Edited by Reinhard Stock

WILEY-VCH

Encyclopedia of Applied High Energy and Particle Physics

This new edition of articles taken from the „Wiley Encyclopedia of Applied Physics“ is devoted to Nuclear and Particle Physics. Most of the articles have been completely rewritten and updated to take proper account of this rapidly changing field; also, new reviews have been included which are devoted to new developments in fundamental research. The volume is edited by 1989 Leibniz Prize winner Reinhard Stock, known for his research on the plasma state of matter in the early Universe.

From the contents:

- Quantum Mechanics
- Special Relativity
- Strong Interaction
- The Standard Model of Elementary Particles
- Weak Interaction
- Particle Physics
- Applied String Theory
- Neutrino Astrophysics
- Nuclear Structure
- Nuclear Reactions
- Radioactivity
- Particle Impact Phenomena
- Cyclotrons
- Design and Application of Cyclotrons
- Electrostatic Accelerators
- Linear Accelerators
- Free Electron Lasers
- Synchrotrons and Storage Rings
- Storage Rings
- Targets for Particle Accelerators
- Calorimeters in Particle Physics
- Semiconductor Tracking
- Tracking in Particle Detectors
- Gamma-Ray Spectrometers
- Managing the Extreme Dataflow of LHC

Professor Reinhard Stock has worked for many years at the Nuclear Research Centre CERN in Geneva, where he performed research on the early universe plasma state. In 1989 he was awarded the prestigious Leibniz Prize from the Deutsche Forschungsgemeinschaft. Until his retirement in 2004 he was Judah Eisenberg Chair Professor at the Physics Department of the Goethe University of Frankfurt/Main.

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ISBN 978-3-527-40691-3

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Physics

Encyclopedia of Applied High Energy and Particle Physics

Edited by
Reinhard Stock

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WILEY-VCH Verlag GmbH & Co. KGaA

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Cover

The ATLAS Experiment at CERN.
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Library of Congress Card No.:
applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at (<http://dnb.d-nb.de>).

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KGaA, Weinheim

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Typesetting Laserwords Private Limited,
Chennai, India
Printing Strauss GmbH, Moerlenbach
Binding Litges & Dopf GmbH, Heppenheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN: 978-3-527-40691-3

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Encyclopedia of Applied High Energy and Particle Physics. Edited by Reinhard Stock
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ISBN: 978-3-527-40691-3

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15.1 Introduction

Electrostatic accelerators opened nuclear physics to extensive experimentation and, after more than half a century, they continue to play an important role. Basic research in nuclear and atomic physics was virtually the sole application of stand-alone electrostatic accelerators until the 1980s, when their uses for applied physics and as injectors to booster accelerators expanded rapidly. They became the powerful tools for the new techniques required for analysis and production in many emerging fields, especially in microelectronics and molecular biology. They were the natural choice for the injectors needed as heavy ion research reached for higher energies and heavier mass beams. Advances in the designs and construction of electrostatic accelerators have given them the precision, reliability, simplicity, and versatility needed for these broad roles. These unique capabilities, developed during decades of use in basic research, armed them for these new tasks.

The widespread and varied applied uses of electrostatic accelerators include ion implantation in the manufacture of semiconductor devices, age determination of samples thousands and even millions of years old, and nondestructive analysis

to characterize computer chips, analyze biomedical specimens, monitor pollution, and locate oil. High-power electron beams are used for enhancing insulation on wire, producing shrink tubing, and sterilizing disposable medical products, and for tunable, microwave lasers.

Nuclear physics using heavy ions blossomed through the exploitation of the wide variety of beams conveniently provided by tandem accelerators. It was natural that, as the research expanded to heavier beams, tandem accelerators were the tools on hand for use as injectors into booster accelerators. This has been a major role for the larger tandem accelerators from 1980 to 2005. As research interest shifted toward radioactive ion beams, they were also on hand to accelerate rare and radioactive species produced by other accelerators.

An electrostatic accelerator consists of a high-voltage terminal supported by an insulating column, a means of generating the high voltage, a source of charged particles, and an evacuated acceleration tube through which the particles are accelerated. The potential drop from the high-voltage terminal to ground potential accelerates the charged particles to an energy equal to the charge on the particle times the terminal voltage ($E = qV$).

An electrostatic accelerator that operates above 10^6 volts (1 MV) is usually enclosed

in a steel pressure vessel containing electrically insulating, high-pressure gas. The most widely used such gas is SF_6 whose dielectric strength is 2.7 times that of air at 1 atm (101 kPa). The dielectric strength rises approximately linearly with pressure to 7 atm, where SF_6 sustains $\sim 200 \text{ kV cm}^{-1}$ fields.

For stable operation at high voltages, the insulators of the accelerator support structure and the acceleration tube must be subdivided by metal electrodes that are connected to a resistive voltage divider for voltage grading from the terminal to ground potential.

15.2

Types of Electrostatic Accelerators

Electrostatic accelerators are often identified by the type of high-voltage generator they employ. Those that generate high voltage by rectifying AC voltage are generally used for high-intensity beams at energy up to $\sim 5 \text{ MeV}$. For certain neutron-induced reactions, ion implantation to a few hundred kilo electronvolts, and electron beam applications, the Cockcroft-Walton or symmetric cascade rectifier accelerator may be the most convenient one. Very intense positive ion or electron beams of a few mega electronvolts are most easily obtained by the use of insulating core transformer (ICT) and Dynamitron accelerators.

For analytical precision and for voltages above 5 MV, accelerators using electrostatic charging are far superior. These use a mechanical system to carry the charge to the terminal. Each type of accelerator described below has advantages for specific applications, and each is serving needs in the growing range of uses of accelerators.

15.2.1

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, which drives AC voltage through two stacks of capacitors and rectifiers as illustrated in Figure 15.1.

One terminal of the left-hand capacitor stack is connected to a step-up transformer giving peak voltages of $\pm V$. Voltages at all points along this capacitor stack oscillate over a range of 2 V. Series-connected rectifiers link this capacitor stack to another one connected at one end to the high-voltage terminal and at the other end to ground. As voltages on the transformer-driven stack oscillate, charge is transferred stepwise through the rectifiers from ground to the terminal. The terminal voltage is equal to $2 VN$, where N is the number of stages, but has a voltage ripple superimposed that increases with power drain.

