LARGE ELECTROSTATIC ACCELERATORS

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INTRODUCTION

The increasing importance of energetic heavy ion beams in the study of atomic physics, nuclear physics, and materials science has partially or wholly motivated the construction of a new generation of large electrostatic accelerators designed to operate at terminal potentials of 20 MV or above. In this paper, I will briefly discuss the status of these new accelerators and also discuss several recent technological advances which may be expected to further improve their performance.

The paper will be divided into four parts: (1) a discussion of the motivation for the construction of large electrostatic accelerators, (2) a description and discussion of several large electrostatic accelerators which have been recently completed or are under construction, (3) a description of several recent innovations which may be expected to improve the performance of large electrostatic accelerators in the future, and (4) a description of an innovative new large electrostatic accelerator whose construction is scheduled to begin next year.

Due to time and space constraints, my discussion will be restricted to consideration of only tandem accelerators. For the same reason, I will not discuss the role of tandem accelerators as injectors, for both linear accelerators and cyclotrons, except to note that this is a frequent application.

MOTIVATION

The generic advantages of tandem accelerators have long been recognized. Specifically, tandem accelerators provide beams of low emittance (few π mm-mrad), low energy dispersion (order of 10^{-4}), and high intensity (10^{12} - 10^{13} particles/sec). Beam extraction and control are straightforward, while beam energy, species, and intensity are easily changed. With suitable pulsing and bunching, almost arbitrary beam time structure can be provided. Tandem accelerators typically use simple, low power ion sources. These sources are often long lived (order of weeks), have low feed material consumption rates (order of 1 mg/hour or less), and are quite versatile. To better illustrate this versatility, a list of beams[1] provided during the first full year of operation of the Nuclear Structure Facility at Daresbury is reproduced in Table 1. As can be seen, this list includes not only a large number of ion species, but the isotopically rare species ^{18}O, ^{36}S, and ^{48}Ca. The versatility indicated by this list is typical of the large facilities to be discussed below.

Table 1. Beams Provided at the Nuclear Structure Facility, Daresbury in 1983

Ion	Ion Source	Source Target	Source Gas	Injected Ion
^{1}H	Sputter	Ti	NH_3	H^-
^{4}He	Charge Exchange	—	He	He^-
^{6}Li	Sputter	Li	O_2	Li^-
^{7}Li	"	Li	O_2	Li^-
^{4}He	"	Be	O_2	BeO^-
^{9}Be	"	Be	NH_3	BeH^-
^{12}C	"	C	—	C^-
^{14}N	"	C	NH_3	CN^-
^{16}O	"	Mn	O_2	O^-
^{17}O	"	Mn	O_2	O^-
^{18}O	"	Mn	O_2	O^-
^{19}F	"	Ti	Arklone	F^-
^{24}Mg	"	Mg	NH_3	MgH^-
^{26}Mg	"	Mg	NH_3	MgH^-
^{26}Mg	"	Mg	O_2	MgO^-
^{28}Si	"	Si	—	Si^-
^{29}Si	"	Si	—	Si^-
^{32}S	"	PbS	—	S^-
^{34}S	"	PbS	—	S^-
^{36}S	"	PbS	—	S^-
^{36}S	"	S	—	S^-
^{48}Ca	"	Ca	NH_3	CaH^-
^{48}Ti	"	Ti	NH_3	TiH^-
^{48}Ti		Ti	O_2	TiO^-
^{51}V	"	V	O_2	VO^-
^{58}Ni	"	Ni	—	Ni^-
^{79}Br	"	Br	—	Br^-
^{92}Mo	"	Mo	O_2	MoO_2^-

The principal terminal voltage dependent property of tandem accelerators is beam energy. For light, fully stripped ions, beam energy is simply a linear function of terminal potential. For heavier, partially stripped ions, maximum beam energy rises faster than terminal potential since the charge state after terminal stripping is also a function of terminal potential. This is illustrated in Figure 1 where the ion mass which can be accelerated to the Coulomb barrier for that ion incident on ^{238}U (approximately 6 MeV/nucleon) is plotted as a function of terminal potential for four stripper combinations. Clearly, for tandem accelerators used as heavy ion accelerators, especially without boosters, there is a strong motivation to have as high a terminal potential as is possible.

