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ACCELERATOR TUBES

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Résumé. — On a résumé les caractéristiques et les performances des tubes accélérateurs nécessités par la nouvelle génération de grands accélérateurs Tandem et par l'augmentation en performance des machines existantes.

Des expériences de décharge en surface des isolateurs dans le vide et le contrôle des charges de surface sont relatés brièvement. On examine les théories courantes sur les phénomènes de microdécharge et on discute leur application en fonctionnement dans l'ultravide et pour les tubes conventionnels. Le rôle des microparticules, la mise en évidence de leur existence et leur influence sur les décharges sont décrites à la lumière d'expériences récentes utilisant la diffusion laser et la microscopie électronique.

Enfin, on compare la pratique courante et les développements avec les données présentées en 1952 par Cranberg et avec certaines conclusions sur les progrès et développements futurs.

Abstract. — The characteristics and performance of accelerator tubes required by the new generation of large tandem accelerators and by the upgrading of existing machines are summarized.

Recent experiments on surface flashover of insulators in vacuum and on the control of surface charging are briefly reviewed. Current theories of the microdischarge process are examined and their relevance to the operation of UHV and conventional tubes is discussed. The role of microparticles, the evidence for their existence and their influence on breakdown is reported in the light of recent experiments using laser scattering and electron microscopy.

Finally, current practice and achievements are compared with the data presented by Cranberg in 1952 and some conclusions are drawn about future progress and developments.

1. Introduction. — The past few years have seen the progressive upgrading of many large Tandem accelerators and the construction and commissioning of a series of Pelletron machines [1]. These developments have made higher terminal voltages and a wider range of heavy ion beams available, with improved reliability, to the nuclear structure community. One essential aspect of this advance has been a significant improvement in accelerator tube performance. This has come about partly as a result of improvements in design and partly due to better understanding of the operational characteristics of large accelerators.

Nevertheless, most large accelerators have reached higher terminal voltages with the tubes absent than can safely be guaranteed with tubes and beam. Further improvements in tube design would therefore benefit existing accelerators as well as enhancing the performance or reducing the cost of new machines.

Progress in tube design comes about either by applying the results of laboratory experiments on vacuum insulation and breakdown or by using observations on working accelerators to identify and correct the inadequacies of existing designs. In the absence of a large accelerator devoted exclusively to development and testing, the value of operational observations is paramount and the need for adequate instrumentation and accurate recording is obvious and recognised. More sensitive diagnostic instru-

ments, fast telemetry and automatic data-logging all have a part to play. Fortunately, much can be done at modest cost.

Many different aspects of high voltage insulation in vacuum are at present under intensive study [2] because of the widespread applications of the technique. Some have no direct relevance to the design of accelerator tubes and most are limited to modest voltages (1 MV or less). Three processes of special importance in accelerator tubes, surface flashover, microparticles and microdischarges, are much better understood now than they were a few years ago and they are briefly discussed in the next three sections. A summary comparison of different tube designs is then used as a basis for comments on future developments.

2. Surface Breakdown. — It is well known that insulator surfaces break down at lower applied fields than those that can be sustained between smooth, clean conducting electrodes in vacuum. The evidence, in the form of hairline tracks across glass insulators, is familiar to most users of accelerator tubes. The consequences, as fine tracks develop with repeated breakdowns into eroded, conducting channels and even into shattered glass, are to place a limit on the voltage and life of operating tubes and to restrict freedom of operation in order to reduce breakdown frequency.

The mechanism of this and other types of surface

breakdown are still not fully understood but the recent work of Srivastava, Cross and other workers [3, 4, 5, 6, 7] has transformed our understanding of the phenomena and enabled insulator design to be put on a more scientific footing.

The electric field across an insulator surface between plane parallel electrodes is made up of three components, that due directly to the applied voltage, that due to dielectric polarization and that due to surface charging. Measurements with a field probe close to the electrode insulator vacuum interface [6] and using the deflection of an electron beam passing tangential to the insulator surface [4], are in good agreement with analytic [8] and Monte Carlo calculations [5]. They indicate an enhancement of the field at the cathode interface, depending on the dielectric constant of the insulator, which is sufficient to explain electron field emission at the applied fields achieved in accelerator tubes. Field emission at this point may be affected by the presence of adsorbed gas and will depend on the detailed geometry at the interface where, in addition to the electrode and the bulk insulator, there will be either an insulating layer of adhesive (usually polyvinyl acetate), a metallic bonding foil of aluminium, or worst of all a void due to imperfections in the bonding film. Bubbles in the glue film, sharp edges on the aluminium foil and failure of the bonding film to extend to the inner surface of the insulator all result in field enhancement.

