5 Electrostatics

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5.1 Introduction

The first electrostatic accelerators were air-insulated, operating without air-conditioning in humid surroundings, sometimes even in the open air. The designers faced many of the same challenges as high-voltage power-line engineers, whose accumulated experience guided them in specifying the size of buildings and the shape of components needed to avoid sparking. A major challenge was preventing corona discharge from the sharp edges of conductors and leakage currents across the surfaces of damp or dirty insulators.

However, the low dielectric strength of air and the bulky nature of contemporary high-voltage components combined to make compact designs impractical. Photographs of early machines reveal the generous layouts adopted in most laboratories (Fig. 5.1).

They also disclose weaknesses imposed by unsuitable buildings. The roof structure of the Round Hill hangar, in which Van de Graaff achieved 5.1 MV between the twin columns of his large generator, clearly affected the sparking voltage (Fig. 5.2). The overall performance can hardly have been helped by

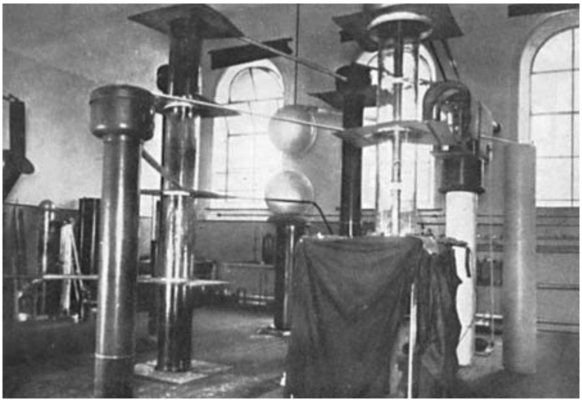

Fig. 5.1. Cockcroft and Walton's 800 kV accelerator in the Cavendish Laboratory, Cambridge, in 1932 (Reprinted from [1], copyright (1932) with permission from the Royal Society)

Fig. 5.2. Van de Graaff's twin-column electrostatic accelerator sparking to the roof and the walls in the Round Hill hangar in Connecticut in 1932 (Reprinted from [2], copyright (1974) with permission from Elsevier)

the incursion of seawater at spring tides. Air at atmospheric pressure and the use of available but inconvenient buildings ensured that the design of these early accelerators was far removed from the ideal electrostatic form. The story of these early developments was summarized by Bromley [2] in a review of large electrostatic accelerators.

The introduction of compressed air, quickly replaced by inert gases at high pressure, required but also made possible the adoption of more sophisticated electrostatic designs. By controlling the gas pressure and composition, it was possible to specify a safe working field with confidence. At the same time, the removal of moisture and dirt delayed the onset of surface leakage currents. Improved high-voltage components became smaller, making it possible to exploit the high dielectric strength of the gas in a compact design. These changes are obvious if one compares the layout of the Round Hill accelerators of Fig. 5.2 with Herb's "Long Tank" accelerator that operated at over 4 MV (Fig. 5.3) in 0.8 MPa of compressed air.

As long as ambient conditions were poorly controlled and imperfectly understood, it was reasonable for designers to rely on precedent and experience. But if the properties of insulators and the presence of water vapor could be measured and controlled, electrostatic-field calculations were needed to enable designers to meet the relevant criteria for avoiding breakdown.

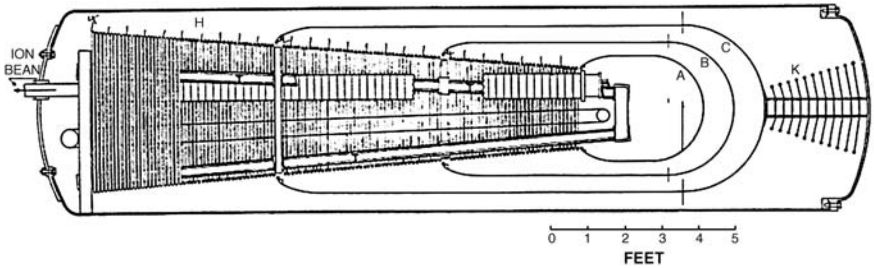

Fig. 5.3. Herb's horizontal accelerator, operating in compressed air with a dash of Freon at over 4 MV (Reprinted from [3], copyright (1940) with permission from APS)

Analytical solutions of Laplace's equation for simple geometries, such as concentric spheres and cylinders, coupled with reliable data for the electrical strength of gases, provide such a basis for designing machines to work at a specified voltage. Unfortunately, the highest fields in real machines occur where the geometry is not simple and the solutions are not analytic, as seen in the field distribution of a typical small accelerator (Fig. 5.4).

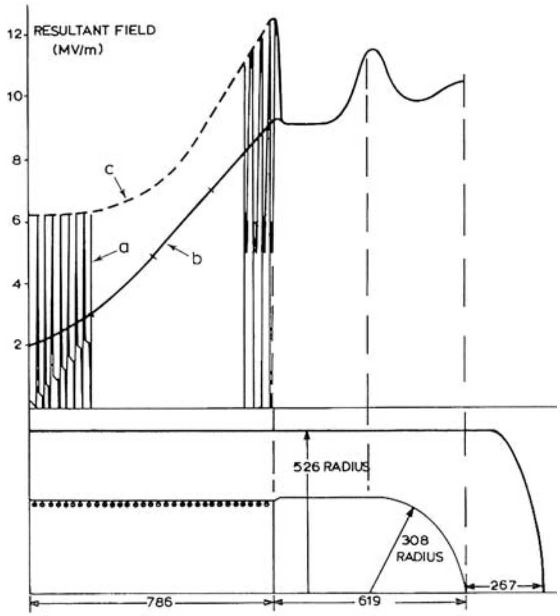

Fig. 5.4. Field distribution on the surfaces of the terminal and column in a 1.5 MV electrostatic accelerator operating in SF_6 at 0.3 MPa [4]. Dimensions in mm. (**a**) Fine structure due to hoops. (**b**) Field of equivalent smooth column. (**c**) Envelope of resultant field (Reprinted from [4])

