PARTICLE ACCELERATORS

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Preface

The history of particle accelerators has not yet been compiled. Most of the literature on the subject is published in research journals or in laboratory reports, available only to a restricted group of readers. A few monographs have been published on selected subjects; a few journal issues have described individual machines; and several review volumes have included survey chapters on accelerators. But there are no books published in which the scientist, the engineer, or the student can find complete and general descriptions of the physical principles of all types of accelerators.

A comparative, critical analysis of the several accelerators can show the relative advantages and disadvantages for the different energy ranges. It will illustrate the way in which the different machines supplement each other as tools for the study of the broad range of phenomena in nuclear physics and high-energy particle physics. It can demonstrate one of the most significant features in accelerator development, the cross-fertilization between science and engineering which leads to the transfer of ideas and techniques between experts working on different parts of the problem or on different types of accelerators.

The need for such a critical study and compilation is clear. Many a student wants to know more about basic principles to guide his further studies; nuclear physicists must understand accelerators to evaluate experimental evidence; scientists or engineers in the field of atomic energy are curious about the machines which are the sources of nuclear data; and directors of laboratories need to appreciate the relative merits of the several machines as a basis for plans or decisions.

The layman gets his information about accelerators largely from newspapers or illustrated magazine articles. Newspapers have done much toward popularizing the field, but very little toward informing the public on basic principles. In the eyes of the press the "atom smasher" is a mysterious symbol of science. The layman has been led to think of atom smashers as huge, complicated "Rube Goldberg" machines, built by prodigies with long beards for futile or slightly dangerous purposes. Yet many laymen are intrigued by their mechanisms and show much interest in qualitative descriptions. This is because most accelerators are simple in their basic principles, and a technically trained person finds that he can grasp these principles easily. Accelerators are no more complex than other machines which are commonly understood and accepted, such as the modern automobile or the synchronous motor; they are no more huge than many of the accepted devices of our civilization, such as the diesel locomotive or the multimotored aircraft. Their complexity depends on the detail with which they are studied. Basic principles of all accelerators are understandable in relatively simple concepts available to any technically trained person, and analogues can be found to extrapolate thinking to the more complicated principles.

A dozen authors would be required to describe expertly all the machines and techniques in the accelerator field. However, a compendium by many authors suffers from differences in content and style and cannot show the pattern of growth and development in the field. The authors of this volume recognize their limitations and have made every effort to supplement their personal experience by study of references and discussions with other experts. It is possible that some significant publications have been missed, unintentionally. This is an unfortunate consequence of the breadth of this rapidly developing field, lying as it does on the borderline between physics and engineering. A great deal of the material in this book is based on the authors' personal experiences in the accelerator field, covering the cyclotron, betatron, electron synchrotron, proton synchrotron, linear accelerator, and alternating-gradient synchrotrons. Much of the information has been acquired through private discussions, ranging over the whole field of accelerators. The authors wish to acknowledge their debt to the following for their generous and helpful criticisms and valuable advice: Mrs. M. Hildred Blewett, Prof. Sanborn Brown, Dr. F. T. Cole, Prof. E. L. Ginzton, Prof. D. W. Kerst, Dr. S. J. Lindenbaum, Prof. B. J. Malenka, Prof. J. C. Trump, Prof. Lloyd Smith, Prof. C. M. Van Atta, and Prof. Richard Wilson.

The organization of the material is primarily in terms of individual accelerators. Each type has been treated in a separate chapter essentially complete in itself. The emphasis is on the physical principles of operation, particle orbits and their controlling fields, and the design principles of the basic components. No attempt is made at complete coverage, but certain installations are chosen as typical and are described in some detail to demonstrate a particularly effective and well-coordinated system. Certain components such as ion sources, magnets, and shielding, which are common to many accelerators, are discussed in separate chapters. It has been the urge of the authors to show the similarities in principle of the several machines, especially in the way they depend on the basic equations of motion of particles in electric and magnetic fields. To emphasize the similarities and to minimize repetition, the mathematical analysis of particle motion as applied to most accelerators is presented with a consistent nomenclature in separate chapters where the common features of acceleration, focusing, and stability are derived from the equations of motion.

