NEW DEVELOPMENTS IN HIGH VOLTAGE TECHNOLOGY

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SUMMARY

The electrostatic and electromagnetic straight-line accelerators originated by Robert Van de Graaff for nuclear science have, for very heavy ions, moved toward the GeV level through advances in high voltage technology applied to the multi-stage (tandem) acceleration of multi-stripped ions. An account is given of the discreet steps in this exponential progress which depends basically on the maximum reliable voltage of one or a series of terminals. Recent studies on compressed gas insulation and on the control of electrical processes within long high-gradient acceleration tubes are described. These indicate the possibility of further substantial increases in terminal and column gradients applicable later to existing accelerators and to enlarged goals for new ones.

INTRODUCTION

In Rutherford's retiring presidential address to the Royal Society in 1927 he expressed his long felt hope for a more potent source of energetic heavy particles. That need for higher particle energy and beam intensity for nuclear structure research and high energy physics has since steadily intensified. Today, particle accelerator technology finds itself driven by the extraordinary accomplishments of nuclear science during the past 4 decades but impeded by the rapidly growing costs of large systems. It now faces the economic necessity of attaining higher particle energies by vastly improved acceleration methods and by substantial increases in the operating gradient and power density of the accelerating system.

It is thus appropriate that I discuss this afternoon several new lines of thought and developments in high voltage technology which can again upgrade our ability to produce more energetic particles in increasing numbers and in variety covering the entire atomic table, yet accurately selectable in energy, mass, and charge state.

ROBERT JEMISON VAN DE GRAAFF

I intend to center this discussion around the Van de Graaff accelerator, meaning thereby the system of electrostatic belt generator and tube which Robert Van de Graaff originated some 36 years ago, and which in these intervening years has attained international recognition as the precision source of nuclear projectiles for nuclear science. This familiar electrostatic high voltage source is now supplemented by the electromagnetic constant-potential source known as Insulated-Core-Transformer. This is the first embodiment of a new electromagnetic method of power generation and transformation originated and encouraged by Van de Graaff during the last decade of his life to meet the need which he forsaw for far greater increases in output particle energy and power. Indeed these new principles and techniques of managing electric and magnetic fields are again so direct and powerful that they can be applied not only to the production of intense high energy particle sources but also to the future energy conversion equipments of high voltage electric power systems, particularly those involving the higher voltages and the larger units of power.

Many of the members of this conference and of the world of physical science were saddened by the death of Robert Van de Graaff on January 16 of this year. I, who had the privilege of his teaching and inspiration and encouragement and warm friendship for many years, dedicate this presentation to Robert Jemison Van de Graaff with the deepest gratitude and appreciation.

THE EXPONENTIAL PROGRESS OF ELECTROSTATIC ACCELERATORS

Power density of electrical equipment refers to the output power per unit weight or unit volume. The electrical power systems of our country have been moving their power capacity and power density upward for more than eighty years with important accompanying advantages of efficiency and reliability. In particle accelerator technology the corresponding increases in particle energy and power density have been equally impressive and have come through a succession of definable steps.

The first great advance in power compactness came by the exploitation of the superior insulating properties of compressed gases. Through the work of Paschen, Natterer, Townsend, and many others the beneficial influence of higher gas pressures and of electronegative gas molecules were already appreciated at the time of Van de Graaff's dramatic innovation in 1930. Though the earliest Van de Graaffs were conveniently insulated in atmospheric air, the trend toward compressed gases was immediate and irreversible.[1]

The principle was well understood that an increase by the factor k in the dielectric strength of the medium surrounding a high voltage electrostatic system permits a k-fold reduction of all its linear dimensions. In the belt generator this superior dielectric also increases the permissible electric field arising from the conveyor belt charge. In the limit, such a better dielectric results in a k^3 reduction in the volume of the apparatus for the same voltage and generator power. Thus, long before the large air-insulated electrostatic accelerator at M.I.T. completed its two decades of research and was transferred to its present site at the Boston Museum of Science, equivalent pressure-insulated accelerators had become available which required less than 1 thousandth the volume to confine their electric fields. Far more important, of course, was the fact that this increasing voltage and power density made practical the attainment of higher particle energy.