The charged particles from the ion (or electron) source are accelerated through the evacuated acceleration tube that is connected to the terminal. The acceleration tube sections may be connected to the power supply stages as in Figure 15.1 or may be equipped with resistors for potential grading from high voltage to ground.

Cockcroft-Walton accelerators, operating in open air near 1 MV, are large and require a very large room to avoid voltage flashover. Figure 15.2 shows an 850-keV accelerator of this type in a room that is many meters in all dimensions. It generates pulsed hydrogen ion beams for injection into the high-intensity linear accelerator at the Los Alamos National

Fig. 15.1 Schematic of a Cockcroft-Walton accelerator with three voltage multiplier stages.

Laboratory for production of intense meson beams.

Cockcroft-Walton accelerators are in widespread use throughout the world and are especially advantageous for applications requiring beam currents of a few milliamperes at up to few hundred kilovolts. Many are used to accelerate deuterons to bombard targets containing deuterium or tritium to yield neutrons, for example, for neutron activation analysis.

15.2.2

Symmetric Cascaded Voltage Multiplier Accelerator

G. Reinhold of Haefely has shown that, up to a few hundred kilovolts, voltages developed by cascade voltage multipliers using the circuit of Figure 15.1 do not depart greatly from $2VN$. Above about 500 kV, however, voltages achieved fall substantially below this value. He

developed a symmetrical cascade rectifier, which eliminates most shortcomings of the Cockcroft-Walton circuit. It employs two transformers and two AC capacitor stacks feeding one DC capacitor stack. Using this symmetric system, Haefely built an open-air voltage generator without an acceleration tube that operated to 2.5 MV.

Such open-air accelerator systems with symmetric circuit charging are used for 500-kV ion implantation and ion-beam analysis. Air-insulated accelerators ranging from 20 kV to over 500 kV are utilized as injectors for almost all mega electronvolt and giga electronvolt accelerators. Size and space requirements for open-air systems increase rapidly with voltage and appear to set a practical upper limit of about 1.5 MV. Using high-pressure gas for insulation greatly reduces the size of higher voltage accelerators but at the cost of more difficult access to the components for maintenance.

Fig. 15.2 An 850-keV Haefely accelerator for injection of pulses of hydrogen ion into a linear accelerator at the Los Alamos National Laboratory. (Photo courtesy of Emile Haefely & Co., Ltd.)

15.2.3 Dynamitron Accelerator

Cleland invented a cascaded rectifier system called the *Dynamitron*, in which the rectifiers are driven in parallel (Figure 15.3). Rectifiers, connected in series between ground potential and the high-voltage terminal, are in two rows on opposite sides of the acceleration tube. The high-voltage column is enclosed by half rings with smooth exterior surfaces to inhibit corona and spark discharge. Large, semicylindrical radiofrequency (RF) electrodes, mounted near the wall of the tank, surround the accelerator column. As indicated in Figure 15.3, the half rings on the column provide capacitive coupling between the rectifiers and the large RF electrodes. The RF electrodes form the tuning capacitance of an LC resonant circuit driven

by a separate high-frequency (~ 100 kHz) power supply.

Since RF power is fed in parallel to each of the rectifiers, there is no requirement for the large storage capacitors between successive stages in other cascaded rectifier systems. This reduces stored energy to levels comparable with accelerators using electrostatic charging. Minimizing stored energy is important, especially in multimegavolt accelerators, because large stored energy released in a discharge can damage capacitors, rectifiers, column components, and acceleration tubes. Single-stage and tandem Dynamitrons up to 4 MV are commercially available for research applications requiring high beam current. Most Dynamitrons are built to accelerate electrons for industrial polymerization and sterilization.

Fig. 15.3 Schematic of a Dynamitron accelerator in a pressure tank. The half ring to RF electrode capacitors shown are not physical elements but only represent the effective capacitance of the pairs of electrodes.

These applications require electron beam power ranging from 50 kW at 0.5 MV to 200 kW at 5 MV.

15.2.4 Insulating Core Transformer (ICT) Accelerator

The High Voltage Engineering Corporation, HVEC, developed the ICT circuit for high-current electron beam applications. Power is coupled magnetically in the ICT in contrast to the capacitively coupled devices just described. Rectifiers are on modular, flat, circular decks that are stacked one above the other and separated by insulation layers. Nominal 460-V, three-phase, 50- or 60-Hz line power drives the primary coil of the power supply transformer. Input power is magnetically coupled through the insulation layers to secondary coils (three per deck) by a laminated three-phase iron core. The secondary coils on each deck energize the rectifier circuit on that deck. This minimizes electrical stresses within the stack. HVEC builds ICT electron accelerators for energies from 0.3 to 3 MeV and

beam power up to 100 kW, primarily for electron beam processing systems.

15.2.5 Van de Graaff Accelerator

Accelerators that use an insulating belt to carry charge to the high-voltage terminal are named after Robert Van de Graaff, who first successfully demonstrated high-voltage generation with belt charging in 1929.

In this device, illustrated in Figure 15.4, electric charge is deposited on the insulating belt at the ground end. The motor-driven belt carries the charge to the spherical metal terminal.

To charge the belt, a corona discharge is maintained from sharp needles or from a fine wire held at high voltage to the grounded lower pulley on the opposite side of the belt. If the corona needles are at a positive voltage, the belt surface intercepts positive ions moving from them toward the grounded pulley. The belt carries the positive charge into the spherical terminal, where another corona

Fig. 15.4 Schematic of a Van de Graaff generator for operation in open air.

discharge from another array of needles removes the charge. The charge then passes to the outer surface of the terminal. The positive voltage on the terminal rises until the charging current is matched by current paths to ground. These may be combination of a resistor string along the insulating support and ion current through an acceleration tube. A negative terminal voltage is produced by operating the charging needles at negative voltage for the acceleration of electrons or negative ions.

The first use of a Van de Graaff voltage generator to accelerate ions was in 1932 at the Department of Terrestrial Magnetism of the Carnegie Institution, Washington, DC. By 1934, this institution had built a second accelerator, which was used extensively for nuclear physics research at energies to 1.2 MeV and is now on display at the Smithsonian Institute in Washington, DC. Other

belt-type accelerators built for 2–3 MV in open air were very large (to over 12-m high).