The meticulous reader will note some inconsistencies in the use of symbols and units. The authors feel it is wiser in some instances to retain traditional and accepted symbols than to force a new symbolic terminology. Some of the fields discussed in the separate chapters have developed almost independently, and the same symbols have been used for different parameters in these fields. In some instances the symbols used in this volume have two or more definitions; these definitions are listed in the Table of Symbols. Similarly, several different systems of units have become customary in different fields. The authors prefer to use mks units wherever possible, primarily because of the major simplifications in the fields of electricity and electrical engineering which result. However, most scientists still use cgs units in many areas of scientific research and the data are frequently reported in these units; also, the mechanical engineering profession in the United States is wedded to the English system of units (inches, pounds, etc.). For consistency with the published data, the authors have chosen to use these alternate systems of units, with suitable conversion factors to the mks system where needed for clarity.

Accelerators are undergoing continuous development, and some of the material published here must necessarily be out of date. It is hoped that the basic principles presented and the general conclusions derived are now scientifically established, although it is expected that later work will extend the phenomena and improve on techniques and design.

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List of Symbols

(Page references are included to indicate the pages where nonstandard symbols are first defined)

c	velocity of light, m/sec
e	particle charge, coulombs
f	frequency, cycles/sec
h	harmonic order in synchrotrons (p. 302)
i	total current, amp
k	constant in water-flow formulas (p. 261)
m	particle mass, kg
m_0	particle rest mass, kg
p	particle momentum, kg-m/sec
p_0	momentum of equilibrium particle, kg-m/sec (p. 290)
p^*	$p_0/(m_0c)$ (p. 296)
r	radius in cylindrical coordinates (goes with θ and z)
s	position coordinate along an orbit, m
t	time, sec
u	scalar potential for magnetic field (p. 251)
v	velocity, m/sec
v_g	group velocity (p. 321)
A	vector potential (p. 252)
	atomic weight
B	magnetic flux density, webers/m^2 (p. 118)
	build-up factor (p. 521)
C	capacitance, farads
E	electric field, volts/m
F	force, newtons
G	gradient of a field (p. 112)

H	magnetic field, amp/m
I	current density, amp/m²
J_n	Bessel function of order n
K	abbreviation used in phase-stability theory (p. 298)
	abbreviation used in synchrotron theory (p. 304)
L	inductance, henry
N	Avogadro's number
N_n	Neumann function of order n
P	pressure
Q	quantity of charge, coulombs
R	resistance, ohms
T	kinetic energy, joules or ev
	temperature
U	power, watts
V	potential difference, volts
W	total particle energy, joules or ev
W_0	rest energy, joules or ev
Z	atomic number
α	first Townsend coefficient (p. 75)
β	$= v/c$
γ	second Townsend coefficient (p. 77)
ϵ (or ϵ_0)	dielectric constant of free space, farads/m
η	$= (\mu_0/E_0)^{1/2} = 377$ ohms
	wavelength, m
μ (or μ_0)	permeability of free space, henrys/m
μ	microns: a parameter in AG theory; X-ray absorption coefficient
ρ	resistivity, ohms/m
	radius of curvature
σ	charge density
	collision cross section
ϕ	phase angle
ϕ_0	equilibrium phase (p. 297)
ω	$2\pi f$

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Introduction

1-1. THE ROLE OF ACCELERATORS IN NUCLEAR SCIENCE

Particle accelerators have undergone a tremendously rapid development during the past 30 years. In few fields of science has progress been so spectacular. During this relatively short time, particle energies available for research have increased from a few hundred kilovolts to many billions of volts. Research in nuclear physics and on the properties of fundamental particles owes much of its progress to the continuously increasing energy achieved by a series of electronuclear machines, each larger and more effective than its predecessor. Also, much of the public awareness and support of the field of nuclear physics rests on popular interest in these gigantic atom smashers.