LARGE TANDEM ACCELERATORS RECENTLY COMPLETED OR UNDER CONSTRUCTION

The large tandem accelerators which I will describe and discuss in this section are those which have a design terminal potential of 20 MV or more and which have either been completed or are under construction.[2] They are, in order of completion, the Holifield Heavy Ion Research Facility at Oak Ridge (ORNL), USA,[3-9] the Japan Atomic Energy Research Institute at Tokai, Japan (JAERI),[10-12] the Nuclear Structure Facility at Daresbury, UK,[13-17] and the Buenos Aires Tandem Accelerator Facility at Buenos Aires, Argentina (TANDAR).[18-20] Pertinent features of these facilities are summarized in Table 2. Notable features of these facilities include use of a folded configuration[3,21,22] in the ORNL and JAERI facilities, use of an intershield in the Daresbury facility, and use of terminal charge state separators.

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*Operated by U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

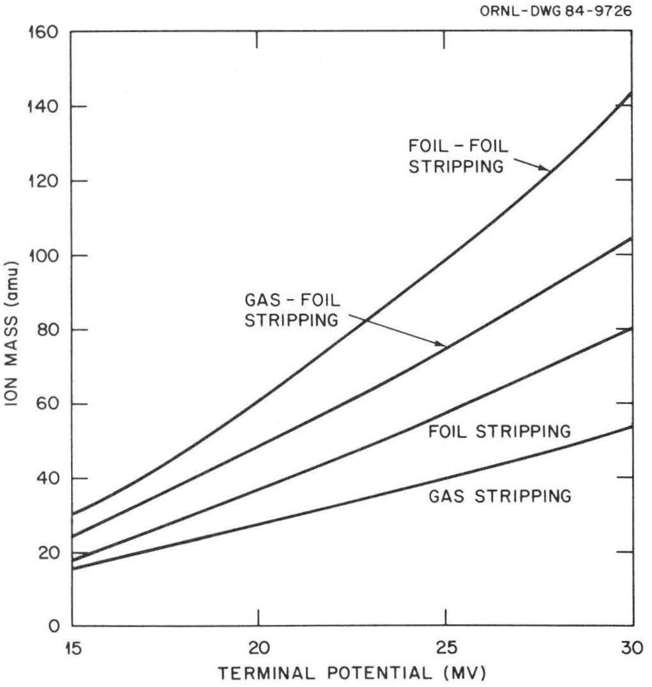

Fig. 1. The ion mass which can be accelerated in a tandem accelerator to the Coulomb barrier for that ion incident on ^{238}U (approximately 6 MeV/nucleon) is plotted as a function of terminal potential for four stripper combinations. Foil Stripping and Gas Stripping refer to a single terminal stripper. Gas-Foil Stripping and Foil-Foil Stripping refer to use of a terminal stripper of the type indicated plus a second foil stripper located at the two-thirds terminal potential position in the high-energy acceleration tube. These functions have been calculated using most probable charge states.

All of these accelerators use discrete element charging systems,[23,24] pure SF_6 insulating gas, and an acceleration tube technology based on alumina insulators and titanium electrodes.[23,25] All but the Daresbury accelerator have been manufactured by the National Electrostatics Corporation (NEC).[26] The ORNL accelerator is equipped with a k=100 cyclotron booster.[27] Figures 2, 3, and 4 show aspects of the Daresbury facility. Figure 5 is a photograph of the TANDAR facility under construction.

As indicated in Table 2, the ORNL, JAERI, and Daresbury facilities were completed in the summer of 1982. Each of these facilities has begun an active research program and each accelerator has demonstrated the generic advantages described above. It is especially gratifying to note that these machines are also exhibiting excellent reliability. For the ORNL accelerator, for example, it is not unusual to record only a few hours per month of unscheduled maintenance and multi-month intervals between tank openings.

Terminal voltage performance of these accelerators is summarized in Table 3. In each case, voltage tests of the column structures without acceleration tubes[6,7,11,16,20] show that the voltage capability of the column structure comfortably exceeds the initial design terminal potential. Unfortunately, voltage performance of the three completed accelerators with acceleration tubes has been, at least to the present time, somewhat less encouraging.[1,9,12,17,28-31] Both the ORNL and JAERI accelerators have experienced spark-induced deconditioning and gradual tube damage while the Daresbury accelerator has experienced more dramatic spark-induced tube damage requiring, on several occasions, replacement of tube modules.