Numerical methods (or analog measurements with resistance networks or electrolytic tanks) are required to determine the field in and around the column and at transitions between spherical and cylindrical electrodes. Until such techniques became accurate and widely available, it was tempting to neglect the fine structure. A more serious miscalculation in the design of early machines was the assumption that the column components, particularly the accelerator tube, would be able to sustain the same longitudinal field independent of the total voltage. The reasons for this "total-voltage effect" are discussed elsewhere (Chap. 8).

5.2 Field Distributions

Most pressurized electrostatic accelerators conform to one of two basic geometries. Single-ended machines consist of a cylindrical column bounded by toroidal hoops, terminating in a smooth, cylindrical high-voltage terminal with a hemispherical end (Fig. 5.4). The minor diameter of the hoops is small compared with the column diameter. The hoops are separated by gaps somewhat less than their minor diameter. The voltage between adjacent hoops and the macroscopic longitudinal field inside the column are constant. The column and terminal are mounted axially inside a cylindrical tank that has flat or domed ends. Sometimes the cylindrical part of the tank opposite the terminal is joined to a conical section that tapers to a reduced diameter towards the column base, where the field is lower. A field-free region between the base of the column and the tank contains the charging system, motors, controls etc.

Tandem accelerators are symmetrical about the center plane of the terminal. The column, usually constant in radius, extends from end to end of the tank, which is often cylindrical, but may incorporate conical sections in larger machines. The column geometry is similar to that in single-ended machines. In some of the larger machines, one or more intermediate electrodes (or intershields) are installed between the terminal and the tank, as shown in Fig. 5.5. They are supported from and electrically connected to the column and are at the same potential as the points of support. They reduce the peak radial fields and allow an increase in voltage for the same tank diameter. Outside the column, folded tandems are electrostatically similar to single-ended machines.

5.2.1 Macroscopic Field in Cylindrical Geometry

The radial field between concentric cylindrical conductors is given by

$$E(r) = V/(r \ln(r_2/r_1)) \tag{5.1}$$

where V is the potential difference between the two conductors, r_1 is the radius of the inner conductor and r_2 that of the outer. The maximum field,

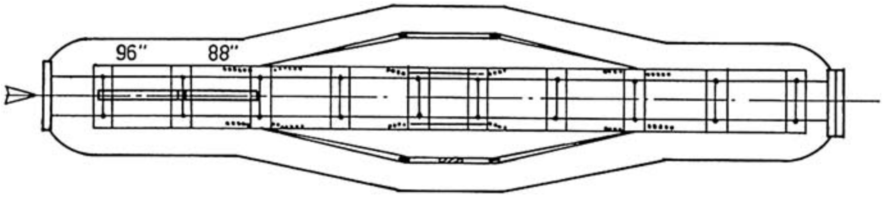

Fig. 5.5. HVEC model MP tandem accelerator with intershield, as modified by Letournel (Reprinted from [5], copyright (1984) with permission from Elsevier)

$$E_{max} = V/(r_1 \ln(r_2/r_1))$$

occurs on the surface of the inner conductor. For fixed values of r_2 and E_{max}, V depends on r_1:

$$V(r_1) = E_{max} r_1 \ln(r_2/r_1) \quad (5.2)$$

The maximum value of V is obtained by setting the partial differential $\partial V/\partial r_1 = E_{max}[\ln(r_2/r_1 - 1)] = 0$, whence $r_2/r_1 = e$ and $V_{max} = E_{max} r_2/e$. However, it is not always possible to achieve this geometry. For example, the ideal terminal radius of a 4 MV accelerator operating in SF_6 at 0.8 MPa, assuming a safe working value of E_{max}=16 MV/m (see Sect. 5.3), is only 0.25 m. This is only just big enough to accommodate a small charging belt and a small accelerator tube. At lower voltages the ratio r_2/r_1 may need to be greater than $1/e$ if the terminal is to be big enough. Fortunately, quite large departures from $r_2/r_1 = e$ have little effect on the maximum voltage, as shown in Fig. 5.6. As the design voltage increases so do the dimensions, and it becomes easier to meet the structural and spatial requirements for column and terminal without prejudicing the electrostatic design.

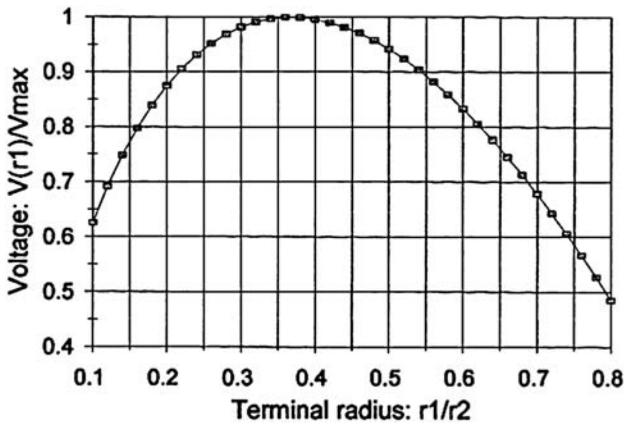

Fig. 5.6. Variation of maximum voltage with terminal radius in cylindrical geometry, normalized to unit maximum field and unit tank radius

5.2.2 Macroscopic Field in Spherical Geometry

The radial field between two concentric spheres is

$$E(r) = V[r_1 r_2/(r^2(r_2 - r_1))] \tag{5.3}$$

where r_1 and r_2 are the radii of the inner and outer conductors. The field at the surface of the inner conductor is $E(r_1) = V[r_2/(r_1(r_2 - r_1))]$ and the condition for maximum voltage, E and r_2 constant, is $r_2/r_1 = 2$.