The next major step in increasing particle energy while maintaining power density was the adoption of the tandem acceleration principle. In the tandem accelerator the polarity of the linearly accelerated particle is switched while passing through a high voltage terminal. This important concept, first proposed by W. H. Bennett,[2] had waited nearly two decades for the adequate emergence of both need and technology. Beginning in the early 50s, Van de Graaff, who as a Rhodes Scholar in J. J. Townsend's laboratory at Oxford had studied the mobility of gaseous ions, persuaded and fought and finally convinced his associates at High Voltage Engineering to adopt this method of multi-stage particle acceleration.

Applied to the acceleration of light uni-charged nuclear particles, the tandem polarity-switching method makes possible a two-fold energy gain with a single high voltage terminal. From a power density viewpoint - since the volume of a pressure-insulated high voltage system tends to vary with the cube of the voltage - the simplest two-stage application of the tandem principle doubles the output energy of singly-charged particles with less than a two-fold increase of tank volume.

An added advantage of far-reaching importance of the tandem method over the prior single-stage accelerators is the location, external to the tank-enclosed pressure-insulated high-gradient accelerating system, of the ion source and the initial beam-forming equipment. This vastly improves the flexibility and versatility of the ion injector at the same time increasing the reliability of the overall system. During the past ten years these benefits of two-stage tandem acceleration have been extended to scientists in a dozen countries where more than 40 Van de Graaff tandem accelerators are in active research or being installed in leading laboratories of nuclear science.

In his quest for far higher particle energies Van de Graaff devised three and four-stage tandems. The 3-stage tandem uses two accelerators in series, usually each in a separate tank and with opposite terminal polarities. The first or injector stage, initiates the acceleration process by producing a source of negative ions at the negative high voltage terminal. Although these negative ions could be formed by an ion source within the terminal, they are preferably formed by attachment of electrons to a directed stream of neutral particles originating outside the tank. The accelerated and focussed negative ions continue into the second tank and gain energy as they approach the positive terminal where conversion to positive ions by foil or gas stripping takes place. These positive ions return to ground potential during the third stage of acceleration and become available external to the tank as a parallel beam of essentially monoenergetic particles. The first such 3-stage Van de Graaff tandem accelerator with neutral beam injection designed for the production of up to 18 MeV protons is now near completion at the University of Pittsburg; another 3-stage system for still higher proton energies is following at the University of Washington.

The third outstandingly important step creatively advanced by Robert Van de Graaff during the past 10 years for the attainment of far higher heavy particle energies concerns the exploitation of the multiply-charged nature of most nuclear particles. This exploitation is just well begun.

It was characteristic of Van de Graaff that he could see, long before most others and with extraordinary physical clarity and intuition, the essence of a new physical approach and its consequences to nuclear science. Thereafter he would direct his planning and enthusiasm and persuasion to bringing about a demonstration of this new approach to the very limit then attainable.

For Van de Graaff the ultimate citadel to be assailed by energetic atomic particles were the nuclei of the heaviest atoms, particularly those of the uranium atom. As early as March of 1931, when he and his associates at M.I.T. were fully engaged in building the huge air-insulated generators at Round Hill, he had written in a report[3] for President Karl T. Compton "Homogeneous beams of protons of voltages that may be expected from the present work could be used for many simple experiments of fundamental nature. Among these would be an investigation of effect of their impacts on uranium and thorium. These nuclei are already unstable, and it would be interesting to see if an impacting proton of great speed would precipitate immediate disintegration. On the other hand it might be that the proton would be captured by the nucleus, thus opening up the possibility of creating new elements of atomic number greater than 92."

