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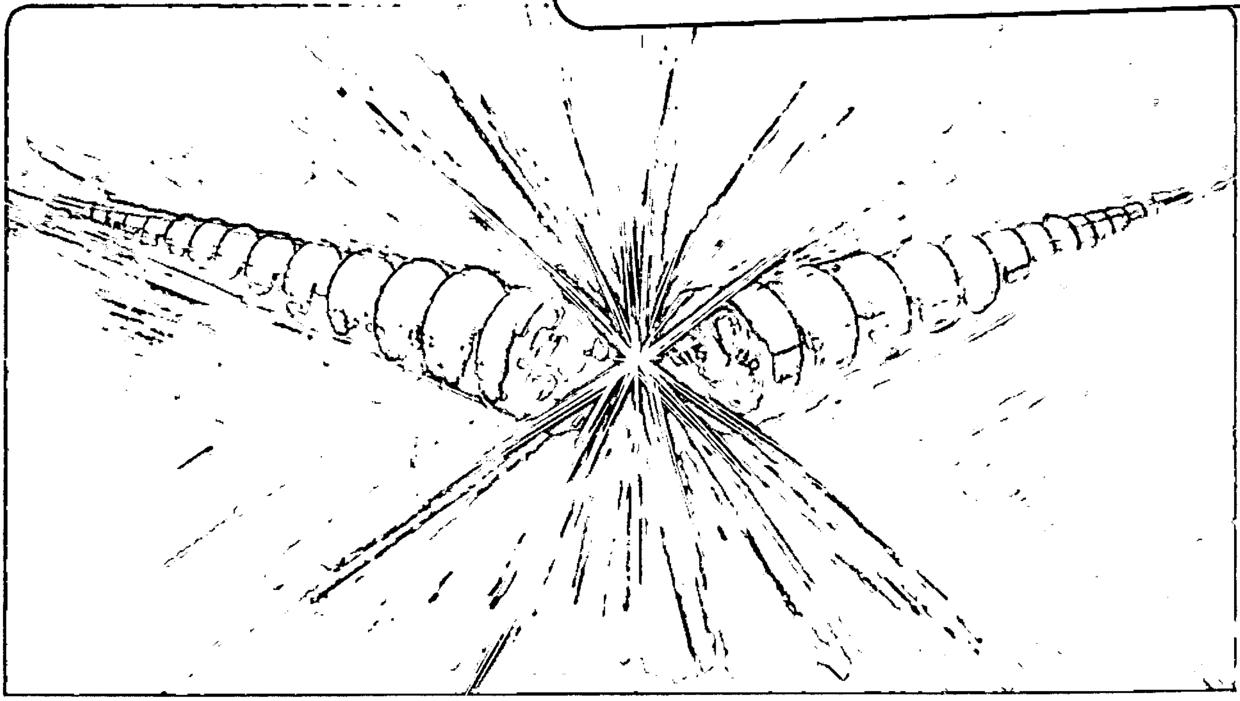

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ACCELERATOR, PARTICLE

Particle accelerators are electromagnetic devices used to generate energetic beams of charged particles--electrons, protons or other ions. They are widely used in research in many fields of physical science and they have many practical applications in medicine, manufacture, and engineering.

The earliest forerunners of particle accelerators were the gas discharge tubes and x-ray tubes of the late 1800's. They provided some of the early technological base for accelerator development, but they were special in purpose, very limited in voltage, and not the motivation for accelerator development.

The need for particle accelerators became apparent in the 1920's after Rutherford had demonstrated the existence (1911) and the disintegration (1919) of the atomic nucleus using alpha particles from a radioactive substance to probe the structure of the atom. Clearly these experiments gave promise of a radical new understanding of the nature of matter. But just as clearly, particles from radioactive substances were not adequate for the task of exploring atomic and nuclear structure. Beams from such sources were very limited in intensity, poor in collimation, lacked control of energy, and were limited to β-rays (electrons) and α-particles (helium nuclei). Reviewing the need for particle accelerators and the technological base for developing them, Rutherford stated in a famous address in 1927:

> "It would be of great scientific interest if it were possible in laboratory experiments to have a supply of electrons and atoms of matter in general, of which the individual energy of motion is greater even than that of the α-particle. This would open up an

> extraordinarily interesting field of investigation which could not fail to give us information of great value, not only on the constitution and stability of atomic nuclei but in many other directions. ...but it is obvious that many experimental difficulties will have to be surmounted before this can be realised."