For this value of r_2/r_1, the spherical surface field is 39% greater than the cylindrical surface field and for the optimum cylindrical geometry, $r_2/r_1 = e$, the ratio is 59%. Such a discrepancy in peak fields is clearly unsatisfactory and calls for a different geometry. Using a flat plate or shallow dome at the end of the tank and increasing the clearance between it and the terminal from $0.5\,r_2$ to $0.9\,r_2$ makes the field at the end of the terminal equal to the cylindrical field when $r_2/r_1 = 2$.

5.2.3 Intershields

In the ideal cylindrical geometry, $E(r_1)/E(r_2) = e$. Much of the insulating gas is therefore working at low stress. Especially in large machines, this suggests the use of an intermediate electrode, or intershield, to make the field more uniform and reduce size and cost. The voltage and field are now related by

$$V_t = V_1 + V_2 = E_1 r_1 \ln(r_2/r_1) + E_2 r_2 \ln(r_3/r_2) \tag{5.4}$$

where V_t is the voltage between terminal and tank, V_1 the voltage between terminal and intershield and V_2 the voltage between intershield and tank; E_1 and E_2 are the radial fields on the outer surfaces of the terminal and intershield, and r_1, r_2 and r_3 are the radii of the terminal, intershield and tank, respectively. Since the gas conditions inside and outside the intershield are the same, the values of V_1, V_2 and r_2 should be chosen so that E_1 and E_2 are equal. Whatever the values of E_1, r_2 and r_3, it is obvious that the maximum value of V_1 will occur when $r_2/r_1 = e$.

It is convenient to normalize the radii by setting $r_3 = 1$. Equation (5.4) then becomes

$$V_t = V_1 + V_2 = Er_2/e + Er_2 \ln(1/r_2) \tag{5.5}$$

The maximum value of V_t requires that

$$\partial V_t/\partial r_2 = E[1/e + \ln(1/r_2) - 1] = 0$$

and

$$r_2/r_3 = e^{(1-e)/e} = 0.5315$$
$$r_1/r_3 = e^{(1-2e)/e} = 0.1955$$

An intershield of the right radius and voltage increases the maximum voltage by 44% compared with a machine of the same tank radius with no intershield and the optimum terminal radius. But this improvement comes at the cost of a very small terminal. Even a 10 MV machine, assuming $E_{max} =$ 16 MV/m, would be limited to a terminal radius of 0.25 m. A more realistic value of 0.5 m would correspond to a tank radius of 2.5 m and a terminal voltage of 21 MV.

A better guide to the value of an intershield comes from calculating the voltage gain over the range $0.1995 < r_1/r_3 < 1$. (There can be no advantage in making $r_1 < 0.1995$.) For $0.1955 < r_1/r_3 < 0.368$, the improvement is given by the ratio of V_t to $E_{max}r_3/e$, the voltage in the ideal geometry without an intershield. For the range $0.368 < r_1/r_3 < 1$, the comparison must be with $E_{max}r_1 \ln(r_3/r_1)$. The results are shown in Fig. 5.7. Again, the maximum voltage is not very sensitive to small changes in these quantities.

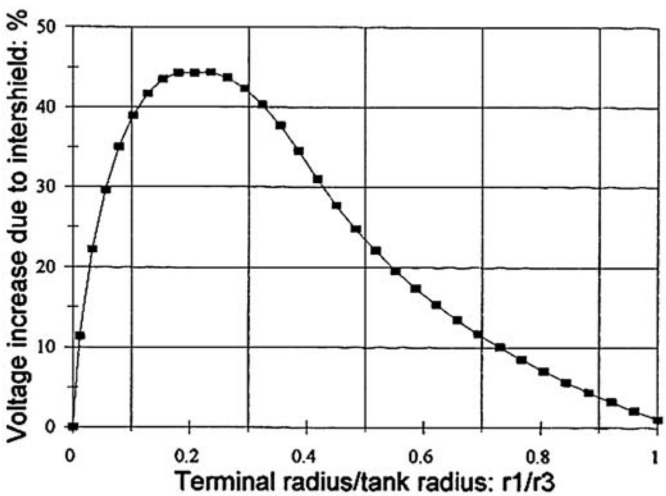

Fig. 5.7. Voltage gain due to a single intershield in cylindrical geometry. For $r_1 < r_3/e$, the gain is relative to the case with no intershield and the ideal geometry ($r_1 = r_3/e$). For $r_1 > r_3/e$, the comparison is with no intershield and the same terminal radius

As the design voltage increases, the economic case for an intershield becomes very strong. For a 20 MV tandem, for example, an ideal intershield would decrease the tank diameter from 3.4 to 2.36 m, the terminal diameter from 1.25 to 0.46 m and the gas inventory by over 50%, from 72 to 35 tonnes. But these cost savings come at a price: access for maintenance is more difficult, additional systems are needed to control the intershield voltage, and the stored energy of the intershield can threaten surge damage to the column.

Some early single-ended machines were designed with multiple intershields, partly in response to the low dielectric strengths of the gases then in use. But the voltage was usually limited by failure of the accelerator tube to work at the required field, and the full advantage was never realized.

