High-energy charged-particle accelerators

Yu. M. Ado

Institute of High Energy Physics, Serpukhov (Moscow region)

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A review is given of accelerators and colliding-beam installations operating at center-of-mass energies between 7 GeV and about 50 TeV. The basic principles underlying the design of such systems and ways of increasing the energy and intensity of accelerated-particle beams are briefly discussed. The scale of modern machines is illustrated by considering the examples of the proton synchrotron at the Institute of High Energy Physics at Serpukhov, the accelerating and storage complex at CERN, the accelerators at the Fermi National Accelerator Laboratory in the USA, the electron-positron storage complex in Hamburg, and the Stanford Linear Accelerator in the USA.

INTRODUCTION

The charged-particle accelerator is an indispensable tool in nuclear and elementary-particle physics in which it is used in studies of phenomena occuring in the nuclear interior and at subnuclear distances. Accelerators are unique in the sense that they produce beams of different types of particle with predetermined characteristics, which is very important for the interpretation of physical experiments. Indeed, it was precisely this fact that attracted physicists to accelerators immediately after the discovery of the nucleus. Since then, advances in the study of the structure of matter have been intimately linked with the development of accelerators. Current problems in physics continue to stimulate the development of new accelerators and, conversely, advances in accelerator technology have opened up new possibilities for experimental physics.

A large number of fundamental discoveries has been made using accelerators producing particles of energy up to 100 GeV. They include, for example, the conservation of vector current in weak interactions; the discovery of antiprotons, meson multiplets, and various types of hyperons; the difference between the electron and muon neutrinos; the cumulative effect in collisions between relativistic nuclei; the discovery of the J/ψ and Υ particles; the parton structure of nucleons; the synthesis of transuranic elements; the synthesis of antimatter (antihelium, antitritium, antideuterium); the demonstration of scaling invariance; the Serpukhov effect in total cross sections; and the discovery of the τ-lepton. Investigations performed at higher energies have led to the discovery of the theoretically predicted heavy intermediate bosons $W^\pm$ and Z^0 that convey the weak interaction and have masses of about 81 and 96 GeV/c^2.

These data contain the extensive information necessary for the correct understanding of elementary-particle physics. Fundamentally new properties of the microworld have been discovered, including, for example, the quark structure of elementary particles and new quantum numbers such as strangeness, charm, flavor, fractional electric charge, and color charge of quarks and gluons. Studies of the interactions between colored charges have led to the new subject of quantum chromodynamics. Discoveries made in the course of the last few years have now given us a basis for constructing a general theory capable of unifying strong, weak, and electromagnetic interactions between elementary particles. This began with the unification of weak and electromagnetic interactions, the possibility of which was confirmed experimentally by the discovery of the $W^\pm$ and Z^0 bosons. Discoveries made as a result of accelerator experiments have forced us to adopt a new approach to the description of nature at the fundamental-particle level, and their significance cannot be overestimated.

In a relatively short period of time, charged-particle accelerators have become transformed from small-scale laboratory systems into major installations with linear dimensions of tens of kilometers. Simple methods of acceleration have been replaced by new principles of producing high-intensity beams of particles with gigantic energies, comparable with cosmic-ray energies. A particularly important step toward the attainment of high interacting-particle energies was taken through the practical implementation of the method of colliding beams. The high rate of advancement in the development of accelerators can be judged from Fig. 1 which plots the maximum attainable energy against time. The graph shows some of the accelerator installations representing the corresponding energy frontier. For colliding-beam installations, we show the so-called equivalent energy, defined as the energy of particles in one beam in the frame in which particles in the other beam are at rest.

The particle energy that can be attained under laboratory conditions has continued to increase roughly exponentially and independently of the advent of new ideas and new types of accelerator, and there is, as yet, no sign of any slowing down of this rapid advance. Since 1930, the energy of accelerated particles has continued to increase by roughly an order of magnitude every eight years. The highest-energy particles are produced in synchrotron-type machines. The

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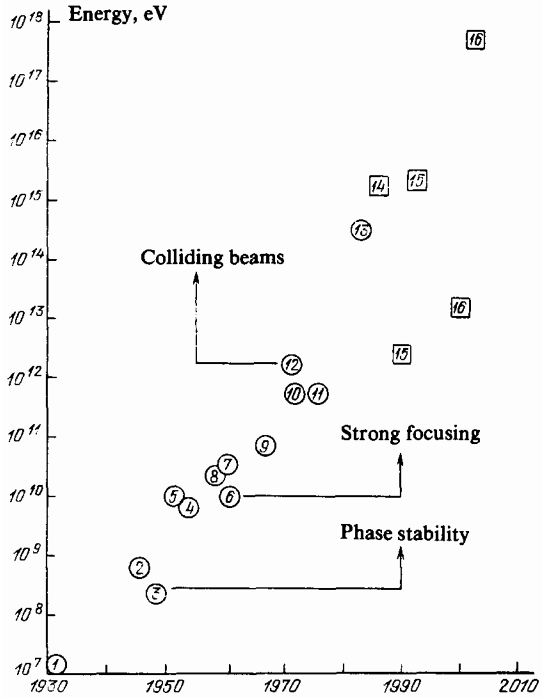

FIG. 1. Particle energy produced by acceleration as a function of time: 1—cyclotron; 2—synchrocyclotron (Joint Institute for Nuclear Research, USSR); 3—electron synchrotron (Physics Institute of the Academy of Sciences, USSR); 4—proton synchrotron (Berkeley, USA); 5—proton synchrotron (Joint Insitute for Nuclear Research); strong-focusing proton synchrotrons: 6—Institute of Theoretical and Experimental Physics, USSR; 7—Brookhaven, USA; 8—CERN; 9—Institute of High Energy Physics (IHEP), USSR; 10—Fermilab, USA; 11—CERN. Colliding-beam installations: 12—proton-proton (CERN); 13—proton-antiproton (CERN). Proposed: 14—Tevatron 1 (Fermilab); 15—UNK, fixed target and colliding beams (IHEP); 16—superconducting supercollider, fixed target and colliding beams (USA).

highest center-of-mass energies are produced in colliding-beam systems. However, this does not mean that they will necessarily become preeminent. Accelerators using stationary targets can be used to generate beams of different types of secondary particle for experiments that cannot be performed with colliding beams. In fact, accelerators and colliding-beam systems must be regarded as mutually complementary.

Over twenty proton and electron accelerators and more than ten colliding-beam systems with energies exceeding 1 GeV are now working at research centers in USSR, USA, Great Britain, Switzerland, the Federal Republic of Germany, Italy, and Japan. The maximum particle energy that has been attained under laboratory conditions is now close to the 1000 GeV (1 TeV) frontier. Plans are being made to build accelerators for energies up to 20 TeV, and colliding-beam systems with equivalent energy of up to 8.5×10^5 TeV. Center-of-mass energies of a few tens of TeV are of considerable interest to modern physics because it is expected that experiments performed at these energies will yield fundamentally new information about space and time over lengths of the order of 10^{-16}–10^{-17} cm. However, it is important to ensure that the desire to proceed further and further along the energy scale must not result in a reduction in the level of activity at energies already attained, at which improved methods may lead to the discovery of new fundamental phenomena. This is illustrated by the discoveries made on accelerators at the Serpukhov Institute of High Energy Physics, at the Brookhaven National Laboratory, and at other established institutions. This underlines the importance of continuing work on the improvement of existing installations and, especially, work directed toward increasing the intensity of particle beams. Realistic attempts are being made at present to produce beams with intensity in excess of 10^{13} particles per second. The mean power delivered by such beams in a 1-TeV accelerator will exceed 2 MW.

An important class of high-current accelerators consists of the so-called meson factories that have provided experimental nuclear physics with high-intensity beams of pions and muons as well as other secondary particles. There is considerable interest, especially from the point of view of relativistic physics, in beams of accelerated nuclei of practically all elments in the periodic table. Such beams can be produced by both linear and circular acclerators. After some modernization of existing proton accelerators, it will be possible to use them to accelerate nuclei of light elements.

Charged-particle accelerators have began to play a major role in the solution of many practical problems. They have recently been successfully used in medicine, biology, materials science, isotope separation, fabrication of integrated circuits, and elsewhere in science and technology. There have been many suggestions for the use of high-current accelerators in nuclear power engineering. These suggestions rely on the use of special accelerators, such as, for example, high-current machines for the production of high neutron fluxes, circular electron accelerators and storage rings for the generation of synchrotron radiation, and so on.

