ENCYCLOPEDIA OF PHYSICS

Edited by

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Foreword by

Walter Sullivan

The New York Times

ADDISON-WESLEY PUBLISHING COMPANY, Inc.
Advanced Book Program
Reading, Massachusetts

London · Amsterdam · Don Mills Ontario · Sydney · Tokyo

ENCYCLOPEDIA OF PHYSICS

First printing, 1981
Second printing, 1981
Third printing, 1982

Library of Congress Cataloging in Publication Data

Main entry under title:

Encyclopedia of physics.

Includes bibliographies and index.
1. Physics—Dictionaries. I. Lerner, Rita G.
II. Trigg, George L.
QC5.E545 530'.03'21 80-21175
ISBN 0-201-04313-0

CDEFGHIJKL-MU-898765432

Manufactured in the United States of America

FOREWORD

Physics is the study of nature at its most fundamental level and hence this encyclopedia covers an extraordinary diversity of subjects—from the smallest known particles to the cosmos as a whole. Furthermore, the rapidity with which physics is evolving is manifest in its treatment of many subjects unheard of a decade or two ago. Then, other subjects would barely have merited mention, for their significance had not yet emerged. The Encyclopedia therefore serves as a dramatic index of recent developments in physics and astrophysics. Among the contributors are leading participants in those developments.

Some of the subjects, such as Bohr theory and Rayleigh scattering, have become an established part of our scientific heritage. Others, such as quasars, are subjects of ongoing dispute. The article on that subject is by Margaret Burbidge, a key participant in quasar studies.

Several speculative subjects are dealt with by leading theorists in those fields, such as tachyons (by Gerald Feinberg) and black holes (by Stephen Hawking). It is probably safe to say that most physicists hope the existence of tachyons will never be demonstrated. As for black holes, some believe that Hawking's theorem whereby, through quantum effects, a black hole can radiate and (particularly if very small) "evaporate," is a major theoretical advance, achieving at least a partial marriage between quantum theory (as it affects particle behavior) and general relativity (as it governs gravitational effects). Others, however, question the reality of such extreme manifestations of relativity as black holes.

In this volume, as well, the reader will find useful background material for current and rapidly advancing developments, such as the search for gravitational waves (J. Anthony Tyson) and the drive towards a grand unification theory of physical laws and particle characteristics, with its dependence on gauge theories, notably those of Yang and Mills (described by the late Benjamin W. Lee), as well as on SU(3) and higher symmetries (treated by Sheldon Glashow). The applicability of physics to a wide range of practical problems is reflected in such articles as those on geochronology (Willard F. Libby), laser fusion (Heiner W. Meldner), isotope separation (William Spindel), integrated circuits (R. A. Henle), and Josephson effects (Douglas J. Scalapino).

Both specialists and laymen are greatly in need of so useful and authoritative a reference work. Rita G. Lerner and George L. Trigg are to be commended for bringing it into being.

One cannot but wonder what new developments will demand recognition in future editions of this work. It seems almost certain that physics stands on the threshold of great discoveries and insights. The door to a "grand unification" seems to have cracked open and there are hints of brillant illumination beyond. Such a unification could span the full scale of observed phenomena, from particle behavior to the entire cosmos—the origin of the cosmic blackbody radiation and the apparent predominance of matter over antimatter.

Articles covering future developments will presumably deal in large measure with discoveries made with devices now in preparation, planned—or as yet undreamed of. If all goes well, the space shuttle will not only open up new vistas in astronomy and astrophysics, notably by orbiting the Space Telescope, but will make possible more precise tests of general relativity and a more thorough search for sources of high energy radiation from the celestial sphere, such as the most energetic component of cosmic rays, the diffuse X-ray background, the periodic and spasmodic outbursts of X-radiation, and the occasional gamma-ray bursts. Toward the opposite end of the spectrum, infrared techniques are helping to fill in an awesome picture of dynamic events in the cosmos.

New observing techniques are also opening new frontiers in plasma physics (with direct bearing on efforts to control fusion), in solid state physics, and in efforts to understand superconductivity and superfluidity. Holding out prospects for important discoveries are new generations of lasers, scanning electron microscopes, powerful sources of synchrotron radiation, and focused beams that can be used to study miniscule samples of material.

Subterranean experiments in the United States and elsewhere, using as detectors large volumes of water or masses of metal, should ultimately detect the proton decay predicted by "grand unification" theories or set a lower limit for the life of the proton in excess of 10^{33} years. Detection of the decay could help explain the large and odd numerical difference in the mass of the proton and that of the positron, even though both have identical electric charges. Other experiments may at last resolve the mystery concerning the deficiency of neutrinos in the energy range expected from assumed fusion reactions within the sun.