Twenty years ago, Letournel [5] introduced the "portico", a novel design of intershield for tandems, in which the conventional cylinder is replaced by a set of narrow electrodes shaped and placed so as to generate the same radial field pattern. When these have been retrofitted to MP tandems, there has been disagreement as to whether performance has been enhanced. On the other hand, when a single "portico" was fitted to a machine designed for an intershield, a significant voltage gain was achieved [6].

Subsequent three-dimensional finite-element field calculations [7] have revealed that the peak field on the rounded edges of "portico" electrodes is extremely sensitive to small variations in the column gradient, so much so that even small perturbations in the gradient are prone to trigger radial breakdown. When a spark reduces the voltage between portico and terminal to zero, the resulting increase in field on the edges of the portico electrodes is so great that multiple breakdowns occur instantly between tank and portico; see Fig. 5.8. The benefit of a portico is only realized when the column gradient is strictly controlled.

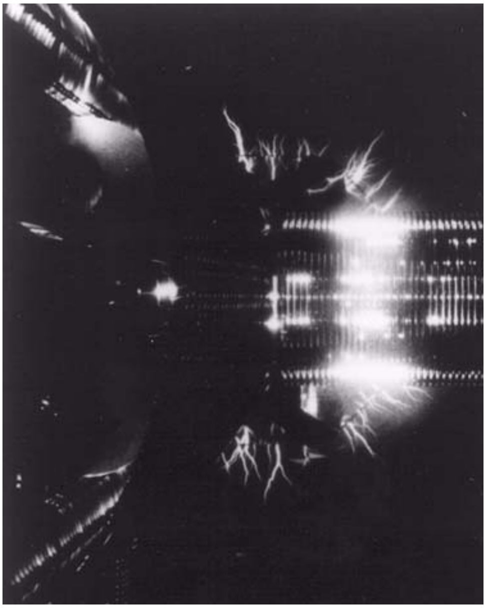

Fig. 5.8. Multiple discharges from the portico electrodes of the Yale ESTU tandem, following a spark between terminal and portico. One of the transverse bracing columns is visible to the right of the main column

5.2.4 The Effect of Terminal Shape

Figure 5.4 shows that the highest field in a simple single-ended machine is near the junction of the column and terminal. A smaller peak occurs where the cylindrical and spherical parts of the terminal join. Finite-element analysis is necessary to determine these fields. A typical value for the peak field at the junction of the cylindrical and spherical sections of the terminal is 15% above the cylindrical value. The field enhancement where the terminal joins the column is caused by the necessary rounding of the end of the terminal and by the small minor radius of the hoops that surround the column. A comparison of the field distributions in several tandem accelerators, using finite-element calculations, was presented by Rabinovitz [8].

Field enhancement at either end of the terminal can be reduced by replacing the abrupt transition from cylindrical to spherical geometry with a more complex shape involving a gradual change in the longitudinal radius of curvature. Replacing a cylindrical terminal with a third-order paraboloid of revolution, Koltay and Kiss [9] improved field uniformity and reduced the peak field enhancement. Their design had the further advantage that the increased radius of the terminal "shadowed" the first few hoops near the terminal so that they no longer carried the peak stress. Complexity and cost have discouraged widespread use of their design, but most large generators have cylindrical terminals greater in radius than the column, thus reducing the peak field at the most vulnerable part of the column.

5.2.5 Hoop Design

The field between adjacent hoops of circular cross section may be obtained from the analytic expression for the field between a pair of infinite cylinders, assuming the hoop minor radius to be much smaller than the column radius. Using the method of images, it can be shown that, for a fixed hoop pitch $2d$ and maximum field E_{max}, the highest voltage between the hoops is achieved when the hoop radius $a = 0.342\,d$. For this ratio, $V = 0.831\,E_{max}d$; see Fig. 5.9.

In a typical accelerator with a column pitch of $2d = 25\,\mathrm{mm}$ and a working field of 16 MV/m, the maximum voltage between adjacent hoops would be 166 kV and the uniform field along the column 6.65 MV/m. But because accelerator tubes are limited to a field of 2.5 MV/m or less, it is preferable to increase the minor radius of the hoops to $a/d = 0.6{-}0.7$, thus reducing the critical radial field. A further reduction in radial field can be obtained by increasing the hoop pitch to a multiple of the column insulator pitch.

As long ago as 1953, Boag [10] suggested the use of oval hoops to reduce radial-field enhancement. Neglecting the column gradient, he calculated that stress multiplication could be reduced from 1.6 for circular hoops to 1.4 for elliptical hoops when $a/d = 0.66$. Eastham [11], however, has shown that when a realistic longitudinal field is used in finite-element calculations, the

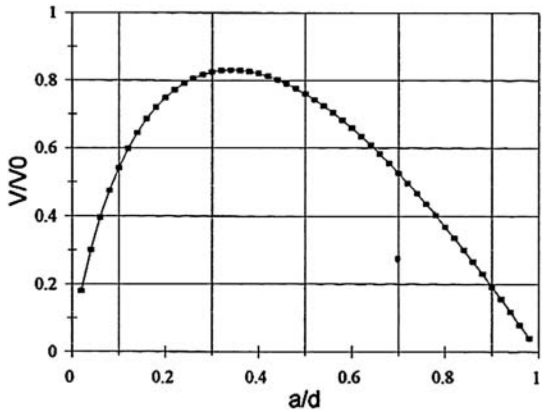

Fig. 5.9. Maximum voltage V between two infinite cylinders of radius a, center separation $2d$, relative to $V_0 = E_{max}d$, where V_0 is the voltage between two parallel planes separated by d and subject to the same limiting field E_{max}

expected improvement is lost. Letournel has fitted a few oval hoops near the terminals of horizontal tandems with intershields, in conjunction with terminals equal in radius to the column. The results are inconclusive. More recently, there has been renewed interest in hoops of noncircular cross section [12], but it is not clear whether the lower field translates into a voltage gain big enough to justify the added cost.