The history of charged-particle accelerators begins in the mid-twenties with the construction of dc machines producing particle energies of up to 1 MeV. The most interesting installations developed at the time included the electrostatic accelerator of R. Van de Graaff (1931) and the cascade generator of J. D. Cockcroft and E. T. S. Walton (1932).[2] The principle of the linear resonance accelerator was put forward by the Swedish Scientist G. Ising[3] in 1924. A working model of this machine was built in 1932 by E. O. Lawrence and D. H. Sloan.[4] The American scientist E. O. Lawrence took the major step in the further development of accelerators by suggesting a circular modification of the linear resonance machine. In the new machine, the particles spiral out in a magnetic field, crossing the same accelerating gap many times (this is the principle of the cyclotron)[5]. Until 1944, most nuclear physics research was performed on cyclotrons and elecrostatic generators producing particle energies of up to 25 MeV. In 1940, D. W. Kerst began the development of the circular electron accelerator—the betatron (originally proposed by Wideröe[6] in 1928) in which the particles are accelerated by an induced electric field. A large number of such accelerators was built, but the energy of the accelerated particles could not be taken beyond a few hundred MeV. It was only after the discovery in 1944 of the principle of phase stability by the Soviet physicist V. I. Veksler[7] that the limitation on the accelerated-particle energy was removed. An analogous principle was put forward later, in 1945, by the American physicist E. M. McMillan.[8] All modern high-energy accelerators and the next generation of machines that is being planned are based on this principle of charged-particle acceleration.

The present review of devoted to one of the most important topics in accelerator technology, namely, high-energy accelerators and storage systems for charged particles. Its aim is to provide the reader with an overall view of particle dynamics in such systems (with emphasis on circular machines), to say something about the largest modern accelerator complexes, and to discuss possible future developments aimed at increasing the intensity and energy of charged-particle beams.

1. SOME PROBLEMS IN THE PHYSICS AND TECHNOLOGY OF ACCELERATORS AND STORAGE RINGS

This section presents some of the physical principles underlying the operation of charged-particle accelerators and storage rings, the acceleration of high-current particle beams, and certain technological problems encountered in the development of high-energy installations.

A. Principle of phase stability

The principle of phase stability determines the conditions under which longitudinal stability of the motion of particles is possible in resonance accelerators. Its essence may be summarized as follows. It is well-known that the acceleration of charged particles in linear and cyclic accelerators is produced by an electric-field wave traveling in the direction s of motion of the particle with phase velocity v_{ph} equal to the mean particle velocity. The traveling electric wave is either excited in a radiofrequency waveguide or is produced by high-frequency resonators arranged one after another along s. As the particle energy increases, the wave velocity v_{ph} must increase in step with the particle velocity. It is clear that this can be achieved only for particles having a particular phase φ_0, referred to as the equilibrium phase. Particles with other phases relative to the traveling wave (nonequilibrium particles) will receive either too little or too much energy, and become shifted in phase relative to the traveling wave. They will begin to lose their synchronism with the wave and may even experience a retarding electric field. However, the principle of phase stability shows that, when the electric-field amplitude is high enough, the phase shift of such nonequilibrium particles is limited, and a shift in a particular direction is replaced by motion in the reverse direction. Nonequilibrium particles thus begin to oscillate around the equilibrium phase φ_0 (these are the particle phase oscillations) and acquire the same energy per period as the equilibrium particles. A potential well filled with particles centered on φ_0 is formed in the direction of s, and travels with the velocity of the traveling wave. The depth of the potential well (region of stability) is determined by the frequency and amplitude of the electric field. As applied to circular accelerators the principle of phase stability is also valid if we ignore the special effects that arise near the so-called critical particle energy at which the region of stability becomes sharply deformed. A large number of longitudinal regions of stability can be formed along the orbit of a circular accelerator. This number is referred to as acceleration multiplicity.

The significance of the principle of phase stability was that it removed the fundamental limitation on the energy of accelerated particles that could be attained in accelerators. The design energy of accelerators thus became a function of economic consideration alone.

A large number of cyclic resonance accelerators was constructed on the basis of the principle of phase stability in a short period of time. The first of them was apparently the 30-MeV electron synchrotron, built in 1948 at the Lebedev Physics Institute of the Academy of Sciences of the USSR under the direction of V. I. Veksler and P. A. Cherenkov.

B. Lateral focusing of particles

The dynamic stability of particles in r and z directions perpendicular to the direction of s is assured by magnetic fields distributed along s and producing lateral focusing of the particle beam. The principle of strong focusing has assumed a dominant position in high-energy accelerator design. It is similar to the well-known method whereby an optical system with a short focal length can be assembled from a number of alternately focusing and defocusing lenses. Strongly-focusing magneto-optical channels with high phase-volume transmission can be constructed for high-density particle beams of small cross section. Strong focusing is widely used in both linear and circular accelerators. Cicular high-energy accelerators would have been impossible without strong focusing. The first paper on strong focusing was published in 1952 by E. D. Courant, M. S. Livingston, and H. S. Snyder.[9] According to unpublished information, this principle was first proposed by the Greek engineer N. Christophilos in 1950. Even before this, in 1944, an analogous method of focusing of charged-particle beams was developed by the Soviet physicist V. S. Fursov (unpublished). It is interesting to note that the principle of strong focusing is based on the theory of dynamic stability that has been known for a long time and is described by differential equations with periodic coefficients, first put forward by E. Mathieu in 1868.[10]

Modern magneto-optical systems for circular accelerators have separated functions, i.e., the dipole component of the magnetic field that controls the closed orbit and the quadrupole component that assures lateral focusing are produced by different magnet elements. This separation of functions facilitates the design of magnets for circular accelerators and storage rings with a given variation in the shape of the particle beam envelope along the orbit.

The injection of particles into an accelertor results in the filling of the regions of dynamic stability in the coordinates s, r, z. The particles begin to execute slow radial-phase oscillations along s and fast betatron oscillations along r and z within the confines of these regions. Their motion is similar to that of a physical pendulum. The process of acceleration may be visualized as the accelerated motion of these stability regions together with the particles injected into them. To ensure that the particles are retained, it is necessary, first, to ensure slow enough acceleration so that the particles acquire the necessary energy in one period of the phase oscillation and, second, to minimize the effect of various perturbing factors resulting in the growth in the particle-oscillation amplitude within the stability regions. The difference between the actual magnetic fields and the ideal distribution in circular accelerators gives rise to periodic forces on the particles, whose period is a multiple of the oribital period. At frequencies approaching resonance values of the particle oscillation frequencies, this may give rise to growth in their amplitude, an increase in the effective beam emittance, and particle losses to the accelerator chamber walls. The resonance betatron oscillation frequencies can be calculated from

$$k_r Q_r + k_z Q_z = K, \tag{1}$$

where Q_r and Q_z are the betatron frequencies expressed in terms of the number of wavelengths fitting into the orbit and k_r, k_z, and K are integers.

The form of (2) shows that, for any choice of Q_r and Q_z (the working point), we can always find a triple k_r, k_z, K for which a resonance will occur near the working point. However, the strength of the resonances and, correspondingly, their effect on the particles, decrease rapidly with increasing order $|k_r| + |k_z|$. In practice, it is sufficient to suppress resonances up to the fourth order. The greatest danger is presented by integral resonances $Q_{r,z} = K$, which distort the orbit, and parametric resonances $2Q_{r,z} = K$. Third-and fourth-order resonances $2Q_{r,z} + Q_{z,r} = K$ and $2Q_{r,z} + 2Q_{z,r} = K$ appear in high-current accelerators and colliding-beam systems when the electromagnetic field produced by the beam itself forces the betatron oscillation frequencies closer to these resonances [see (2)].

The suppression of betatron oscillation resonances is one of the principal aims of accelerator technology. Large accelerators are equipped with complex magnetic-field correction systems (they control the components of dipole and quadrupole magnetic fields that are harmonic along the orbit, magnetic-field nonlinearities, and so on).

C. Effect on particle dynamics of the electromagnetic field due to the beam

High-intensity particle beams are essential for the investigation of rare events in high-energy physics, and for a number of applied problems. In modern circular accelerators and storage rings, the orbiting-particle currents reach values of the order of ten amperes, and the energy stored in such beams exceeds hundreds of megajoules. The electromagnetic field due to the beam acts on the individual particles and on the beam as a whole. It modifies the acceleration dynamics and can restrict the current of particles in orbit. In directions perpendicular to the orbit, the particles experience a defocusing force due to the electric field of the beam spacecharge, and a focusing force due to the magnetic field produced by the beam. The resultant force turns out to be defocusing (with respect to the orbit). This reduces the focusing forces produced by the quadrupole components of the magnetic field in the accelerator and lowers the frequencies $2Q_{r,z}$ of betatron oscillations, shifting them toward the hazardous resonance values given by (1). When the beam charge is distributed uniformly in both the r and z directions, and when beam images in the conducting walls of the vacuum chamber can be neglected, the shift of the betatron oscillation frequencies can be calculated from the formula[11]

$$\Delta Q_{r,z} = -\frac{r_0 RNB}{\pi \delta_{r,z}(\delta_{r,z}+\delta_{z,r})\beta^2\gamma^3 Q_{r,z}}, \tag{2}$$

where $r_0 = q^2/M_0c^2$ is the classical radius of the accelerated particles, R is the orbital radius, N is the number of particles in orbit, B is the particle bunching factor, equal to the ratio of the particle density in the bunch to the average density in orbit, $2\delta_{r,z}$ are the transverse dimensions of the beam in the r and z directions, γ is the relativistic factor, $\beta = v/c$, and v is the particle velocity.

