in the absence of any load. If the peak voltage of the transformer is  $100 \text{ kV}$ , five stages will produce a terminal voltage of  $1 \text{ MV}$ . Each capacitor and rectifier needs to withstand only  $200 \text{ kV}$

If the generator is connected to an accelerator tube through which flows a beam with an intensity  $i$ , the capacitors will discharge partially during each period. Calculations show that the relative voltage variation will be :

$$\frac{\delta V}{V} = \frac{n(n+1)}{2} \frac{i}{fC} \quad (3)$$

In order to reduce the ripple, the product  $fC$  must be large. Typically, the capacitances are equal to several nF and frequencies of several tens of kHz are used.

These machines are used in high energy electron microscopes, industrial irradiation or as preaccelerators ( $750 \text{ kV } 12 \text{ mA}$  injector at Los Alamos,  $750 \text{ kV } 200 \text{ mA}$  injector at CERN).

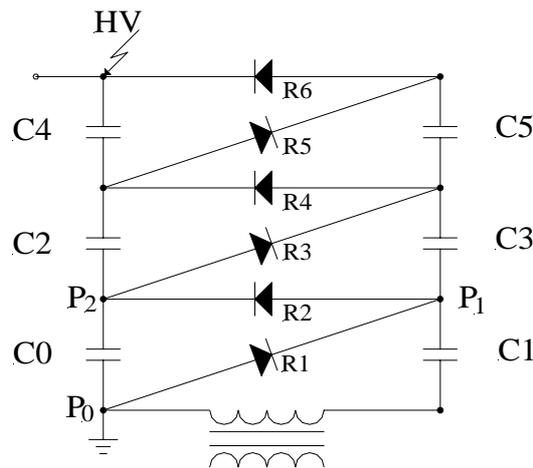


Fig. 3 Cascade generator.

### 3.1.2 Parallel fed cascade generators

As the terminal voltage increased, the cascade generators were enclosed in high pressure tanks and their design improved. Radiation Dynamics Inc developed the Dynamitron [13, 14] in the 60's (Fig. 4a). The voltage generator is composed of an equal number of rectifier tubes on each side of the column structure, assembled in cascades. Semi-circular corona rings are attached to the anode and cathode of each rectifier in the cascade. Two rf electrodes are mounted near the inner surface of the tank. This circuit with a resonance frequency around 100 kHz is coupled inductively with an oscillator. Because of high power, the oscillator sits in a separate tank. Parallel coupling of the cascade to the liners is accomplished through the electrode to corona ring capacitance. These generators can accelerate 100s of mA. Because of the high frequency, the voltage output has only a small ripple despite the lack of smoothing capacitors. Nowadays, RDI manufactures electron accelerators for irradiation purpose.

Tandetrans manufactured by HVEE [15], were developed by General Ionex along the same lines for accelerator mass spectrometry. The oscillator operates at 30 kHz. The generator is mounted in the pressure vessel perpendicular to the beam centerline to protect it against transients associated with vacuum discharges. This setup gives Tandetrans their famous T shape (Fig. 4b).

### 3.2 Insulating core transformer

The insulating core transformer [16] was developed to deliver high currents for industrial irradiation . The core of a transformer is divided into insulated segments, each having a secondary winding which drives its own rectifier (Fig. 5). The high magnetic flux through the core induces alternating voltages up to several hundreds of kV in each individual sections. The rectifier outputs are connected in series to produce the high voltage. As in the cascade generator, the series-connected dc voltages of the individual sections yield an output voltage of the order of several hundred thousand or several million volts. These generators can accelerate high intensity beams.

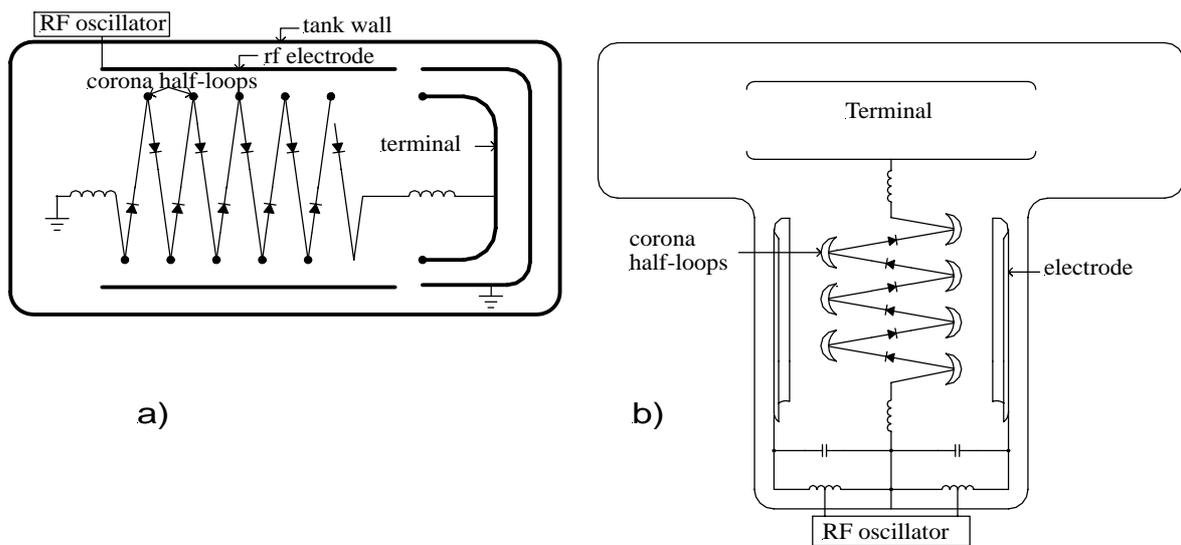


Fig. 4 Schematics of a) the Dynamitron b) the Tandetron

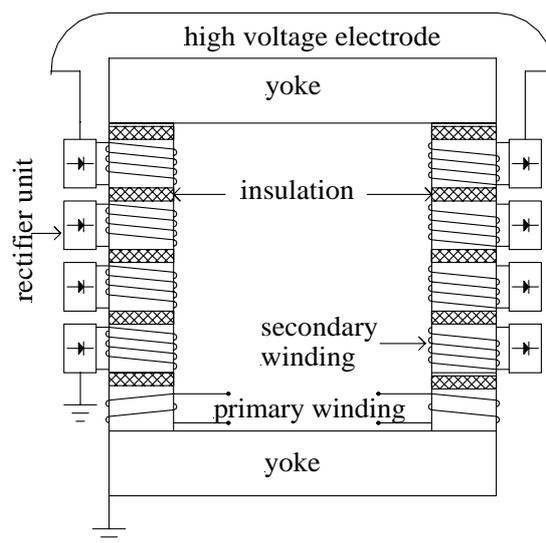


Fig.5 Schematics of an ICT generator

### 3.3 Van de Graaff generators

The basic idea of a belt type generator probably goes as far back as Lord Kelvin who suggested at the end of the 19<sup>th</sup> century an electrostatic generator in which charge would be carried to the high-voltage terminal either by a belt or by a belt conveyor consisting of alternate insulating and metal segments.