To better understand this problem, it is useful to compare the performance of the three large accelerators to smaller accelerators. This has been done in Figure 6, where insulator gradient (i.e., the voltage per gap/insulator length per gap) has been plotted as a function of total active insulator length for several accelerators. In each case, the data points represent the highest gradient for which experiments have been performed. For the three new large accelerators, vertical lines also indicate the highest gradient for which the accelerator has been operated with beam. As an aside, it should be noted that for the ORNL accelerator, the highest terminal potential with beam of 22.5 MV is a recent result and that the large difference between this potential and the highest terminal potential for experiments, 19.0 MV, is an artifact of scheduling. Closed circles indicate accelerators utilizing alumina-titanium acceleration tubes.[32] Closed triangles indicate accelerators utilizing glass-stainless steel or, in the case of the Rochester MP, glass-titanium acceleration tubes.[33-38] The approximately horizontal line is an arbitrary trend line for accelerators utilizing alumina-titanium acceleration tubes.

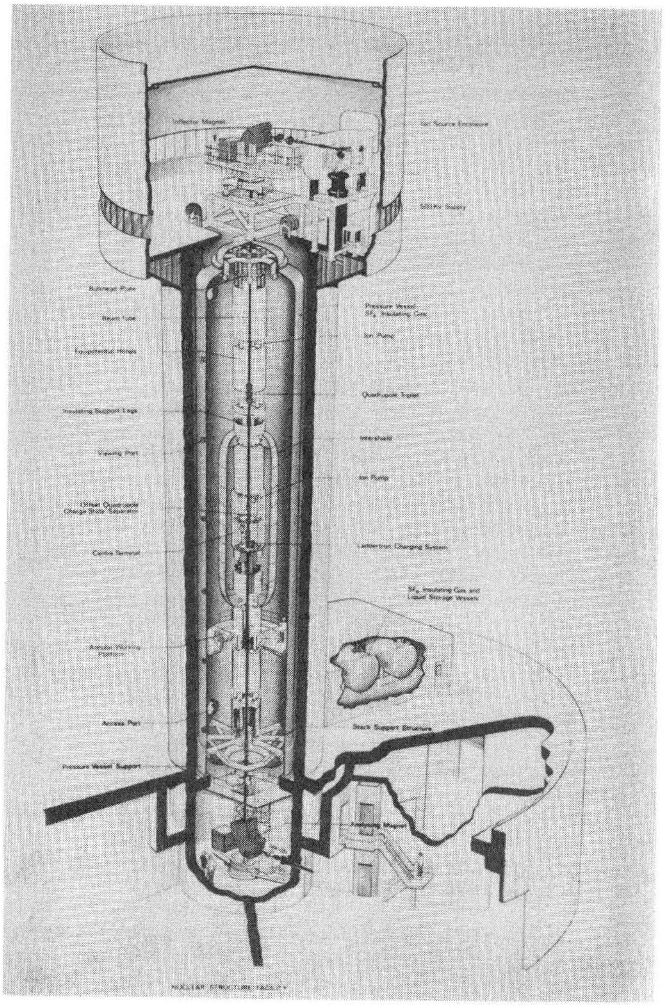

Fig. 2. Major components of the Daresbury Nuclear Structure Facility accelerator.

Table 2. Large Tandem Accelerators: Recently Completed or Under Construction

Facility	Holifield Heavy Ion Research Facility, Oak Ridge, USA (ORNL)	Japan Atomic Energy Research Institute, Tokai, Japan (JAERI)	Daresbury Laboratory Daresbury, England	Buenos Aires Tandem Accelerator Facility Buenos Aires, Argentina (TANDAR)
Completion Date	June '82	August '82	Sept. '82	Under Construction
Design Terminal Potential	25 MV	20 MV	23/30 MV	20 MV
Configuration	Folded	Folded	Linear (with intershield)	Linear
Charging System	Pelletron	Pelletron	Laddertron	Pelletron
Voltage Grading	Corona Points	Corona Points	Resistors	Corona Points
Insulating Gas	SF_6	SF_6	SF_6	SF_6
Acceleration Tube	Al_2O_3/Ti	Al_2O_3/Ti	Al_2O_3/Ti	Al_2O_3/Ti
Terminal Charge State Separator	180° Magnet	180° Magnet	Offset Magnetic Quadrupole Triplet	Offset Electrostatic Quadrupole Triplet
Lenses at Elevated Potential	3 (electrostatic)	5 (electrostatic)	3 (magnetic)	3 (electrostatic)
Manufacturer	NEC	NEC	Daresbury	NEC
Booster	Cyclotron (k = 100)	Linac Planned	Linac Planned	