It is reasonable to hope that observations in the next decade or two will at last resolve such issues as the true value of the Hubble constant and of the deceleration factor in expansion of the universe. The Hubble constant, the rate at which the recession velocity of galaxies increases with distance, determines the yardstick whereby large astronomical distances are measured and bears on the age of the universe. The deceleration parameter defines the extent to which the rate of expansion has slowed. If the factor is sufficiently large, expansion will ultimately stop and the universe collapse upon itself.

The new colliding beam machines should at last demonstrate existence of the long-sought intermediate vector bosons (or show they probably do not exist, throwing theoretical physics into turmoil). Perhaps it will become clear whether or not quarks are the bottom tier of the structural hierarchy. If so, why are there so many varieties? Does the multiplicity of their characteristics imply some internal structure? Will the tau lepton prove to be the last in the sequence of increasingly massive members of the lepton family?

These questions were eloquently stated by Victor F. Weisskopf, Emeritus Professor of Physics at the Massachusetts Institute of Technology, in his 1978 review, "Contemporary Frontiers in Physics," presented at the General Electric 100th Anniversary Symposium in Schenectady (published in *Science,* **203,** 1979, 240–244).

He noted that nuclear matter normally is composed only of the two quarks of lowest mass (the "up" and "down" quarks). Likewise leptons normally occur only in their lowest mass form, as electrons. The more massive quarks and leptons could remain stable only under extreme conditions, such as those during the infancy of the universe. "It is completely unknown," said Weisskopf, "why nature needs the heavier quarks that are the constituents of the 'strange' and 'charmed' hadrons, which are all short-lived products of energetic collisions that quickly decay into more ordinary particles such as nucleons, electrons, and neutrinos."

It may well be, he added, that quarks and electrons "are also composite systems and that the proliferation of new types is nothing but the beginning of a series of excited states of these systems. Will we," he asked, "find an unending series of worlds within worlds when we continue to penetrate deeper into matter to smaller distances and higher energies? The answers to most of these questions can be found only by more observations." It is to be hoped that future editions of this Encyclopedia will be enriched by the fruits of such observations. From past experience, however, it can be expected that some of the most exciting discoveries will come in completely unexpected quarters.

WALTER SULLIVAN

PREFACE

Research in physics has been compared to an an attempt to tidy up the basement of a house, only to find a trapdoor leading to a sub-basement. When the sub-basement is cleaned out, one finds a trapdoor leading to yet another sub-basement, and so forth, ad infinitum. Therefore, this volume describes physics only as of this moment in time, as we attempt to understand and organize our knowledge of the physical world.

This Encyclopedia is intended as a comprehensive introductory reference source in a single volume. Our aim has been to make the broad range of ideas of modern physics readily accessible to physicists seeking information about fields outside their own, as well as to serve other scientists, students, and non-scientists interested in the subject. It includes survey articles of the major areas of physics, and fields at the interfaces between physics and other sciences, as well as specialized articles in each field, written by experts in the subject. The paramount concern has been to provide a discussion which is authoritative, succinct, and intelligible to the intended readership. Each article is self-contained; extensive cross-references and bibliographies allow the reader to pursue the subject in greater depth.

Articles are arranged in alphabetical order; in some cases, titles have been inverted so that related articles would appear next to each other, e.g., Relativity, General Theory, and Relativity, Special. At the end of most articles, cross-references are given to related articles in this volume. Most of the authors have provided a list of references; these are suggestions for further reading. An E, I, or A following a particular literature reference indicates that the level is elementary, intermediate, or advanced.

The rules for abbreviations are those given in the *American Institute of Physics Style Manual*. Numerical quantities are generally given in SI (Système Internationale) metric units. An extensive index is included at the end of this volume, referring the reader to those places in the text where significant information may be found.

The compilation of this Encyclopedia would not have been possible without the gracious cooperation of more than five hundred friends and colleagues in the physics community, who generously offered suggestions, contributed articles, and refereed manuscripts. The authors' names follow the title of each article, and they are also listed alphabetically at the end of this volume. We are especially grateful for advice and help from Norman Balabanian, Stanley S. Ballard, J. Warren Blaker, Rhodes Fairbridge, E. K. Gannett, Peter Gray, John S. Laughlin, R. Bruce Lindsay, and Eric Proskauer. The Editors would also like to express their appreciation to A. Milo Dowden, who suggested this project; to Lore Henlein and her associates of the Advanced Book Program of Addison-Wesley Publishing Company for enthusiastic support, and to Arnold Lerner and the late Dorothy Trigg for their steadfast encouragement.