An endless insulating belt runs between two pulleys at a constant linear speed of several to tens of m/s as shown on Fig. 6. A metallic charging point or screen at a voltage of several kV acts as emitter. A corona discharge sets in and the gas surrounding the points is ionized. According to the polarity of the screen, positive or negative charges are deposited on the belt and carried up to the terminal electrode. The current  $i_0$  transported by the belt is equal to :

$$i_0 = vl\sigma \quad (4)$$

where :

- $v$  is the constant linear speed of the belt
- $l$  is the width of the belt
- $\sigma$  is the surface density on the belt

In the terminal, a collector screen "picks" the charge off the belt. The field created by the charges on the belt ionizes the gas around the points and the charges can "leave" the belt. The return strand can be sprayed with charges of opposite sign to double the total charging current. (Fig. 6)

In some tandems, the belt goes through the whole machine and all four strands are charged to increase the current capability of the machine as on the Vivitron in Strasbourg [17] or on the 2MV implanter Aramis in Orsay [18].

The characteristics of the ideal belt should be :

- high resistivity  $10^{13} - 10^{14} \Omega$
- little stretch
- moisture resistant
- smooth surface
- sufficient mechanical strength
- reasonably priced

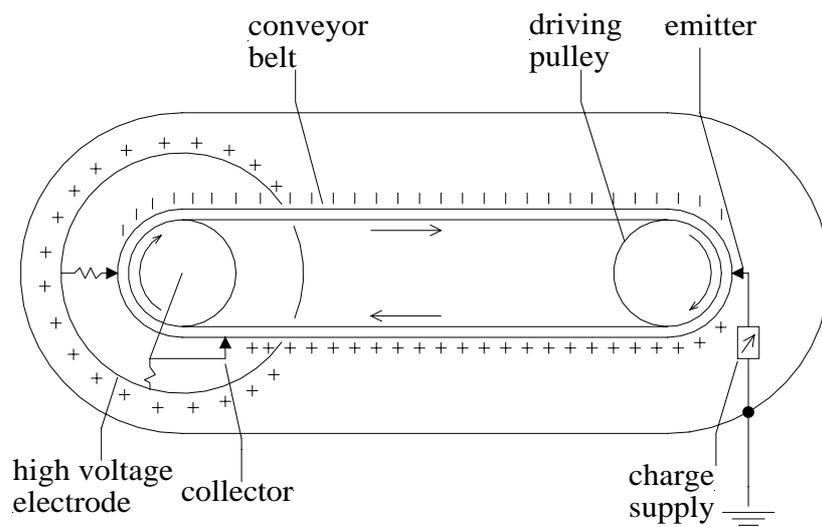


Fig. 6 Schematics of a Van de Graaff generator

Belts have been made of cotton or silk between two layers of rubber. Lifetime of some belts, especially in the big tandems, can be dramatically short (some 1000's of hours). Some belts performed much better in  $N_2 + CO_2$  gas mixtures than when exposed to  $SF_6$  especially at high voltages. Many attempts have been made to find longer lasting belts. A poly C belt was tried in different labs [19] but the behavior of these belts did not live up to the expectations. A Swedish asymmetric two ply polyester with nitril rubber covering seemed very promising [19] but once again had to be abandoned [20]. Another considerable drawback of these belts is the considerable amount of dust generated in the tank.

Another charging system was developed by NEC called the Pelletron [21]. This chain consists of metal cylinders with well rounded ends joined by links of solid plastic. The links swing on pins which are provided with self lubricating sleeves that require no oil. The pulleys have nylon rims to minimize wear and are equipped with metallic bands for electrical contact to pellets. Figure 7 shows a sketch of the pulley and induction system used to charge the chains [22]. NEC charging chains are commonly run at speeds of about 15 m/s and can carry about  $75 \mu\text{A}$  to the terminal and  $75 \mu\text{A}$  of opposite charge from the terminal to give a total current of  $150 \mu\text{A}$  in 6 atm of  $\text{SF}_6$ . Several chains can be installed to increase this total current.

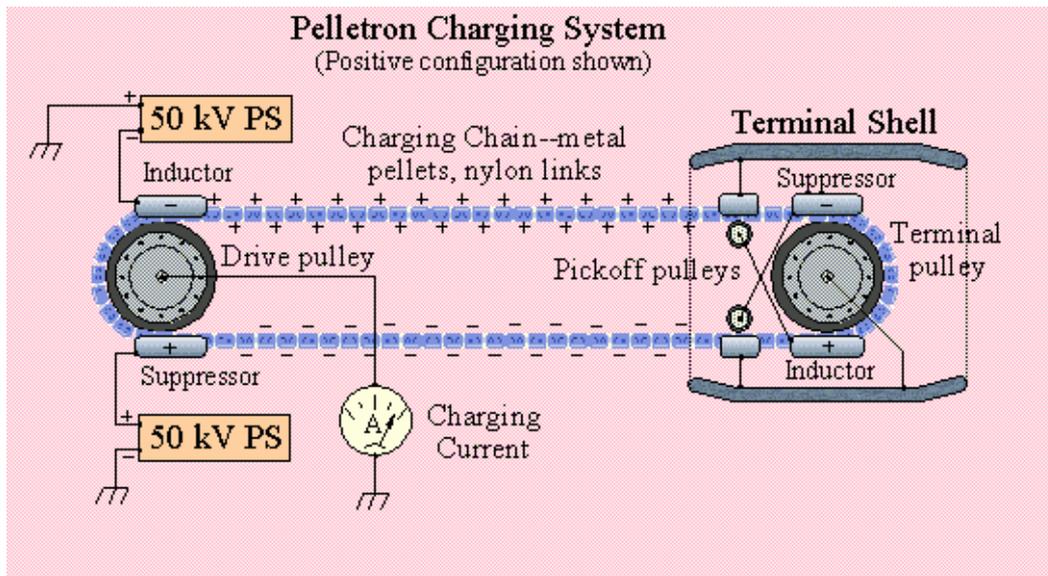


Fig.7 Schematics of the Pelletron charging system [22]

The University of Reading and Daresbury Laboratory for the largest electrostatic accelerator ever built, the NSF tandem designed to run at 30 MV, developed yet another charging system called the Laddertron [23]. It combines the high current carrying properties of a belt with the advantages of the induction charged system such as modular construction, protection against discharges, absence of corona discharges and stability of charging. It consists of cross-bars of relatively large surface area joined together by insulating links at each end to form an endless chain.

Laddertrons and Pelletrons have also replaced traditional belt charging system in existing machines.