Inventors and experimenters were already at work to overcome the difficulties with a variety of approaches: electrostatic devices, Tesla coils, transformers, voltage multipliers, radio-frequency resonance acceleration, even atmospheric electricity. By the early 1930's several types of particle accelerators had been invented and successfully used in nuclear experiments.

The electric force is the only macroscopic force strong enough to accelerate particles. The magnetic force, while also strong, is exerted perpendicular to a line of motion, and thus may be used to change the direction of, but not to accelerate, particles. Applying these forces, many kinds of accelerators have been developed, but all are based on a few physical concepts. The emergence of these concepts will be used as a framework to discuss the principal types of accelerators.

DIRECT-POTENTIAL-DROP ACCELERATORS

The simplest particle accelerator concept entails a source of charged particles at one end of an insulating evacuated tube and a source of high voltage placed across the ends of the tube. The particles are accelerated from the source end of the tube to the target end by the electric field and gain kinetic energy. The energy of accelerated particles is universally expressed in electron-volts, eV, the energy gained by a particle bearing a charge equal to that of an electron accelerated through a potential difference of one volt. The energies that are of interest in nuclear studies are several hundred kilo-electron-volts, keV, and upwards without a presently perceived limit. The technological difficulties encountered in the realization of this concept are connected with generating the high voltage and with electrical breakdown both internally and externally in the accelerating tube.

J. D. Cockcroft and E. T. S. Walton, who were the first to achieve nuclear disintegration by electrically-accelerated particles in 1932, used a voltage-multiplying rectifier circuit of four stages which effectively charged capacitors in parallel and discharged them in series to reach about 400 kV. They used a glass accelerating tube which was divided into two segments with an intermediate electrode at mid-potential. The ion source was a low-voltage discharge in hydrogen yielding a supply of protons. This type of accelerator has been continuously improved by increasing the number of power supply stages and the segments of the accelerating tube, increasing the frequency of the charging circuit, immersing the voltage supply and the accelerating tube in insulating fluid or pressurized gas to reduce breakdown and other variations and refinements. The Cockcroft-Walton accelerator remains in use today in many applications up to a few MeV and as a preaccelerator typically operating at 750 keV to inject beam into a higher energy accelerator.

The other application of the simple concept of direct application of voltage to an accelerating tube that has had enduring success is the Van de Graaff or electrostatic accelerator. In this accelerator the potential is supplied electrostatically by an insulating belt transporting charges between ground and a large, usually spherical, high voltage terminal. R.J. Van de Graff demonstrated an electrostatic generator of this type in 1931 and the first application to nuclear studies was made by a group headed by M. A. Tuve at the Carnegie Institution in Washington in 1933 with a beam of 600 kV protons. This type of accelerator has also been subject to many improvements and variations. The charging belt and the accelerating tube may be vertical or horizontal. After the earliest examples these accelerators were invariably housed in pressure tanks to exploit the superior voltage holding properties of various gases at high pressures. Refinements in the design of segmented accelerating tubes and the use of shells at intermediate potentials between the grounded pressure tank and the high voltage terminal have been the main factors leading to reliable operation of Van de Graaff accelerators at over 10 MeV. More than twice that voltage is achieved in the tandem design in which negative ions are accelerated from ground potential to a positive terminal where they are stripped of electrons to form positive ions and then further accelerated to ground potential.

Both the Cockcroft-Walton and the Van de Graaff accelerators are characterized by good regulation, easy control of voltage, and excellent beam collimation. They also work with either sign of charged particle and a comparatively simple change of ion source may permit acceleration of partially or completely stripped nuclei of any element.