Compact belt-charged accelerators in steel tanks containing high-pressure insulating gas were developed at the University of Wisconsin in the 1930s under the direction of Herb. Many basic design features of electrostatic accelerators, still relied on today, were developed in these early machines. In 1940, Wisconsin completed a 4.5-MeV accelerator, which was used for precise nuclear physics measurements. In 1947, HVEC began commercially manufacturing belt-charged accelerators insulated by high-pressure gas for electrons and positive ions to 4 MeV.

15.2.6

Two-Stage (Tandem) Accelerators

In 1958, HVEC demonstrated an electrostatic accelerator that produced high-energy

Fig. 15.5 Schematic of a two-stage (tandem) electrostatic accelerator in a pressure tank.

beams by accelerating ions twice. In this two-stage or "tandem" accelerator, illustrated in Figure 15.5, injected negative ions are accelerated from ground potential to a positively charged high-voltage terminal. In the terminal, a thin gas or foil target strips electrons from the ions. The resulting positively charged ions are accelerated a second time, away from the terminal, back to ground potential.

Tandems accelerate protons to an energy of $2eV$, where e is the electron charge and V is the terminal voltage. Heavier ions, which can be stripped to multiple positive

charge states, are accelerated to even higher energies. For example, negative oxygen ions injected into a tandem operating at 10 MV are first accelerated to the positive terminal to 10 MeV. Some of the oxygen ions are stripped of all electrons and emerge from the terminal with a charge of $+8e$ and gain an additional 80 MeV in the second acceleration for a total energy of 90 MeV.

The tandem principle was originally patented in 1935 by Bennett of Ohio State University. HVEC built many tandem accelerators, which are in operation in

laboratories around the world. The largest reach terminal voltages of over 16 MV.

15.2.7

Tandetron Accelerator

In 1980, Purser designed the Tandetron line of compact tandem accelerators for materials analysis, accelerator mass spectrometry, mega electronvolt ion implantation, and basic research. The high-voltage generator is a Dynamitron-type parallel-driven cascade rectifier circuit with silicon rectifiers and a 50-kHz driver. It delivers several hundred microamperes of beam current at up to 3 MV with high stability. For accessibility, the high-voltage stack is at right angles to the accelerator column and SF_6 , at a pressure of about 5 atm, insulates the accelerator and power supply.

15.2.8

Pelletron Accelerator

Pelletron accelerators use a charging chain, rather than a belt or rectifier stack, to deliver charge to the terminal in order to generate high voltage (NEC). The chain, shown in Figure 15.6, consists of steel cylindrical pellets joined by links of solid insulating material such as nylon. Pellet charging current is adjustable and highly

uniform, so that terminal voltages are easily maintained at very precise values with very little voltage ripple. This high charging stability is important and, in some cases, essential for applied uses.

The pellets are charged inductively, so there is no contact with the charging electrodes called *inductors* and no electrical discharge between the pellets and inductors.

The pellets carry the charge into the terminal, where the charge is removed at another pulley. The pellets are then negatively charged in the terminal, so that the up-going and down-going runs of the chain contribute equally to charging. Laddertron charging systems, built by HVEC, are similar except that a pair of pellets is joined by a rung forming a ladder structure. Of the 21 tandem accelerators operating above 8 MV, 18 use or are installing Pelletron charging systems, 3 use Laddertrons, and only 2 still rely on belts.

The highest voltage electrostatic accelerator, the NEC 25 MV tandem accelerator, is at the Oak Ridge National Laboratory (ORNL) and is shown in Figure 15.7. It is also one of the few “folded” tandems. In the folded design, both acceleration tubes are mounted in a single insulating support column. Ions are accelerated up to the terminal and stripped of some electrons. Then

Fig. 15.6 Pelletron charging chain and terminal pulley in a 1.7-MV NEC tandem accelerator.

Fig. 15.7 Drawing of the 25-MV folded tandem at the Oak Ridge National Laboratory, showing the 180° magnet in the high-voltage terminal. The cylinder (lower left) is a 500-keV ion injector. (Drawing courtesy of National Electrostatics Corp.)

a 180° magnet reverses the beam direction for the second acceleration down to the target locations. The magnet completely filters out ions of unwanted charge states from the stripper before the second acceleration, so there are no extraneous beams loading the accelerating tube. The folded design, first successfully used by Naylor in New Zealand, conveniently locates both ion source and sample chamber near the system control room. For very large tandems (20 MV and higher), the folded design reduces the size and costs for the building, insulating gas, and pressure vessel.

15.3 Applications of Low-Energy Electrostatic Accelerators

Basic research in nuclear and atomic physics drove the development of electrostatic accelerators from their beginnings in the early 1930s until well into the 1970s. In the 1980s, a broad range of new applications of accelerators rapidly expanded their use. By the end of the 1980s, nearly all new electrostatic accelerators had terminal voltages less than 5 MV and were designed for applied work. Many existing smaller

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tandem accelerators, with voltages up to 10 MV that were originally built for nuclear physics research, were converted for use for applied physics. Most of the larger ones, voltages of 10 MV and above, expanded their role from stand-alone heavy ion accelerators to include injecting into other accelerators to provide heavy ion beams with higher energies and heavier masses.

There are three main areas of application of electrostatic accelerators, in terminal voltages up to about 5 MV, which employ a variety of electrostatic accelerators. For applications needing energies of up to several hundred kilovolts, insulated core transformers and open-air symmetric cascade generators are chosen. Higher voltages employ Dynamitrons, Van de Graaffs, and Pelletrons in competition with RF linacs.

15.3.1

Material Transformation

The first class of operation is the use of the beam particles themselves to alter the material on which they impinge transforming it in some way.