#### 4. INSULATING GAS – DISCHARGE

High pressure air was the first insulating gas used in accelerators [4] but fire hazards convinced users that it was not a good choice. The dielectric strength of a gas or mixture of gases depends not only on the pressure but is critically determined by the behavior of the electrons, ions and photons present and especially by those processes which produce, deplete or slow down free electrons [24]. For an electronegative gas, that is an electron attaching gas such as  $\text{SF}_6$ , the free electrons can be prevented from initiating breakdown by attaching themselves to gas molecules to form stable negative ions.

Studies show that the total attachment cross section  $\sigma_a$  is large for low energy electrons. This means that only slow electrons will be efficiently removed by electron attachment. For the gas dielectric strength to be optimized, not only should the electron impact ionization cross section  $\sigma_i$  be small and  $\sigma_a$  large but the electrons must also be slowed down.

The dielectric properties of gases can be optimized by a combination of two or more gases to provide for example, the best effective combination of electron attaching and electron slowing down components. Table 1 shows some combinations that have been used [25]. The problem is of course to

have good control over these proportions. Many users of SF<sub>6</sub> as insulating gas report a serious contamination with air [25] that can degrade the voltage capability of the machine.

Table 1  
Different combinations of insulating gases

SF <sub>6</sub>	N <sub>2</sub>	CO <sub>2</sub>	pressure (atm)	max voltage (MV)
	80 %	20 %	14	9.6
20 %	60 %	20 %	18	4.0
	75 %	25 %	25	
60 %	40 %		6	9.7
100 %			7	13.0
100 %				25.0

SF<sub>6</sub> is a very good dielectric gas with a high breakdown field > 40 MV/m at 8 bars. But studies have shown that the ion chemistry of SF<sub>6</sub> discharges is strongly dependent on gas purity [24]. In the presence of humidity, HF can exist as shown on Fig. 8 so that it is important that SF<sub>6</sub> be dried continuously by going through an alumina column. The humidity content of the gas must also be frequently checked. The toxicity of certain byproducts have been studied and this can become a problem in very large machines. But in industry and medicine, we are mostly dealing with small machines and this is not an issue.

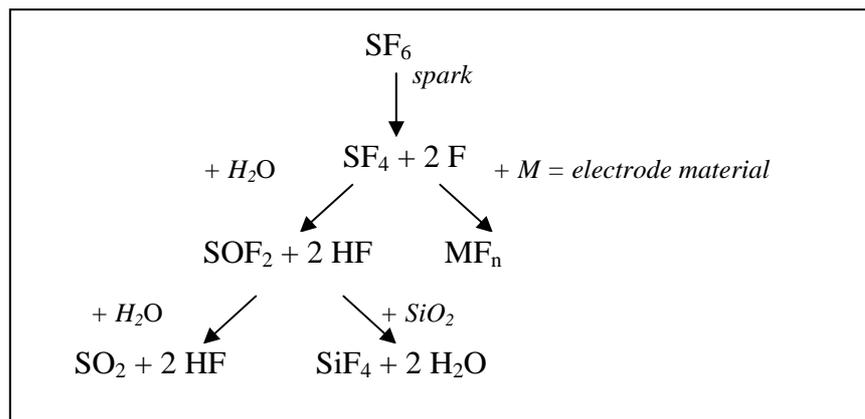


Fig. 8 By products of SF<sub>6</sub>[24]

## 5. ACCELERATOR TUBES

### 5.1 Description

The beam travels between the high voltage terminal and ground potential through a highly evacuated accelerator tube. Figure 9 shows the basic structure of an accelerator tube. Metal electrodes are sealed to dense, low outgassing insulating rings. Different types of bonding have been successfully used :

- glass sealed with polyvinylacetate to aluminum, titanium or stainless steel electrodes
- high density alumina ceramic sealed with aluminum metal to titanium electrodes

Bonding is of course an important issue with respect to the mechanical strength of the tube and its tightness to vacuum.

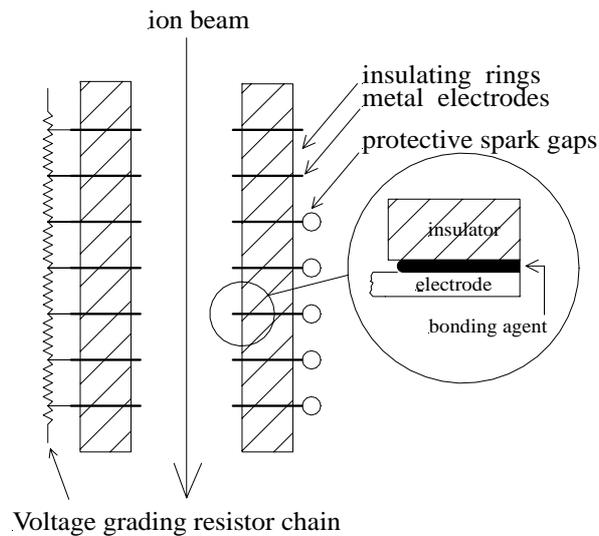


Fig. 9 Structure of an accelerator tube

It is generally found that a comfortable reliable gradient of 2 MV/m can be achieved with modern accelerator tubes.

Spark gaps protect the fragile insulators against sparks. The voltage between the electrodes is established by resistors or corona points draining current from the high voltage terminal.

The performance of accelerator tubes in an electrostatic machine depends, among other things, on the vacuum conditions in the tubes. In the absence of vacuum pumps within the pressure tank, the quality of the vacuum depends on the gas load and the conductance of the tubes. The metal electrode is of course fitted with a central aperture for the passage of the beam. This aperture follows the envelop of the beam along the tubes. It is essential to provide additional apertures for adequate pumping. The relative position of these apertures are shifted from one electrode to the other so as to prevent the acceleration of secondary electrons.

The ideal insulator has the following properties [26] :

- high volume breakdown strength
- low dielectric constant
- secondary emission coefficient < 1
- no voids in the adhesive film
- no sharp edges in the bonding foil or no stress raisers in the adhesive fillet
- insulator profile shaped to minimize the fields due to polarization and surface charge if present

The entrance to an accelerating tube is a very strong focusing lens and the exit lens is diverging. For circular apertures, the focal length  $f$  may be approximated by [27]:

$$f \approx \frac{4V}{\delta(E)} \quad (5)$$

where :

$V$  is the potential corresponding to the ion energy

$\delta(E)$  is the change in gradient across the aperture

The action of the first lens on the beam is crucial since the particles have little energy when they go through it. One must keep in mind these lenses to match the emittance of the beam to the acceptance of the tube. Different injection schemes are used to inject the beam so as to produce a waist at the stripper location in the case of a tandem. These include :

- forming a waist just in front of the entrance lens
- eliminating the entrance lens effect by installing a grid of fine wire mesh across the entrance and using an external lens
- using an intermediate lens within the tube.