Examination of Figure 6 shows a clear downward trend for accelerators utilizing alumina-titanium acceleration tubes — a trend that would be only weakly present if the corresponding data had been presented for glass-stainless steel tubes. At least three interrelated reasons have been suggested for this trend: The first is lack of maturity. In particular, it has been a consistent pattern that the performance of large electrostatic accelerators has improved with time. For example, the MP accelerator began operation at terminal potentials in the order of 10 MV, corresponding to an insulator gradient of about 15 kV/cm.[39] The second is statistics. As a generalization, performance is limited by the weakest element. As size is increased, there are more elements and a higher probability for the presence of weak elements. The third is electrostatic stored energy. When the accelerator sparks, most of the electrostatic energy is dissipated in the insulating gas. However, a small fraction is coupled into the acceleration tube with the consequent possibility of overvoltages, vacuum arcs, and insulator flashover.

Perhaps the most difficult of these problems is stored energy. Since stored energy is proportional to the product of capacitance and the square of the voltage, and since the capacitance of the column structure is roughly proportional to the column length, the total stored energy scales roughly as the product of the design terminal potential and the square of the actual terminal potential. Furthermore, the magnitude of the stored energy can be large. For example, the electrostatic stored energy in the ORNL accelerator at 20 MV is about 120 kJ.

At least three techniques may be used to reduce the effects of stored energy. The first is choice of a column configuration with lower capacitance. For example, for accelerators of the size of the ORNL accelerator, the folded configuration has about 30% less capacitance than the linear configuration. The second is reduction of coupling of stored energy into the acceleration tube. Important factors in this regard are thought to be the geometry and configuration of the column, tube location in the column, tube-column coupling elements, spark gap design, and the volume distribution of stored energy in the space between the column and tank.[40-41] The third technique is development of acceleration tubes which are more resistant to transient induced damage.[29]

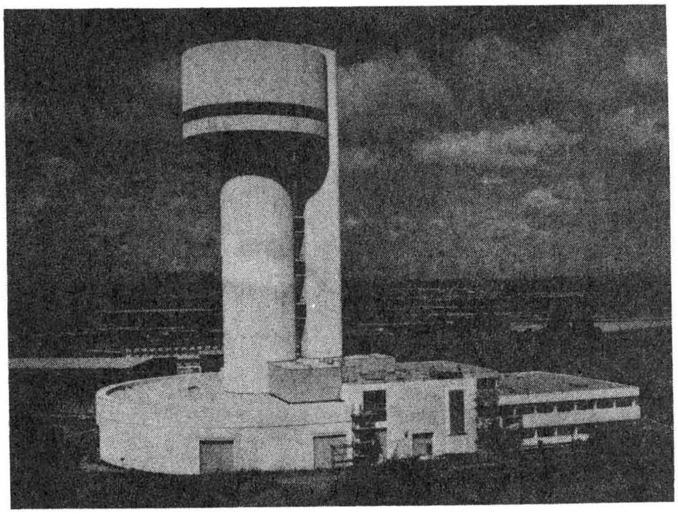

Fig. 3. External view of the Daresbury Nuclear Structure Facility under construction.

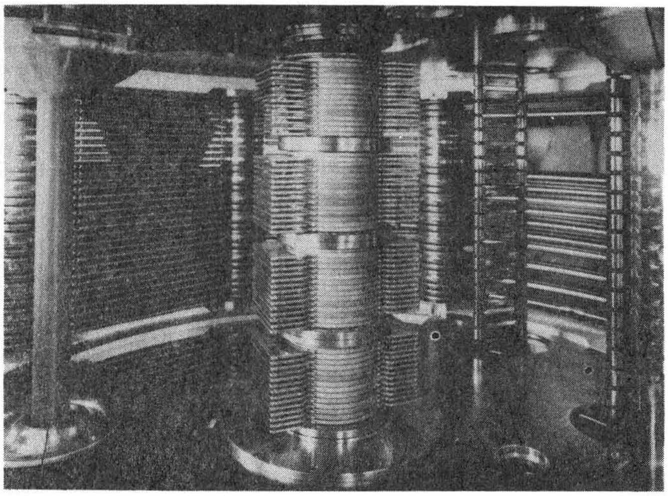

Fig. 4. An internal view of the Daresbury Nuclear Structure Facility column structure.