For the 70-GeV proton synchroton at the Institute of High Energy Physics, the maximum shift ΔQ for an injection energy of 100 MeV is close to unity when $N = 6\times 10^{12}$. The magnitude of N for which $\Delta Q = 1$ must be regarded as the limit for a given accelerator because further increase in the number of accelerated particles unavoidably forces the betatron oscillation frequencies into the zone of whole-number resonances.

By analyzing (2) we can identify ways of increasing the intensity of accelerated-particle beams. For example, the electromagnetic field due to the beam itself can be reduced in the course of particle acceleration by using stronger lateral focusing and by reducing the wavelength $2\pi R/Q$ of the betatron oscillations. The most radical way of increasing the beam intensity in existing accelerations is to use higher injection energy ($N \sim \beta^2\gamma^3$). For example, in the 28-GeV proton synchroton at CERN, the injection energy has been raised from 50 to 800 MeV, whilst at the Institute of High Energy Physics it is planned to raise the injection energy from 100 MeV to 1.5 GeV.

In the longitudinal direction s, the reduction in the particle density along a bunch and toward its edges gives rise to a longitudinal electric field that acts on the particles in a manner analogous to the external accelerating voltage. For beam intensities that have been attained, this again begins to affect the particle dynamics and may even violate phase stability. The electric field has a particularly strong effect on the acceleration regime in the region of the critical energy where it increases because of the considerable compression of the particle bunches in the longitudinal direction.

The electromagnetic field produced by the accelerated-particle beam itself gives rise to many other phenomena that become hazardous at high beam currents, e.g., various kinds of coherent beam instability resulting from the interaction between the particle-beam current and the image current flowing in the conducting walls of the vacuum chamber. They include, for example, the so-called resistive instability or instability resulting from the finite electrical conductivity of the chamber walls. An instability of longitudinal oscillations may also arise when beam particles interact with electromagnetic fields produced by the beam in different cavities of the vacuum chamber that resonate at frequencies close to multiples of the particle orbital frequency. Unless special measures are taken to reduce resonator shunting of the accelerating system, this may also give rise to this kind of instability.

One of the phenomena occurring in cyclic accelerators has been referred to as the negative-mass instability. This is due to the longitudinal electric field that appears when the density is a fluctuating function of the coordinate s. Particles located in front of an increased-density region are accelerated whilst those behind it are slowed down. The longitudinal motion of particles with momentum p relative to the equilibrium phase φ_0 is described by the pendulum equation with effective mass

$$M = M_0 \frac{\gamma^3}{1-\alpha\gamma^2} ,$$

where $\alpha = (p/R)\, dR/dp$ is the orbit expansion factor.[12] When $\alpha\gamma^2 > 1$, i.e., after the critical energy, we have $M < 0$ and a gain in energy leads to a reduction in the angular velocity of orbiting particles, whereas an energy loss leads to an increase in this velocity. Thus, particles lying both in front and behind the region of increased density are effectively drawn into the bunch, so that the initial inhomogeneity is enhanced still further. An increase in density arising at any particular point on the beam is found to initiate bunching along the entire beam length. The separation between these bunches is of the order of the diameter of the vaccum chamber.

Thus, to produce high-intensity particle beams, we must remove a large number of effects that disturb the acceleration process. This is achieved in accelerator technology by using complex systems designed to suppress unstable longitudinal and lateral oscillation modes, by introducing an additional spread of particle oscillation frequencies in order to exploit the Landau damping effect,[13] and by correcting betatron oscillation resonances.

D. Superconductivity in accelerator technology

The dimensions of circular accelerators are determined by the radius of curvature R of the particle orbit that can be produced in a magnetic field B:

$$R = \frac{pc}{qB}. \tag{3}$$

In conventional electromagnets, the magnetic field is restricted by the saturation of iron and cannot exceed 2T. The radius of curvature of the proton orbit in a 1000-GeV accelerator is in excess of 1.7 km and the perimeter of the orbit, including the rectilinear gaps, is roughly 12 km. Such large accelerators draw a great deal of power from the power grid (the average power consumed by a large accelerator complex is of the order of hundreds of megawatts). Magnets with superconducting coils, which are free from resistive energy loss, have been under intensive development in recent years. In superconducting magnets, in which the magnetic field is produced by current-carrying superconducting coils, the limiting field is determined by the critical magnetic field characteristic for the chosen superconductor.

The development of high-energy accelerators with superconducting magnets is a totally realistic prospect involving well-established superconducting magnet technology that relies on the availability of superconductors with parameter values necessary for operation in varying magnetic fields and on modern cryogenic technology. The reduction in the size of accelerators resulting from an increase in B by a substantial factor can give rise to considerable cost savings. The first accelerator incorporating superconducting magnets was the 1000-GeV machine built at the Fermi National Accelerator Laboratory in the United States.

E. Colliding particle beams

A qualitatively new approach to the attainment of high energies was introduced in the mid-fifties, when the technology necessary for implementing the colliding beam idea that had been put forward earlier became available. In conventional accelerators, the accelerated particles interact with a stationary target and only a fraction of their energy is expended in studying some particular process due to particle scattering or the creation of new particles. Most of the particle energy is taken up by the center of mass of the incident and resting particles, and is effectively lost.

The useful energy W in the interaction between two identical particles of rest energy M_0c^2 is given by

$$W = 2M_0c^2 \left(\sqrt{1+\frac{W_0}{2M_0c^2}} - 1 \right), \tag{4}$$

where W_0 is the energy of the incident particle. For example, when a 100-GeV proton collides with a proton at rest ($M_0c^2 = 938$ MeV), we find that the useful energy is $W = 12$ GeV. When particles of equal energy W_0 collide, the energy that can go into the reaction is their combined energy $2W_0$ because the center of mass is at rest. It is useful to consider the so-called equivalent energy W_e of a particle colliding with a particle at rest, for which the useful energy becomes equal to the energy of the colliding particles. For the relativistic case,

$$W_e = 2\frac{W_0^2}{M_0c^2}. \tag{5}$$

For colliding protons with $W_0 = 100$ GeV, this equivalent energy turns out to be 21 400 GeV. The colliding beam method became widely accepted after D. W. Kerst pointed out in 1956 that sufficiently intense colliding beams could be produced in strongly focusing magnetic structures.[14] Such systems have been under intensive development ever since, and colliding-beam systems are now successfully used in the physics of elementary particles at energies that are inaccessible in fixed-target accelerators. The number η of events per unit time, involving a particular process is proportional to the cross section σ for the process: $\eta = L\sigma$. The proportionality factor L is a measure of the efficiency of the colliding-beam system and is referred to as its luminosity. For circular installations with continuous beams, the luminosity L can be expressed in terms of the beam parameters as follows:[15]

$$L = \frac{N_1N_2}{cST^2}\, l_e \ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}), \tag{6}$$

where N_1 and N_2 are, respectively, the numbers of particles in the colliding beams, S is the cross section of the beam at the point encounter, T is the orbital period of the particles, and l_e is the extent of the experimental region along the orbit.

When the colliding beams are in the form of particle bunches, which follow with frequency f, the expression for the luminosity is conveniently written in the form

$$L = \frac{n_1 n_2}{S} fm, \quad (6')$$

where n_1 and n_2 are, respectively, the numbers of particles in the individual bunches and m is the number of points of collision (the entire region of interaction is in the field of view of the recording equipment).

It is clear from the above expressions that high luminosity can be attained by increasing the intensity of the colliding beams and reducing the beam cross sections at the point of encounter.

Accelerator technology now has at its disposal high-intensity sources of electrons and protons, so that problems involved in producing electron-electron, proton-proton, or proton-electron colliding beams of sufficient luminosity can be solved relatively simply. To produce e^-e^-- and pp-collisions, one constructs two circular accelerating systems in which particle motion takes place in opposite directions and the two orbits cross at one or more points. There are no direct sources of antiparticles, so that positrons are created through e^-e^+-pair production by bremsstrahlung gamma rays from decelerating electrons with energies of a few tens or a few hundred MeV. Antiprotons are produced in proton-antiproton pairs generated by protons accelerated to energies of the order of a few tens of GeV. The energy threshold for $p\bar{p}$ production is approximately 5.6 GeV or about 2 GeV in the center-of-mass system [see (4)]. The antiparticles are generated with very low efficiency, so that sufficiently intense particle beams can be produced only as a result of prolonged storage through successive injection of a large number of antiparticle bunches into storage rings.