## 5.2 Electron suppression

As the terminal voltage of electrostatic accelerators increased, a 'total voltage effect' appeared. A linear increase in voltage did not go along with an increase in tube-length for a fixed voltage gradient along the tube. The voltage was limited by electron loading currents. These currents increase rapidly with terminal voltage to the point where their magnitude approaches the charge carrying capacity of the high voltage generator. Basically, loading currents arise from electrons which are accelerated through all or part of the accelerator tube and produce bremsstrahlung and secondary electrons on impact with some part of the tube. Secondary electrons take part in further cascades and electron production. Bremsstrahlung causes ionization of the tank gas. Both processes drain current from the terminal, and both depend strongly on the total energy. The probability of ionization by bremsstrahlung is high in large tanks and at high pressures. For these reasons, electron suppression is essential in large high voltage machines. The objective is to intercept electrons as soon as possible before they gain enough energy to become a problem.

### 5.2.1 Inclined field tubes

Van de Graaff [28] inclined the central plane of the electrodes to the axis of the tube (Fig. 10). The electric field is considered as uniform. Secondary particles are supposed to be liberated with negligible energy.

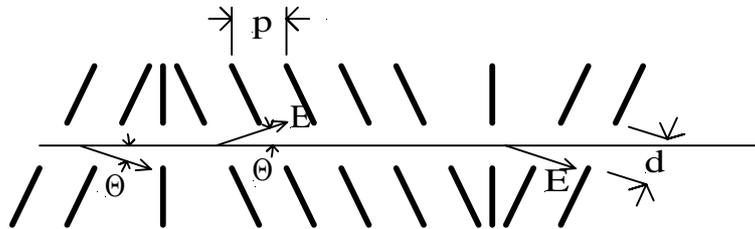


Fig. 10 Inclined field electrodes

The maximum energy  $W_{\max}$  a particle, liberated on one electrode, will acquire in this geometry is given by :

$$W_{\max} = p + \frac{d}{\sin \Theta} eE \quad (6)$$

where :

$p$  is axial inter-electrode spacing

$d$  is the dimension of the tube opening in the direction of inclination

$\Theta$  is the angle of inclination of the electrodes

$e$  is the charge of the electron

$E$  is the axial voltage gradient

Sections of the tube are alternately inclined so that the overall path of charged particles through the tube is very nearly axial.

At the same time, Allen [29] suggested an alternative arrangement of the same basic idea in which the transverse field vector rotates first clockwise then anticlockwise about the beam axis. [30, 31]

### 5.2.2 Magnetic suppression

Using transverse magnetic fields is another way of suppressing effectively electron loading in accelerator tubes by deflecting the electrons onto the electrodes according to :

$$Br = cst \sqrt{\frac{MW}{q^2}} \quad (7)$$

where :

$B$  is the magnetic field

$r$  is the radius of deflection

$M$ ,  $W$  and  $q$  are respectively the mass, the energy and the charge state of the particles to be deflected.

The location of the magnets is calculated so as to deflect electrons off the beam axis [32]. The direction of the magnetic field rotates once clockwise through a certain number of electrodes and then counterclockwise through the next series of electrodes so that the overall trajectory of the beam is nearly axial.

Since the inclined-field tube discriminates between the beam and unwanted particles solely by energy, electrostatic suppression should not be used at the entrance of the low energy tube and a short magnetically suppressed section can be incorporated.

### 5.2.3 NEC tubes

NEC developed accelerator tubes made of standard 8" modules (Fig. 11 a). Three such tube sections are used in each standard 1 MV tube, separated by a decoupling diaphragm. Secondary electrons collide with this diaphragm before they gain too much energy. The titanium sheet metal rings that are bonded to the ceramic rings extend only a short distance inward from the ceramic surface and are provided with notches. Inner electrodes provided with ears can be inserted and locked into position. This organic free structure is bakeable. NEC accelerator tubes could be run well above 100°C in normal operation, maintained at this high temperature by radiant energy transfer from the diaphragm unit heated at high temperature at dead sections of the accelerator tube. This design prevented contaminant buildup and helped in maintaining low vacuum in the tubes. But only 75 % of these tubes were actually insulating material [33]. In order to increase the voltage capability of these tubes, NEC replaced the heatable apertures by simple inserted apertures as shown in Fig. 11 b and shaped the electrodes to produce cylindrically symmetric focusing fields that deflect low energy particles onto adjacent electrodes.

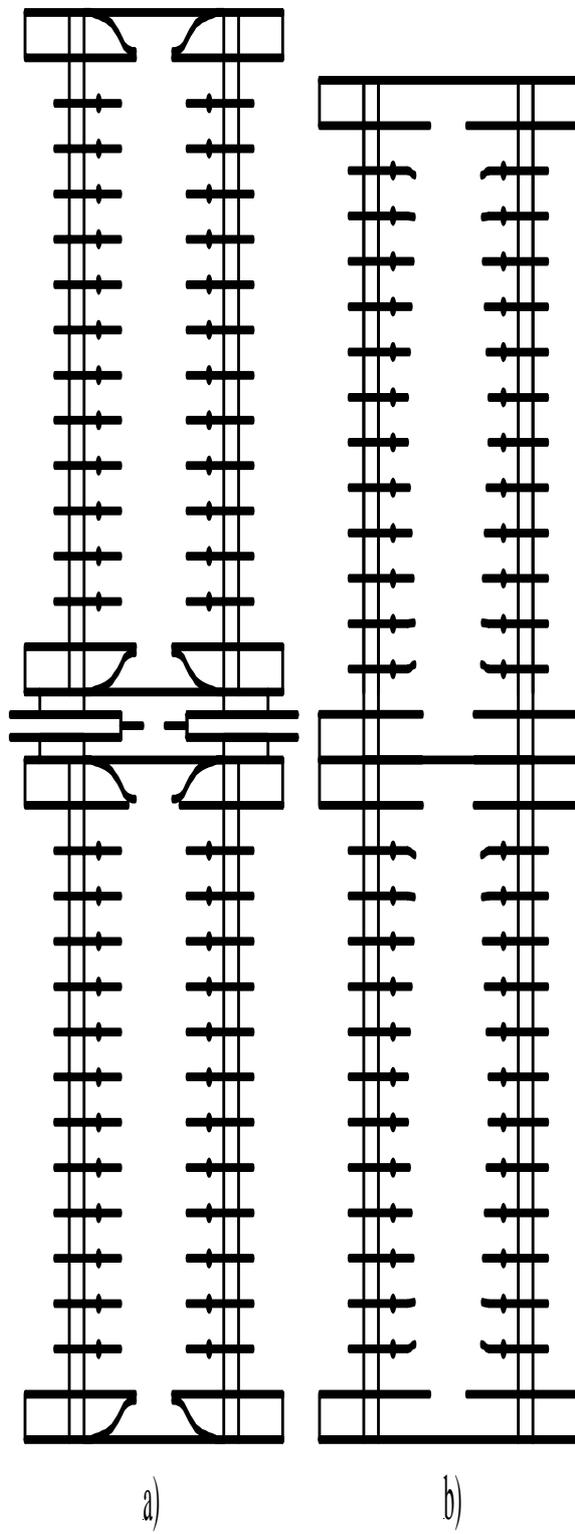


Fig.11 Structure of NEC tubes : a) initial design b) compressed design

### 5.3 Tube conditioning

An electrostatic accelerator requires conditioning to achieve high potential especially when the tubes have been exposed to atmospheric pressure. Some deconditioning tends to occur when the accelerator is operated for extended periods at low potential.