Active programs are now in progress, especially at ORNL[9] and Daresbury[29] to improve the voltage performance of the new large accelerators, and it is hoped that a continuing improvement in performance will reduce the negative slope of the trend line in Figure 6.

RECENT INNOVATIONS

In this section I wish to discuss several recent developments which may be expected to improve the performance of electrostatic accelerators in general and large electrostatic accelerators in particular.

Hydrogen Arc Discharge Cleaning

Low pressure hydrogen arc discharge cleaning of acceleration tubes was first demonstrated by Isoya et al.[42] and has subsequently been studied by Korschinek et al.[43] and by Stelson, Raatz and Ziegler.[44] An essential element of the technique is use of a separate thermonic emission cathode to provide electrons for the discharge. Typical parameters for the arc discharge are hydrogen pressure: 50 mTorr, arc current: 4 A, voltage drop: 3-4 V/cm, treatment time: 1-2 hours. Phenomena thought to be important are baking (with high electrode temperatures), sputtering, and chemical reactions (possibly with atomic hydrogen).

Fig. 5. External view of the Buenos Aires Tandem Accelerator Facility under construction.

Table 3. Voltage Performance of Large Tandem Accelerators

Facility	Holifield Heavy Ion Research Facility	Japan Atomic Energy Research Institute	Daresbury Laboratory	Buenos Aires Tandem Accelerator Facility
Design Terminal Potential (MV)	25	20	23/30	20
Highest Terminal Potential Without Acceleration Tubes (MV)	30.9	23.5	29.7	24.7
Highest Terminal Potential With Beam (MV)	22.5	18.5	20.1	—
Highest Terminal Potential for Experiments (MV)	19.0	18.0	19.2	—

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Results in small systems (up to 111 cm total insulator length) include substantial elevation of conditioning thresholds, typically from less than 22 kV/cm insulator gradient to more than 40 kV/cm insulator gradient, and minimization of deconditioning with time. In preliminary tests involving one section of the Munich MP accelerator (which is equipped with alumina-titanium tubes) an improvement in both maximum gradient and tolerance to sparks was observed. This technique is an example of a possible way in which an acceleration tube may be modified, in this case by cleaning, so as to better tolerate transients.

Increased Total Insulator Length

The basic idea of the developments to be described in this section is that for a given acceleration tube gradient, the terminal potential can be increased by increasing total insulator length. In the MP accelerator, this has been accomplished with an "extended tube" configuration first suggested by LeTournel.[35] In this configuration, the acceleration tubes are allowed to extend into dead sections, the terminal, and column ends to provide an increase in total insulator length of about 22%. To date, this configuration has been implemented at Brookhaven,[37] Strasbourg,[35] and Catania.[45] The results of this implementation at Brookhaven and Strasbourg are shown in Figure 6. Specifically, the maximum terminal potential at which experiments have been performed for MP 7 at Brookhaven has risen from 14.7 MV to 16.5 MV and at Strasbourg has risen from 13.1 MV to 16.0 MV (Strasbourg Phase I in Figure 6).

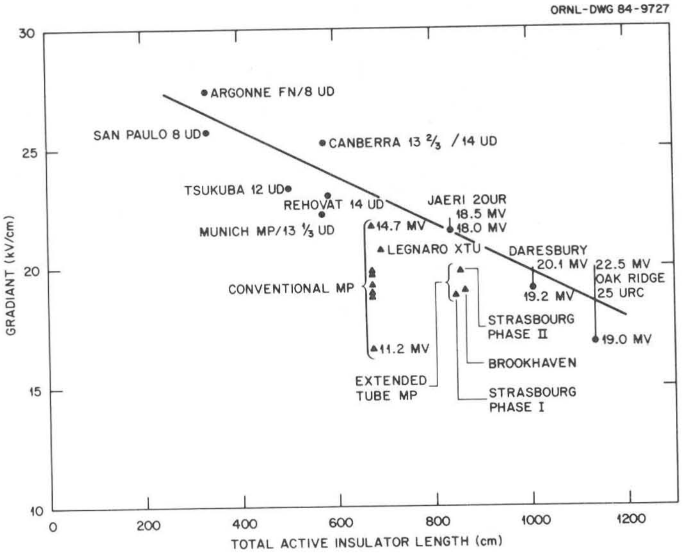

Fig. 6. Insulator gradient (voltage per gap/insulator length per gap) is plotted as a function of total active insulator length. Data points represent the highest gradient at which experiments have been performed. Closed circles indicate accelerators utilizing alumina-titanium acceleration tubes. Closed triangles indicate accelerators utilizing glass-stainless steel or glass-titanium acceleration tubes. Vertical lines indicate the highest gradient for which the accelerator has been operated with beam. The approximately horizontal line is an arbitrary trend line for accelerators utilizing alumina-titanium acceleration tubes.