The mechanisms of storage of light and heavy particles are fundamentally different. The motion of light particles in storage systems is accompanied by the emission of electromagnetic radiation (synchroton radiation), where the emitted power P is a rapidly-varying function of energy[16]

$$P = \frac{2}{3} \frac{q^2 c}{R^2} \gamma^4. \quad (7)$$

The emission of synchroton radiation produces a damping of particle oscillations, and the beam is compressed both in real and in phase space. This establishes the conditions for multiple injection of particles into the same phase space of the accelerator. The restriction on the increase in beam phase density, which follows from the Liouville theorem, is removed, and the storage of positrons presents no fundamental difficulties. For antiprotons, on the other hand, the power P is lower by several orders of magnitude and storage can be achieved only by simultaneously allowing the beam phase volume to increase. To produce antiproton beams, we must introduce forced compression of the beam phase volume or, in other words, we must "cool" the beam. An original and efficient method for cooling antiproton beams or beams of other ions by electrons was proposed by G. I. Budker.[17,18] The physical principles of electron cooling are as follows. An electron beam of velocity equal to the mean longitudinal velocity of the heavy particles is injected into one of the straight-line sections of the accelerator in the direction of the orbit. The resulting Coulomb scattering of electrons by the ions, the cross section for which is large for low relative velocities, leads to intensive momentum transfers. The injected electron beam has a much smaller momentum spread than the ion beam, and momentum transfers occur mainly from the ion to the electron beams. In other words, the electron beam heats up and the ion beam cools down. After the interaction with the ion beam, the electrons are removed from the accelerator and carry off a proportion of the energy of transverse and longitudinal oscillations. This means that the ion beam is no longer a conservative system. A cold electron beam is continuously circulated through the region of interaction with ions.

Another method of cooling heavy particles was proposed at CERN by Van der Meer.[19] It is referred to as the stochastic method and is based on the extraction of particle interaction energy by means of external electric fields. Bunches of particles circulating in storage rings in closed orbits exhibit random fluctuations in particle density, which give rise to the appearance of regions of enhanced density. Oscillations of these enhanced-density regions relative to the orbit can be recorded by electrodes with sufficiently large transmission bandwidth (of the order of gigahertz) and can be quenched (cooled) by using the signal from an electrode placed at a point on orbit and by applying a transverse electric field in antiphase with the transverse velocities of these density bunches. By acting in this way on the beam for long periods of time, it is possible to compress it as a whole. Since the method relies on fluctuations in particle density, its efficiency decreases with increasing number of particles in the storage ring, and the beam cooling time may become as long as tens of hours. These methods of cooling heavy-particle beams form the basis for installations with colliding $p\bar{p}$-beams.

Physical experiments with colliding-beams particles require the availability of straight-line segments along the particle orbit, the length of which may reach some hundreds of meters or more at high energies. The magnetic optics of these segments is designed so that the lateral size of the colliding beams is a minimum at the point of collision. When employed together with the cooling of antiparticle beams, this will produce high-luminosity colliding particle-antiparticle beams in a single storage ring.

The colliding beam method imposes stringent restrictions on the residual-gas pressure along the entire length of the orbit and, especially, at points at which the detecting equipment is introduced. The vacuum must be good enough to ensure adequate particle lifetime, so that the particle storage operation need not be frequently repeated and the background in the detecting equipment due to the interaction between stored particles and residual gas nuclei can be minimized. For example, in the proton-proton intersecting storage rings at CERN (ISR), designed for 31.4 GeV, the mean residual gas pressure in the vacuum chamber is about 5×10^{-10} Pa, whereas the pressure in the collision zone less than 1.3×10^{-10} Pa. The proton storage process occupies 2–

4 hours. The current in orbit is up to 35 A (7×10^{14} protons), and can be maintained at this level for more than 50 hours.

The development of circular accelerators and storage rings for high-energy positrons and electrons is seriously complicated by the emission of powerful synchroton radiation by these particles. The radiated power can be reduced by using large orbit radii (low magnetic fields). An example of this is the electron-positron storage ring (LEP) being built at CERN for a center-of-mass energy of 200 GeV. Its orbit radius is 27 km (Ref. 20) and the energy loss by radiation is 2.56 GeV per revolution. When the beam current is 9.15 mA, the power radiated by the two beams is 47.4 MW. A powerful high-frequency system is installed to compensate for this radiation loss. It appears that there is little point in constructing circular light-particle accelerators for still higher energies, and ways must be found for using linear accelerators, which are practically free from energy loss by radiation. For example, if we take the figure of 11 MeV/m as the acceleration rate, and this has been achieved in the Stanford linear accelerator,[21] the length of a 100-GeV linac would be about 9 km, which nowadays is not an excessive figure. It may also be possible to increase the rate of acceleration. One way of doing this is proposed by Balakin *et al* [22] who suggest the use of resonant high-frequency structures in which the electric fields are close to the limit of vacuum breakdown and field emission of electrons. The expected acceleration rate in these structures is in excess of 100 MeV/m.

Colliding e^-e^- and e^-e^+ beams can be produced by two linear accelerators firing at each other. This is the basis for the VLEPP project.[19] The idea was also considered by Tigner[23] in 1965. The basic problem is how to achieve the necessary luminosity. The proposal is that a luminosity of 10^{32} $cm^{-2}s^{-1}$ could be attained by reducing the cross section of the beam down to $10^{-7}cm^2$ at the point of collision.

G. I. Budker, A. A. Naumov, A. I. Skrinskiĭ, *et al* have made considerable contributions to the development of the colliding beam method at the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences. Since 1965, the Institute has built the 160-MeV electron-electron collider VEP-1, the 700-MeV electron-positron collider VEPP-2, and the 7 GeV electron-positron collider VEPP-4. Experiments performed at the Physics Institute of the Academy of Sciences (FIAN) in the sixties[24] were among the first attempts to implement the electron-positron colliding beam method.

D. The tandem principle

It is convenient to base high-energy accelerating complexes on the tandem principle whereby the final energy is reached after acceleration in a number of sequentially arranged accelerators, each of which acts as the injector for the next. This means that one can use lateral adiabatic compression of the accelerated beam as the principle energy increases, and design magneto-optics elements to have smaller pole-gap dimensions. This results in a saving in both capital investment and running expenditure. The tandem configuration is also essential if one is to avoid stray magnetic fields at injection, at which the magnetic-field topography is very sensitive to residual magnetic fields that arise in magnets with iron cores (because of hysteresis) and in superconducting magnets (because of frozen-in currents).

Figure 2 illustrates schematically the tandem arrangement of the 3000-GeV proton accelerating and storage system UNK that is being developed at the Institute of High-Energy Physics (IHEP).[25]

The preliminary acceleration of protons is performed in the linear accelerator incorporating quadrupole focusing by the accelerating electric field. This technique was developed by V. A. Teplyakov and I. M. Kapchinskiĭ.[26] The feasibility of quadrupole electric fields, produced by altering the high-frequency field configuration in the accelerating gaps of the linear accelerator, was first examined by V. V. Vladimirskiĭ.[27] The particles are first accelerated to 1.5 GeV in a fast-cycling synchrotron (first stage) and are injected into the proton synchrotron of the second stage where the required number of particles is produced by 30-fold injection over a period of 1.5 s during which the magnetic field in the second stage is held constant. The protons enter the next stage after they have reached 70 GeV. One portion of the accelerated particles is used to fill part of the orbit of the accelerator in the third stage. Twelve-fold injection, occuping 71.5 s, is required to fill the entire orbit of this accelerator. The protons are accelerated to 600 GeV in the third stage, and are then transferred to the superconducting accelerator in which their energy is raised to the final value of 3000 GeV. The 600- and 3000-GeV machines will be built in a single circular tunnel. This means that the UNK project provides for the possibility of proton-proton colliding beams derived from these machines with a center of mass energy of 2.2 TeV (Table I).

The present stage of accelerator development is characterized by the extensive use of computers in technological diagnostics, in beam-parameter diagnostics, and, most importantly, in accelerator control.[28] This is particularly effective in the optimization of the operation of an accelerating complex with respect to a large number of parameters, and in maintaining the operation of the system within narrow tolerances. Computers also play a major role in the automa-

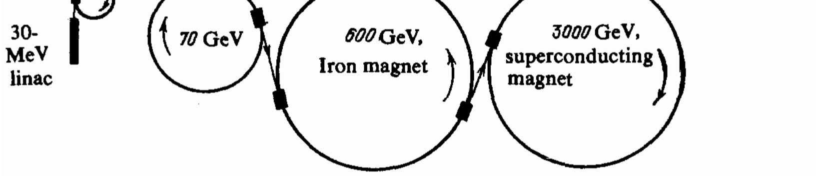

FIG. 2. Tandem arrangement of the accelerating and storage complex at the Institute of High Energy Physics. The 600-and 3000-GeV accelerators are located in the same tunnel.

TABLE I. Some of the parameters of the accelerating and storage complex UNK at IHEP.