When exposed to high field gradients, gas and microparticles are evolved within the accelerator tube. Some of this gas is pumped away but much is redistributed. The object of conditioning is to complete the pumping and redistribution of the gas and microparticles to regions of low field stress without, at any time, evolving sufficient gas to initiate a discharge within the tube.

To condition the tubes, the potential is raised slowly until some activity occurs and this can be followed by the pressure rise on the vacuum gauges at either the low or high energy end of the pressure tank or by a lack of stability of terminal potential. When this occurs, this potential is held constant until this activity has declined when a further small increase in potential is applied. This process is continued until the required potential is reached or more usually just exceeded to yield higher stability when the potential is reduced to the operating value [34].

Other methods are also used that include injecting some beam or stripper gas into the tubes to increase the speed of conditioning. But this technique tends to mask the effects of conditioning and requires considerable care.

A big improvement consists in alternately driving the potential up and down about a mean level. This method makes it possible to drive the gas out without allowing conditions to exist that would cause a discharge. Starting at a voltage a little below where conditioning occurs, the terminal voltage is varied along a saw tooth pattern and rises rapidly to 30 to 50 kV above the conditioning base line then immediately, before any discharge sets off, the potential is rapidly returned to its original level. This cycle is repeated continuously, the baseline being slowly increased as conditioning proceeds. This enables the gas to be driven out and pumped away. In practice it is found that this enables conditioning to proceed with minimum sparking. The column currents flowing down the resistance grading chains of both the high and low energy columns, photomultipliers or radiation monitors can be used as conditioning monitors.

## 6. VOLTAGE DISTRIBUTION

The voltage distribution between the terminal and the tank in a DC accelerator can be compared to that existing between two concentric cylinders of infinite length. The breakdown voltage is maximum when the radius  $r$  of the inner cylinder is equal to the radius  $R$  of the tank divided by  $e$  (Fig. 12).

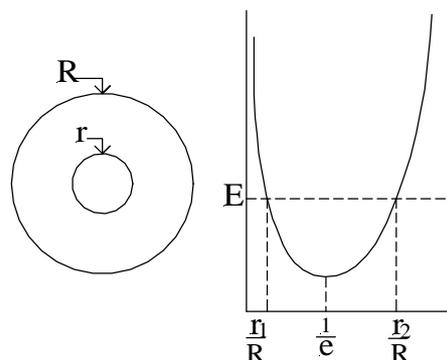


Fig. 12 Electric field at the surface of the inner cylinder

When the terminal dimensions become too large due to space requirements, intermediate electrodes can then be provided in the terminal gap such that the radii of successive shells  $r_1, r_2$  etc... are chosen

according to equation (8). The potential of each electrode is fixed through the connection to the column at appropriate values.

$$\frac{r_1}{r_2} = \frac{r_2}{r_3} = \dots \quad (8)$$

The machine Herb and coworkers built at the University of Wisconsin in 1935 [4] was the first machine in which the electrostatic potential along the column was graded in order to provide a region of uniform field enclosing the charging belt, the insulating column and the accelerator tube. All DC accelerators from then on will be built along that principle. This region is limited by a series of conducting hoops along the column, made of tubing (Fig. 13 a). Each hoop is connected to the column structure. The hoops are insulated from one another except for a small current provided by a system of resistors of high ohmage - 100's of  $M\Omega$  - (Fig. 13 b) . The interval between each hoop serves as spark gaps.

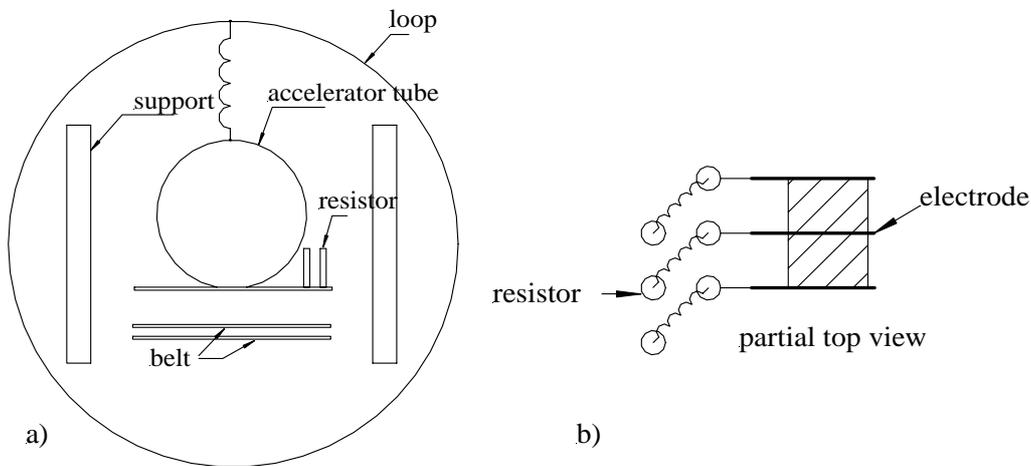


Fig. 13 voltage grading structure

A lot of work has gone into improving the reliability of the grading systems on DC accelerators [35]. Poor grading performance not only causes voltage holding and electron suppression problems but also damages beam transmission in inclined field accelerator tubes. Different designs have been developed to improve the reliability and lifetime of resistors. NEC has used corona point grading systems (Fig. 14). These were sensitive to geometry, wear of the points and insulating gas breakdown products deposition especially with  $SF_6$ . Corona currents generate  $SF_6$  breakdown products that attack the charging chains. The next step was to enclose the corona point systems but this was costly and resulted in a system that could not be inspected nor maintained easily.

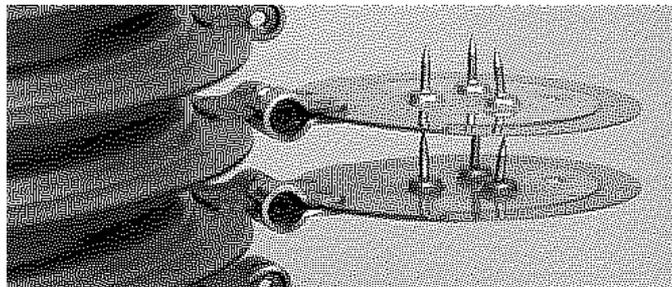


Fig. 14 Corona point grading system (courtesy of NEC)

## 7. VOLTAGE REGULATION

The charging process in electrostatic accelerators is rather slow. The charges deposited at ground potential either on the belt or on the chain take a certain time to reach the terminal ; this time is in the range of seconds or 100's of ms. A fast responding regulating system is needed to compensate for the sudden loss of the beam due to a breakdown in the ion source for example. Different signals are available as can be seen on Fig. 15.