For NEC acceleration tubes, a significant increase in active insulator length has been achieved in a "compressed geometry" configuration first implemented and tested by Assmann, Korschinek, and Munzer.[46] In this configuration, the approximately 3 cm long heatable aperture assembly which is located in the conventional NEC geometry on a 20 cm modulus is replaced by a simple aperture resulting in an approximately 18% reduction in tube length. The results of preliminary tests on a 111 cm insulator length acceleration tube with this configuration are encouraging. After hydrogen arc discharge cleaning, Assmann et al. were able to demonstrate stable operation at a gradient of 32 kV/cm total tube length (40 kV/cm insulator length), a factor of two higher than the normal operating gradient of 16 kV/cm total tube length which would be expected for a conventional NEC tube configuration. While gradients of this magnitude could not be expected for a large accelerator, due to stored energy effects, this result does suggest that a compressed geometry configuration may result in improved performance in large accelerators.

Discrete Electrode Intershields

This development, also based on work by LeTournel,[36,40,41] may be described as a discrete electrode intershield. LeTournel's insight is that an intershield does not have to be continuous. That is, a group of discrete electrodes can be arranged in the general configuration of an intershield and perform the same functions. These functions are reduction of surface fields and change in the spatial distribution of stored energy. The device has been named by LeTournel, a "portico." Figure 7 shows installation of a portico on the Strasbourg MP accelerator.

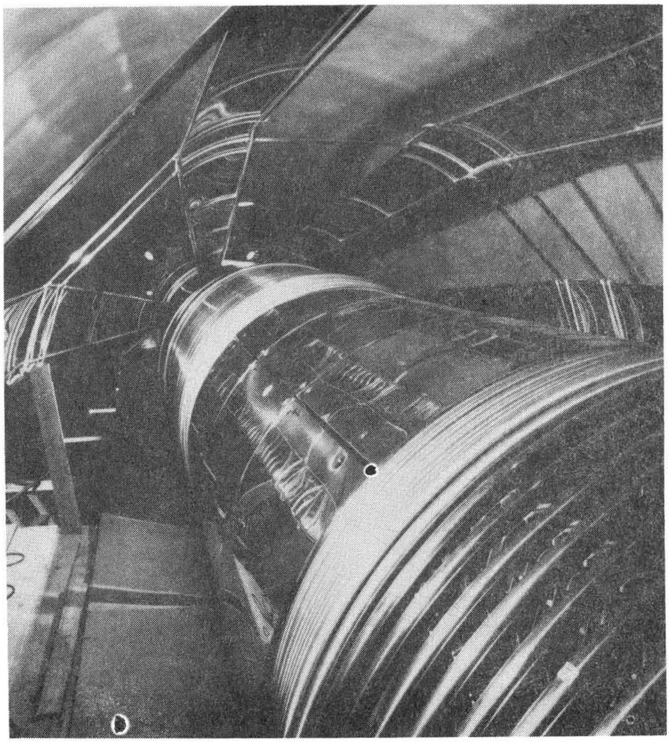

Fig. 7. A photograph of the Strasbourg MP accelerator portico during installation.

Porticos have been installed on MP accelerators at Strasbourg and Munich and installation of a portico on MP 7 at Brookhaven is planned for the summer of 1984. At this time, operating data is available only for the Strasbourg MP accelerator. The maximum terminal potential for which experiments have been performed has increased from 16 MV to 17 MV (Strasbourg Phase I to Strasbourg Phase II in Figure 6) and the maximum terminal potential achieved with beam has increased to 18 MV. In addition, the accelerator appears to better tolerate sparks at high terminal potential without tube damage. The portico appears to be a good example of a technique in which the effects of stored energy may be reduced by a redistribution of the spatial distribution of stored energy and possibly altered coupling of the stored energy into the column and tube structures.