15.3.1.1 Ion Implantation

The major application of low-energy accelerators is the ion implantation into semiconductor material to produce microscopic electronic circuits. Mega electron-volt implanters produce ion beams at energies from a few hundred kilo electronvolts to over 1 MeV. At the higher energies, ions penetrate deeper into the semiconductor wafer. Deeper implants permit higher density circuits and can create conducting or insulating layers below surface circuitry to inhibit effects from stray charges, for example, in computer memory chips. Multiple implants at different energies to over 1 MeV are used to produce deep complementary metal

oxide semiconductor (CMOS) wells, with economic and performance advantages over wells produced by slower thermal diffusion. Mega electronvolt ion implantation in III-V materials such as gallium arsenide produces very high speed switching circuits and light-emitting and light-sensitive solid-state devices. Mega electronvolt implants can program logic circuits late in their production cycle and enhance circuit resistance to radio frequency and radiation interference.

15.3.1.2 Surface Processing

Ion implantation is also used to improve the corrosion and wear resistance of metal surfaces. Implanting nitrogen into low carbon steel increases surface hardness for improved resistance to abrasive wear. Implanting titanium into steel reduces the coefficient of friction. Implants of elements such as Cr, Ta, Pd, P, and B into metals can reduce the chemical reactivity of the metals, for example, for longer component lifetime in chemical processing systems.

15.3.1.3 Electron-Beam-Induced Radiation Damage

The radiation damage produced by electron beams is used to increase the mechanical toughness of plastic insulation on electrical cable, to cure thin coatings, to improve adhesives, for sterilization of single item medical disposables, for crystal modification for permanent color in glass and gems, in the treatment of drinking water, disinfection of municipal sewage, and treatment of SO₂ and oxides of nitrogen in industrial smokestack exhausts.

15.3.2

Materials Analysis with Ion Beams

Materials analysis is a pervasive application of electrostatic accelerators in which the

ions are used to interrogate the composition of the material rather than to transform it. These nondestructive techniques use mega electronvolt ion beams to identify elements and measure their concentrations and locations in a wide range of materials.

15.3.2.1 Particle-Induced X-Ray Emission (PIXE)

Particle-induced X-ray emission (PIXE) identifies elements and their relative abundances from the energies of characteristic X-rays emitted by atoms in the sample, which are excited by an incident mega electronvolt ion beam. It is used to measure trace elements in biomedical samples, ceramics, petroleum, polymers, and crystals, and on the surfaces of metals and semiconductor materials. PIXE analysis of air samples is used to monitor aerosol pollution. With a scanning proton microprobe ion source, PIXE provides high-resolution lateral mapping of trace element distributions in organic tissues, minerals, and so on.

15.3.2.2 Rutherford Backscattering Analysis (RBS)

Rutherford backscattering analysis (RBS) measures depth and density profiles of elements at and near the surface of samples. Nuclei in the sample elastically scatter incident mega electronvolt helium ions to a backward angle where their energies are measured.

Rutherford scattering is simply elastic scattering due to the electrostatic repulsion of the positively charged incident and target nuclei. The energy of scattered particles and the counting rate can be calculated from first principles. For a given incident beam, the energy of the scattered ions increases with increasing target mass. The cross section, the probability of scattering, is proportional to the square of

the target atomic number (Z) divided by the incident energy. From the calculated cross section and the measured incident beam current, RBS can measure elemental concentrations directly, so calibration standards are not required. RBS is often used to measure concentrations of known target elements, for example, in surface layers created by vapor deposition or ion implantation.

The fast, simple, quantitative, and non-destructive nature of RBS analysis has opened many applications. RBS systems typically use small tandem accelerators, which produce microampere helium beams over a wide range of selectable energies. Lower energy beams increase depth resolution in thin films. Higher energies probe deeper and improve mass resolution for heavy elements.

15.3.2.3 Channeling

Channeling, an effect seen in RBS analysis of crystals, decreases backscatter yields by as much as 98% when the beam is aligned with a crystal axis. Ions incident parallel to the axis (within about 1°) are steered by correlated small-angle deflections along the axis, preventing their close approach to crystal lattice atoms. Since close approach is required for large angle scattering, only lattice imperfections and impurities in the crystal will result in significant large angle yield.

Channeling is used, especially in the semiconductor industry, to measure crystal perfection, the amount and depth of lattice disorder, locations of substitutional and interstitial impurities, and lattice damage from ion implantation in silicon and subsequent crystal regrowth after annealing. Surface defects and amorphous surface layers increase the angular divergence of the beam, so that some of the beam cannot be channeled by the crystal below the surface.

This effect is used to measure thickness and crystallinity in surface layers. Channeling improves RBS sensitivity to surface impurities by reducing backscatter from the substrate and permits deeper analysis with PIXE and nuclear resonance analysis in crystals.

15.3.2.4 Elastic Recoil Detection (ERD)

Elastic recoil detection (ERD) is like RBS analysis, but measures the recoiling target ions at forward angles instead of the scattered beam particles. In applications on thick samples, the incident beam and detector are at grazing angles to the sample surface. Thin foil samples are exposed to the beam at normal incidence with the detector at 0° , where recoil cross sections are largest.

ERD is sensitive to light elements in heavy substrates and is used to profile hydrogen in metals and semiconductors. Although nuclear reaction analysis gives better depth resolution, ERD is faster and easy to analyze.

15.3.2.5 Resonance Scattering

Resonances increase the scattering cross section at particular energies and angles. Proton backscattering from carbon, resonant at 1.73 MeV, is used to measure photo resist thickness on wafers coated with a metal, such as gold. Resonance scattering is superior to helium RBS in which the high background of backscatter from Au obscures the carbon signal. Elemental concentrations can be measured with resonance scattering if the detection system is calibrated using standard targets of known concentrations.

15.3.2.6 Nuclear Reaction Analysis (NRA)

As beam energy increases and the scattering no longer follows the Rutherford formula, the use of nuclear reactions becomes

possible. The reaction $^1\text{H}(^{15}\text{N}, \alpha\gamma)$ is resonant at 6.4 MeV and provides good depth resolution for profiling hydrogen in metals, semiconductors, and glass. Unlike ions, γ rays do not suffer energy loss in the material. Using channeled beams to induce γ -emitting reactions, nuclear reaction analysis (NRA) locates impurities deep within a crystal. The sensitivity of reactions to specific isotopes is useful for analyses in several fields, including mineralogy and biomedicine.