Van de Graaff never lost sight of this nuclear objective - the bombardment of uranium and even of transuranic nuclei. While nuclear structure physics remained occupied with the acceleration of the lightest group of atoms, Van de Graaff traversed the entire atomic table and decisively selected uranium as the nuclear projectile of most intense value. He vigorously advocated the bombardment of uranium by uranium as the most worthy first heavy particle experiment - the one both most likely to produce profoundly new nuclear information and most convincing in demonstrating the powerfulness of the straight-line high-gradient multi-stage multi-charged particle acceleration method.

Van de Graaff had been consciously working for more than a decade toward the day when a sufficiently powerful accelerator would be available for the multiple stripping of electrons from the uranium atom. With the EN tandem accelerator development with its guaranteed 5 million volt terminal reduced to practice at High Voltage Engineering, followed by the FN tandem and its 7.5 million volt terminal and then by the Emperor tandem accelerator with its 10 million volt terminal, the opportunity he had long sought and worked for came in sight. Such an Emperor tandem accelerator had become available as an engineering test bed at the Burlington plant where concurrent development effort had, not at all accidentally, also produced a diode uranium ion source and other beam-controlling instrumentation.

URANIUM ON URANIUM - "THE SUMMER PROGRAM OF 1966"

The intense, often three-shift research program which Van inspired and directed as a nuclear scientist at the High Voltage Engineering Corporation this past summer and fall of 1966 was to be his greatest personal assault on the uranium nuclear citadel. Like a skillful general Van de Graaff had assembled an able team of scientists, engineers and technicians from HVEC and M.I.T. With his associates he had planned with great care the tactics and instrumentation which would maximize the nuclear information attainable in the relatively short time allotted to this tremendous effort. Van knew that at the very minimum the crash research program would gain information and experience invaluable for the next more powerful attempt. It could not fail to produce new quantitative information on the number of electrons stripped from uranium atoms as a function of their energy, on the relative stripping performance of foil and gas targets, on the range-energy relation of uranium and other heavy particles. It would also demonstrate the new selector which, by the sequential use of magnetic and electric fields, would once again restore to the output end of the multi-stripped Emperor tandem the 'directed beam of nuclear particles homogeneous in mass, energy, and charge' which he regarded as indispensible for good research.

Further, Van expected, with support from other nuclear physicists, that even in this first research trial the uranium projectiles would cause coulomb excitation of the bombarded uranium nuclei. At the very most - a real long chance at this stage - Van hoped the energy of the accelerated uranium projectiles might conceivably reach the threshhold at which the fission of the bombarded uranium nuclei was possible.

The results of this exciting summer program are not part of this paper. I can summarize by saying that with the single 2-stage Emperor tandem uranium atoms reached energies well in excess of 200 MeV but inadequate for uranium fission. The newly designed homogeneous beam selector performed perfectly from the start. As many as 50 electrons were removed from accelerated uranium atoms. Important new data on the range and stripping coefficients of very heavy particles moving through matter were obtained as well as valuable operational system experience.

Robert Van de Graaff's vision to build and use a far more powerful experimental tandem is now an active program of the High Voltage Engineering Corporation. This accelerator, the XTU, will be placed in line with the present Emperor facility. This 3-stage tandem combination, with multiple stripping, will have the possibility of producing uranium atoms with energies approaching 1 billion electron-volts. As this energy is achieved and exceeded the prospect includes not only the fission but the fusion of two uranium nuclei. The inevitable disintegration of such an extraordinarily energetic compound nucleus could produce, as Van de Graaff had predicted in 1931, new combinations of matter including possibly transuranic elements. This, as he wrote again in August 1966, would be a "new type of exothermic nuclear reaction greatly exceeding uranium fission in the energy release per fused nucleus."[4]

THE INSULATION OF VERY HIGH VOLTAGE TERMINALS

The foregoing presents both background and justification for my discussion of new developments in high voltage technology. For, though by multi-stage and multi-stripping means the ultimate heavy particle energy can surpass the GeV level, the output particle energy of all direct straight-line accelerators continues to depend basically on the steady reliable and controllable potential of one or a series of high voltage terminals along the path of the accelerating particle. It is therefore on developments in the insulation of such high voltage terminals and their associated acceleration tubes that I propose now to direct my remarks.