RESONANCE ACCELERATION

The concept of resonance acceleration, that is, repeated acceleration by radio-frequency power at relatively low voltages to produce high energy particles, made it possible to avoid the severe technological problem of electrical breakdown at high voltage. R. Wideröe in 1928 demonstrated the principle with a single tubular electrode supplied with radio-frequency power mounted between two grounded electrodes. Sodium ions, Na^+, were accelerated into the electrode while it was negative, passed thru and were further accelerated at the other end when the potential of the tube became positive, thus attaining an energy corresponding to twice the applied radio-frequency voltage. In 1929 E. O. Lawrence elaborated the concept to include the effect of a magnetic field and invented the Cyclotron. If, in a uniform magnetic field ions are accelerated perpendicular to the field by a radio-frequency voltage applied to a reentrant electrode, then for appropriate values of the field and frequency the ions will pursue a circular path and return to the opening of the electrode when the voltage has reversed and the ions will again be accelerated. Continuing, the ions will describe a spiral path increasing in radius and energy as they enter and leave the accelerating electrode in resonance with the applied radio-frequency voltage, making it possible to reach energies corresponding to hundreds of times the applied voltage. An additional requirement is that the ions remain in the mid-plane of the Cyclotron; that requirement, focusing, is met by a slight decrease of the magnetic field with radius. The great advantage of achieving high energies without the necessity of generating high voltages led to the rapid development of the cyclotron as an accelerator of protons, deuterons and alpha particles to energies of several tens of MeV. It was the leading type of accelerator until the end of World War II and over a hundred were in operation in laboratories all over the world. As the requirements of research called for increasing energy the limitation of the classical cyclotron became apparent. The cyclotron resonance condition specifies a frequency of the accelerating voltage equal to the rotational frequency and proportional to the magnetic field and the charge to mass ratio of the ions, but as the energy of the ion increases the mass of the ion increases (relativistic effect), decreasing the rotational frequency and violating the resonance condition. This limits the number of turns that the ions will stay in phase with the accelerating voltage and limits the energy of the cyclotron to some tens of MeV.

THE INDUCTION ACCELERATOR

There were many attempts in the 1920's and 30's to devise an accelerator using the electric field induced by a changing magnetic flux (transformer action) to accelerate ions . The requirements of a magnetic field to hold ions in a circular orbit and to provide a changing flux linking the orbit to accelerate the ions were demanding, and success was not achieved until 1941 when D. Kerst demonstrated electron acceleration in his Betatron. The Betatron was immediately recognized as being very well adapted to accelerate electrons for high energy x-ray production, and it was commercially developed and extensively used for that purpose. A typical energy was about 25 MeV. It was also developed as a research tool to an energy of about 300 MeV but was soon rendered obsolete by other developments.

More recently, special purpose linear induction accelerators have been developed to provide very intense, short bursts of electrons at energies of a few MeV.

THE PRINCIPLE OF PHASE STABILITY

In 1944 and 1945 V. Veksler and E. McMillan, seeking a means of circumventing the energy limitation of the cyclotron, independently formulated the principle of phase stability. They pointed out that in the acceleration of charged particles by a radio-frequency field, particles in a certain phase band were stable; that is, if they had small errors of phase with respect to the accelerating field or of energy, the acceleration itself automatically tended to correct the error. This principle had far-reaching consequences; it effectively removed the energy limitation (except the economic one) of accelerators and it led to the development of several new designs.

In the Synchrocyclotron, as the ions are accelerated and their mass increases, the frequency of the accelerating voltage is slowly decreased. The ions automatically remain in the proper phase and increase in energy to the limit imposed by the size of the magnet. Synchrocyclotrons were rapidly developed for protons, deuterons and alpha particles to energies of hundreds of MeV. The magnets weighed several thousand tons and had pole diameters up to about 5 meters. The size and cost of the magnet became the limiting factor as the need for higher energies in nuclear research continued.