RITA G. LERNER
GEORGE L. TRIGG

MAIN ENTRIES

Symbols, Units, and Nomenclature
Symmetry Breaking, Spontaneous
Synchrotron
Synchrotron Radiation

Tachyons
Temperature
Thermal Analysis
Thermal Expansion
Thermionic Emission
Thermodynamic Data
Thermodynamics, Equilibrium
Thermodynamics, Nonequilibrium
Thermoelectric Effects
Thermoluminescence
Thermometry
Thin Films
Three-Body Problem, Classical
Three-Body Problem, Quantum Mechanical
Time
Transducers
Transistors
Transition Elements
Transmission Lines and Antennas
Transport Properties
Transport Theory
Transuranium Elements
Tribology
Tunneling
Turbulence
Twin Paradox

Ultrasonic Biophysics
Ultrasonics
Uncertainty Principle
Universe

Vacuums and Vacuum Technology
Vapor Pressure
Vector and Tensor Analysis
Vibrations, Mechanical
Viscosity
Visible and Ultraviolet Spectroscopy
Vision and Color
Vortices

Water
Waves
Weak Interactions
Weak Neutral Currents
Whiskers
Work Function

X-Ray Spectra and X-Ray Spectroscopy
Xerography

Zeeman and Stark Effects

CONTENTS

Absorption Coefficient

F. L. Galeener

The absorption coefficient α measures the spatial decrease in intensity of a propagating beam of waves or particles due to progressive conversion of the beam into different forms of energy or matter. Absorption usually implies the creation of some form of internal energy in the traversed medium, e.g., the production of heat; however, it may also be associated with other inelastic scattering events, such as the ultimate conversion of incident particles into new types, or the change in frequency of waves from their incident values. Removal of intensity from the beam merely by diversion into new directions is called elastic scattering, and this process is not properly included in the absorption coefficient.

The extinction coefficient α_e measures the reduction in beam intensity due to *all* contributing processes and is often represented as a sum $\alpha_e = \alpha + \alpha_s$, where α_s is the coefficient associated with elastic scattering. Additional subdivisions of processes that remove intensity from the beam are possible and sometimes used.

These coefficients appear in the Bouguer or Lambert–Beer law in the form $I(x) = I(0)e^{-\alpha_e x}$, where $I(x)$ is the beam intensity after it has traveled a distance x in the medium, while α_e, α, and α_s have units of inverse length, often written cm^{-1}.

The absorption coefficient α appears frequently in discussions of the optical properties of homogeneous solids, liquids, and gases, where α may be a strong function of the wavelength of the light involved, the temperature, and various sample parameters. The theory of electromagnetic waves relates α to the complex permittivity ϵ and permeability μ of the medium.

See also ELECTROMAGNETIC RADIATION.

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Accelerators, Linear

E. A. Knapp

INTRODUCTION

Linear accelerators, or "linacs," constitute a rather restricted class of accelerators that accelerate nuclear or subnuclear particles in a straight line by means of a series of small impulses, each impulse being considerably smaller than the final overall energy gain achieved. Conceptually simple, the linac only recently has been developed to the same extent as other particle-accelerator systems. Efficient, high-powered microwave power sources were required before linac technology could progress. In general, the individual impulses involved in acceleration in the linac are produced by an oscillating electric field formed in radio-frequency resonant cavities. The cavities are usually coupled in such a way that the velocity of the accelerated particle traveling through them matches the time of electric field maxima in the chain or string of cavities as the particle energy increases. Figure 1 shows schematically a series of resonant cavities, each excited in the TM_{010} electromagnetic mode and arranged with an electric field distribution on axis suitable for particle acceleration.

Basic Principles and Equations

The linac is a particle accelerator that operates on the principle of phase stability, applicable to a variety of accelerator types. In the case of linacs, the phase stability is conceptually particularly simple. In analogy to riding on the leading edge of a wave, if a particle lags behind the proper or synchronous phase ϕ_s, it receives additional acceleration and "catches up" to the proper point; if ahead on the wave, it falls back toward the proper point. A particle that starts away from the synchronous phase or energy oscillates in phase about the synchronous phase and in energy about the synchronous energy, tracing out an elliptical trajectory in the phase–energy plane. Figure 2 shows a typical stability diagram in energy and phase for a proton linear accelerator. Associated with this phase stability is a radial defocusing of the accelerated particles by the radio-frequency electric fields. In early linacs this defocusing was overcome by electric field distortions produced by grids in the beam aperture. All modern proton and electron linacs use quadrupole magnets or solenoidal magnetic fields for radial beam confinement.

The requirements for high-frequency microwave power in linear accelerators make the generators of this power the major consideration in the system design. In fact, the lack of viable high-frequency rf power sources delayed the development of linacs substantially. A quantity relating acceleration achieved to power dissipated is the shunt impedance (ZT^2), conventionally defined as

$$ZT^2 = \frac{V^2}{P \cdot L} \tag{1}$$

where V is the maximum energy gain in a length L and P is the rf power dissipated in that length L.