The onset of field emission results in a further modification of the field. Some electrons emitted from the cathode interface may return to and strike the insulator. Secondary electrons will be then released and since the secondary emission coefficient is generally different from unity the surface will acquire charge. If the coefficient is greater than unity, the charge is positive and subsequent electrons will be more strongly attracted. This reduces the energy gained by the impinging electrons until the coefficient falls to one. At this point equilibrium is obtained, typically with a surface charge of $20\text{--}30\text{ }\mu\text{C.m}^{-2}$ for conventional accelerator tube gradients [4].

Surface charge is observed to build up to equilibrium within a few microseconds and to persist for minutes or even longer in good vacua ($\sim 10^{-4}\text{ Pa}$) after the applied voltage has been removed and in the absence of ionization.

The lower the energy at which the secondary emission coefficient becomes equal to one, the higher the equilibrium charge density on the insulator and the greater the field enhancement at the cathode. Trump *et al* [9] suggested that the charge density might be reduced by coating the insulator surface with carbon, which has a low secondary emission coefficient. Recently Sudarshan and Cross [10] have coated alumina insulators for which δ (the secondary emission coefficient) is 1 at 200 eV, rising to 6.4 at 650 eV and then slowly declining, with Cr_2O_3 , for which $\delta < 1$ at all energies. This should leave the surface negatively

charged, reducing the field at the cathode and repelling electrons. They report an increase in electrical strength of 2.7 and good resistance to repeated surging.

The effect of surface charges is modified by the geometry of the insulator. If the surface is not perpendicular to the electrodes the surface charge is reduced, in one case because the inclination prevents electrons from reaching the surface, in the other because the applied field combines with the field due to surface charge to increase the attractive force on the electrons. The effects are substantial and have been measured by Watson [11]. There is general agreement with calculation. Considerable use has of course been made of insulator profiles more complex than a truncated cone. Small scale tests on the flashover voltages of these complex shapes have often shown substantial improvements in performance over simple profiles [9, 12, 13]. In operation, the expected gains do not always materialise because of the development of insulator damage under transient conditions more severe than those of the tests. In addition to the hairline tracks referred to earlier, the insulator profile of figure 1 also

FIG. 1. — Insulator profile, showing paths of electrons and secondary ions.

gives rise to ion bombardment of the cathode, as evidenced by surface markings directly below the central protrusion. This effect must certainly be influenced by surface charge. Chipping of the glue film and pitting of the electrode is often observed at the cathode end of hairline tracks and is more serious with aluminium electrodes than with titanium or stainless steel (Figs. 2, 3, 4). The metal eroded from the pits is partly redeposited on the electrode and partly on the insulator, where it can eventually lead to failure of the section (Fig. 5).

The appearance of small cracks below the surface of the glass has been noted in several accelerators operating at high voltages. If allowed to develop, these cracks extend to the surface of the glass which then shatters (Fig. 6).

Re-entrant insulator profiles have gained favour in recent years as a solution to the modes of failure

FIG. 2. — Pit marks on an aluminium electrode/insulator interface after surface breakdown. Note the adjacent area of ion bombardment and a small aluminium flake.

FIG. 3. — Pit marks at the electrode/insulator interface of a stainless steel electrode. Note evidence for metal deposition near the pit.

FIG. 4. — Pit mark at the electrode/insulator interface of a titanium electrode. Note the area of ion bombardment.

described above. Calculations have shown that surface charging and polarization effects may be ameliorated by suitable concave profiles. Mechanical fragility and the susceptibility of sharp corners to electrical damage impose practical constraints on possible profiles. Nevertheless grooved insulators are much less prone to hairline tracking and to shattering and are now widely used.

FIG. 5. — Track marks and sputtered metal on insulator surface.