Stage	1	2	3	4
Orbit length, m	99,16	1484	20772	20772
Proton energy, GeV	1,5	70	600	3000
Duration of accelerator cycle, including storage, s	6,5 between series of 30 cycles	6,5	78	78
Number of protons per orbit	$1{,}7\cdot10^{12}$	$5\cdot10^{13}$	$6\cdot10^{14}$	$6\cdot10^{14}$
Energy stored in the beam, MJ	0,002	0,56	19	286
Dimensions of vaccum chamber (horizontal and vertical), cm	14×6,1	20×11,4	12×6.5	7×6

tion of the complex equipment used in physics experiments with particle beams produced by accelerators. Research into the application of cybernetic principles to the operation of accelerating complexes was began in 1960 by A. L. Mints, A. A. Vasil'ev, V. A. Petukhov, S. M. Rubchinskiĭ, and E. L. Burshteĭn.[29]

2. EXISTING ACCELERATORS AND STORAGE RINGS

High-energy accelerators and storage rings are usually understood to be machines for charged-particle energies in excess of 1 GeV. Weak-focusing proton synchrotrons were being built prior to the advent of the strong-focusing principle in accelerator technology. The particle energy in these earlier machines did not exceed 10 GeV. The largest accelerators of this type that are working at present are the following (the year of commissioning is indicated in each case):

—Synchrophasotron (10-GeV proton synchrotron), Joint Institute for Nuclear Research, Dubna, 1957. This machine was subsequently modernized[30] to enable it to accelerate light nuclei with $Z/A = 0.5$;

—Bevatron (6.2 GeV), Lawrence Laboratory of the University of California at Berkeley, USA, 1954;

—Saturne (3 GeV), National Laboratory, Saclay, France, 1958; the machine was rebuilt as a strong focusing accelerator in 1978.

The strong focusing principle is used in the following machines:

—U-10 (10 GeV), Institute of Experimental and Theoretical Physics, Moscow, 1961;

—Alternating gradient synchrotron (AGS, 33 GeV), Brookhaven National Laboratory, USA, 1960;

—CERN proton synchrotron (CPS, 28 GeV), Switzerland, 1959;

—KEK proton synchrotron (12 GeV), National High-Energy Physics Laboratory, Japan, 1976.

The largest strong focusing proton accelerators are the following:

—70-GeV proton synchrotron, Institute of High-Energy Physics, Serpukhov, Protvino, 1967;

—450-GeV Super Proton Synchrotron (SPS), CERN, Switzerland, 1976;

—200/500-GeV synchrotron, Fermi National Accelerator Laboratory, commissioned in 1972 at 200 GeV; the energy reached 500 GeV in 1976. The DOUBLER was commissioned in July 1983. It incorporates superconducting magnets, producing fields up to 4 T. Its design energy is 1000 GeV. At present, 800-GeV protons are being produced.

The 33.4-GeV Stanford electron linear accelerator (SLAC), built in 1966, is a unique machine among high-energy accelerators.

Storage rings are usually constructed separately, using accelerators as injectors, or beams of particles and antiparticles are arranged to collide directly in accelerating systems as suggested in Ref. 31.

The following CERN installations will serve as examples:

—Intersecting storage ring (ISR) with colliding proton-proton or proton-antiproton beams of 31.4 GeV (1971);

—Proton-antiproton colliding beams of 270 GeV in the SPS proton synchrotron.

The largest storage rings with colliding electron-positron beams that are working at present are:

—PETRA, particle energy 22.5 GeV, Hamburg, FRG, 1978;

—PEP, particle energy 18 GeV, Stanford, USA, 1980.

We now proceed to a brief description of the charged-particle accelerators and storage rings that constitute the experimental basis of the leading high-energy research centers.

A. 70-GeV proton synchrotron at IHEP

The accelerator is illustrated schematically in Fig. 3 which also gives some of the dimensions. The particle orbit is nearly circular and has a perimeter of 1.5 km. The orbit is formed in a magnetic field produced by an electromagnet consisting of 120 separate sectors. The magnetic field in the pole gap of each sector has both dipole and quadrupole components, which are necessary for holding the particles in orbit and for strong lateral focusing ($Q_{r,z} = 9.8$). The necessary magnetic-field topography is defined by the shape of the magnet poles. Focusing and defocusing sectors alternate along the orbit, as shown. Gaps between these magnet sectors contain high-frequency accelerating stations, particle extraction systems, and a variety of diagnostic equipment. The preliminary acceleration of protons to 100 MeV takes place in the I-100 linear accelerator. Pulsed electric fields perpendicular to the orbit are used for multiturn injection of particles. When the linear accelerator current is 100 mA, the number of protons in orbit is 10^{13}. In accordance with the principle of phase stability, the accelerating voltage, whose

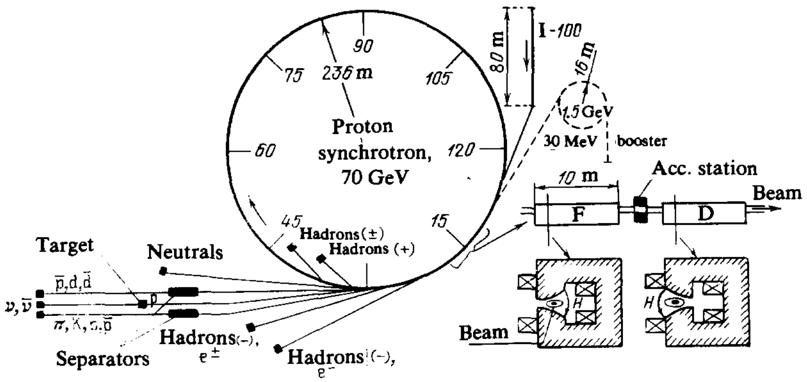

FIG. 3. The 70-GeV proton synchrotron at IHEP.

frequency exceeds the orbital frequency by a factor of 30, produces 30 particle bunches in orbit (30 regions of stability), and takes them to the final energy. The protons acquire approximately 200 keV in each revolution. The acceleration time is 2.85 s, and the path traversed by the particle is 500 000 km. The protons and secondary particles are extracted between sectors 16 and 36, and are transported to the experimental areas along magneto-optical channels.

Figure 4 illustrates the working cycle of the magnetic field of the accelerator, showing the instant of proton injection and one of the possible variants of the distribution of the beam of accelerated protons over the extraction channels. One bunch of protons is extracted from the accelerator while the magnetic field is rising, and is used to generate a beam of particles of a particular type, e.g., pions, K-mesons, or antiprotons. The protons are first directed onto an external target in which they generate the entire possible spectrum of particles. Spatial separation of particles with a required mass is accomplished in a special high-frequency separator after the beam has passed through an extended magneto-optical channel that transmits particles with roughly equal momenta. "Pure" beams produced in this way can be used in bubble chamber experiments. Nineteen particle bunches are rapidly extracted at the beginning of the magnetic-field plateau, and are used on an external target to generate a neutrino beam. After the accelerating voltage is turned off, the remaining ten bunches rapidly spread (because of the particle momentum spread) over the orbit perimeter. During the first half of the magnetic-field plateau, a fraction of the beam is extracted from the accelerator by special systems, and is used in experiments with external targets. The remainder of the beam is used during the second half of the plateau to generate secondary particles on an internal target inside the accelerator vaccum chamber. Particle beams stretched along the time axis are needed for physics experiments using electronic techniques. In this example, the protons are divided between five simultaneously running experiments. The number of accelerated protons per cycle exceeds 5×10^{12} under these conditions. The accelerated protons are used to generate a wide range of secondary particles (they are listed in Table II). Figure 3 shows schematically the disposition of the beam lines.

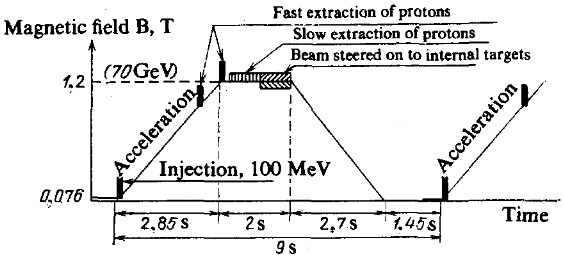

FIG. 4. Magnetic field as a function of time, showing the distribution of accelerated protons in experiments performed at IHEP.

Physics experiments on accelerators are laborious and time consuming. Some experiments require thousands of hours of operation of power consuming equipment. However, the exposure time can be reduced by increasing the beam intensity. It is planned to raise the beam intensity of the accelerator at IHEP to 5×10^{13} protons per cycle by raising the energy at injection to 1.5 GeV. The new injector will take the form of a fast-cycling proton synchrotron (booster),[34] operating in the pulse-packet regime at a frequency of 20 Hz. It is shown by the broken line in Fig. 3, together with the 30-MeV linac and the injection channel. During each acceleration cycle in the booster one of the longitudinal stability regions of the main accelerator will be filled. Thirty-fold injection is necessary to fill all the stability regions. During injection, the magnetic field is held at 0.0386 T for 1.5 s. The photograph in Fig. 5 shows part of the circular electromagnet of the accelerator. Figure 6 shows two of the 40 accelerating stations. The upper parts of these stations contain high-frequency resonators inserted into the accelerator vacuum chamber. The cover of one of these resonators is removed, exposing the ferrite plates used for resonator tuning during the acceleration process.