In calculating the fields on hoop surfaces, mechanical tolerances are usually neglected; the hoops are assumed to be truly planar and their supports rigid. Assuming the column gradient to be constant, there is then no net force between adjacent hoops. But in practice hoops are not always absolutely flat, and the supports may allow some movement about the correct position. Variations in the hoop spacing and column gradient then result in unbalanced forces, which may further deflect the hoops, increasing in strength as the displacement increases. In the extreme case hoops may approach close enough to spark or even touch. This is a compelling reason for choosing a pitch such that the hoop spacing is large compared with any mechanical tolerances.

5.2.6 Field Inside the Column

In the interior of an ideal column, there is a uniform longitudinal field. There should be no transverse field. In a real column, the situation is more complicated. Near the hoops, the longitudinal field and the transverse component vary cyclically across each pitch. The presence of electrodes and dead sections, in both the column structure and the accelerator tube, results in the field across the insulators being higher than the average longitudinal field. Variable charges on the belt or chain induce charges on neighboring conductors that result in fluctuating fields; and following breakdown, very large transient fields, both longitudinal and transverse, travel through the column, leading to secondary sparking and sometimes component damage. All these effects must be taken into account in the column design.

The column structure usually takes the form of a set of two or more legs, each made up of assemblies of insulator disks bonded to thin electrodes. The smaller the column pitch (the distance between each electrode and its neighbor), the greater the field that can be sustained across the insulator surface. In large machines, the hoop pitch is usually a multiple of the column pitch. In some small machines they may be equal. Typical values of column pitches are 40, 25, 20, 12.5 and 10 mm.

A potential divider is required to ensure that the longitudinal field is uniform. This may take the form of a resistor chain or a series of corona points. If the pitches of the column insulators and the tube insulators are the same, and that of the hoops the same or a multiple, a single potential divider may suffice. If the tube pitch is different, a separate divider will be needed. Even if the tube pitch is the same, a separate divider may be desirable to decouple the tube from the column except at the dead sections.

Radial fields inside the column are undesirable. In early machines, every pitch was separated from its neighbor by an equipotential plane. Current practice is to replace these with grading bars that surround the charging system and protect the resistor sticks from surges.

The accelerator tube usually limits the column gradient. This makes it the most critical component in the column. It must be protected from surge damage and decoupled from perturbations that could affect its potential distribution and deflect or defocus the beam. Placing the accelerator tube at the center of the column should minimize the effect of external or radial transients and possibly make it easier to screen. In small machines, however, lack of space may make this impractical. In folded tandems, the two tubes must be symmetrically disposed about the center. Many tandems have operated successfully at very high fields with tubes placed close to the hoops. The actual position seems to be less important than the relative positions of the tube, charging system and potential divider.

In large accelerators, a significant fraction of the column is taken up with dead sections containing mechanical structure, lenses or vacuum pumps. Extending the active length of the accelerator tube into these dead sections can increase the maximum voltage, by as much as 22% for an MP tandem. Care is needed to ensure that adequate clearance is maintained between the tube and the dead section and that suitable grading bars are incorporated to control the field distribution near the dead sections.

Charging systems – belts, chains and ladders (such as Pelletrons and Laddertrons) – are discussed elsewhere, in Chap. 6. They are usually surrounded by grading bars designed so that coupling between the charge they carry and the column components, especially the accelerator tube, is minimized. The field near the charging system is the resultant of the longitudinal field and the field due to the charge on the belt or chain itself. In the absence of grading bars between the two runs, there will be an attractive force between the opposite charges, and displacement of the belt or chain from a straight line. Belts are often restrained between pairs of grading bars separated by only a few mm. Alternate bars will carry ceramic rods to prevent charge transfer from the belt to the bars. This system overcomes belt flap, but at the cost of increasing surface wear.

5.3 Insulating Gases

The first electrostatic generators were insulated by ambient air, sometimes alfresco. The low dielectric strength of air was known and could be allowed for, but the effects of dirt and humidity were less predictable. Dust, foreign bodies and especially metallic particles can all initiate breakdown. Water vapor actually increases the dielectric strength of air, but water adsorbed by solid insulators leads to volume breakdown and surface tracking. The case for staying indoors, eliminating dust and relying on heating or air-conditioning to reduce moisture was early recognized, as was the fact that insulator performance could be improved by coating permeable materials with special varnishes.

The need for something better than air at one atmosphere was soon apparent. The next development was to increase the gas pressure. Early experiments with dry, compressed air confirmed the expected increase in voltage, but also revealed the benefit of adding electronegative vapor, when a small quantity of CCl_4 was accidentally added to the gas [13]. Subsequent experiments reminded the experimenters of the increased flammability of common materials in compressed oxygen. After a few minor fires, air was replaced with nitrogen to which a small percentage of an electronegative gas such as CO_2 or Freon was added. A mixture of 80% N_2 with 20% CO_2 continues to be a popular choice on the basis of cost, chemical inactivity and environmental acceptability. Freon and chlorofluorocarbons are more effective in trapping electrons but are also more corrosive; their use was declining even before it was prohibited.