COMPRESSED GAS INSULATION

There is no need to review the extensive investigative effort in which many laboratories have joined to improve the understanding and the dielectric performance of both ordinary and electronegative gases at elevated pressures. It is more relevent to inquire how far have we come in these past thirty years in the application of compressed gases to high voltage systems and where can we look for further substantial gains.

Not forgetting the importance of high pressure gas in the cooling of the huge ac alternators and in extinguishing the arcs in the circuit breakers of electric power systems, it can be asserted that up to now compressed-gas-insulation has received its most dramatic and extensive utilization for the insulation of Van de Graaff accelerators. During 1966 several Emperor accelerators, beginning with the Emperor tandem at the HVEC and continuing with the Emperor accelerators at New Haven, Rochester, Chalk River, and Minnesota, with their positive terminals and columns insulated in about 15 atmospheres of N_2 and CO_2, have operated at constant voltage levels often well in excess of the guaranteed 10 million volts. At this operating level the voltage gradient lengthwise the acceleration tubes, charge-conveying belt, and terminal-supporting columns has the average value of 35 kV per inch or 420 kV per foot. It is my belief that these present operating gradients along the columns and tubes of Van de Graaff accelerators can in due course be at least doubled and possibly tripled as a consequence of R & D thought and effort now underway.

In voltage tests at Chalk River using sulphur hexafluoride (SF_6) at 85 psi in the Emperor system prior to the installation of the acceleration tubes, it was possible, with gamma ray irradiation of the gaseous region around the terminal, to condition the positive terminal to the 14 MV level. The addition of other procedures to be described enabled a maximum voltage close to 15 MV to be attained during the test period. Negative terminal operation in these tests was found to be distinctly more limited than positive and was much less improved by the same irradiation procedure.

I am confident that these levels of terminal-to-tank voltage insulation, though they represent the highest voltage yet obtained by man, can be substantially bettered. There are reasons for believing that it may in due course become possible to as much as double the present operating gradients in the gas-filled gap for the same gas and pressure. At the same time it is expected that negative terminal performance will more closely match that of positive terminal.

Most of us are aware that the maximum voltage that can be reliably insulated between the electrodes of a compressed-gas-filled system falls considerably below the intrinsic strength of the gaseous medium. This disparity increases the more ambitious the voltage and the larger the system. To explain this costly fractional performance we are likely to cite a number of influential factors. We draw attention to the large electrode areas, to the rapid increase of the electrostatically-stored energy with voltage and size, and to the gradient amplifications arising both from the gross electrode geometry and from minute imperfections on the metallic electrode surfaces.

As higher gas pressure enables the electric field intensity to climb into the hundreds of kV per inch, we refer learnedly to heightened photo-ionization in the gas volume and to the onset of high-field electron emission from the cathode surface. The diffusion of ions is reduced at the higher gas densities. This contributes to the increased space-charge distortion of the electric field and assists in the formation of positive-ion streamers - the high speed transient step toward sparkover.

With larger systems we are assured by statistical reasoning that the variations from average performance become inevitably greater. Electrode conditioning by sustained electric stress becomes both more time-consuming and more likely to lead to irreversible adverse electrode changes. Escape from electrical instabilities caused by free conducting particulates and semi-conducting fibres - DIRT - becomes more nearly impossible. These and other explanations are invoked to account for the departure of very high voltage systems from the predictions of the relatively small nearly perfect academic gaps on which much of our knowledge of the intrinsic strength of gases is based.

Most of these explanations, though valid descriptions of basic electrical processes, are not the present unsurmountable barrier to improved exploitation of the gaseous medium. Studies during the past several years at M.I.T. and HVEC support my conviction that new insights into the causes and control of instabilities in large compressed-gas-insulated systems can bring about substantial gains in the utilization of the inherently high insulation strength of such gases. If these gains materialize they will increase the attainable voltage of new equipment and can be applied retroactively to existing systems.