The purpose of this book is to present a description of the several particle accelerators. Fundamental principles will be discussed, and as much of the theoretical analysis of particle motion will be developed as is necessary to understand the operation of these principles in focusing and accelerating particle beams. The historical development will be outlined for each accelerator, and original contributions credited as fairly as possible. The over-all purpose is to show by comparison of their relative advantages and characteristics how the various accelerators supplement each other as tools for the study of nuclear physics and high-energy particle physics.

The record of accelerators in research is impressive. The complexity of nuclear processes has been demonstrated by hundreds of different reactions coming from artificial disintegration of nuclei by protons, deuterons, neutrons, alpha particles, gamma rays, and electrons, and by several heavy ions. Induced radioactivities produced in targets bombarded by ion beams have been studied in detail to measure the lifetimes and analyze the decay schemes. New modes of disintegration and new complexities in the properties of nuclei have been discovered. Precise measurements of reaction thresholds and studies of the emergent radiations have led to an ever-increasing knowledge of atomic mass values and nuclear energy levels.

Radioactive elements have been used as tracers in many fields of scientific research: physics, chemistry, biology, medicine, metallurgy, and agriculture, to mention a few. A start has been made in the application of the radiations to medical therapy, notably for hyperthyroidism and leukemia. Neutrons from the cyclotron have been used in many fields of research, including cancer therapy. The properties of neutrons have been widely explored, and high-energy neutrons have themselves been utilized for disintegration. More recently the synchroaccelerators have succeeded in producing mesons, previously available only in cosmic rays, and studies of meson production and interactions are leading to important new knowledge about the fundamental nuclear force. New particles have been discovered, such as the neutral meson, the negative proton, and the antineutron, and it is clear that still more new knowledge is awaiting discovery. The record shows that particle accelerators have been most productive tools in exploring the nucleus of the atom.

Accelerators have found a permanent place in the science laboratories of the world. Every modern nuclear research laboratory must have some form of accelerator capable of disintegrating nuclei and producing induced activities; most of the larger laboratories have several machines to cover a wider range of phenomena. Direct-voltage accelerators, such as the electrostatic generator, are most useful in precise studies at low energy, such as the measurement of reaction thresholds or nuclear energy levels. The cyclotron is more powerful and produces particles of higher energy; it has been used as a high-intensity source of neutrons in the production of induced activities and for the study of high-energy disintegration processes. The betatron and electron linear accelerators produce high-energy electrons, and the resulting X rays are uniquely adapted to the study of photonuclear processes. Now the synchroaccelerators are rapidly taking over from cosmic rays the field of high-energy particle physics.

Each type of accelerator has made significant contributions. Because of their different capabilities, they supplement each other in covering the energy range needed for nuclear studies. Each accelerator fills a unique role, and all of them are needed. For example, the Nuclear Science Laboratory at the Massachusetts Institute of Technology has several electrostatic generators, a cyclotron, a linear accelerator, and a synchrotron, and all are being used effectively for research.

By 1940 much of the accumulated knowledge of nuclear physics had come from research using particle accelerators. However, radium-beryllium neutron sources were also in wide use and led in fact to the discovery of fission in 1939. Immediately following the first announcement, accelerators all over the world were applied to studies of this new phenomenon and rapidly exploited the field. Shortly thereafter a voluntary censorship was applied to reports of fission experiments in this country, and work was channeled into secret laboratories where accelerators were teamed with other scientific tools to produce the atomic pile and the atomic bomb. The speed with which accelerators were put to work is indicated by the transfer to Los Alamos of a working electrostatic generator from the University of Wisconsin and a cyclotron from Harvard University; both of these machines were in operation a few weeks after arrival at Los Alamos.