The search for more effective gaseous insulators led to the production and use by the power industry of sulfur hexafluoride, a gas that combines the advantages of high dielectric strength, negligible chemical reactivity and nontoxicity. Christophorou [14] has reviewed its insulating properties. Typically used at pressures below 1 MPa, its breakdown strength exceeds that of N_2/CO_2 mixtures at more than twice the pressure. The low operating pressure reduces the cost of the accelerator tank and, coupled with the fact that it can be liquefied at room temperature, the size of the storage system. High cost and environmental regulations require that leakage from the tanks and transfer system must be strictly controlled. Oil-free pumps are required, since oil is soluble in liquid SF_6 and vice versa. Although itself nontoxic, some of its breakdown products are toxic and reactive, especially when water is present. Fortunately, the gas dryer and circulator needed for successful operation of a high-voltage accelerator are capable of handling this problem and of absorbing and deactivating the toxic breakdown products, such as S_2F_{10}.

The power of SF_6 to quench discharges and prevent breakdown has been extensively studied in the context of its use in power switches and interrupters [15]. These studies do not extend to the very high voltages, long gaps and large surface areas of tandem accelerators. Such measurements as have been made on these machines, usually in haste during the course of commissioning, are often inconsistent, affected by problems unrelated to the properties of clean, dry gas. Nevertheless, the variation of breakdown voltage with pressure, known to be nonlinear, can be estimated from data taken during commissioning and before installation of the accelerator tubes. By relating the pressure not to the voltage but to the field on the terminal, $E = V/(r_1 \ln(r_2/r_1))$, measurements from machines with voltage ratings between 10 and 25 MV and with a variety of terminal shapes and hoop configurations can be compared (Fig. 5.10). The results can be fitted, within a few percent, by the empirical formula $E = 18.6\,p^{0.60}$ (E in MV/m, p in MPa). The observed spread in breakdown voltage is less than would be predicted from the range of peak fields occurring in the different designs.

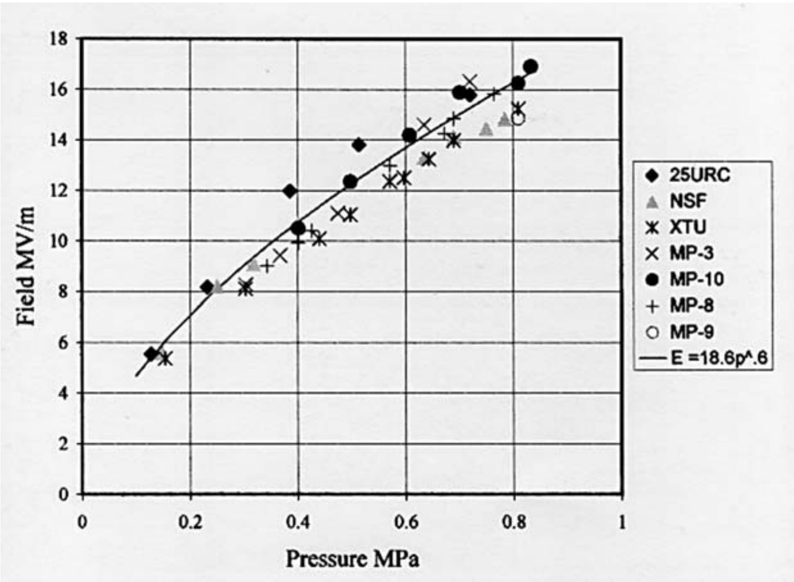

Fig. 5.10. Breakdown field v. pressure of SF_6 for large tandem accelerators

Descriptions of plant for transferring, purifying and drying insulating gas can be found in many reports of accelerator projects, together with accounts of problems experienced in operation, e.g. [16, 17].

5.4 Breakdown and Transient Phenomena

Electrical breakdown in gases is a phenomenon that has been the subject of intense study for over a century. Van Brunt's 1984 bibliography [18] is an important guide to this work. The process is rapid and complex, difficult to measure and sensitive to small changes in gas composition and electrode geometry. Even today, some aspects of breakdown in high-pressure SF_6 are not well understood. Extrapolating the results of laboratory experiments to the voltages and dimensions of large electrostatic accelerators requires a degree of faith and a measure of caution [19].

For the users and designers of electrostatic accelerators, the important questions are:

(a) what initiates breakdown?
(b) how do the pressure and composition of the gas affect the critical field at which breakdown takes place?
(c) what determines the subsequent course of the discharge after initiation?

As the peak field in a gas-insulated high-voltage generator increases, small ionization currents begin to flow. Measurable corona currents are generated by gas multiplication but do not develop into full discharges unless the local field increases above a critical value. Discharge takes place when the ionization coefficient equals or exceeds the attachment coefficient. The critical field at the point of discharge depends on the pressure, on the space charge due to the corona current and on the attachment time, which is very short in SF_6. A theory proposed by Morrow [20] explains the difference between breakdown in air and in SF_6 in terms of the different values of attachment coefficient and attachment time in these gases. The same model can be used to explain the difference between discharge properties in pure SF_6 and in mixtures with nitrogen and carbon dioxide.

For all these gas mixtures, high voltages can be sustained in the presence of large corona currents. Such currents are induced deliberately when corona stabilizers with sharp needle points are inserted into a region of high field between the tank and the terminal. The current that flows from the needles actually inhibits breakdown. The term "corona stabilization" is applied to this effect. But if the needles are blunt, the current decreases, the field increases, the critical condition is passed and breakdown follows. In a similar way, dust and foreign bodies can also trigger breakdowns. Loose metal objects in contact with a conductor, such as the tank, can become sufficiently charged by induction to levitate, move into a region of high field and initiate a spark. Horizontal machines especially suffer from this effect, since loose objects tend to migrate to the bottom of the tank below the terminal. Washers, small screws and even wire ends are enough to prevent stable operation. Insulators have much less effect. Dust particles and nonconducting debris acquire smaller induced charges and are less likely to levitate. One may contrast the behavior of well-conditioned accelerators that will run stably, even with large accumulations of high-resistivity belt dust, with the instabilities common in new machines that spark repeatedly at disappointingly low voltages because of contamination with rust, alumina or metallic debris.