Typically, ZT^2 varies from about 25 to 100 MΩ/m for typical systems, indicating megawatt power requirements for reasonable cavity lengths and energy gains. Klystrons, superpower triodes, and magnetrons are the only developed microwave sources available in this power-level region.

Linacs are classed as traveling-wave or standing-wave in regard to the behavior of the coupling between the cavities providing the impulses and the rf phase shift per cavity in operation. No fundamental difference in the principles of operation exists between the two classes of accelerators. In the case of traveling-wave linacs, the coupling between adjacent cavities results in a phase shift that is not 180° but some intermediate value, a very strong function of driving frequency. At the end of a chain of cavities, the power left

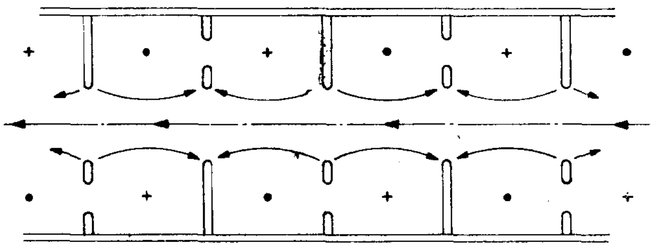

FIG. 1. Series of resonant cavities, each excited in the TM_{010} electromagnetic mode and arranged with an electric field distribution on axis suitable for particle acceleration. Energy coupling from cavity to cavity is via slot in wall.

over is coupled out into a load resistor and no power reflection to the input occurs. Cavity lengths and phase shifts are adjusted to match the crest of the electric field wave passing down the chain of cavities to the particle as it also passes through the cavity chain.

In the case of the standing-wave accelerator structure, the coupling between adjacent cavities is very strong. There is a strong reflection of energy from each end of the cavity chain, and the electric fields in adjacent high-*Q* cavities are constrained, in the limit of zero loss conditions, either to oscillate in phase, to oscillate 180° out of phase, or to be unexcited. This constraint restricts the accelerator designer in his choice of cavity lengths, but provides simplification in control that dramatically improves system design for certain applications. Almost all early electron linacs were of the traveling-wave variety; the side-coupled electron linacs and all proton linacs are of a standing-wave design. In the case of the side-coupled linac structure, an unexcited cavity is moved off axis in order to improve efficiency while retaining some major stability features of the cavity mode, which has alternate cavities unexcited at resonance.

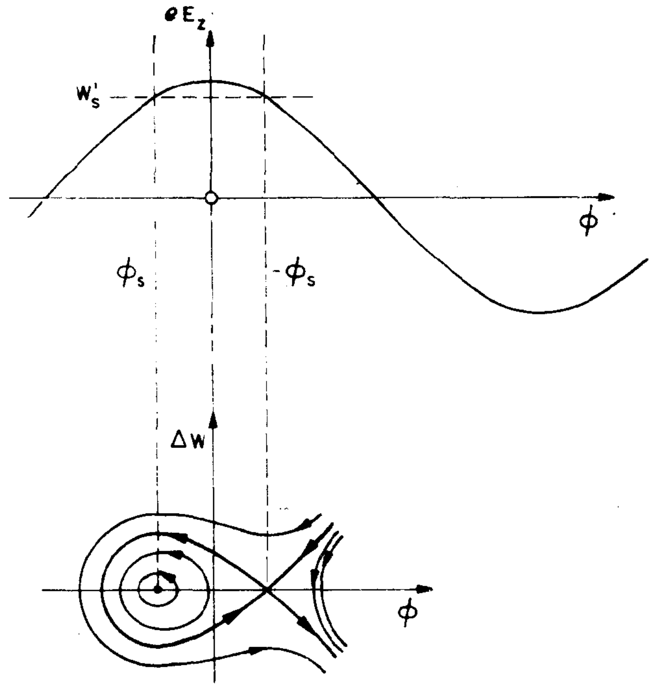

FIG. 2. Energy and phase relations for proton linear accelerator; W is the particle energy, ΔW the deviation from synchronous energy, ϕ the particle phase, ϕ_s the synchronous phase.

ELECTRON LINEAR ACCELERATORS

Development work on early electron linear accelerators was done at Massachusetts Institute of Technology and Stanford in the late 1930s. Both standing-wave (MIT) and traveling-wave (Stanford) designs were built, but in the 1950s it became apparent that the traveling-wave design was in many ways superior to the resonant-cavity design. The Stanford two-mile linear electron accelerator (SLAC) is the largest electron linac built and has achieved 20 GeV of energy with an average current of 50 μA. This machine has proved to be very reliable and has had an extremely productive physics history since its completion in 1964. Recently a new standing-wave accelerator structure, the side-coupled system, has been applied to short, lower-energy linacs for industrial and medical use. Somewhat more efficient than the older traveling-wave systems, this structure has allowed major simplifications in accelerator system design that have reduced costs of modern linac systems substantially and made electron linear accelerators widely available for modern radiotherapy treatment of cancer.