15.3.2.7 Activation Analysis

Particle-induced nuclear reactions are used to generate trace quantities (10^{-10}) of radioactive isotopes at the surface of objects like gears or inside a pipe. Decreases in radioactivity, in excess of natural decay, measure the rate of surface wear or erosion.

Neutron activation analysis is used to locate underground oil deposits. Accelerators to generate the neutrons operate at about 100 kV and are small in diameter (<45 mm) to fit into drill holes. Neutrons are also used to detect explosives in airplane cargo.

15.3.2.8 Ion Beam Microprobe

Typical mega electronvolt ion beams are about 2–4 mm in diameter. While suitable for many applications, this is often too large for measuring lateral distributions of elements in important samples. The microprobe produces a beam spot of 10–20- μm down to <0.3 - μm diameter for measurements with spatial resolution of a few microns or better. It uses energy-analyzed beams from an accelerator and includes a beam collimator, strong focusing lenses, a target chamber with sample holder, detectors, and a means of scanning the beam across the sample. Microprobes mainly use mega electronvolt proton beams and PIXE

analysis, primarily for biomedical studies, but also for archaeology, mechanical engineering, mineralogy, and solid-state studies.

15.3.3

Accelerator Mass Spectrometry (AMS)

Accelerator mass spectrometry (AMS) measures isotopic ratios down to 10^{-16} with high precision using only milligram and smaller samples. Naturally occurring radioisotope concentrations are measured to date art and archaeological objects, ground water, lunar samples, and meteors and to study glaciers, sediment formation, and ocean mixing. AMS of tracer isotopes is used in hydrological and atmospheric studies.

The samples of milligram size, analyzed by AMS are not in a target chamber, but in the ion source, which creates ion beams from the sample. Carbon dating, the primary use of AMS, determines the age of samples from the concentration of ^{14}C , whose half-life is 5.73 ka ($a = \text{year}$). The beam from the ion source contains ^{12}C , ^{13}C , and ^{14}C ions in the same relative abundances as in the sample.

Tandem accelerators are best suited to most AMS applications, because they can transport all of the isotopes without intermediate adjustments and accelerate them to high energy for high discrimination against contaminant beams. Molecular isobaric interferences, a common problem for other mass spectrometers, are eliminated in tandems, because the stripper dissociates molecules, and the fragments are easily resolved by the detector systems. The use of negative ions, required for tandems, fortuitously eliminates potential interference from ^{14}N (much more abundant than ^{14}C) in carbon dating, because negative N

ions are not stable and thus cannot be created. For milligram samples, ages to 5 ka require <1 hour for 0.3% accuracy and ages to 50 ka can be measured with reasonable measurement times.

Tandem accelerators with terminal voltages of ~ 0.5 MV have recently demonstrated comparable performance in ^{14}C dating to the conventional machines with terminal voltages above 1.7 MV. These 0.5-MV tandems are more compact and so better suited to industrial use and small laboratories. The AMS group at the ETH Zurich, Switzerland, has demonstrated that adequate molecular dissociation occurs even at 0.2 MV (Zurich). They have built a 0.2-MV tandem for AMS in which the voltage insulation is achieved by high vacuum instead of a high-pressure gas. Thus, there is no need to separate the vacuum space, which the beam traverses, from the insulating region and so there is no need for an acceleration tube.

Since adequate molecular dissociation is practical at 0.2 MV, NEC has even eliminated the tandem accelerator itself. In their single-stage accelerator mass spectrometer introduced in 2005, Figure 15.8, negative ions are produced in the usual way, from a multisample negative ion source by sputtering with Cesium (Cs) positive ions (NEC). The negative ions emerge with 44-keV energy and then are energy analyzed in a 15° electrostatic deflector, followed by mass analysis using a 90° magnet. They are accelerated by an additional 250 kV for molecular dissociation in a gas stripper. The $+1$ ions are then again magnetically and electrostatically analyzed as in conventional AMS. Precision of better than 0.5% has been demonstrated.

AMS employs several isotopes for exposure age dating, that is, measuring the build-up of the radioactive isotope in a rock surface that has been bombarded by

Courtesy of national electrostatics corp.

Fig. 15.8 NEC single-stage accelerator mass spectrometer.

cosmic rays. Isotopes commonly used are ^{10}Be (1.6-Ma half-life), ^{41}Ca (130 ka), and ^{36}Cl (310 ka). ^{36}Cl is also used for the dating of ground water and ^{26}Al (720 ka) for cosmology and medial physics. The isotope ^{129}I (16 Ma) is used to study petroleum deposit formation and tracing discharges from nuclear plants. The take-up of calcium in animals is studied using ^{41}Ca .

AMS also measures traces of stable isotopes and their distribution in geological samples. Concentrations below 10^{-10} are mapped by using a scanning micro ion beam sputter ion source to bombard the sample and a tandem AMS system to detect the emerging negative ions.

15.4 High-Energy Electrostatic Accelerators

Electrostatic accelerators, with terminal voltage at and above 10 MV, were initially bought for nuclear physics research first with light ions like the hydrogen and helium isotopes, but later with heavier ions. The nuclear physics accessible with these machines was limited to ions lighter than about Ni. As this area of research was exploited, the push to heavier ions drove the expansion of the mass range of beams by the addition of booster accelerators. One might have thought that this relegated the tandems to the injector role. However,

the tandems continued to dominate the research done in such labs because of their ease of operation compared to boosters and the ingenuity of the physics research staff. The productivity of these laboratories continues to earn a substantial place for them at the forefront of research in nuclear physics.

15.4.1

Injectors in Nuclear Physics Research

Electrostatic accelerators became the injectors of choice for facilities requiring higher energy heavy ion beams. The factors in their favor are as follows: they were already the heavy ion workhorses present in the research laboratories; they are easy to operate and reliable; they produce compact beams with the good energy resolution of ~ 2 parts in 10^4 ; and changing beam species is easy because the ion source is accessible at ground potential.

They dominated over positive ion injectors in the injector role for heavy ion research in spite of having much lower beam intensity and the nonexistence of negative noble gas ions other than helium. Indeed, of the 15 post accelerators injected by tandem accelerators only one, at the Hahn Meitner Institute, Berlin (HMI), used a single-ended Van de Graaff. In laboratories with strong backgrounds in cyclotron technology such as Michigan State University (MSU), NAC, National Accelerator Centre, iThemba Laboratory for Accelerator Based Sciences, Capetown South Africa, and Ganil cyclotrons are the chosen injectors.