At the end of World War II, when physicists returned to their laboratories, the enhanced status of nuclear physics was immediately evident. The exciting and dangerous development of atomic energy, with its tremendous implications for national security, stimulated strong popular support for spending government funds on building still larger and higher-energy accelerators. With such impetus the new synchroaccelerators were rapidly developed.

Atomic reactors are finding many uses in research laboratories, but they have in no sense displaced accelerators for nuclear studies. The very high neutron intensities available from large reactors have made them the natural source of supply of induced radioactivities, which are distributed to the scientific world through the Isotope Distribution Division of the Atomic Energy Commission laboratory at Oak Ridge, Tennessee, and similar laboratories in other countries. This has relieved cyclotron laboratories of the tedious chore of production of long-lived isotopes. However, the accelerator is still essential for the radioactivity research laboratory. Positron emitters resulting from proton or alpha-particle bombardment of targets in an accelerator cannot be produced by neutrons. The very-short-lived neutron-induced activities cannot be shipped from the reactor to a distant laboratory and are best produced locally in an accelerator. Special research problems may require higher specific activities than are available from a reactor, but which can be obtained in the high concentration of neutrons in targets mounted directly behind the particle target in a cyclotron.

1-2. PROGRESS IN ACCELERATOR DEVELOPMENT

When Rutherford demonstrated in 1919 that the nitrogen nucleus could be disintegrated by the naturally occurring alpha particles from radium and thorium, a new era was opened in physics. For the first time man was able to modify the structure of the atomic nucleus. The alpha particles used had energies of 5 to 8 million electron volts (Mev), far in excess of the energies available in the laboratory. During the 1920s X-ray techniques were developed so machines could be built for 100 to 200 kev. Development to still higher voltages was limited by corona discharge and insulation breakdown, and the multi-million-volt range seemed out of reach.

Physicists recognized the need for artificial sources of accelerated particles. In a speech before the Royal Society in 1927 Rutherford[1] expressed his hope that accelerators of sufficient energy to disintegrate nuclei could be built. Then in 1928 Gamow[2] and also Condon and Gurney[3] showed how wave mechanics could be used to describe the penetration of nuclear potential barriers by charged particles and made it seem probable that energies of 500 kev or less would be sufficient to observe the disintegration of light nuclei. This more modest goal seemed feasible. Experimentation started around 1929 in several laboratories to develop the necessary accelerating devices. Details of this race for higher voltages are given in the chapters to follow. Urged on by Rutherford, the first to succeed were Cockcroft and Walton[4] in the Cavendish laboratory at Cambridge. They reported the successful disintegration of lithium by protons of about 400 kev energy in 1932. The date of this first artificial transmutation can be taken as the starting point in accelerator history.

Four successive waves of development have swept the accelerator field, characterized by four different concepts in the acceleration of particles. The first stage was the application of direct-voltage techniques in which the particles were accelerated through a single large potential drop. The magnitude of the potential drop was increased to its practical limit by using electrode terminals of large radius of curvature and by improving insulation. Voltage breakdown of the accelerating tube was minimized by subdividing the potential along the length of the column.

The second concept was the application of resonance acceleration, in which the particles were constrained to pass and repass many times through a low potential drop in resonance with an oscillating electric field, until their final energy was many times greater than the maximum potential difference in the apparatus. The chief examples of resonance accelerators are the cyclotron and the early linear accelerators.

The third stage was the application of the principle of phase-stable acceleration to resonance accelerators, from which developed the family of synchroaccelerators. Here, with an exact knowledge of the forces producing stable orbits, it has been possible to keep particles in resonance for an indefinitely large number of accelerations to attain ultimate energies up to 10 billion electron volts (Bev).*

* The symbol "Gev" is used in England and in most European countries to represent 1000 Mev, rather than the symbol "Bev" used in the United States.