PROTON LINEAR ACCELERATORS

The first proton linear accelerator was built at the University of California at Berkeley and first operated in 1946. This accelerator was a "drift-tube" accelerator, built as a single, long, resonant tank with drift tubes hanging inside an outer copper shell. The drift tubes produce a field distribution similar to that produced by a chain of cavities with zero phase shift between them, as described previously. The accelerated particle is effectively "hidden" from the cavity electric fields while inside the drift tube during field reversal. This is a standing-wave accelerator. The largest existing proton accelerator is the LAMPF (Los Alamos Meson Physics Facility) proton linac at the Los Alamos Scientific Laboratory of the University of California. It is capable of accelerating a 1-mA (average current) proton beam to a final energy of 800 MeV. This accelerator consists of a drift-tube linac with quadrupole-magnet focusing and operates in a resonant mode modified by post couplers to an energy of 100 MeV, followed by a side-coupled accelerator structure to accelerate the protons from 100 to the 800-MeV final energy. Simultaneous acceleration of both H^+ and H^- beams to full energy is accomplished in this accelerator. Proton linear accelerators are used as injectors for many large synchrotrons in high-energy physics establishments throughout the world.

HEAVY-ION LINACS

The drift-tube linear accelerator is also used to accelerate heavy ions to high energy. The hilacs at Berkeley and Yale, built around 1952, were the first heavy-ion linear accelerators. The upgraded hilac at LBL is still producing excellent particle beams for research and serves as an injector for the Bevalac project, a synchrotron for heavy-ion acceleration. In the case of heavy-ion acceleration, very low velocities are necessary at the beginning of the accelerator resonator, requiring strong magnetic field focusing and a relatively low frequency of excitation for the system. The LBL superhilac has achieved acceleration of ions to an energy of 8.5 MeV/amu.

Recently a new heavy-ion accelerator utilizing a variety of accelerator cavity schemes and/or modes was completed at Darmstadt, West Germany. Called the Unilac, it is capable of accelerating up to an energy of 7.5 Mev/amu.

NEW INITIATIVES IN LINAC TECHNOLOGY

Recently extensive research and development work has been directed toward applying superconductivity to the resonators of linear accelerator systems. Superconductivity would allow linacs to be built whose cavities dissipate very little power, theoretically yielding highly efficient systems with the capability of continuous operation. Unfortunately, until now the electric field gradients achieved have been disappointing, being limited to approximately 2 MV/m by electron emission from the cavity walls. Research is continuing.

Work has been revived on accelerator structures that use the radio-frequency fields both to accelerate and to focus the accelerated beam simultaneously. A design where the phase of the particle crossing an accelerating gap is changed rapidly from gap to gap down a drift-tube linac cavity is being extensively studied in conjunction with a low-cost linac design suitable for use in a hospital environment for medical irradiations. Also, in the Soviet Union novel accelerator cavity schemes with specially shaped electromagnetic fields within the resonator cavity to both focus and accelerate the particles have been reported.

At present, linear accelerator technology is in a state of rapid flux. Applications of the radiations produced by particle accelerators is increasing, and commercial and medical uses of these accelerators are increasing at a rapid rate. Reliable, low-cost sources of radiations for a variety of purposes, from research to commercial production, will be required and are available from linac systems.

See also MICROWAVES AND MICROWAVE CIRCUITRY.

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Accelerators, Potential-Drop Linear

R. G. Herb

INTRODUCTION

Although potential-drop accelerators were the first to open up nuclear physics to extensive experimentation, they were soon to be far surpassed in energy by the cyclotron, the betatron, and later accelerators that provide very high energies through many small energy increments.

Yet potential-drop accelerators have continued to play a very important, and in many respects dominant, role in nuclear physics. For production of radioactive nuclear species the cyclotron is far superior to other accelerators, but for precise measurement of nuclear-energy-level characteristics, the electrostatic accelerator is far superior. For the laboratory interested in certain neutron-induced reactions the Cockcroft–Walton-type accelerator may be most convenient. Needs for intense beams of positive ions of a few MeV energy or intense beams of electrons of a few MeV are most easily met by the Dynamitron.

Each of the accelerators described under this heading is serving an important need in science and technology, and each is playing an expanding role.