FIG. 6. — Shattered insulator after the development of hairline cracks.

As a result of recent experiments on single insulated sections, enough is now known about the static condition of stressed insulators to make scientific design possible. The ideal insulator has the following properties.

- (i) High volume breakdown strength.
- (ii) Low dielectric constant.
- (iii) Secondary emission coefficient $\delta < 1$.
- (iv) No voids in the adhesive film.
- (v) No sharp edges in the bonding foil or no stress raisers in the adhesive fillet.
- (vi) Insulator profile shaped to minimize the fields due to polarization and surface charge (if present).

In spite of useful advances made possible by high speed photography and fast electronics [7, 14], the processes occurring during transient over-voltages and breakdown are not yet fully understood and may depend on ill-defined factors such as the density and nature of adsorbed gas. Protection of the insulator by spark gaps is important and Marx generator impulse tests [15] indicate that suitable spark gaps do provide protection against large over-voltages, notwithstan-

ding the very rapid development of surface breakdown (≤ 1 ns) reported by Cross and Sudarshan [14] who have suggested that light from spark gaps might trigger surface discharges on translucent insulators. The observed distribution of track marks suggest that this is not important in practice.

3. Microparticles or clumps. — *Clumps* were originally postulated by Cranberg [16] to explain why large gaps tend to break down at lower field strengths than small gaps. Cranberg assumed that breakdown would follow the impact of an accelerated particle on an electrode, provided that the energy density over the area of impact exceeded a threshold value characteristic of the electrode being bombarded. He also assumed that the charge carried by the clump at the moment of detachment was proportional to the field strength. These two assumptions, if correct, give rise to the familiar proportionality of breakdown voltage to the square root of electrode separation.

The mechanism of microparticle triggered breakdown, the relative importance of microparticles in vacuum discharge phenomena, even the very existence of microparticles, have been the subject of continued theory and speculation since 1952. The difficulty of direct observation and the complexity of breakdown processes in general have contributed to the limited progress reported for many years. Recently, however, as a consequence of interest in the industrial applications of vacuum insulation, Chatterton [17], Srivastava [18] and other workers have developed quantitative theories for some of the possible breakdown mechanisms and have made observations of microparticles and their effects with the aid of electron microscopy and laser techniques.

What happens when a microparticle strikes a surface depends on its velocity, which in turn depends on its radius. Low velocity particles rebound elastically, but particles whose velocity exceeds the *plastic velocity* make inelastic collisions in which craters may form, melting and evaporation take place and the

surface may end up with lips or spikes from which enhanced field emission may take place [19]. The critical *plastic velocity*, v_p , depends only on the yield strength and density of the material. The values for three relevant materials are: aluminium - 0.32 km.s^{-1} ; stainless steel - 0.53 km.s^{-1} ; titanium - 1.2 km.s^{-1} [18].

These values can be used, together with the field strengths and gap lengths, to calculate the radii of the largest particles which can undergo inelastic collisions in different accelerators. Some data for large accelerators are given in table I. The superiority of titanium over stainless steel, and of stainless steel over aluminium, is apparent.

Four different types of microparticle impact can be described in terms of the terminal velocity v_t and the radius r [18].

(i) $v_t \gg v_p$, typically $r < 0.1 \text{ } \mu\text{m}$. Such particles vaporise on impact, but the quantity of vapour and ions released is too small to initiate breakdown.

(ii) $v_t \geq v_p$ $0.1 < r < 10 \text{ } \mu\text{m}$. These particles may cause local melting and some evaporation, liberating ions, atoms and liquid droplets. The more energetic particles in this range may produce enough gas and ionization to trigger breakdown. Lipped craters and protrusions may be formed giving rise to field enhancement and cathode instability.

(iii) $v_t < v_p$ $10 < r < 50 \text{ } \mu\text{m}$. These particles cannot gain sufficient energy in a single transit to trigger breakdown. Multiple bouncing impact with charge exchange permits them to acquire more energy and eventually to suffer inelastic collisions as in (ii).

(iv) $v_t < v_p$ $r > 50 \text{ } \mu\text{m}$. If a large slow microparticle approaches a small cathode protrusion the enhanced field between protrusion and particle may result in enough current flow for melting and evaporation to take place [17, 20]. The same process might occur between a microparticle with a protrusion and the anode.