Most breakdowns are initiated by particles randomly located near the tank wall and far from the high-voltage electrodes. Their development, as seen in photographs (Figs. 5.2 and 5.8), depends on the subsequent variation in time and space of the field distribution. The primary arc may lead to the nearest conductor, not necessarily to the point of highest static field. Secondary arcs reflect the field distribution at a later time. Loops can form when the field reverses. Machines that have suffered many breakdowns show a pattern of spark marks that extend over the whole terminal and some of the nearest hoops, with a density distribution related to the local field. This is part of the evidence for the area effect that predicts lower breakdown voltages for large electrodes than for small ones [21]. An empirical relation between breakdown voltage and electrode area for a range of SF_6 pressures was given graphically by Aitken and quoted by Joy [22]; see Fig. 5.11.

A spark between terminal and tank results in collapse of the terminal voltage and the flow of a very large current through an arc channel of low resistance and finite inductance. The tank and column act like a transmission line, and the initial voltage collapse is followed by a damped oscillation with a frequency of a few MHz. Attempts have been made to increase the damping by connecting the base of the column to the tank with resistors having the characteristic impedance of the tank and column, regarded as a transmission line. Disintegration of the first set of resistors that were tried in this way at Rochester showed that significant energy could be absorbed, but when more rugged resistors were fitted the overall benefit was marginal.

The energy stored by an accelerator at voltage is proportional to V^2 and to C, the capacity of the terminal and column to the tank. Since C increases with the length of the column, the total stored energy T varies as V^n, where $2 < n < 3$. Typical values for three different accelerators are:

1 MV analytical tandem for RBS	0.09	kJ
6 MV tandem for AMS	5	kJ
25 MV folded tandem for heavy-ion physics	150	kJ.

Putting this into more familiar terms, a tank spark in a 25 MV tandem is equivalent to vaporizing 10 g of aluminum, detonating 10 g of TNT or dropping 1.5 tonnes through 10 meters. Some of this stored energy is dissipated in the arc, some in the walls of the tank and some in the column. The tank is undamaged by the currents which flow through it. The gas recovers, with

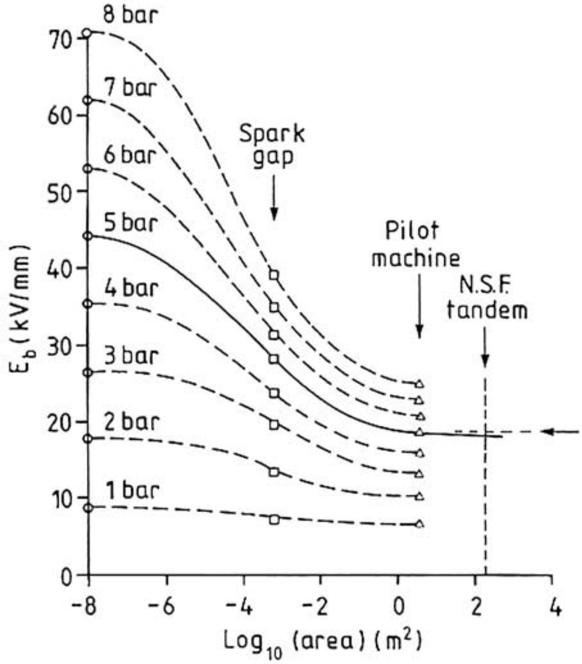

Fig. 5.11. Breakdown voltage v. electrode area at different SF_6 pressures (Reprinted from [22] copyright, (1990) with permission from Elsevier)

some production of unwanted breakdown products. SF_6 has the fortunate property that many of the breakdown products recombine. Sufficient spark energy is dissipated on the terminal or hoops to cause some melting [23], but the resulting craters have a negligible effect on voltage-holding. The dominating concern is the possible damage to column components resulting from the overvoltage that appears between the terminal (or hoop where the spark terminates) and the neighboring hoops.

Even the most cursory glance at Fig. 5.2 suggests that there is a random element in the way sparks develop. The process is also fast and complex, the large transient currents in the arc generating intense electromagnetic fields throughout the tank. There are no instruments capable of measuring these transient voltage distributions along the column. The best that can be done is to make reasonable assumptions about the origin and termination of the arc itself and to combine these with data on the delay times and overvoltages on the column spark gaps in a calculation of the subsequent generation and decay of the electromagnetic radiation. Staniforth [24] has calculated voltage surges in both single-ended and tandem accelerators and has estimated timescales and currents for primary and secondary breakdowns. Such simplified calculations identify the most vulnerable parts of the machine and underline the importance of transverse oscillations inside the column. They do not yet provide accurate and detailed descriptions of the whole process.

5.5 Protection from Surge Damage

A single component that fails in the terminal of a large tandem will interrupt the experimental program for several days, cost several hundred man-hours and involve the users in tedious repetition of calibrations and checks. Failures in industrial accelerators may have equally serious consequences for critical processes and production schedules. It is difficult to exaggerate the importance of protecting mechanical and electrical components from spark-induced damage.

5.5.1 Insulators

Column insulators, tube insulators, liner supports and electrical standoffs typically operate at voltages below 100 kV. They must be protected from overvoltages high enough to cause volume breakdown, surface tracking or even disintegration. Spherical or annular spark gaps, set to fire at two to three times the maximum operating voltage, are adequate for all but the fastest and most extreme surges, such as can develop in the column at the terminal-to-column and intershield-to-column junctions. Spark gaps must be closely spaced if they are to be fully effective, since the overvoltage rises if a change in direction of the discharge creates an inductive impedance to its path. Annular gaps do not suffer from this disadvantage, but the theoretical improvement in protection is not observed in some laboratory experiments. They do make cleaning and examination of the insulators more difficult.