The principle of phase stability coupled with the cyclotron resonance condition provided the means around limitation of the synchrocyclotron also. In the proton synchrotron, low energy ions are injected into a ring-shaped magnet. Both the frequency of the accelerating voltage and the magnetic field are increased, holding the ions in a nearly constant radius orbit as they are accelerated. The weight and cost of a magnet for constant radius orbits are very much less than one for spiral orbits. As in the cyclotron, the ions are focused by a small decrease of field with radius. Proton Synchrotrons of this type extended the practical energy limit to over 10 GeV (10,000 MeV).

Electron Synchrotrons or just Synchrotrons are based on the same principles with one simplifying feature but a new limitation. The simplification is that since an electron attains nearly the constant velocity, c, at an energy of a few MeV, only the magnetic field need be varied if the electrons are introduced into the synchrotron with a few MeV energy. The limitation compared with the proton synchrotron is an energy limitation and is due to the radiative loss of energy of charged particles in circular orbits. It is called synchrotron radiation and is a special case of bremsstrahlung. This effect, which placed a practical energy limit of about 1 GeV on the first generation Synchrotrons, is not significant in proton accelerators because the energy loss varies inversely as the square of the mass of the particle.

LINEAR ACCELERATORS

The concept of the linear accelerator, that is the acceleration of charged particles along a linear path by radiofrequency fields, goes back to the 1920's and early development was carried out in the 1930's. However, the necessary rf power technology was not available at that time and the Cyclotron and the Van de Graaff accelerators were so successful that linear accelerator development languished. Radar and communications developments during World War II resulted in great advances in rf technology and specifically in the availability of high power high frequency tubes of several kinds. This led to the development of two kinds of linear accelerator in the immediate post-war years.

The first was the electron linear accelerator or electron linac by W. Hansen in 1947. In this accelerator a traveling rf wave is introduced into a wave guide which has been loaded with a series of washer-shaped irises to reduce the phase velocity of the wave to c. Electrons pre-accelerated to about 2 MeV where their velocity is 0.98 c ride the crest of the advancing wave as, in analogy, a surfer rides a water wave. Typically the frequency is about 3000 MHz and the diameter of the wave guide accelerating tube is 8 cm. The maximum energy achieved with accelerators of this type has been 24 GeV at the SLAC 2 mile accelerator. In the lower energy range, about 100 MeV, hundreds of these accelerators have been commercially built and are used as x-ray sources both for therapy and radiography.

The second was the proton linac developed by L. Alvarez in 1948. In this accelerator, a standing rf wave is set up in a resonant tank in a mode in which the maximum electric field is along the axis of the tank. A series of "drift tubes" of appropriate length, shape, and spacing are distributed along the axis so that charged particles are accelerated by the rf field when they are between drift tubes, but are shielded from the field during the reverse half cycle. An initial energy at injection is necessary and in the modern proton linac this is typically a Cockcroft-Walton accelerator operating at 750 KeV. Proton linacs themselves are used as injectors into proton synchrotrons. For this purpose their energy may be 50 or 200 MeV. The highest energy proton linac is an 800 MeV accelerator designed to exploit the high current capability of linacs.

Linear accelerators similar in principle to proton linacs may also be used to accelerate nuclei of any atoms, including Uranium. Such heavy ion linear accelerators, hilacs, are more complicated because they must provide for acceleration of particles of various charge-to-mass ratios corresponding to different charge states and different nuclei.

SECTOR-FOCUSED CYCLOTRONS

We have seen that the energy of the classical cyclotron is limited by violation of the resonance condition as the mass of the particle increases with energy. The synchrocyclotron provided a way around this difficulty but only at the expense of intensity because the magnets are pulsed. If the magnetic field of a cyclotron increased with radius, the resonance condition could be matched to the increasing particle mass; however, an increasing field defocuses and all the particles would be lost. L. H. Thomas in 1938 pointed out that a focusing force could be restored if the magnet poles were sectored, producing alternate regions of high field and low field even if the average field increased to match the resonance condition. This idea was not immediately exploited but developments beginning in 1949 resulted in numerous variations of cyclotrons characterized by azimuthally varying magnetic fields and constant rotational frequency. Accelerators of this type have been built for protons to energies of about 600 MeV with currents of 150 μa, a factor of 100 greater than can be achieved with a synchrocyclotron. The sector focusing idea introduced a flexibility into design, making it possible also to build cyclotrons which could accelerate ions of different species and with variable energy. These developments have rendered both the classical cyclotron and the synchrocyclotron obsolescent.