B. The CERN accelerating and storage complex[35]

CERN has the greatest number of accelerating and storing installations as compared with other research centers. CERN is also characterized by a rapid rate of advance in accelerator technology. Figure 7 shows a multicomponent and multipurpose arrangement of the CERN complex. The first to come on stream, in 1959, was the 28-GeV proton synchrotron CPS (= CERN proton synchrotron). The next to be built was the ISR (intersecting storage rings)

TABLE II. Types of particles in the accelerator at the Institute of High Energy Physics[33]

Particles	Range of variation in momentum p (GeV/c)	Number of particles per cycle ($\Delta p/p = 10^{-2}$)	Notes
Protons	70	10^8—10^{12}	Pulse length $\tau = 1$ s.
		10^{11}—$4\cdot 10^{12}$	For 10^{11}: $\tau = 5\times 10^{-8}$ s, for 4×10^{12}: $\tau = 5\times 10^{-6}$ s,
Hadrons (−)	25—65	$5\cdot 10^6$ ($p = 40$ GeV/c)	$\tau = 1$ s
Hadrons (+)	3—17	10^8	ditto
Electrons	2—45	10^5	〃 〃
Positrons	2—15	$8\cdot 10^4$	〃 〃
Neutrinos and antineutrinos	5—6 (average)	$5\cdot 10^9$	$\tau = 5\times 10^{-6}$; broad spectrum
Separated beams for bullet chambers: pions and kaons, protons and antiprotons, deuterons, antideuterons	$\geqslant 40$	~ 5	$\tau \approx 2\times 10^{-6}$ s
	10—12	~ 5	ditto
	ditto	~ 0.7	〃 〃
Neutral particles	70	$\sim 10^6$	total number of particles in the spectrum; $\tau = 1$ s

The number of secondary particles is given per 10^{12} primary protons.

installation consisting of two identical rings with straight-line sections that intersect at eight points. Particles are injected from the CPS into the rings in turn in opposite directions. After the necessary number of particles has been injected into each ring, and after a small amount of additional acceleration, the system contains two beams of protons traveling in opposite directions, each of 31.4 GeV. The 450-GeV Super Proton Synchroton (SPS) was a major step forward in the development of the accelerating and storage complex at CERN. The CPS was used as the proton injector. This is the second (after the Fermilab machine) accelerator with such high particle energy.

An experimental study of electron and stochastic cooling of proton beams was followed by the rapid implementation of the qualitatively new antiproton program. The antiproton storage ring (the AA) was built (and has played a

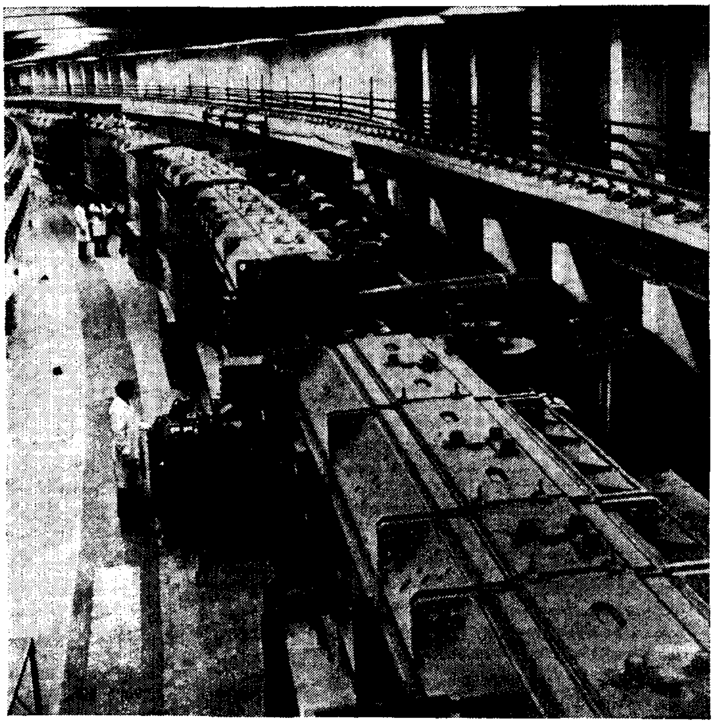

FIG. 5. Part of the circular electromagnet of the accelerator at IHEP.

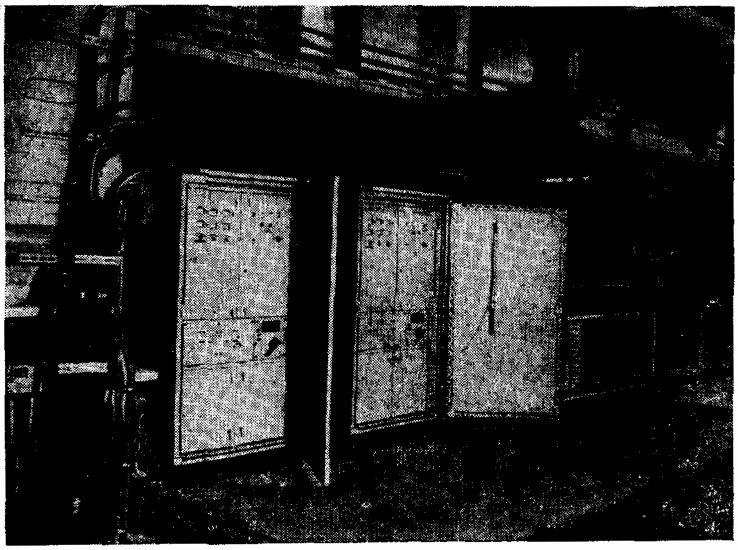

FIG. 6. Two accelerating stations. Lower part contains high-power output stages and the upper part the high-frequency resonators.

decisive role in the scheme), the necessary reconstruction of the ISR and the SPS was carried out, and a branched magneto-optical beam transport system for the p and $\bar{p}$ beams was introduced. This has resulted in a sophisticated technological complex of accelerating installations with extensive experimental capabilities in research with beams extracted from the CPS and SPS, and with colliding proton-proton and proton-antiproton beams in the ISR and SPS.

Antiprotons are accumulated in the AA at 3.3 GeV, using stochastic cooling. They are generated in the target M exposed to protons accelerated in the CPS. Roughly two antiprotons are created from the 10^6 protons in the phase volume necessary for injection. A total of 6×10^{11} antiprotons is necessary to attain the luminosity of 10^{30} cm^{-2}s^{-1} for the colliding beams in the SPS, so that if the CPS intensity is 10^{13} protons per second, the time necessary to complete the storage process is approximately 3 days (assuming storage efficiency of 30%). At the end of the storage process, the antiprotons return on the CPS along the magneto-opticl loop, and are accelerated to 26 GeV. They are then extracted and injected either into the SPS or the ISR. The energy of 540 GeV in the ecenter-of-mass system of the colliding protons and antiprotons in the SPS is the highest attained so far in accelerating installations.

Tables III and IV list data on particle beams that are available at CERN, and also the main parameters of the colliding beams in ISR and SPS.

C. Proton accelerators in the 500–1000 GeV range (FNAL)[38]

The Fermi National Accelerator Laboratory near Chicago is one of the major high-energy physics research centers in the USA. The 500-GeV proton synchroton built by FNAL was the first machine for experiments in high-energy physics at energies in the region of hundreds of GeV. Injection of protons at about 8 GeV from a fast-cycling booster has substantially reduced the effect of the beam spacecharge on acceleration dynamics and has enabled 3×10^{13} protons per pulse to be produced. The magneto-optical system of the accelerator consists of bending dipoles and quadrupole lenses producing strong focusing. This separation of functions was found to be much more effective than the system

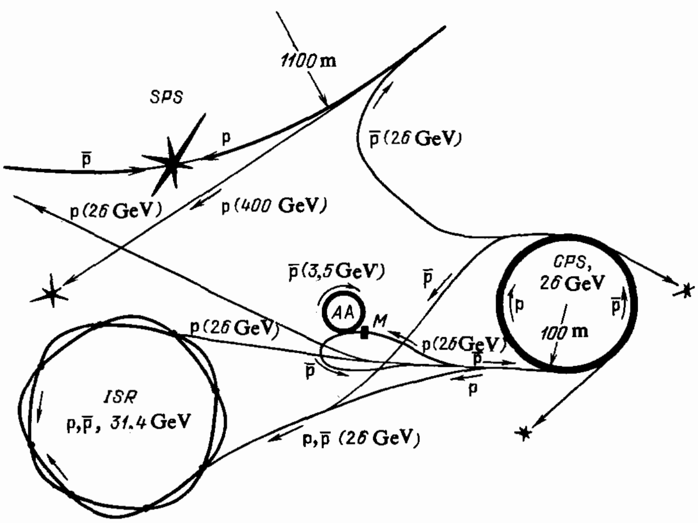

FIG. 7. Accelerating and storage complex at CERN: CPS—28-GeV proton accelerator, injector of protons and antiprotons into ISR and SPS; ISR—storage ring for colliding pp and p$\bar{p}$ beams of 31.4 GeV; SPS—570-GeV proton accelerator, storage ring for p$\bar{p}$ beams of 270 GeV.