TABLE I
Critical radii for inelastic microparticle impacts in large accelerators

Accelerator	Electrode Metal	Extent of trajectory and accelerating voltage							
		Single pitch		Sub-module or suppression length		Module or tube length		Total column	
		V	r	V	r	V	r	V	r
		MV	μm	MV	μm	MV	μm	MV	μm
MP	Aluminium	.035	.015	0.41	.18	2.5	1.08	10	4.3
MP (Upgraded)	S.S.	.041	.004	0.62	.049	3.75	0.30	15	1.19
MP (Upgraded)	Titanium	.041	.0014	0.62	.017	3.75	0.10	15	0.41
NEC (ORNL)	Titanium	.03	.001	0.33	.011	1.0	.034	25	0.86
NSF (Daresbury)	Titanium	.035	.0016	0.28	.013	1.67	.077	30	1.38

The significance of these four processes has been studied experimentally by observations of microparticles in flight and by examination of electrode surfaces before and after breakdown. The presence (or absence) of microparticles on a particular electrode material, prepared and operated in well-defined conditions, is not however proof of microparticle activity in other circumstances. Most direct observations have been made on small gaps (10 mm or less) with electrodes of very good surface finish. Several recent attempts to detect large microparticles ($r > 5 \mu\text{m}$) have been unsuccessful [21, 22]. It therefore seems unlikely that bouncing impacts or triggered discharges are frequent, at least in clean systems with good surface finish. The use of laser scattering techniques and electron microscopy have shown, however, that small particles ($< 3 \mu\text{m}$) are produced in abundance when voltage stresses are applied, even if the surfaces are smooth and clean and care is taken to limit the pre-breakdown current [19, 23, 24]. Jenkins and Chatterton [25] have studied the impulse breakdown of an 8 mm copper vacuum gap and found that breakdown is frequently preceded by the passage of a small microparticle ($\sim 0.2 \mu\text{m}$) travelling with a high velocity, up to $900 \text{ m}\cdot\text{s}^{-1}$. The process by which such small particles initiate breakdown is not yet established, but it is known that breakdown does not follow the much slower passage of larger particles. They were able to observe large numbers of small particles traversing the gap after a breakdown, the number depending on the size of the energy release. They also found that by successive spark conditioning the microparticle yield would fall to zero except when the gap was on the verge of breakdown. Other observers, using scanning electron microscopes, have observed the formation of craters with lips or protrusions and have been able to identify microparticles before detachment and to identify regions of field enhancement due to their impact [26]. These prolific small particles must be less tightly bound to the electrode than was calculated by Boulloud [27]. Beukema [19] has suggested that they arise from inclusions or polishing material in new electrodes and from frozen electrode material, transferred across the gap by spark conditioning, in well-established gaps.

In summary, large microparticles seem to be rare, but small particles are apparently easy to detach and are more likely to trigger off discharges on impact than simple models would suggest. The remedy is to use very clean, smooth titanium electrodes and to limit the maximum voltage through which particles can be accelerated.

4. Microdischarges. — A microdischarge is a self-limiting burst of current flowing in vacuum between electrodes at different potentials. The duration is between 10^{-5} to 10^{-2} second and the total charge 10^{-9} to 10^{-6} coulomb. McKibben and Boyer [28] first

suggested that an ion exchange avalanche process might explain the magnitude and time scale of the effect. Confirmation of this theory was supplied by Arnal [29], who observed the development of a discharge between a pair of inclined electrodes. He identified H^- ions and a variety of positive ions in the discharge. Mansfield [30] reported multiplication constants, K , for the ion regeneration process approaching unity in a realistic accelerator environment.

Gerasimenko [31] calculated that the discharge propagates and eventually collapses as the local density of contaminant atoms is reduced by the action of the discharge itself. This theory predicts a relationship between the growth rate, the size of the discharge and the residual density of the adsorbed layers. Singh and Chatterton [32] have used Monte Carlo methods to calculate the effect of spatial spreading of a discharge and conclude that microdischarges will not propagate unless initiated by a multiple event, and will decay when the discharge has extended to the boundaries of the electrode area. The shape of the pulse depends on the multiplication constant and the spread-time for the initial discharge to extend across the available area.