ALTERNATING-GRADIENT FOCUSING

The Principle of Phase Stability removed the energy limitation of the classical cyclotron and it made possible the design of accelerators using annular magnets, but the focusing requirement was still met as in the case of the cyclotron by introducing a negative gradient of the magnetic field with radius which gives a force restoring ions to the median plane of the magnet (vertical focusing in the usual orientation). This focusing force, which is relatively weak, determines the space required by the beam, hence the size and cost of the magnet. The focusing force cannot be increased simply by increasing the gradient of the magnetic field, because then the ions would not be confined in the radial direction (horizontal defocusing).

N. C. Christophilos in 1950 and E. D. Courant, M. S. Livingston and H. S. Snyder in 1952 independently devised a new focusing scheme called alternating-gradient or strong focusing. If a magnet is divided into segments, alternating segments with vertical focusing and radial defocusing forces with segments having vertical defocusing forces and radial focusing forces the net effect will be focusing in both directions.

Strong focusing incorporated into proton synchrotron design reduced magnet aperture cross sections by a factor of ten or more, making it economically possible to design proton accelerators up to several hundred GeV. The largest of these at the Fermi National Accelerator Laboratory (1972) and at the European Organization for Nuclear Research, CERN, (1976) have annular magnet systems of 2 km major diameter and aperture cross sections of about 5 by 15 cm. The maximum proton energies of these accelerators are 500 and 450 Gev, respectively. The energy of electron synchrotrons incorporating strong focusing is still limited by radiative energy loss, but the advantage of small magnet cross section has made it possible to achieve energies of more than 10 Gev.

COLLIDING BEAMS

In a collision between a moving particle and a stationary target nucleus, not all the kinetic energy is available to induce a reaction. Part of the energy, as required to conserve momentum, goes to the motion of both particles after the collision. For accelerated and target particles of equal mass and for energies where relativistic effects are small, the available energy is approximately one-half the energy of the accelerated particle. This is not a serious loss; however, for particles accelerated to higher energies, an increasing fraction goes to the energy of motion. For protons at relativistic energies striking target protons, the available center of mass energy is approximately $\sqrt{2E}$ GeV, where E is the energy of the incident particle in GeV. Thus the largest proton synchrotrons of about 500 GeV energy can deliver only about 30 GeV to a reaction. If two beams of particles of energy E traveling in opposite directions could be made to collide head on, an energy 2E would be available for reactions. The possibility that this obvious, but very difficult to achieve, objective might be realized, derived from suggestions made independently by D. W. Kerst, G. K. O'Neill and others in 1956. Because even the most intense accelerator beams are not adequate to give a useful interaction rate if two accelerator beams are simply pointed at each other, it is necessary to collect, store and recycle the accelerated particles. This is done by injecting the beam from an accelerator into an annular magnet with a constant magnetic field. If the magnetic field is very precise and if the pressure in the vacuum chamber very low ($< 10^{-9}$ Torr), the beam may be made to circulate for many hours, even days. Such Storage Rings may be constructed in intersecting pairs with provisions for loading them in opposite directions with particles from an accelerator. At the beam inter- sections a small fraction of the particles interact and the non-interacting ones continue around for repeated chances to interact.