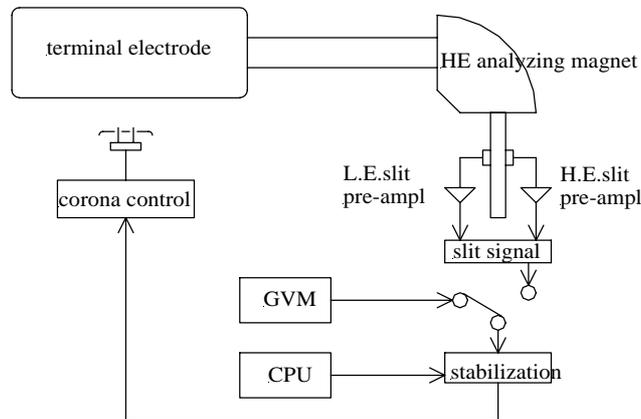


Fig. 15 Regulation loop

The generating voltmeter (GVM) measures the voltage on the terminal (Fig. 16) [36]. It is mounted on the side of the tank, just opposite the high voltage electrode. A rotating vane is mounted flush with the inner surface of the tank. The alternating current generated by the spinning disk is rectified and measured.

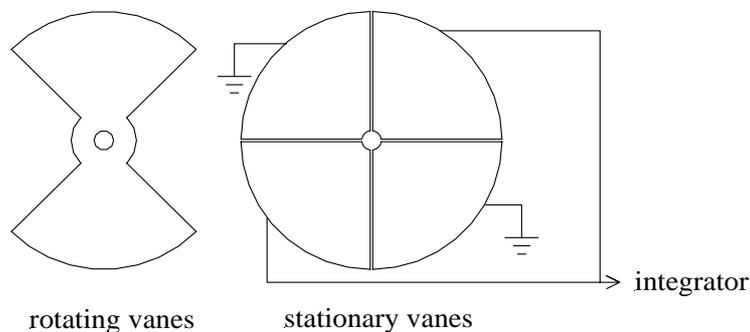


Fig. 16 Schematics of a generating voltmeter

Ashy and Hanson [37] introduced the grid-controlled corona discharge as a means of stabilization of the terminal voltage (Fig. 17). The cathode of the discharge is formed of a series of sharp needles. The anode is the terminal electrode. The mushroom shaped electrode around the corona needles functions as a grid and is normally at ground potential. All together form a triode. A combination of the following three signals drive this triode to stabilize the fluctuations of the terminal voltage :

- the slow drift of the terminal voltage will be stabilized with the signal coming from the GVM or with the signal measuring the difference between the currents falling on two slits at the exit of the high-energy analyzing magnet (according to equation 5, the radius of deflection of the particles is directly related to their energy)

- the fast fluctuations, in the ms to the 100's of ms, will be dealt with the signal from the capacitive pick-up plates opposite from the terminal electrode.

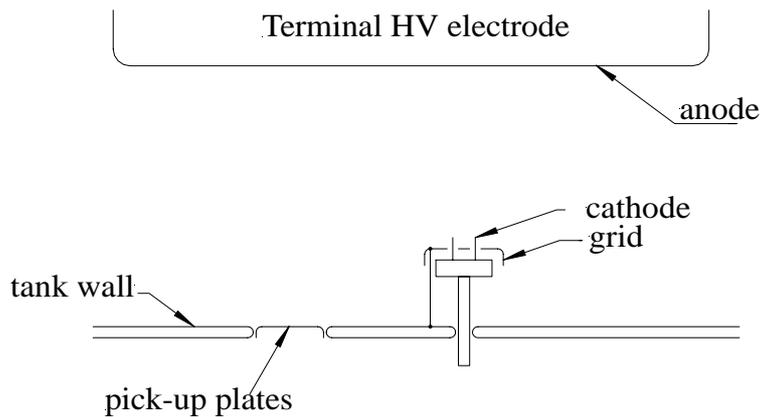


Fig. 17 Corona stabilization system

Electrodynamic machines such as Tandetrans and Dynamitrons do not use this corona discharge stabilization system. The signals from the GVM and the capacitive pick-up plates are fed back into the cascade generator.

The GVM must be calibrated. A common way to go about this calibration is to use nuclear resonances chosen to fit the energy interval of the machine. Some available reactions are shown in table 2.

Table 2  
Some nuclear resonances used to calibrate the GVM

nuclear reaction	incident ion energy (MeV)
$^{19}\text{F} (p, \alpha\gamma) ^{16}\text{O}$	0.5 - 2.2
$^{16}\text{O} (d, p) ^{17}\text{O}$	0.4 - 3.0
$^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$	0.992

## 8. ION SOURCES

Both positive and negative ion sources are needed. Positive ions can be produced by electron bombardment of a gas or vapor containing the atoms to be ionized and by surface ionization. According to the electron density and energy, the most probable charge state can vary between 1 and 20. Producing negative ions is more difficult because the electron-atom binding energy is low ( $< 3$  eV). Despite this difficulty, negative ion sources are absolutely necessary on tandem accelerators. Some of the main ion sources that can be found on dc accelerators are presented.

### 8.1 Positive ion sources

#### 8.1.1 Plasma ion sources

##### 8.1.1.1 Penning ion source

Figure 18 shows a sketch of a Penning ion source composed of two symmetrical cold cathodes on each side of a cylindrical anode and a high axial magnetic field. This results in a very efficient electrostatic and magnetic electron confinement that compensates for the poor electron production yield by the ionic bombardment of the cold cathodes. Some sources use hot cathodes that emit electrons thermally to initiate the discharge. The cathode may be heated directly or indirectly. Ions are extracted through an aperture in the end of the cathode or through an aperture in the anode. A gas inlet with an adjustable leak controls the flow of gas to initiate the discharge.

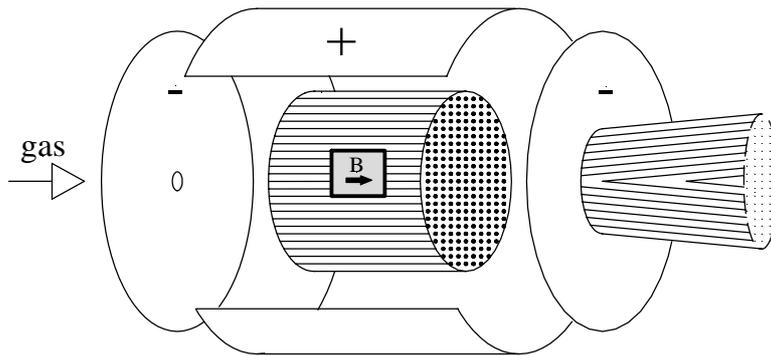


Fig. 18 Schematics of a Penning Ion Source

The discharge mechanism is quite complex. Electrons oscillate between the cathodes that are both perpendicular to the axis and held at the same potential. The electrons drift gradually towards the anode without striking it because their radial motion is constrained by the magnetic field. They collide with the atoms of the gas and liberate other electrons which are accelerated and so on.