The broad conclusions of these theories are not in question, but the details are far from clear. Little is known about the effect of the composition and density of surface layers on the multiplication constant [33]. The exact factors that cause the discharge to quench and control the amplitude and duration of the current pulse are also uncertain. Equally the sequence of events which may cause a transition from microdischarge to complete vacuum breakdown is not well understood. The means of answering at least some of these questions are now available. The multiplication constant, K , is defined as $K = K_+ K_-$, where K_+ is the probability of a positive ion being liberated at the anode as a result of negative ion bombardment, and K_- is the probability of a negative ion being liberated at the cathode by positive ion bombardment. K must be greater than one for a microdischarge to develop. The effect of electrons in these processes has been shown to be unimportant. Under ion bombardment, atoms of the target material may be released by sputtering and atoms of surface contaminants by desorption. Both these processes depend on the mass and energy of the bombarding ion, on the nature of the surface and on the angle of impact. Sputtering yields typically exhibit maxima at energies of 10-100 keV. Desorption may be important at lower energies. Jurela [34] has measured the yield of positive (K_+) and negative (K_-) ions from metal targets bombarded by 45 keV argon ions. He was able to show a strong correlation between the positive ion yield and the ionization potential and between the negative ion yield and the attachment coefficient C_A . In fact the positive ion yield is proportional to $(I' - \phi)^{-1}$ where I' is a corrected ionization potential and ϕ is the work function. Some typical values are as follows:

TABLE II

Metal Z	K_+ ions/ion %	$(I' - \emptyset)^{-1}$ eV ⁻¹	K_- ions/ion %	C_a eV
C 6	0.027	0.17	0.024	1.27
Al 13	10	8.1	0.01	0.46
Ti 22	0.4	—	0.001	0.2
Fe 26	0.4	—	—	0.25
Cr 24	0.5	—	—	0.66
Ni 28	0.33	0.92	0.01	1.15

Assuming that the yield of secondary ions does not depend on the polarity of the bombarding particles, these numbers show that sputtering of the parent electrode material is unlikely to yield a value of K in excess of one. They also indicate that the multiplication process is asymmetric. In general $K_+ \gg K_-$.

By invoking the sputtering or desorption of impurities, especially adsorbed gases and vapours, much higher values of K may be expected. The production of positive ions for example is known to be enhanced by a surface layer of oxygen.

Our knowledge of negative ion production by sputtering and desorption has increased dramatically as a result of the invention and development of the Middleton sputter source [35]. In the course of this work prolific yields of negative ions have been obtained from many elements with large attachment coefficients. The effect of adsorbed vapours and surface layers of alkali metals in promoting negative ion yields has long been recognized. The catalytic action of caesium was first reported by Krohn [36]. Other alkali metals are also effective. Abdullayeva [37] has reported values of K_- greater than 2 for copper surfaces bombarded by caesium and continuously coated with sodium. Joy and Eastham ⁽¹⁾ have observed anomalous threshold energies for microdischarge initiation from surfaces contaminated with sodium by soda-glass bead cleaning. Positive sodium ions are released in profusion from the anode but it is probable that the more serious effect is the catalysis of negative ion formation at the cathode. Hydrocarbon vapours have long been suspected of promoting microdischarges, probably because of the prolific yield of C^- ions. Hydrogen, oxygen and ammonia also enhance negative ion yields in certain circumstances [38].

In conventional unbaked accelerator tubes, the conditioning process that accompanies microdischarges is largely reversible. Each discharge reduces the local contaminant density and therefore permits a higher stable voltage to be attained. However, many of the desorbed atoms will be readsorbed on other stressed surfaces within the accelerator tube. By increasing the surface density at the point of readsorption one microdischarge may trigger another in an

adjacent section of the accelerator. This effect is seen in a conditioning record of MP-7 at BNL (Fig. 7). The four traces are photomultiplier records of visible light emitted from the four low energy tube sections. Impurities with high sticking probabilities may take part in many discharges before leaving the stressed region. The chance of such particles ever reaching external residual gas analysers is small so that it is difficult to determine which species take part in the discharge.