The ISR (Intersecting Storage Rings) at CERN provides for collisions of proton beams at 30 GeV, giving a total energy of 60 GeV. A single beam of 30 GeV on a target would give only about 7.75 GeV. A single storage ring may also be used to store two counter rotating beams of particles of the opposite sign. Thus PETRA at Hamburg and PEP at Stanford are single storage rings designed for electrons and positrons at about 20 GeV each. At CERN the 450 GeV proton synchrotron has been reconfigured with a complicated set of auxiliary rings to accelerate, store, and collide protons and antiprotons at 270 GeV, giving collisions of 540 GeV. To produce this collision energy with a single accelerator and a fixed target would require an energy of about 15 TeV (15×10^{12} eV)!

USES OF ACCELERATORS

While the demands of nuclear and particle physics research have been the strongest driving force in the development of new accelerators and the achievement of high energies, the applications of accelerators in other sciences and in industry has been widespread and the contributions very important. Usually the accelerators designed for practical applications operate at less than the maximum energy for their type, but they may often be required to meet other demands at the limit of technology--intensity, reliability, compact size, etc.

In medicine, accelerator-produced radioisotopes are routinely used to image internal structures and to monitor functions. Thousands of small compact electron linear accelerators are used in hospitals to generate penetrating x-rays for cancer therapy. Accelerated particles ranging from protons to silicon nuclei and secondary beams of neutrons and pions are also used for cancer therapy but on an experimental basis. In engineering and manufacturing, electron accelerators are used to generate penetrating x-rays to examine large structures; small ion accelerators are used to implant controlled impurities in the fabrication of semiconductor devices. Radioisotope tracers are used to study and monitor chemical reactions, wear, and other processes. Small accelerators are used to log oil wells and other bore holes by analysis of the characteristic radiation from various elements when excited by neutrons. Plastics with superior electrical and chemical properties are produced by curing organic polymers with electron beams. Extremely sensitive and non-destructive analysis can be accomplished by inducing characteristic x-ray emission by proton or alpha-particle beams from cyclotrons or electrostatic accelerators. Synchrotron radiation, electromagnetic radiation from energetic electrons confined to orbits by magnetic fields, a limiting factor in the energy of electron accelerators, is an extremely useful source of intense, highly collimated radiation extending from the infra-red to x-rays. There are many applications of this radiation in chemistry, metallurgy, and biology.

11. THE FUTURE OF ACCELERATORS

The course of accelerator development may be displayed in an interesting way in a plot first due to M. S. Livingston. The maximum energy achieved with each type of accelerator is plotted against the year it was achieved, see Fig. 1. It will be noted that, as each type of accelerator reaches or approaches a limiting energy, a new type appears. A linear envelope of these curves shows that maximum accelerator energy has increased by a factor of about 8 each decade for 50 years. There appears to be no letup in the demand for higher energies for research directed towards the ultimate structure of matter; yet the sizes of the largest accelerators are measured in kilometers and the cost in hundreds of millions of dollars. It seems likely then that further advances in accelerator performance will depend upon the emergence of new concepts to circumvent the limits of size and cost. Superconductivity is already coming into use to provide higher magnetic fields at lower power costs and will be exploited more fully. Strong electric fields are associated with intense laser beams; a way may be found to apply these fields to accelerate particles. The very strong magnetic fields associated with an intense electron beam may be useful to confine other particles. The collective effects of a swarm of particles may be used to transfer energy to other particles. Invention and development are continuing and there will be new concepts almost surely leading to new types of accelerators with performance going well beyond the present large accelerators.