COCKCROFT–WALTON VOLTAGE MULTIPLIER ACCELERATOR

This accelerator was the first to be used successfully for nuclear transmutation and gained wide recognition when results were published in 1932. It employs a circuit developed by H. Greinacher in 1920, as illustrated in Fig. 1, which utilizes two stacks of series connected condensers. One condenser stack is fixed in voltage except for voltage ripple with one terminal connected to ground and the other to the load which, in this case, is an evacuated accelerating tube.

One terminal of the second condenser stack is connected to a transformer giving peak voltages of $\pm V$, and voltages at all points along the second condenser stack oscillate over a voltage range of $2V$. The two condenser stacks are linked

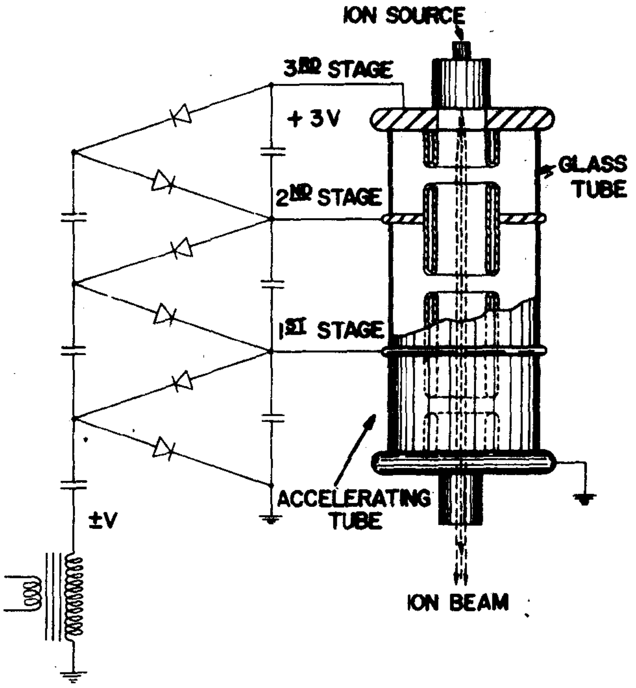

FIG. 1. Schematic drawing of a Cockcroft–Walton accelerator utilizing three stages.

by series-connected rectifiers. As voltage on the second stack oscillates, charge is transferred stepwise from ground to the high-voltage terminal. Voltage here is steady except for ripple caused by power drain and stray capacitance. Its value is approximately $2VN$, where N is the number of stages. The power supply furnishes power to an evacuated accelerating tube equipped with an ion source. Usually the tube and ion source are continually pumped and the multisection tube may have one tube section per accelerator stage.

These machines are in widespread use throughout the world and are especially advantageous for applications requiring ion beams of a few milliamperes in the voltage range of a few hundred kilovolts. Many are used to accelerate deuterons for bombardment of targets containing deuterium or tritium to yield neutrons. Accelerators for neutron production are now available commercially from a number of manufacturers.

Cockcroft–Walton accelerators operating in open air at 1 million volts are large in size and must be housed in a very large room to avoid voltage flashover. Figure 2 shows an 850-keV accelerator of this type built by Emile Haefely & Co. Ltd. It serves to inject pulses of hydrogen ions into a high-intensity linear accelerator at the Los Alamos Scientific Laboratory for production of intense meson beams.

Size and space requirements increase rapidly as voltage is extended above 1 million volts in open air and the practical upper voltage limit for these accelerators appears to be about 1.5 MV.