The relatively low field along the column makes it unnecessary to convolute the external surfaces of column or tube insulators when operating in dry, compressed gas. The inner surfaces of tube insulators can benefit from tapering or convoluting, which helps to control surface charging and ion bombardment and thus improves voltage withstand. However, some convoluted surfaces are prone to physical damage if spark gaps fail to protect against fast-rising surges.

The dielectric constant of ceramics and glasses lies between 5 and 10. Bubbles and voids between insulators and electrodes therefore generate high fields, much greater than the average field in the column. If volume breakdown occurs in insulators, it is very likely to be initiated at these faults.

Many accelerators use long ungraded insulators as drive shafts, control rods and optical fibers for data transmission. A few designs rely on tension rods or plastic plates to support the column. The VIVITRON at Strasbourg depends on molded epoxy-resin posts to support the intershields and column.

With proper design, shafts and rods have been made to work reliably while sustaining voltages up to 5 MV. The choice of material is important. It must be homogeneous, free from defects, not hygroscopic and with consistent electrical characteristics. Methacrylates and polycarbonates are among the plastics of choice. Epoxy resins, loaded with silica or alumina flour, have been used where strength is critical. Glass-fiber-reinforced resins are also used where the anisotropy introduced by the fibers can be tolerated.

The most critical design feature in these components is the connection between the ends of the insulators and the metal structure. Screws and pins must be deeply recessed inside shaped electrodes surrounding the rod or plate. These electrodes must be thick and fully radiused so that the point of contact between insulator and metal is in a low-field region. The insulators must be located away from the spark gaps or other paths taken by discharges during surges. Surface charging must be minimized, and for this reason tubes and sheathed fibers are less reliable than solid rods and monofilaments. In some machines it has been found best to drape fiber-optics along the surface of grading bars or hoops, presumably thus ensuring a controlled field along the surface.

The use of post insulators is controversial. In particular, designs that rely on an internal boss to lower the field at the insulator/electrode junction cannot be relied on to survive surge overvoltages. When failure does occur, it may take the form of an undetectable track through the interior of the insulator, begun during a surge and developing during normal operation either to explosive disintegration of the post or to the point where the leakage current prevents continued operation. It is usually impractical to surround a post designed for several megavolts with protection in the form of a cylindrical metal shield and an annular spark gap.

Charging systems must support the full terminal voltage across their length. Grading may be possible at dead sections where they run over idler rollers or pulleys. In between dead sections, the normal practice is to surround them with grading bars that have the dual function of controlling coupling to the beam and shielding them from transient fields.

Pelletrons and Laddertrons are self-protected because the space between links acts as a spark gap for the insulating link inside. Belts do not have this protection. They usually run in a narrow slot between pairs of grading bars. In this geometry, the longitudinal field is closely controlled and belts that have been properly dried rarely suffer surge damage.

5.5.2 Electrical Components

Resistors or corona points acting as potential dividers are inevitably exposed to the field in the column. Corona points turn into spark gaps when subjected to large overvoltages; the result is to evaporate material from the points and alter the voltage/current characteristic. Resistor specifications rarely allow for overvoltages as large as those seen during tank sparks; when they occur, resistor values change and, in the end, resistors shatter or go open-circuit. Protection is vital.

Successive levels of resistor protection can be achieved by placing the assemblies between grading bars or equipotential plates; by radiusing the element end caps to prevent surface tracking; by surrounding the end of each resistor with a metal tube to lower the transient field; by incorporating a small inductance between the resistor and the grading bar; and, eventually, by surrounding each resistor string with a metallic tube, one end of which acts as an annular spark gap. Resistors using rare-earth inks on a solid ceramic substrate have survived years of operation undamaged at very high voltages with this degree of protection.

The protection of high-voltage power supplies feeding exposed components such as belt-charging screens, Pelletron inductors and electrostatic lenses requires circuits capable of attenuating surges with rise times of a few nanoseconds and amplitudes of hundreds of kilovolts. The circuits themselves must be immune to damage from the surges. The solution proposed by Johnstone [25] is to use two coaxial RC filters in series, the first preceded by a cylindrical spark gap and consisting of a low, noninductive resistance and a gas-insulated capacitor. This slows down the rising edge of the surge to the point where a second stage with a longer time constant can be used without risk of damage. A smaller version of this device can be used to protect conditioning circuits for column currents, takeoff currents and similar data inputs.

Motors and power supplies operating at line voltage can be protected with conventional screening and semiconductor surge limiters. Power and other leads must be routed so that they do not couple inductively to the high currents flowing during sparks. Connectors and wires need to be well recessed into the terminal or below the column base so as to avoid transient fields that can penetrate into these Faraday cages through apertures.

The most vulnerable components in an electrostatic accelerator are undoubtedly the semiconductors in the control and data transmission systems. Surge voltages in the terminal must be attenuated from megavolts down to volts in order to protect them. Two stages of screening are required to achieve this. One satisfactory design consists of nested aluminum boxes made of thick plate, ventilated by holes with a length-to-diameter ratio of 3:1, with access panels clamped over conductive gauze. In-line filters are fitted to every conductor where it enters or leaves either box. Power lines are fully screened and provided with surge filters before and after entry. Signal and output cables are contained within two coaxial screens, usually made of flexible bellows. Care is taken to avoid multiple earths and to connect the external screens with robust contacts, such as Conflat flanges. With such precautions, the record of reliable operation is impressive, many machines operating for years without a single surge-induced component failure.

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