ACCELERATORS OF THE FUTURE

When one considers accelerators significantly larger than those previously described in this paper, two problems become dominant. The first is stored energy. Stored energy is thought to make a significant, if not dominating, contribution to the reduction in achievable gradient which appears to be associated with increased active insulator length. (It should be noted again that this effect appears to be less pronounced for glass-stainless steel tubes.) The second problem is related to tank size. For conventional designs, the volume of the tank scales roughly as the cube of design terminal potential. With conventional design, significantly higher design terminal potentials result in tank sizes and insulating gas inventories which are prohibitively large.

Both of these problems have been addressed in a proposal for a 35 MV tandem accelerator now under serious consideration at Strasbourg.[41] As shown in Figure 8, this accelerator, which has been named "Vivitron" has a number of innovative features. Perhaps the most striking feature of the design is provision of a seven-layer portico which results in an approximately uniform radial electric field distribution which in turn allows a substantial reduction in tank diameter (in comparison to a more conventional design). Specifically, it is this technique, along with tapered ends, which results in a tank volume of only 1300 m^3, approximately 60% that of the ORNL and Daresbury accelerators. A second major design innovation is support of the portico structure and column by radial insulating posts.

The problem of stored energy in this accelerator has been addressed in two principal ways. The first is by provision of the portico structure which redistributes the stored energy into somewhat decoupled regions so that the full stored energy cannot easily be dissipated at one point. The second is by provision of a novel column structure in which the equipotential rings utilized in conventional designs are replaced with longer continuous covers which serve as large shields and spark gaps to protect the column interior.

Inclined field, glass-stainless steel acceleration tubes, manufactured by the High Voltage Engineering Corporation[47] will be utilized in the Vivitron. With a total insulator length of 2032 cm, they will operate at an insulator gradient of 17.2 kV/cm at the design terminal potential of 35 MV.

Construction of the Vivitron is scheduled to begin in 1985 and be completed in 1990. This accelerator, if successful, will clearly represent a significant advance in electrostatic accelerator technology and is a project which will be watched with great interest.

SUMMARY

The present generation of large tandem accelerators is, with one exception, complete and in routine operation. Each of the three completed accelerators has demonstrated an ability to provide high quality beams of a variety of ion species and has shown good reliability. Initial voltage performance of the completed accelerators has been somewhat disappointing in that none of the accelerators has yet achieved routine operation at design voltage. This problem is ascribed primarily to effects associated with electrostatic stored energy.

Several innovations which may be expected to improve the performance of electrostatic accelerators are now in the process of active study and development. These include low pressure hydrogen arc discharge cleaning, methods to increase the ratio of total insulator length to column length, and discrete electrode intershields. Construction of an especially innovative very large electrostatic accelerator is scheduled to begin in 1985. If successful, this new accelerator may be expected to have a profound effect on future electrostatic accelerator technology.

ACKNOWLEDGEMENTS

It is a pleasure to express my appreciation to the following individuals who have graciously provided information for this paper: W. Assmann, C. H. Goldie, F. Hass, G. Korschinek, M. LeTournel, M. A. J. Mariscotti, M. Maruyama, R. D. Rathmell, N. R. S. Tait, P. Thieberger, and P. Twin.

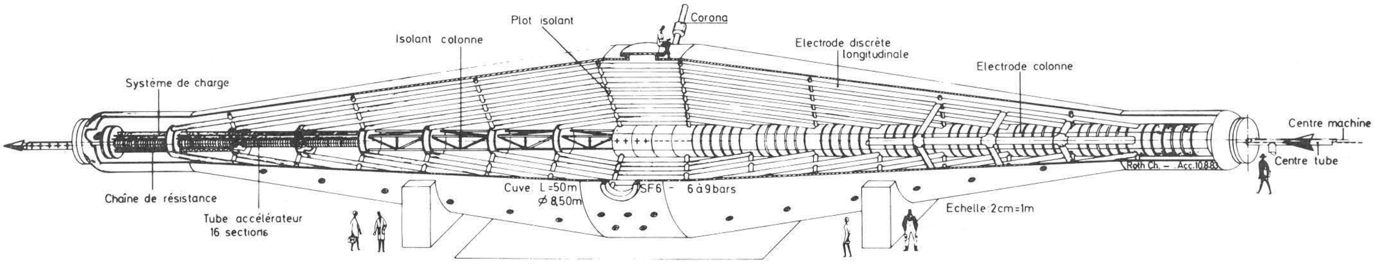

Fig. 8. Major elements of the proposed Strasbourg 35 MV Vivitron accelerator.

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CH1996-3/84/0000-0503 $1.00 © 1984 IEEE