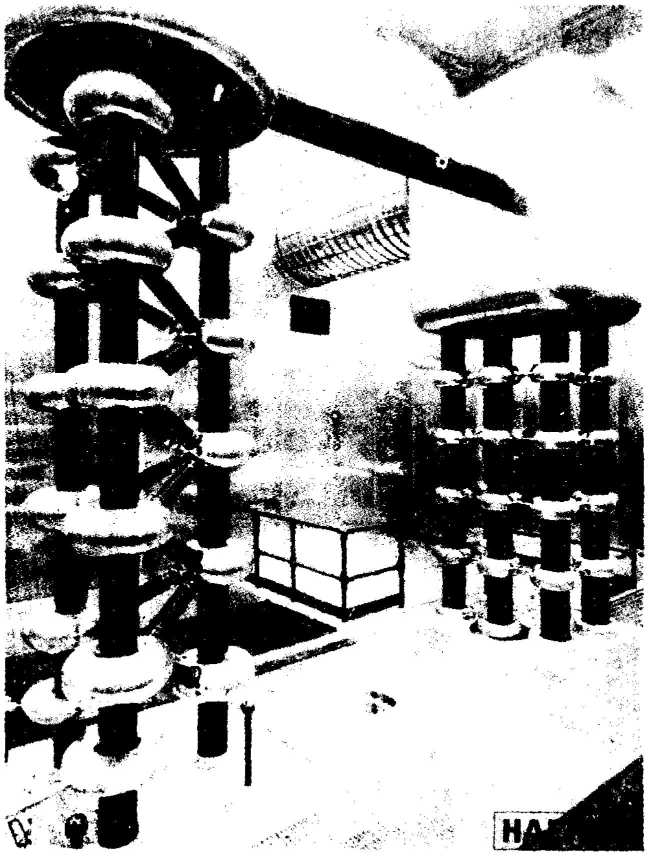

FIG. 2. 850-keV Haefely accelerator which serves to inject pulses of hydrogen ions into a linear accelerator at the Los Alamos Scientific Laboratory.

G. Reinhold of Emile Haefely & Co. Ltd. has shown that the terminal voltage developed by multipliers, using the circuit of Fig. 1, does not depart greatly from $2VN$ for multipliers going to a few hundred kilovolts. However, above about 500 kV, voltages achieved fall substantially below values given by this simple expression because of stray capacitances and other effects. He has developed another circuit called a symmetrical cascade rectifier in which the shortcomings of the simple circuit are largely eliminated. It employs two transformers and two condenser stacks that oscillate in voltage. Both feed one fixed condenser stack. Using this symmetric system, Emile Haefely & Co. Ltd. has built an open air rectifier without an accelerating tube going to 2.5 million volts.

The N. V. Philips Gloeilampenfabrieken and Emile Haefely & Co. Ltd. have built accelerators utilizing voltage multipliers housed in tanks containing insulating gases such as SF_6 or a mixture of N_2 and CO_2. These machines have ranged in voltage from about 1 million up to 4 million volts. The use of insulating gases at high pressure permits great savings in the size of equipment for a given voltage.

DYNAMITRON ACCELERATOR

M. R. Cleland invented a cascaded rectifier system termed the Dynamitron in which series connected rectifiers are driven in parallel. The circuit is shown schematically in Fig. 3, and Fig. 4 is a photograph of a 4-million-volt positive ion Dynamitron accelerator.

Rectifiers connected in series between ground and the high-voltage terminal are positioned in two columns on opposite sides of the accelerating tube of the Dynamitron and the high-voltage column is enclosed by half rings that have a smooth exterior surface to inhibit corona and spark discharge. The half-rings serve as condenser plates coupled capacitively to the large semiclylindrical rf electrodes positioned between the walls of the tank and the high-voltage column of the accelerator. The rf electrodes form the tuning capacitance of an LC resonant circuit which is driven by a seperate power supply through an oscillator tube.

Since ac power is fed in parallel to each of the series-connected rectifiers, the relatively large storage condensers that are connected between successive stages of other cascaded rectifier systems are not required. Stored energy in the Dynamitron is low and does not differ greatly from that in electrostatic machines. This feature is important since damage due to discharge can be a serious problem in multimillion volt accelerators, especially for discharge in the accelerating tubes.

These accelerators are enclosed in pressure tanks containing high-pressure SF_6 gas. At a pressure of 1 atm, this gas has a dielectric strength about 2.7 times that of air at the same pressure. Its dielectric strength rises approximately linearly with pressure up to a few atmospheres and at a pressure of about 7 atm it will sustain fields of about 200 kV/cm.

Dynamitrons are manufactured by Radiation Dynamics. Both single stage and double stage (tandem) positive ion