TABLE III. CPS and SPS accelerators.

Installation	Number of accelerated protons	Secondary-particle beams	Momentum range, GeV/c
CPS	$1{,}8\cdot10^{13}$ Protons per cycle	Protons	$\leqslant 28$
		Antiprotons	$\leqslant 1{,}5$
	$1{,}0\cdot10^{13}$ Protons per second	Protons and pions	$\leqslant 14$
		Positive pions	$\leqslant 2{,}5$
SPS	$2{,}5\cdot10^{13}$ Protons per cycle	Protons	250–450
		Hadrons	$\leqslant 350$
	$2{,}5\cdot10^{12}$ Protons per second	Neutrinos	$\leqslant 275$ (narrow spectrum) ~ 30 (broad spectrum)
		μ-Muons	$\leqslant 280$
		Electrons	$\leqslant 150$

with combined functions (used in the accelerator at IHEP), and has been adopted in subsequent high-energy accelerator projects.

During the last decade, FNAL has been engaged in the development of the 1000-GeV proton accelerator DOUBLER. The accelerator magnet consists of superconducting dipole magnets and quadrupole lenses using NbTi coils. The dipoles and quadrupoles operate within very narrow magnetic-field tolerances, and were built as a result of an extensive technological development program. The accelerator is located in the same tunnel as the basic FNAL machine, which is used as the injector of 150-GeV protons. The time necessary to accelerate the protons to maximum energy is limited by the capabilities of the superconductors, and amounts to about 15 s. The main physics research program will utilize the extracted proton beam. Provision is made for slow (up to 10 s) and fast (1 ms) extraction of protons from the machine. The accelerator was commissioned in 1983. In the history of accelerator technology, DOUBLER will figure as the first superconducting machine of the TeV range. The FNAL accelerating complex is now a tandem system consisting of a linear accelerator (200 MeV), a fast-cycling booster synchrotron (8 GeV), a proton synchrotron (150–500 GeV), and DOUBLER (1000 GeV). Table V lists some of the parameters of the main accelerating installations.

Figure 8 illustrates schematically the order in which the accelerated proton beams are used in physics experiments. Secondary particles are generated on external targets. Secondary-particle channels point in three directions, forming the meson, neutrino, and proton areas. The proton beam extracted from the accelerator is distributed by special systems among these directions in a predetermined ratio. Experiments are also performed directly with the internal beam circulating in the accelerator chamber. Very thin (e.g., gas jet) targets are used to keep disturbances to the beam within tolerable limits. This technique was first used on the IHEP accelerator. Beams of different secondary particles can be produced in the experimental areas in a wide momentum range, e.g., hadrons with 20–400 GeV/c, electrons with 40–300 GeV/c, neutrinos with 10–300 GeV/c, muons with 25–270 GeV/c, and gamma rays with 10–280 GeV/c. With the advent of the superconducting accelerator the experimental areas will acquire the facility of secondary particles with roughly doubled momenta.

Further plans for the development of the FNAL accelerating complex include the development of an antiproton program. It is proposed to build an antiproton storage ring and to produce in the DOUBLER proton-antiproton colliding beams with center-of-mass energy of 2000 GeV.

D. Electron-positron storage ring PETRA at Hamburg[37]

The Positron Electron Tandem Ring Accelerator (PETRA) was commissioned in 1978 and is the largest accelerating and storage installation for positrons and electrons. Electron-positron colliding beams with center-of-mass energy of up to 45 GeV have recently been produced in this machine. So far, this is the highest light-particle energy that has been attained in circular accelerators. The first accelerator constructed at the Hamburg research center was the 7.5-GeV electron synchrotron DESY (Deutsches Elektronen Synchrotron). It was followed by the 5.1-MeV electron-positron colliding-beam ring DORIS. Figure 9 illustrates schematically the arrangement of the accelerating installations. Posi-

TABLE IV. Colliding beams

Installation	Particle energy, GeV	Beam current, A	Luminosity, $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
ISR:			
pp-Beams	31,4	50	$5\cdot10^{31}$
$p\bar{p}$-Beams	31,4	p : 50 $\bar{p}$: 30	10^{29}
SPS:			
$p\bar{p}$-Beams	270	4,35	10^{30}

TABLE V. Basic parameters of Fermilab accelerators

Basic proton synchrotron	
Maximum proton energy	500 GeV
Number of accelerated protons	$3\cdot10^{13}$ protons per cycle $3{,}75\cdot10^{12}$ protons per second
Mean ring radius	1000 m
Injection energy	8 GeV
Maximum magnetic field	2,23 T
Mean power consumption	40 MW
Number of acceleration cycles per minute	7,5
Frequency of betatron oscillations Q	19,4
DOUBLER	
Maximum proton energy	1000 GeV
Injection energy	150 GeV
Maximum magnetic field	4,42 T
Number of magnetic dipoles	774
Number of magnetic quadrupoles	216
Frequency of betatron oscillations Q	19.4

trons are injected into PETRA from the synchrotron DESY (operating at 50 Hz) and the storage ring DORIS. The production and preliminary acceleration of positrons to 300 MeV is performed in a linear accelerator. Positrons are stored in the ring in two stages. First, intermediate storage in DORIS is performed at 2.2 GeV. The linac-DESY-DORIS chain continues to operate at this stage for the time necessary to accumulate in the DORIS orbit the maximum number of positrons allowed by beam stability conditions. The positrons are then returned to DESY where they are accelerated to 7 GeV and are injected into the main storage ring. The cycle is repeated until the design current of 80 mA is reached in PETRA's orbit. When the electron current in the initial portion of the linac is 0.2 A, it takes about 10 min to accumulate the required number of positrons in PETRA. An electron beam of sufficient intensity is produced in DESY in one acceleration cycle. The energy of particles stored in this way is then raised from 7 GeV to the required figure by a high-frequency accelerating system, with the magnetic field rising *simultaneously on the orbit. The main parameters of the* storage ring are listed in Table VI.

The design energy of the accelerated particles (19 GeV) is limited by the resultant amplitude of the high-frequency accelerating voltage used to compensate energy losses by the emission of synchrotron radiation. The power delivered by the accelerating devices determines the maximum colliding-beam currents. The number of 500-MHz resonators used for the compensation of synchrotron losses (almost 100 MeV per revolution of each stored particle) had to be doubled to attain the required energy of 45 GeV. These resonators (total number 112) occupy about 10% of the orbit perimeter. Further increase in the energy can be achieved by using superconducting resonators.

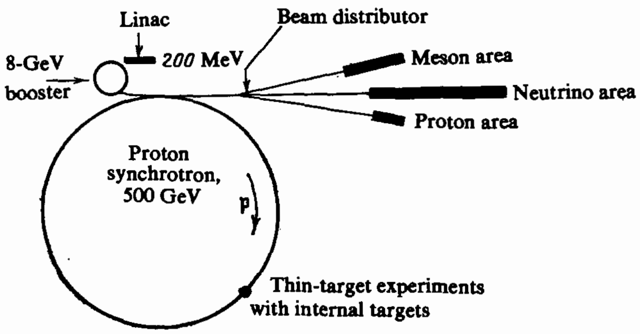

FIG. 8. Fermilab system showing the distribution of the extracted proton beam over different experimental areas.

E. The SLAC linear electron accelerator[21]

The Stanford Linear Accelerator Center (SLAC) of the Stanford University near San Francisco has a unique electron that is the largest machine of this kind in the world (see Table VII). The electrons are usually accelerated to 24 GeV. However, the energy can be raised to 33.4 GeV by turning on additional high-frequency devices that increase the acceleration rate. Positrons can also be accelerated. They are generated in a tungsten target presented to the accelerated-electron beam at the end of the first one-third of the length of the machine. A small fraction of positrons produced in this way proceeds in the same direction as the primary electrons, and *is accelerated in the remainder of the linac to* 15 GeV. The number of positrons trapped in the acceleration process is about 8% of the number of primary electrons incident on the target.