The first of these studies is related to that conspicuous trouble maker in all dielectric media - the detached and mobile conducting particle. In a horizontal concentric cylindrical system such as an electrostatic accelerator or a transmission line, such free solid bodies are permanently trapped in the radial field unless they fortuitously originate near an outwardly fringing field at either end. The particle acquires by contact and induction a charge q related to its geometry and the local field E at the electrode surface. Urged by the electrostatic force qE, the particle leaves its electrode and traverses the gaseous gap. There it reverses its polarity by contact with the opposite electrode and repeats the process. Such conducting particulates may traverse a typical high voltage gap scores of times per second and thus constitute a measurably current loss. On the other hand they may remain at and near one electrode surface in a kind of mobile dynamic equilibrium involving polarity reversals by repeated charge exchanges at the electrode and in the nearby gas.

Far more important to compressed gas performance is the fact that such particles, while attached to an electrode surface at high gradient, constitute projections which deliver a field-distorting current and space charge into the gaseous region. It is this acute disturbance of the electric field distribution which leads to electrical instability and sparkover.

The M.I.T. experiment introduced conducting particles into a long horizontal concentric-cylinder pressure-insulated transmission line previously held to a steady quiescent voltage and gradient. This injection immediately precipitated corona and sparkover and lowered the operating level to approximately 60%. The trapped condition of these particulates was also made clear by the inability to improve the system performance either by sustained maintenance of electric stress or by repeated sparkover. Qualitatively similar results were obtained for particulates ranging in size from 100 Å carbon spheroids to aluminum chips averaging 75 microns in their maximum dimension.

I shall mention three distinct techniques for inactivating the free conducting particles in a gaseous gap. First I wish to refer to the removal method which has been reduced to practice at HVEC and which was part of the M.I.T. studies, the electrostatic precipitation of the particles and their entrappment in a specially provided low field region. This can be done most conveniently by installing a multi-perforated electrode inside of and spaced from the grounded tank wall so as to cover a substantial part of the bottom surface of the tank. In their repeated traverses across the gas-filled gap the unwanted particle will soon pass through an aperture into the shielded space beneath. At the shielded tank surface, by proper geometrical design, the electric field intensity can easily be reduced by a factor of 10^3 and more. The electrical force acting to lift the particle out of the trap is therefore diminished by the square of this factor.

This precipitation method was studied at M.I.T. It was found that instabilities caused by the sudden injection of particulates cleared up in an average time of 20 sec. after which the serenity and voltage-insulating capability of the system was restored.

A second method of inactivating these ubiquitous trouble makers which has been studied and utilized at HVEC makes use of the irradiation of the gaseous region surrounding the high voltage terminal with X-rays or gamma rays. This method appears to become effective the moment the radiation is introduced and terminates soon after the ionization is removed. It may be significant that the highest Emperor voltages, in the 14 to 15 MV range were insulated at Chalk River when both the electrostatic precipitator and the irradiation were active.

Among several explanations for the inactivation of microscopic conducting particles by ionizing radiation, the one that appeals most to me makes use of the neutralization of the charged fragments by attachment of positive or negative ions during their passage through the gas. This dramatic influence of ionization in the gas volume on the voltage stability and performance does not necessarily require the introduction of an artificial radiation source. In many particle accelerators the ionizing radiation produced along the length of the acceleration tube or in the vicinity of its anode electrodes is adequate to perform this valuable function. Unfortunately, irradiation appears to be less effective when the high gradient surface is of negative polarity.

THE DIELECTRIC ELECTRODE SURFACE

A new development which may have important consequences for gas-insulated particle accelerators involves the substitution of a selected dielectric surface for the conventional metallic electrodes. In electrostatic high voltage systems the metallic electrodes have the primary function of defining the electric field distribution. The conductivity requirement of the electrode is minimal and is satisfied sufficiently if the electrode follows with a reasonable time constant the voltage variations which are an operational requirement. Yet electrostatic high voltage systems have traditionally used metallic surfaces to acquire and hold the surface charges and thus determine the electric field distribution between terminal and ground. The high electrical conductivity of these metallic electrodes is related to the need for absolute surface smoothness and for the avoidance of microscopic conducting projections.