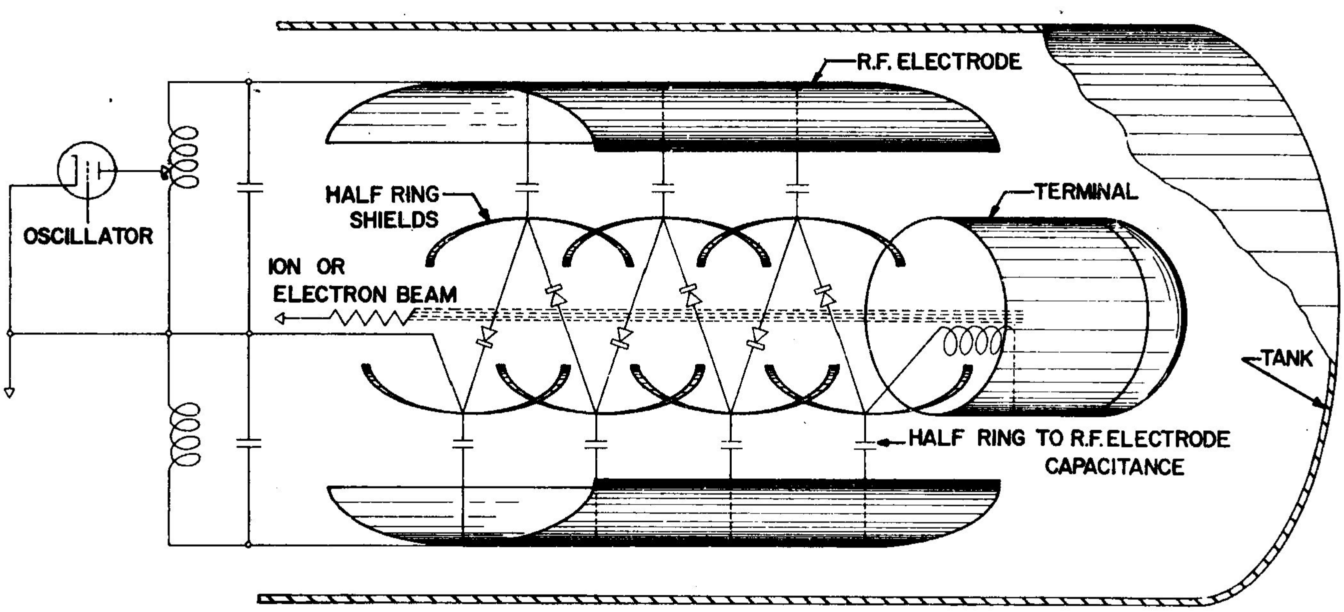

FIG. 3. Schematic diagram of a Dynamitron accelerator in a pressure tank.

Dynamitrons have been manufactured giving terminal potentials up to 4 MV. They are especially advantageous for applications requiring high currents.

A larger proportion of Dynamitrons manufactured have been electron accelerators for industrial applications such as polymerization of plastics and sterilization of disposable medical products. These applications require electron energies up to a few MeV and from 10 to 100 kilowatts of electron beam power.

The most powerful machines built by Radiation Dynamics up to 1976 include a 0.5-MV machine with an electron beam power of 50 kW, a 1-MV machine giving 100 kW of electron beam power, a 1.5-MV machine providing 75 kW, and a 3-MV machine providing electron beam power of 150 kW.

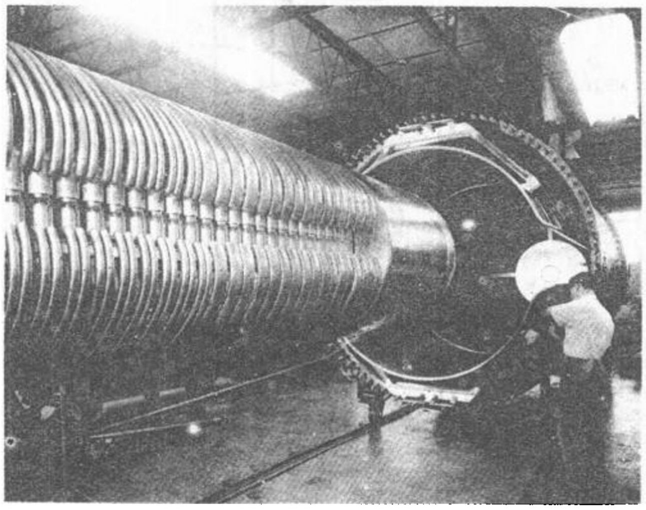

FIG. 4. A 4-MeV Dynamitron positive-ion accelerator with pressure tank rolled away from the high-voltage column.

VAN DE GRAAFF ACCELERATOR

In this accelerator, power is supplied at high voltage by means of an insulating belt which carries charge from ground to the high-voltage terminal. Robert Van de Graaff built the first successful belt-charged high-voltage generator in 1929.

In this device, which is illustrated in Fig. 5, electrical charge is deposited on an insulating belt and is carried into a smooth, well-rounded metal shell which is shown in the figure as a sphere. Here charge is removed from the belt and passes to the sphere which rises in voltage until the sphere is discharged by a spark or until the charging current is balanced by a load current.

To charge the belt, a corona discharge is maintained between a series of points or a fine wire on one side of the belt and the grounded lower pulley or a well-rounded, grounded, inductor plate on the other side of the belt. If the corona needles are at a positive potential, the belt intercepts positive ions as they move from needle points toward the grounded pulley. Charge is carried into the sphere where it is removed by an array of needle points and passes to the outer surface of the sphere.

The generator can provide a high negative voltage if the corona needles are operated at a negative voltage with respect to the grounded pulley. Belt charging electrodes must be well shielded from the field of the high-voltage terminal and charge must be carried well within the sphere before removal is attempted. Charging current is then completely independent of voltage on the terminal and voltage will rise until limited by corona of sparkover to ground, by leakage current along insulators, or by a load such as ion current through an accelerating tube.

The Van de Graaff belt-type generator was first used to