FIG. 7. — Conditioning activity in the L. E. column of MP-7.

Two further factors are worth considering. Although adsorbed atoms may take part in many discharges, adsorbed molecules are likely to be decomposed by ion bombardment. Thus if deleterious hydrocarbons are released during the adhesive bonding process, microdischarge conditioning that decomposes them should be permanent. Similarly, oil vapours that enter the system during manufacture but are rigorously excluded under good vacuum conditions should be permanently removed by conditioning.

Secondly, observations on sputter sources have revealed prolific molecular negative ion beams. Such molecules may be important if the total energy available is sufficient to give them optimum velocities for high sputter yields (i.e. 10-100 keV/atom).

(1) T. Joy and D. A. Eastham, private communication.

Summarizing, microdischarges require adsorbed impurities and, probably, catalysts to augment the positive and especially the negative ion yields. The size of the discharges can be limited by reducing the electrode area on which a single discharge can feed and by controlling the rate of voltage rise so that the multiplication constant remains close to unity. Total activity must be controlled so that the pressure rise due to many simultaneous discharges does not permit voltage collapse. The correct choice of electrode material and the attainment of ultra-high vacua should ensure negligible gas release and freedom from electrode damage and metal deposition on insulators.

5. Present and future tube designs. — In 1952 Cranberg [16] collected data from many sources which supported his hypothesis that the performance of long accelerator tubes was controlled by *clumps* traversing the tube length and causing breakdown. Much thought and measurement has been devoted to overcoming the *total voltage effect* and some of the achievements of the past twenty-five years are presented in figure 8. Cranberg's original trend line, expressed as $V = kd^{1/2}$ where V is the voltage sustained across an insulated length d , is seen to fall below the performance achieved by the standard commercial accelerators of the past fifteen years. The upgraded accelerators and those using new technologies tend more nearly to a linear relation between voltage and distance, $V = k'd$.

Two contrasting designs of accelerator tube have evolved in response to the problems of high voltage insulation discussed in the previous sections. The design criteria for both types were formulated before many of today's large heavy ion accelerators were specified. Some of the contrasting features of these two designs are listed in table III, together with data relevant to the aluminium electrodes used at lower gradients. Many of these features arise from the choice of bonding agent.

The operating parameters of several large accelerators are given in table IV, from which it is clear that increases in scale have been accompanied by increases

TABLE III
Physical properties of accelerator tubes

Type	Conventional		UHV	
<i>Bonding agent</i>	PVA (AYAT resin)		Aluminium foil	
Thickness mm	0.015		0.1	
Bond strength MPa	30		49	
Dielectric constant	4		(conductor)	
<i>Insulator</i>	Borosilicate glass		High density alumina	
Coeff. of thermal expansion °C ⁻¹	3.8 × 10 ⁻⁶		7.6 × 10 ⁻⁶	
Elastic modulus GN/m ²	68		344	
Breaking strength MPa	35 — 140		360	
Log vol. resistivity Ω cm	> 10 ¹⁵		> 10 ¹⁴	
Dielectric constant	4.2		9.5	
Dielectric strength MV/m	120 — 180 [39]		50 — 70 [39]	
Secondary emission coefficient	3 (max) at 350 eV		8 (max) at 600 eV	
<i>Electrode</i>	Aluminium	S.S.	Titanium	
Coeff. of thermal expansion °C ⁻¹	2.3 × 10 ⁻⁵	9.3 × 10 ⁻⁶	7.9 × 10 ⁻⁶	
Elastic modulus GN/m ²	69	193	110	
Yield strength MPa	145	760	830	
Melting point °C	660	1 530	1 800	
<i>Construction</i>				
Pitch mm	18 (Oxford)	24 (HVEC)	10 (NSF)	11.7 (NEC)
Internal diameter mm	280	180,305	150	100
Profile	Convolute, concave		Recessed (?),	Flat
Sub-assembly length mm	1 830 — 2 440		140 (NSF)	170 (NEC)
Maximum temperature	60 °C		300 °C	
Working pressure Pa	< 7 × 10 ⁻⁴		< 1.3 × 10 ⁻⁵	
<i>Suppression</i>	Alternating or rotating transverse electrostatic field with auxiliary magnetic dipoles		Axial modulation of accelerating field with discrete apertures	
<i>Protection</i>	Discrete hemispherical spark gaps 4 mm		Annular spark gaps 3 mm	
<i>Grading</i>	Ohmic. 400 MΩ per pitch (typical)		Non-ohmic. Variable pressure corona points	