Typical working conditions are the following :

- discharge voltage : 1 - 6 kV
- discharge current : 1 - 20 mA
- magnetic field : 0.5 - 1.5 kG
- pressure :  $10^{-4}$  -  $10^{-3}$  torr

The Penning Ion Source has been widely used on accelerators [38] and gives the following output currents [39] :

- 1 + 100  $\mu$ A to several mA
- 2 + several  $\mu$ A to 100s  $\mu$ A
- 3 + 100s nA to several  $\mu$ A

Permanent magnets can be used which makes it even easier to install it in the high voltage terminal of a single ended machine. It is of course more difficult to imagine installing a hot cathode source in the terminal because of the relatively short lifetime of the filament, typically less than 100 hours. But such sources have been developed and give excellent results for ion implantation [40].

#### 8.1.1 .2 Duoplasmatron ion source

The duoplasmatron ion source (Fig. 19) is used for the production of high-intensity ion beams from gaseous material. A low pressure discharge is maintained between a cathode and an anode in which a small aperture is pierced (diameter 0.5 – 1.5 mm). The discharge is concentrated under the electrostatic action of an intermediate electrode and the action of a strong axial inhomogeneous magnetic field (3 – 10 kG) between this intermediate electrode and the anode, both being made of soft iron. The gap between the intermediate electrode and the anode varies from 2 to 5 mm. The current extracted is greatest when the maximum of the magnetic field lies in the plane of the aperture in the anode. The arc density may reach  $10^{14}$  ions/cm<sup>2</sup> in this region.

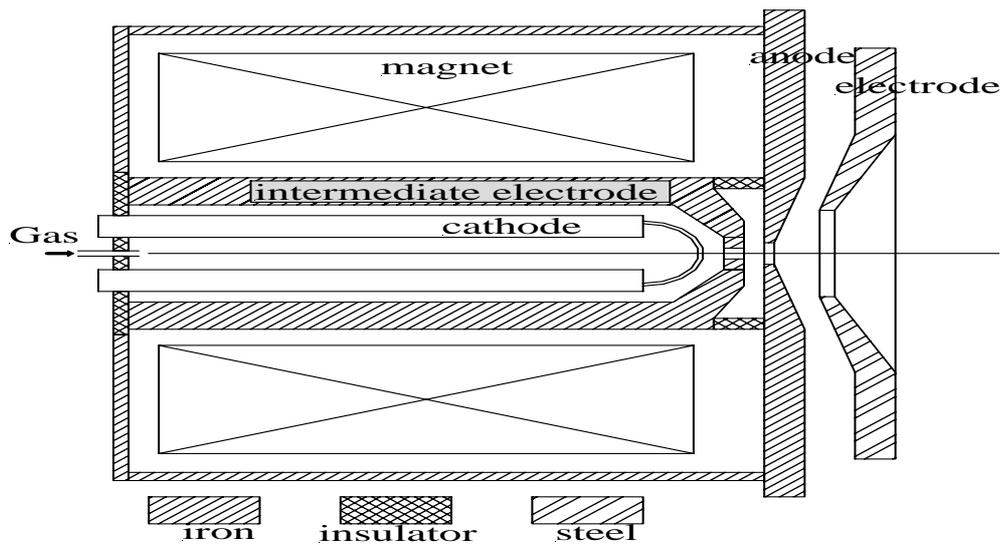


Fig. 19 Schematics of a duoplasmatron ion source

The ion density in the beam extracted from the anode aperture is always very high [41] and the beam diverges strongly. To reduce the angular distribution leading to possible beam losses, the anode is equipped with a expansion cup which allows the plasma to expand and therefore to cool.

The duoplasmatron ion source has a very good ionization efficiency and can produce intense beams from gaseous feed materials covering a range of intensities from 1 to 100 mA. Versions have been developed that can be used with low vapor pressure and corrosive materials. Several 100's of mA of deuteron beams have been produced [42].

### 8.1.1.3 RF ion source

The RF source (Fig. 21) is a reliable instrument to produce light ions from gases [40]. The plasma is generated by the coupling of a 10 to 30 MHz radio-frequency power of a few hundred watts to a gas with a pressure of  $10^{-3}$  to  $10^{-2}$  torr. The gas is contained in a container made of glass, quartz or ceramic. The RF generator is coupled to the discharge either through a coil (inductive coupling) or through two electrodes (capacitive coupling) placed outside the envelope. The plasma is biased relative to the outlet and the ions are extracted through a rather narrow channel. These sources have been extensively used on single ended machine and can produce 1 to 20 mA beams but have a rather large energy dispersion that can run up to several hundred eV.

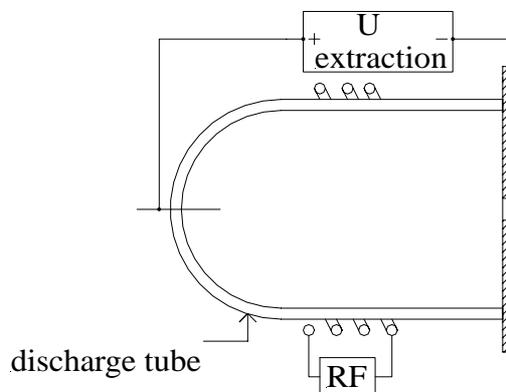


Fig. 20 Schematics of a RF ion source

## 8.2 Negative ion sources

The attachment of an electron to a neutral atom is an exothermic process. The electron affinity  $E_a$  of an element is a good measure of the stability of the negative ion.  $E_a$  is defined as the difference of energy between the ground states of the neutral atom and of the negative ion.  $E_a$  must be positive of course for negative ion formation. Table 3 shows the electron affinities for the elements of the periodic table. Rare gases, He, Mg and some others have negative electron affinities and thus will not form negative ions. Halogens have  $E_a$  around 3 eV and all the others have electron affinities below 2 eV.

Many molecular negative ion beams have been observed. Molecular negative ions containing the atom of interest may, in many cases have much higher electron affinities than the atom itself. In tandems, the molecule will break up during the stripping process. For certain elements such as N that do not form stable negative ions, the molecule can be the only alternative.  $\text{NH}_2^-$  is stable and thus accelerating N in a tandem becomes possible.