The DC beam from an electrostatic injector is not directly compatible with the booster's pulsed acceleration process. The two types of boosters, linear accelerators (LINACs) and cyclotrons, both are driven with megahertz RF. Thus, they accelerate

best over a limited number of degrees of an RF cycle – about 5° for a 150-MHz LINAC. Therefore, the DC beam must be bunched for injection – a process that reduces the available beam intensity.

There are several factors that contribute to the relatively low beam intensity from electrostatic tandem injectors: the negative ion current is one to two orders of magnitude smaller than that from a positive ion source; the fractionation of that beam, due to the stripping process in the terminal, costs a factor of about 4–7; and the loss due to bunching the DC beam into tight time bunches to match the booster RF phase acceptance accounts for about up to factor of 2. Another significant drawback of tandem accelerators as injectors is the limited lifetime of the carbon foils used to strip electrons from the negative ions in the terminal. The down time associated with opening the accelerator pressure vessel to replace the broken foils limits the availability of facility.

However, it is only from the mid-1990s that positive ion injectors have started to compete with tandems in existing labs. Argonne National Lab (ANL) has used positive ion injectors routinely but, in 2007, still relied on its FN tandem 20% of the time. Tandem injectors still coexist with positive ion sources at Legnaro and Catania. New facilities like the one at TRIUMF, without tandems to hand, opt for positive ion injectors.

15.4.2

Electrostatic Accelerator Injectors

The existing population of electrostatic accelerators determined the choice of injectors pressed into service for the expansion of nuclear physics research. Although many were manufactured by HVEC, many of these were modified to

include Pelletron charging systems and/or Dowlish accelerating tubes.

At the low energy end (6–8 MV), these accelerators included the HVEC CN injecting a cyclotron at HMI, Berlin, the EN at Kansas State University (KSU) and the 8UD Pelletron in USP, Departamento de Fisica Nuclear, University of Sao Paulo, Sao Paulo, Brazil, the latter two injecting superconducting LINACs. The next rank of injectors comprised the HVEC, 8–10 MV FNs servicing superconducting LINACs at ANL, the State University of New York at Stonybrook (SUNY), the University of Washington at Seattle, Florida State University at Tallahassee (FSU) and Centre d'Etudes Nucleaires (Saclay) France.

The higher energy electrostatic accelerators were generally used in larger laboratories and were adapted to inject a wider variety of boosters. Although the nuclear physics research of the combined accelerator pair was still targeted at beams at 5–10 MeV A^{-1} , where A is the projectile mass in atomic mass units, the range of masses was biased to heavier beams in these larger facilities.

The HVEC MPs and XTUs are capable of 12–16 MV on terminal and could deliver beams with β ranging from 0.06 to 0.08, where β is the ratio of the beam velocity to the velocity of light. The boosters would then further accelerate the beam to a β of 0.1–0.15. This was accomplished with superconducting LINACs at Istituto Nazionale di Fisica Nucleare Laboratori Nazionali (Legnaro), LNL, Italy. A room-temperature LINAC is injected by an MP at MPI (Heidelberg) and a superconducting cyclotron at Catania, Italy. Chalk River National Lab, Canada (CRNL) had an MP–superconducting cyclotron combination that has now been shut down.

15.4.2.1 LNS Catania Injector and Radioactive Ion Beam Accelerators

The Catania facility was reconfigured as shown in Figure 15.9. The cyclotron, using spallation reactions, produces radioactive species, which are then accelerated in the electrostatic accelerator (Catania).

15.4.2.2 ORNL Injector and Radioactive Ion Beam Accelerator

The large NEC Pelletron accelerators were newer than the HVEC cohort and so more of them were adapted as injectors. The largest such facility, the 25URC in Oak Ridge, is capable of more than 25 MV on terminal (ORNL). Figure 15.7 shows the 25URC in stand-alone mode.

The 25URC was always intended to inject beam into the Oak Ridge Isochronous Cyclotron (ORIC) as shown in Figure 15.10. In this floor plan, the tandem is vertically above the partial circle at the lower left, and injects beam into ORIC on its axis. The first coupled operation beam was 400 MeV ^{16}O followed by 28 different ion species, ranging from Li to Pb. The portion of beam time in coupled operation ranged between 35 and 45%, went down to 25–30% during the years 1986–1989, and then to 16.5% in 1990 when coupled operation ceased.

The fashion in physics moved from boosted beams of stable isotopes to radioactive beams and so the ORNL combination of accelerators was reversed as shown in Figure 15.11. Here, again, the tandem is above the partial circle on the left but now, ORIC delivers its proton beam to one of two target/ion sources in the heavily shielded rooms. There, the radioactive atoms are transformed to negative ions and then mass analyzed for injection into the tandem for acceleration.

The accelerator combinations at Catania and Oak Ridge are in the first generation

Fig. 15.9 The radioactive ion beam facility at LNS, Catania. The cyclotron beam produces radionuclide in a target ion source where they are converted to negative ions for injection into the tandem for acceleration. (Courtesy of the INFN LNS.)

of radioactive ion beam facilities defined as those that exploit existing infrastructure and provide beams at and below the coulomb barrier for light and medium mass ions. Research over the full range of masses and energies will be the domain of purpose-designed facilities, which will not include electrostatic accelerators.

15.4.2.3 Brookhaven National Laboratory – Dual MP Injectors

One of the most successful examples of electrostatic accelerators performing the injector role is the MPs at Brookhaven National Lab, (BNL) (RHIC). It is commonplace in high-energy laboratories for a sequence of accelerators to be used to produce the final beam and for newer, larger accelerators to stand on the shoulders of their predecessors. This is also the path

taken at BNL, in the journey toward the Relativistic Heavy Ion Collider (RHIC).

There already existed at BNL a historic high-energy physics program using the Alternating Gradient Synchrotron, (AGS), which provided multi-GeV proton beams. In addition, BNL had a vigorous nuclear physics program based on two MP tandem accelerators. These accelerators were well equipped for the injector task since they had the newest style of acceleration tubes for stable operation at 14 MV, Pelletron charging systems for good energy stability, modern resistor grading, and high-intensity negative ion sources.