TABLE IV
Operating parameters of large electrostatic accelerators

Accelerator	Voltage MV	Thickness of insulator mm	Gradients MV/m		Ratio of Gradients Insulator/ Column
			Column	Insulator	
Oxford Injector	8	36	1.31	1.45	1.11
Oxford (Upgraded)	10	18	1.64	1.82	1.11
Oxford FOLTAN	12	18	1.97	2.18	1.11
MP	10	23.2	1.09	1.5	1.41
MP (Upgraded)	13	24.4	1.42	1.85	1.30
XTU	16	24.4	1.75	2.28	1.30
NEC (ANU)	14	12	1.64	2.53	1.54
NEC (ORNL)	25	12	1.32	2.34	1.77
NSF	30	10	1.68	3.48	2.07

FIG. 8. — Cranberg's plot of voltage vs. insulated length with subsequent data.

in gradient, especially in accelerators using axial field modulation to achieve suppression. These accelerators require a large overhead in column length to accommodate the lenses, pumps and structure made necessary by their inherent length. It is this trend which probably puts an economic barrier on the construction of even larger electrostatic accelerators.

Much of our present understanding of insulation and breakdown comes from experiments and theories completed since the present generation of accelerators were designed. It is therefore reasonable to expect that further improvements in performance may result from design changes made in the light of new knowledge and performance goals. Some of the possible areas for design improvement are indicated below.

Experience suggests that a small pitch increases the critical field strength for insulator breakdown. Because of the necessary minimum thickness of 1 mm

for electrodes, reduction of the present minimum ceramic pitch of 11 mm to 5.5 mm would increase the stress on the insulator by 10 %. It is questionable whether the improvement in performance would outweigh this. Doubling the number of insulators and electrodes would increase tube costs by 50 % or more. By contrast, reduction of the normal glass pitch from 25.4 mm to 12.7 mm is probably justified on technical grounds and presents few technical problems other than that of supporting a resistor chain or corona system decoupled from the column.

Further tests of insulator profiles are required, both small scale and operational, to establish the most rugged geometry for large accelerators. Large scale tests of coated insulators are needed to verify the benefits of Cr_2O_3 surfaces. This technique is likely to be more important in ceramic than in glass tubes, because of the lower dielectric constant and secondary emission coefficient of the latter.

The search for an inexpensive insulator, capable of high temperature bonding, transparent to facilitate quality control, mechanically and electrically strong and with low values of dielectric constant and secondary emission coefficient, should be pursued.

The use of transverse suppression fields in UHV tubes offers the possibility of dispensing with axial gradient modulation, a technique which necessarily increases the insulator stress above the mean axial gradient. In view of the sparsity of adsorbed gases, secondary loading in UHV tubes should be small and transverse electrostatic suppression should not introduce significant instability, provided that the internal diameter of the insulator is large enough to ensure adequate separation from any beam-initiated electrical activity. Because of the continuous removal of all secondary particles achieved by the use of spiral inclined fields this suppression system, combined with UHV conditions, offers the best prospect of transmitting very intense beams of heavy ions without total voltage effects.

Further studies of metal surfaces and the effect of different polishing treatments are desirable in order to confirm the apparent correlation of mechanical toughness with breakdown performance. The ideal process would leave the surface free of ionizing catalysts, loose particles and protrusions. The nature of any adsorbed layers should be such as to inhibit field emission.

Finally, the provision of vacuum pumping at frequent intervals and the ability to outgas tubes *in situ* at elevated temperatures would materially improve the performance with the heaviest beams at the highest voltages.

If progress in these areas continues at the rate achieved in the past few years, then the next twenty-five years may see the extrapolation of a linear vol-

tage/distance trend on Cranberg's plot, although it is doubtful if a further fourfold increase in voltage will be achieved, but the limitation will be economic and not technical.

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