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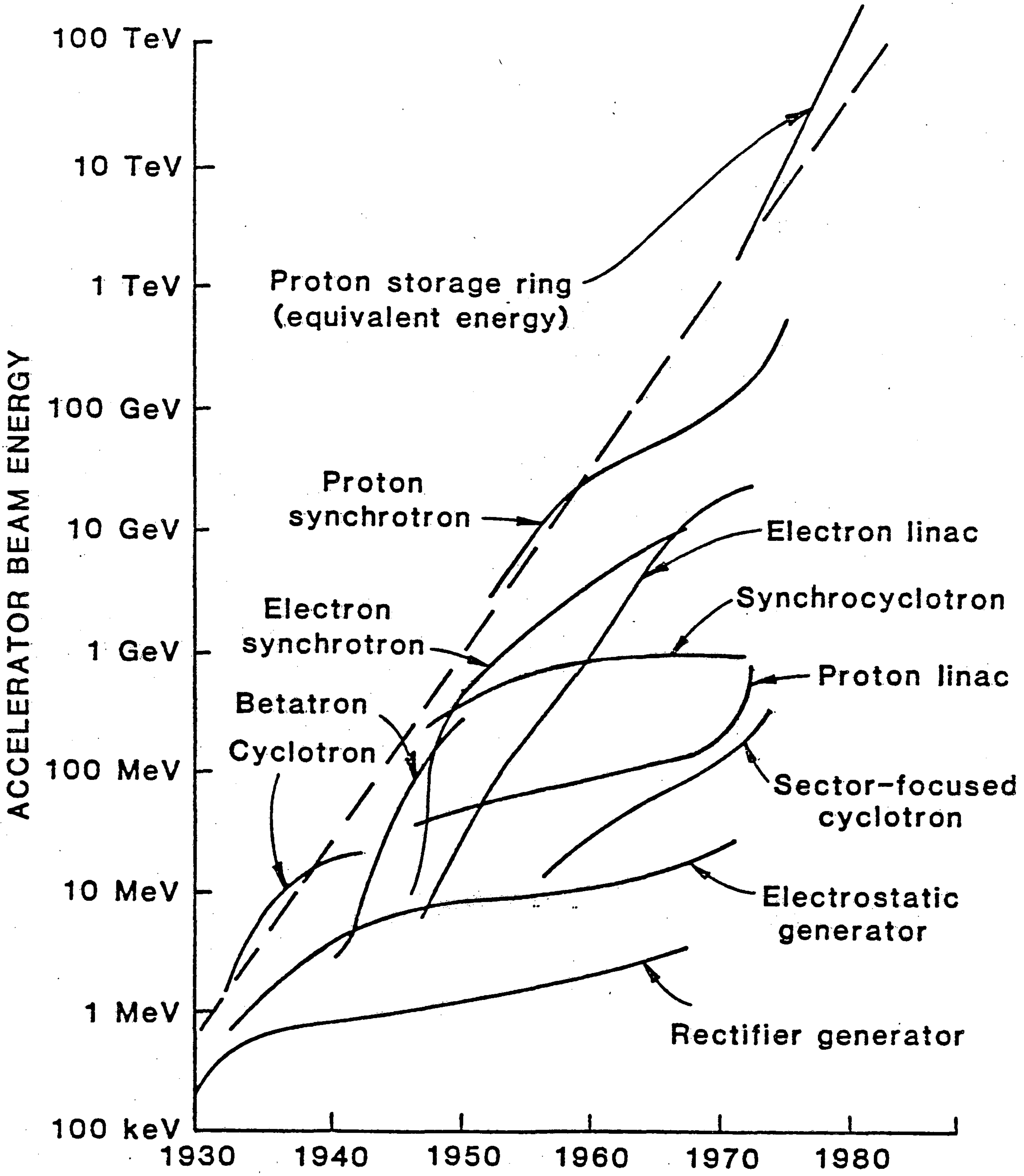
Cross-References: ACCELERATORS, LINEAR; ACCELERATORS, VAN DE GRAAFF; BETATRON; CYCLOTRON; SYNCHROTRON.

Figure Caption

Fig. 1. The maximum energy for each type of accelerator is plotted against the year it was achieved. For colliding beams, the energy of an equivalent fixed target accelerator is plotted. Maximum energy has increased by about 8 orders of magnitude in 5 decades.



ACCELERATOR BEAM ENERGY
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 keV
1930
1940
1950
1960
1970
1980
Proton storage ring (equivalent energy)
Proton synchrotron
Electron linac
Synchrocyclotron
Electron synchrotron
Betatron
Cyclotron
Proton linac
Sector-focused cyclotron
Electrostatic generator
Rectifier generator

Fig. 1

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