Recent studies have examined the effect of placing a dielectric coating of considerable thickness over one or both of the opposing electrode surfaces. Although this dielectric coating was itself adequate to withhold potentials of several hundred kV or more, the dielectric thickness was small in comparison with the interelectrode gap and the selected resistivity of the dielectric was such that substantially all of the voltage would be insulated across the gas-filled gap under all conditions.

In a uniform field test with small electrodes in compressed gas using dc voltages up to 1 MV it was found that the gaseous gap could be reduced by a factor of 2 by dielectric coating one of the two opposing electrodes. With dielectric surfaces on both electrodes a further gap reduction of 2 was obtained. The interelectrode current at the maximum sustained voltage was such that the calculated gradient in the two dielectric layers was below 10^4 volts per inch. In the case of the two dielectric electrodes the calculated gradient across the gas-filled gap for a N_2 - CO_2 mixture at 300 psi was over 3 MV per inch.

ACCELERATION TUBE STUDIES

Most practitioners of direct particle acceleration agree that the insulating strength along the evacuated interior of the acceleration tube constitutes the most formidable limitation in present system performance. The investigation of the factors which affect acceleration tube performance and the study of methods of securing higher tube voltages and gradients therefore became the highest priority objective of a broad study program at HVEC called HETA. The Greek goddess connotation of the name HETA is coincidental; these four letters referred originally to HIGH GRADIENT TEST APPARATUS - the 4 MV test system specially designed to supply rapid realistic answers to searching questions about insulation performance in compressed gases and in high vacuum. The avowed goal of this HETA program, which has been in progress for the past 3 years, is the attainment of operating gradients of 100kV per inch along the insulating length of long tubes.

These studies first examined the flashover strength along solid insulator surfaces of single glass tube sections with internal vacuum. I can now report that there has been accumulated solid experimental support for expecting a reliable d-c flashover strength across such individual tube rings of over 150 kV per inch with surface flashover strengths above 250 kV per inch often predictably obtained. Thus an important but not sufficient prerequisite to high voltage high-gradient tube performance has been realized.

Further studies on the HETA project were directed at electrode-to-electrode strength in high vacuum and included the comparative examination of several materials notably aluminum and 304 stainless steel. This work confirmed that, after suitable conditioning, polished stainless steel electrodes could insulate up to 300 kV across a 1 inch parallel gap with less than 10^{-9} amp. of average current and less than 1 spark in a 10 minute interval. Aluminum electrodes could be brought to this level with more difficulty, were more subject to irreversible retrogressive changes under conditioning procedures, and showed a far greater tendency to evaporate metal under sparkover. The practical superiority of stainless steel over aluminum for very high gradient applications has since been confirmed on HVEC test tubes both without and with intense positive ion beams.

The HETA project then proceeded to examine a variety of methods by which this high performance of individual tube sections could be maintained in the high voltage series structure which constitutes the modern acceleration tube.

Among these total-voltage controlling methods were the INCLINED FIELD TUBE principles originated by Van de Graaff a decade ago. These inclined field methods may use either electric or magnetic fields or a combination of them. The fields purposefully contain a transverse component which deflects unwanted low energy secondary electrons and ions into the metallic electrodes; the direction of the transverse field is periodically reversed so as to permit the essentially undisturbed passage of the particle beam undergoing acceleration.

The HETA studies have now added further confirmation of the effectiveness of the inclined field method in preventing secondary electrons and ions from gaining more than a small fraction of the total tube voltage. Inclined field tubes invariably have a vastly reduced X-ray background. HETA studies on inclined field tubes have repeatedly shown a linear relationship between tube voltage and tube length. The improved surface flashover and electrode-electrode configurations, combined with the inclined field principle, have been tested with encouraging indications that working gradients of 100 kV per inch on long acceleration tubes can be attained.