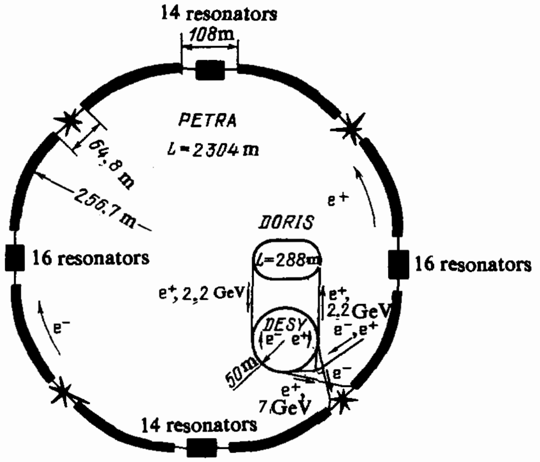

FIG. 9. PETRA electron-position storage system.

TABLE VI. Design parameters of PETRA.

Maximum e^+e^- energy	19 GeV
Current in each beam	80 mA
Particle lifetime	10 hr
Number of crossings per orbit	4
Beam dimensions at points of encounter	
horizontal	0,8 mm
vertical	0,03 mm
Luminosity	10^{32} $cm^{-2}s^{-1}$

Physics experiments are performed both with the primary beam of accelerated electrons and with secondary particles generated by electrons on external targets. In addition to meson, proton, antiproton, and bremsstrahlung γ-ray beams, the accelerator produces a beam of monochromatic γ-rays of 20 GeV. This beam is formed as a result of the backscattering of laser photons traveling in the opposite direction to the accelerated electrons. The beam intensity is up to 3.6×10^4 photons per second. The idea of using colliding beams of accelerated electrons and laser photons to produce this unique source of γ-rays was first put forward at the Erevan Physics Institute of the USSR Academy of Sciences[38] and, independently but later, abroad.[39]

The experimental facilities of the accelerator center were substantially expanded after the advent of the electron-positron storage ring SPEAR at 4.2 GeV and PEP (Positron Electron Project) at 18 GeV. The SLAC linear accelerator was the particle injector in both cases. A luminosity of 10^{31} $cm^{-2}s^{-1}$ is achieved in SPEAR when each beam carries a current of 0.1 A. Roughly the same luminosity is achieved in PEP. The parameters of these installations are very similar to those of DORIS and PETRA. Generally speaking, the Stanford and Hamburg centers have much in common as far as the nature of their development is concerned, since both centers are based on electron accelerators of roughly the same energy.

In addition to the high-energy physics program, SPEAR is being used in extensive research in chemistry, biology, and metallurgy, using the synchrotron beams whose spectrum extends far into the ultraviolet and x-ray ranges. This research is arranged to run parallel to the main program, and substantially extends the scientific and practical importance of electron storage systems.

3. POSSIBLE FUTURE DEVELOPMENTS

The accelerator and storage systems for charged particles mentioned in the above examples can no longer be referred to as laboratory installations. In their size and technological capabilities, they more closely resemble major industrial complexes requiring considerable capital investment and running expenditure as well as a large staff. Projects being discussed at present are estimated to require budgets of billions of dollars. As far as the energy of accelerated particles is concerned, the needs of physics run in advance of the possibilities of accelerator technology. Discoveries made at the maximum energies available at present create problems that can only be solved at still higher energies. At present, there are only relatively limited possibilities for the optimum development of accelerators in this direction. Accelerator technology continues to develop on the basis of known acceleration principles, and an increase in the energy of accelerated particles in the immediate future will necessarily involve an increase in the dimensions of accelerators. The application of cybernetic principles to accelerator design, and the use of superconductvity to produce magnetic and high-frequency electromagnetic fields, will reduce the cost per unit energy of accelerated particles. This will be widely exploited in accelerators of the next generation. It will also enable us to reduce by a factor of 2–3 the dimensions of circular accelerators per unit energy. This has already been done in the planned 3000-GeV accelerating and storage complex at IHEP.

Accelerating and storage systems working at hundreds or thousands of GeV in the center-of-mass system will come on stream in the immediate future at a number of science centers (SPS is the first installation in this range).[40] The Nuclear Physics Institute of the Siberian Division of the USSR Academy of Sciences is working on the electron-positron collider VLEPP, which exploits single collisions of particles accelerated in two linear accelerators pointing at each other. It is proposed to begin with the construction of 150-GeV linear accelerators. Their length will then be extended to raise the energy to 500 GeV. An analogous method of producing colliding beams with single particle collisions, but

TABLE VII. Basic parameters of SLAC accelerator.

Accelerator length	3050 m
Mean beam current	
electrons	48 μA
positrons	0,6 μA
Length of current pulse	1,6 μs
Pulse repetition frequency	360 Hz
High-frequency accelerating electric field	2856 MHz
High-frequency power	
peak	7300 MW
average	7 MW

using a single accelerator, is being implemented at SLAC. The energy of the accelerated electrons and positrons will be raised to 50 GeV after the appropriate modernization of the high-frequency system. Beam collisions are brought about by magneto-optical channels producing beam diameters of about 4 μm at the point of encounter.[41] At Fermilab, it is planned to use DOUBLER to produce colliding proton-antiproton beams with energies of 1 TeV. The DESY research center at Hamburg is developing the HERA installation for colliding electron-proton beams with energies of 30 GeV and 820 GeV, respectively. The proton ring will use superconducting magnets. CERN is building the electron-positron LEP ring with a perimeter of 27 km. It is also proposed to use it tunnel to contain a ring with superconducting magnets for proton-antiproton colliding beams with energies of 5–10 TeV. The National Laboratory for High Energy Physics in Japan is planning TRISTAN which will produce colliding electron-positron beams of 33 GeV (with subsequent increases). The accelerating system will incorporate high-frequency superconducting resonators.

American specialists have recently proposed a proton accelerator complex producing 20 TeV. This plan provides for two rings with energy ensuring that colliding beams will have 40 TeV in the center-of-mass system. The expected luminosity is 10^{32}–10^{33} cm^{-2}s^{-1}. The magnetic-ring structures will consist of superconducting focusing and bending magnets. Two magnet designs are being examined. One has an iron core and a superconducting coil. The required magnetic-field configuration is defined by the pole geometry. The maximum magnetic field in such magnets is limited by the saturation of iron. The principal advantage of the magnets is their simplicity of fabrication and exploitation. The perimeter of rings producing 2T in the bending magnets is in excess of 200 km. With some further complication of the design of the dipole magnets, and with special disposition of the superconducting coils, it will be possible to achieve geometric composition of the magnetic field in the gap, and raise the magnetic field to about 3T without substantial saturation of iron.[42] The ring perimeter will be greatly reduced by using magnets with superconducting current coils, and by increasing the magnetic field to 5T. The final design of the magnets is not as yet settled.

Higher magnetic fields have to be used to reduce the dimensions of circular accelerators. There is a number of options here. Currently used superconductors are based on the alloy NbTi with critical magnetic field of 10T. By using Nb_3Sn (critical field 25T), it will be possible to develop superconducting magnets producing fields of up to 10T, whereas fields of up to 20T are possible with V_3Ga (critical field 35T). However, many complex technological problems will have to be solved before the use of such high magnetic fields in accelerator technology will become a practical reality. The development of additional methods of acceleration is running in parallel with intensive searches for new principles capable of sharply increasing the rate of acceleration. As noted earlier, the Nuclear Physics Institute of the Siberian Division of the USSR Academy of Sciences is developing the high-frequency structure of a linear accelerator with a design acceleration rate of 100 MeV/m, which is greater by an order of magnitude than the figure used in modern accelerators so far. Many ideas are based on fundamentally new acceleration mechanisms.[43] For example, one of the ideas that has been considered is the transfer of energy to charged particles from powerful laser beams that produce high electric fields. Some of the schemes that have been proposed involve the use of effects in their inverse form, for example, the inverse Vavilov-Cherenkov effect, in which the charged particle absorbs energy from a laser beam crossing its orbit at the characteristic angle for this radiation. Calculations have shown that an acceleration rate of 500 MeV/m can be achieved in this way. Comparable acceleration rates can be attained by pointing laser beams at free electrons.

In many of the proposed methods, charged particles are accelerated by exploiting electromagnetic phenomena in plasma to produce progressive electric-field waves with phase velocities lower than the velocity of light. Such waves can be generated, for example, by a density-modulated high-current electron beam, or by placing the plasma in two interfering laser beams. The expected acceleration gradients produced in this way are up to 1 GeV/m. However, as yet such studies have been confined to theoretical and laboratory work and it is still premature to speak of their practical implementation.

It seems that advances in accelerator technology in the course of the next decade will rely on improvements in the technology of construction of more economical accelerating and storage systems whose operation will be based on established principles.

It may be expected that new-generation accelerators using colliding hadron beams will produce total energies of up to 40 TeV (see Fig. 1). One cannot, of course, exclude the possibility that new ideas for the production of ultrahigh-energy particles will emerge, but such events usually occur unexpectedly in the history of science and technology, and cannot be predicted in advance.

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