### 8.2.1 Sputter ion source

The process describing negative ion formation by sputtering is similar to surface ionization [43]. The process of direct-surface ionization from a hot metal surface at temperature T is statistical in nature and the Langmuir - Saha equation (equation 9) predicts the proportion of negative ion for atoms with an electron affinity  $E_a$  interacting with a hot metal surface at absolute temperature T and constant work function P :

$$\frac{n_-}{n_0} = \frac{w_-}{w_0} \exp \frac{E_a - P}{kT} \quad (9)$$

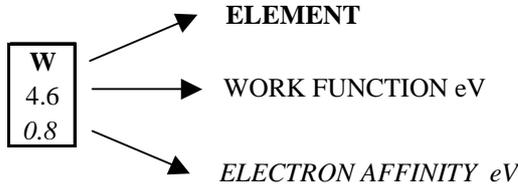
It is evident that negative ion yields will be high only if the work function P is  $\leq$  to the electron affinity  $E_a$  which is seldom the case (Table 3) :

- P in the range 2.5 – 5.5 eV
- $E_a$  in the range 1 - 2 eV apart from the halogens  $E_a = 3.1 - 3.6$  eV

But it was shown [40, 43] that the presence of a thin layer of cesium on the sputter surface significantly reduces the work function and dramatically improves negative ion yields. Middleton showed that the effective work function is at minimum at a little over one-half monolayer coverage and at this value, is less than that of pure cesium ( $\sim 2.14$  eV).

Table 3  
Electron affinity and work function of the elements

IA																VIII A	
H											III A	IV A	V A	VI A	VII A	< 0	
0.8	II A											B	C	N	O	F	Ne
Li	Be											4.5	5.0	< 0	1.5	3.4	< 0
2.9	5.0											0.3	1.3	< 0	1.5	3.4	< 0
0.6	0.2											Al	Si	P	S	Cl	Ar
Na	Mg											4.3	4.8				
2.8	3.7	III B	IV B	V B	VI B	VII B	VIII			I B	II B	0.4	1.4	0.7	2.1	3.6	< 0
0.5	< 0	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
2.3	2.9	3.5	4.3	4.3	4.5	4.1	4.6	5.0	5.2	4.6	4.3	4.2	5.0	3.8	5.9		
0.5	< 0	0.2	0.1	0.5	0.7	< 0	0.2	0.7	1.2	1.2	< 0	0.3	1.2	0.8	2.0	3.4	< 0
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
2.2	2.6	3.1	4.1	4.3	4.6		4.7	5.0	5.1	4.6	4.2	4.1	4.4	4.6	5.0		
0.5	< 0	0.3	0.4	0.9	0.8	0.6	1.1	1.1	0.6	1.3	< 0	0.3	1.2	1.1	2.0	3.1	< 0
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
2.1	2.7	3.5	3.9	4.3	4.6	5.1	4.8	5.4	5.7	5.3	4.5	3.8	4.3	4.2			
0.5	< 0	0.5	0	0.3	0.8	0.2	1.1	1.6	2.1	2.3	< 0	0.3	0.4	0.9	1.9	2.8	< 0



R. Middleton pioneered a lot of the work on sputter ion sources [43]. A positive ion beam is formed by surface ionization of an alkaline element like cesium in the vapor phase (Fig. 21). These positive ions are accelerated under several kV and sputter the cathode containing the element of interest. This cathode is cooled so that a thin layer of cesium covers it.

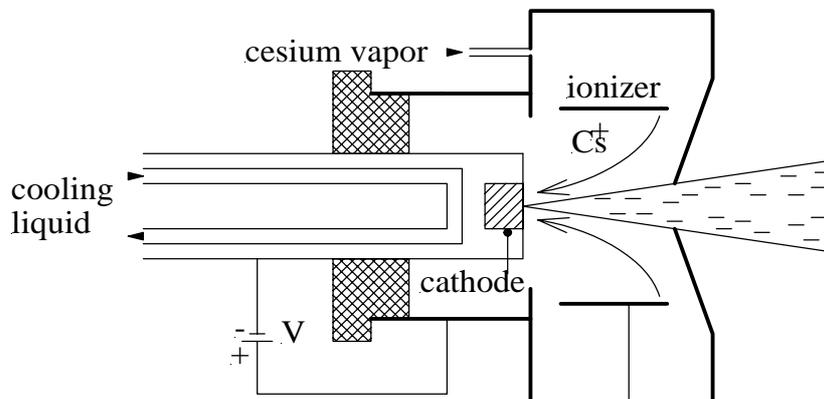


Fig. 21 Schematics of a sputter ion source

Maintaining such a layer of cesium can be difficult to achieve with elements that sputter easily. For example, carbon and copper have almost identical electron affinities ( 1.27 eV) but Cu sputters at 10 to 15 times the rate of carbon. So the yield of C is almost an order of magnitude higher than that of Cu. The sputter energy has to be adapted to the element of interest.

The advantages of the sputter sources are multiple :

- negative ions can be formed from almost all elements
- ion species can be quickly changed

- intensities are fairly high
- the ionization efficiency is good
- the emittance and the energy spread are low
- the source is able to operate for long periods with minimum maintenance

A lot of work has been done on the influence of the shape of the ionizer and the most efficient is spherical.

### 8.2.2 Charge exchange ion source

The electron capture and loss processes which take place during collisions between energetic ions and atoms in a vapor result in a distribution of charge states of the emergent beam as in the stripping process. Now the same process can be used to produce negative ion beams. The efficient production of negative ions through charge exchange depends on the ion energy, the electron affinity of the element of interest and of the electron binding energy of the donor. Equilibrium fractions of many negative ions in different vapors have been measured between 0.5 to over 90 % [40]. In this review one can see that Mg is a more effective electron donor for high electron affinity elements and that Na is a better donor for lower electron affinity elements.

Through charge exchange, some negative ions can be formed in an excited state of the element. That is true for He for instance and everyone knows the importance of He in ion beam analysis techniques. The negative ion may live for extended periods of time if the decay of the excited compound state is forbidden.

The charge exchange cell is filled with an alkaline vapor. Following are the melting points of some alkaline elements :

- Li      180°C
- Na      98°C
- K       63°C
- Rb      39°C
- Cs      29°C

Different combinations can be found on machines. Duoplasmatron sources can be associated with a Li charge exchange cell as at Yale or Orsay. At the Louvre, Aglae is equipped with a RF source equipped with a Rb charge exchange cell.

### 8.2.3 Other negative ion sources

Many other sources have been used to produce negative ion beams especially H<sup>-</sup> and D<sup>-</sup> beams. Among them :

- Penning ion sources
- Duoplasmatron sources operated with reversed extraction polarity. The negative ions are abundant in the periphery of the plasma

## 9. CONCLUSIONS

DC accelerators have played an essential role in nuclear physics, ion beam analysis and high energy implantation. They are still widely used. The main advantages of these machines are :

- any charged particles can be accelerated
- the energy dispersion is quite low

- the terminal voltage and thus the energy of the particles can be varied quite easily
- the intensity of the beam is continuous.

The main disadvantages of these machines is the limitation of terminal voltage due to voltage breakdowns. The limitation seems to lie around 25 MV.

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