The HETA program has included a careful analysis of the electrical processes dependent on voltage and gradient which act within a long high-gradient acceleration tube to produce the steady or transient disturbances which ultimately limit the tube's voltage and beam capability. These processes include:

1. Ionization of residual gas by the positive, negative, or neutral beam.
2. Scattering of the primary beam by residual gas and by faulty beam optics.
3. Secondary emission of electrons from negative electrode surfaces bombarded by scattered positive ions.
4. High field emission from negative electrode surfaces.
5. X-ray emission from electron-bombarded surfaces. These X-rays, acting on the surrounding compressed gas, may seriously alter the voltage distribution along the accelerator column.
6. Increased vacuum pressure because of neutral particle emission from electrodes and glass by direct bombardment and by outgassing at higher electrode temperatures.
7. Charge accumulation on solid insulator surfaces and their field distorting effects.
8. Tube termination effects including electron injection from the cathode end and positive ion and X-ray injection from the anode end.

Assignment of relative importance to these electrical processes has led to new electrostatic and magnetic configurations designed to avoid or reduce the disturbing effects of electron emissions from the above causes while minimizing the perturbations of the main particle beam. In the HETA tube test length of 3 feet so far without beam, it has been possible to reach and surpass the gradient goal of 100 kV per inch. Extension of the work to include ion beams and longer tubes is underway.

There is not time to more than mention other high gradient studies which are part of the HETA objectives. Improved high voltage resistors, higher belt charge density, more effective use of the returning run of belt as a charge conveyor, reduction of terminal voltage variations, and increased margin of insulation on all compressed-gas-insulated components are among them. Also among them is the further reduction to practice of high power dc electromagnetic voltage sources depending on the previously-mentioned insulating core principles.

Together these efforts should increase the voltage and power density of all direct straight-line particle accelerators. The gains should in due course become available to upgrade the performance of any of the single-stage and tandem accelerators already in use around the world. But for the future these new developments in high voltage technology, exponentially assisted on heavy particles by multi-stage acceleration and multiple-charge stripping principles, will open up new goals and new research opportunities which, as Robert Van de Graaff steadfastly predicted throughout his inspirational and creative life, could profoundly benefit nuclear science and human welfare.

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ACKNOWLEDGEMENTS

The author wishes to acknowledge his indebtedness to his associates and staff at the High Voltage Engineering Corporation, and also to his associates at the High Voltage Research Laboratory at M.I.T. where some of the reported studies were supported in part by the National Science Foundation through NSF contract GK 134.

Fig. 1. Dr. Robert Jemison Van de Graaff in 1966, seated before the chart of elements extending far into the transuranics which he used to demonstrate the progress and future of nuclear collisions.

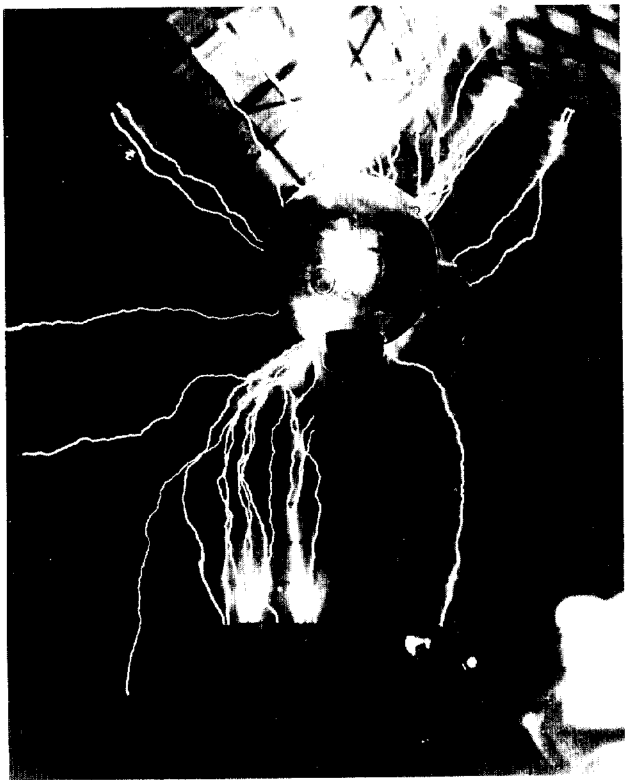

Fig. 2. The large air-insulated electrostatic belt generators built by Van de Graaff and his associates at M.I.T. in the first public demonstration of high voltage sparks in 1932.