The AGS evolved into a heavy ion accelerator in a proof-of-principle exercise in which ions were injected by one of the MP tandem accelerators for fixed target experiments. For head-on collisions

Fig. 15.10 Lay out of the ORNL 25 URC injecting ORIC along its central axis. The Tandem is vertically above the partial circle.

envisioned for RHIC, the center of mass energy, that is the energy available for reactions, would be more than doubled. The higher energy is required for the shift to research on quark-gluon plasma. This physics demanded very energetic heavy ion beams that could be produced by using the AGS to populate counter-rotating GeV heavy ion beams in a collider ring, RHIC. The layout of the BNL accelerator facility is shown in Figure 15.12.

Electron Stripping and Energy Gain The stripping of electrons from ion beams is an essential process in all heavy ion facilities and is illustrated in Figure 15.13 using the BNL arrangement. The factor that determines the fate of a heavy ion, between the ion source and the target, is its interactions with matter. These collisions

determine its charge state and its charge state determines how much energy it can gain in the electric fields of the accelerators.

At the ion source, an extra electron is attached to the neutral atom, often in the sputtering process using Cs ions, at energies of a few kilo electronvolts. The velocity of the negative ion increases as it is accelerated on its way to the terminal of the tandem accelerator. If it strikes a residual gas molecule during this segment of its journey, it will be neutralized or made positive and so gain no further energy. The survivors reach the terminal with, for example, 14-MeV energy. Here, an interaction with matter is imposed since it is necessary to change the charge state from negative to as high a positive charge state as possible. The higher the charge state, the higher the energy the ion will

Fig. 15.11 The ORNL Radioactive Ion Accelerator system with ORIC bombarding a target in one of two well-shielded rooms each containing a negative ion source. The ions are then accelerated in the tandem. (Drawing courtesy of Oak Ridge National Laboratory.)

Fig. 15.12 The RHIC complex showing the tandem Van de Graaff injection via the booster and the AGS. (Illustration courtesy of Brookhaven National Laboratory.)

gain by of acceleration from the positive terminal to ground potential.

The highest charge states are achieved by using a carbon stripper foil with thickness of a few micrograms per square centimeter. This stripper foil will, unfortunately, also scatter the ions causing some of the beams to be not transmitted through the rest of the machine. The thinner the foil, the lesser the scattering, but thin foils are so fragile that they are easily broken even before being exposed to the beam. A $4\text{ }\mu\text{g cm}^{-2}$ typical carbon stripper foil in a tandem terminal is 99% transparent. The other factor that enhances the higher charge states is high ion velocity. That is why higher energy tandems predominate as injectors especially for heavier ions.

If the ion, in its travels from the tandem, encounters residual gas molecules, more electrons will be stripped from it thus reducing its radius of curvature in the

deflecting magnets along the path to the booster. These ions would be lost to the beam unless the stripping process is confined to where the ions can be retained in the beam. The second stripping is desirable because the booster will add energy in proportion to the charge state of the ions presented to it. Since the number of electrons stripped increases with the ion velocity, the higher energy ions emerging from the tandem can be stripped to charge states much higher than that achieved in the tandem terminal.

In the case of Au ions from an MP at BNL operating with 14 MV on the terminal, charge state +12 is chosen resulting in a final beam energy of $14(1 + 12) = 182\text{ MeV}$. In Figure 15.13, the stripper in the terminal of each MP is labeled S1. This beam, after tandem acceleration, is further stripped at S2 to +31 for its travel along the $\sim 850\text{-m}$ -long transfer line to the booster.

Fig. 15.13 The RHIC combination of accelerators starting with the pair of HVEC MPs. The carbon strippers are shown as S1, in the terminals of the tandems; S2, at entry to the transfer line leading to the booster; S3, between the booster and the AGS; and finally S4, at the entrance to the RHIC transfer line. (Illustration courtesy of Brookhaven National Laboratory.)

If the +31 ion interacts with residual gas in this section, it is less likely to change charge state and be lost to the beam since its charge state is already typical for interactions at this velocity.

As seen in the figure, there are two additional foil strippers. The one after the booster, S3, takes the beam from +31 to +77 to maximize the energy gain and minimize the charge changing loss in the AGS. For similar reasons, a fourth stripper, S4, is placed before RHIC to fully strip the Au to +79, precluding any further change of charge state.

All these stripping actions impose losses in intensity because only a fraction of the beam incident on a stripper foil will emerge in a particular charge state. In each of the first two stripping events, only about 15% of the incident beam goes to the desired charge states, +12 and +31. The stripping efficiency between the booster and AGS, S3 is much higher, 65%, because +77 Au is helium-like. It retains only the two very tightly bound K-shell electrons and readily sheds all the other less tightly bound ones. Thus, $0.15 \times 0.15 \times 0.65 = 0.015$ of the negative ion beam will reach the fourth stripper

only if there are no other losses due to apertures. The last stripping, S4, is >99% efficient since, at this highest energy, only the last two electrons need to be removed.

The BNL electrostatic accelerators have provided pulses of Au, Cu, and deuterons for RHIC. The Au ions from either tandem travel through the tandem-to-booster transfer line to a booster synchrotron, which accelerates the beam to $\beta = 0.37$ for further injection into the AGS. There, the beam is stacked and accelerated to $\beta = 0.997$ in the AGS before being sent to RHIC to circulate in either the clockwise or counterclockwise direction. The counter-circulating beams are made to collide at six interaction points where the experiments are mounted.

Having two MPs allows for either to operate while the other is being serviced. Using both machines, collisions can be arranged between different beam species for example, deuterons from one MP and Au ions from the other. The MPs also provide heavy ion beams via the booster synchrotron to the NASA Space Radiation Lab as well as MP-only beams to a large user community.

Now that the ground work for RHIC has been done with the MPs, a purpose-designed positive ion injector is expected to be commissioned in 2010. This comprises an electron beam ion source, an RF quadrupole accelerator, followed by a LINAC. This combination has the advantages over the MPs of higher intensity, noble gas beams, and shorter beam pulses to better match the time structure required by the booster synchrotron. If history is any guide, the MPs will continue to provide alternative injection service to RHIC and beam for the NASA Space Radiation Lab and stand-alone operation for other users.