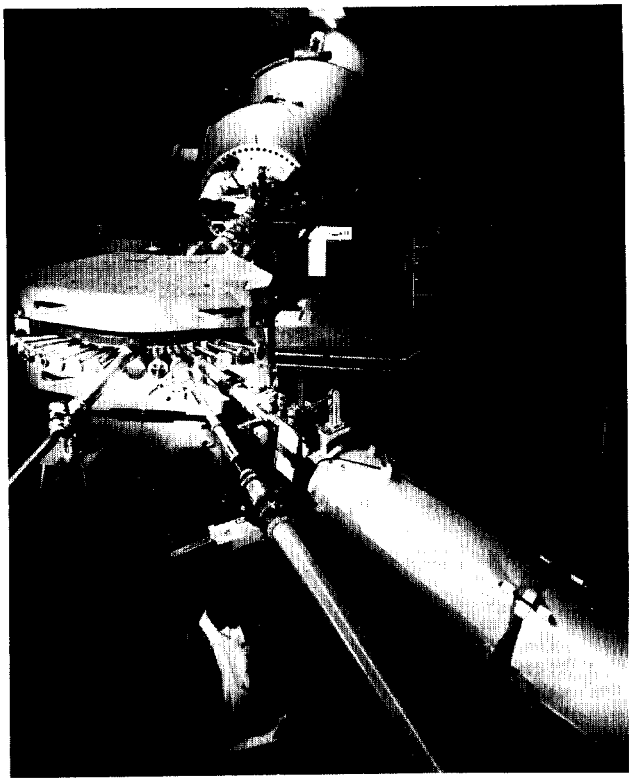

Fig. 4. The Emperor tandem accelerator at HVEC used in the uranium studies of 1966, viewed from the high energy output end with the sequential magnetic and electrostatic selector nearest the camera.

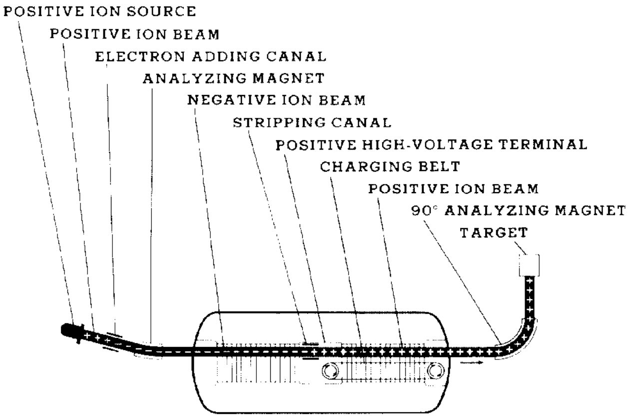

Fig. 3. Diagram of the 2-stage tandem accelerator with terminal stripping.

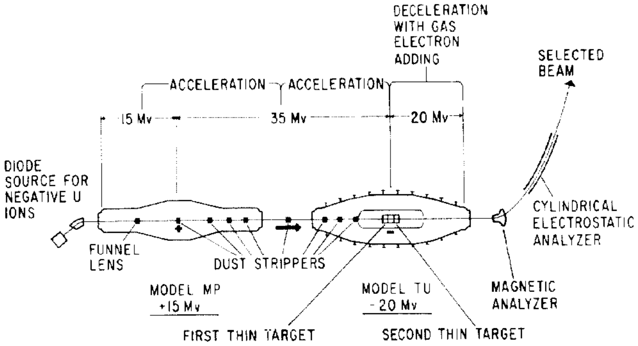

Fig. 5. The projected 3-stage Emperor and XTU tandem accelerator planned for over 30 MV between the two high voltage terminals to yield, by repeated charge stripping, uranium ions approaching the GeV level.