15.4.2.4 Argonne National Lab – ATLAS

The ATLAS booster, a superconducting LINAC, was first injected by a HVEC FN electrostatic accelerator. It has been upgraded with NEC accelerator tubes, a Pelletron charging system, and modern resistor grading system. Here too, the FN was the convenient workhorse to get the heavy ion LINAC program off the ground and continues to inject beam 20% of the time even though two excellent positive ion injectors are available (ANL).

Figure 15.14 shows the three complementary injectors at the ATLAS accelerator facility at Argonne National Laboratory.

As is the case in BNL, the beam is stripped several times to optimize the energy gain provided by the LINACs. In addition to the stripping in the terminal of the FN from negative to multicharged positive, there is another stripper in front of the booster and another in front of the ATLAS section. The terminal voltage of the FN is only 8.5 MV, which results in lower charge states than is the case for the 14-MV BNL machines and thus limits the FN injection to beams of masses up to Ni.

The booster accelerating devices are superconducting split ring resonators operating at 48 MHz. The time structure of the booster requires the tandem DC beam first to be bunched into 1-nanosecond-wide pulses. This is accomplished with a 4-harmonic gridded buncher, which captures 75% of the DC beam. The beam is then further compressed into 0.1 nanosecond bunches using a superconducting resonator for acceleration in the LINAC. The ANL superconducting resonator technology and beam pulsing techniques underpin booster projects in Sao Paulo, Brazil, in Florida State University (FSU), in Kansas State University (KSU), in Japan Atomic Energy Research Institute (JAERI), Tokai,

Fig. 15.14 ATLAS layout showing the FN tandem injector and the two positive ion injectors. The negative ion beam is stripped in the terminal of the tandem before injection into the booster LINAC and before entry to the ATLAS LINAC. (Illustration courtesy of ANL.)

Japan (JAEA), and in the Inter-University Accelerator Centre, (IUAC), New Delhi, India. All these facilities use tandem accelerators as injectors.

15.4.2.5 NEC 14–16UD Injectors

NEC accelerators that are used as injectors are the 20URC at the Japan Atomic Energy Agency (JAEA) and the 14–16UDs at the ANU, Canberra, Australia, at Inter-University Accelerator Centre, (IUAC), New Delhi, India, and at the Tata Institute for Fundamental Research, (TIFR), Mumbai. At these facilities, NEC tandems inject into superconducting LINACs for a growing part of their research programs.

The large electrostatic tandem accelerator developed at the Nuclear Science Centre in Daresbury, England, mirrored some of the NEC design features. It was intended to have a 20-MV terminal and was adapted to inject a superconducting LINAC, but

funding was diverted just as the first boosted beams were demonstrated. The LINAC was resurrected at the ANU where it was developed further and the tandem in Daresbury scrapped.

Another family of accelerator facilities, in which electrostatic tandem accelerators are used as injectors, use variants of LINAC accelerating resonators based on a Caltech design of a split loop resonator and/or a quarter wave resonator developed by Ilan Ben Zvi at the Weizman Institute (Rohovot) Israel, in conjunction with the University of Washington, Seattle and the University of the State of New York, Stonybrook, USA (SUNY). Although a booster facility was not achieved at Rohovot, their contributions to the technology played an important role at several other labs including Legnaro, Stonybrook SUNY, University of Washington, the ANU Canberra, and at TIFR (Mumbai).

Fig. 15.15 The 14UD injector at the ANU providing beam to superconducting LINAC.

Figure 15.15 shows the layout of the facility in Canberra. It is typical of such facilities that the arrangement of beam transport from the existing electrostatic accelerator to the booster is complex and unique for each installation.

Summary

Electrostatic accelerators have provided the earliest and most productive tools for nuclear research. Their variety and robustness ensured their wide application in industry and diverse areas of science. As tandem accelerators became the preferred devices for heavy ion physics, their roles expanded to injectors into boosters. Their

place in the evolution of heavy ion physics was and is the link to future generations of accelerator systems. Because of their multiple strengths, they continue to make crucial contributions to research at the leading edge of heavy ion physics including the study of the quark-gluon plasma and the physics revealed with radioactive beams.

Acknowledgments

This is an update of "Potential Drop Accelerators" by R. G. Herb and G. M. Klody in the "Encyclopedia of Applied High Energy and Particle Physics" WILEY-VCH Verlag GmbH & Co KGaA, 1989. Much of

the history and descriptions of applications is based upon that article. I would like to thank all the colleagues and institutions that have generously provided illustrations and information. Greg Norton at NEC has been a crucial resource as have Keith Fifield at ANU, Dannie Steski at BNL, Richard Pardo at ANL, and Martha Meigs at ORNL.

Glossary

Atm: Atmospheric pressure.

Dielectric Strength: The ability of an insulating material to sustain electric fields without breaking down.

HVEC: High Voltage Engineering Corporation – Manufacturer of CN, EN, FN, and MP Van de Graaff and ICT accelerators. The company is no longer operating.

Ion Implantation: The insertion of energetic ions into a material.

Lattice Atoms: The structural atoms organized in a regular pattern that comprises a crystal.

LC Resonant Circuit: A combination of inductors and capacitors through which electric current will oscillate at a fixed stable frequency.

NEC: National Electrostatics Corporation – Manufacturer of Pelletron accelerators.

Nuclear Transmutation: The conversion of a highly radioactive isotope into a less radioactive one using a nuclear reaction caused by ion-beam bombardment.

RF Electrode: One plate of a capacitor in a radio frequency circuit used to couple power.

Semiconductor: Materials such as silicon and germanium serving as the host for electrical devices.

SF₆: Sulfur hexafluoride gas used to insulate high electric fields.

Sputtering: The energetic liberation of atoms from a solid caused by the impingement of high-velocity atoms or ions.

Stripping: The process in which electrons are removed from an ion during its passage through either a low-pressure gas region or a thin carbon foil.

Tandem: An accelerator in which a negative ion is accelerated to a positive terminal where electrons are stripped from it to produce a positive ion, which is then accelerated again to ground.

Terminal: The high-voltage terminal of an accelerator.

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