ON THE SIXTIETH ANNIVERSARY OF ACADEMICIAN V. I. VEKSLER

On March 3 and 4 of this year, the Division of Nuclear Physics of the USSR Academy of Sciences, the P. N. Lebedev Physics Institute of the USSR Academy of Sicences, and the Joint Institute for Nuclear Research held a scientific session devoted to the sixtieth birthday of the outstanding Soviet scientist Academician V. I. Veksler.

Following introductory remarks by the vice-president of the USSR Academy of Sciences, Academician V. P. Konstantinov, the following papers were read to the session:

A. A. Kolomenskii, Development of V. I. Veksler's Ideas in the Field of Accelerators.

I. V. Chuvilo, V. I. Veksler and Research on High-energy Physics.

A. I. Alikhanyan, The Erevan 6-GeV Electron Synchrotron.

A. L. Mints, The Cybernetic Accelerator.

P. A. Cerenkov, V. I. Veksler and Research on the Photoproduction of Mesons and Photodisintegration of Light Nuclei.

Ya. B. Faĭnberg, Acceleration of Particles in a Plasma.

Yu. M. Ado, The Serpukhov 70-GeV Proton Synchrotron.

N. L. Grigorov, Study of the Interaction of High-energy Cosmic Rays with Nuclei.

In the present issue of our journal we publish the papers of A. A. Kolomenskiĭ, A. L. Mints, and Ya. B. Faĭnberg.

DEVELOPMENT OF V. I. VEKSLER'S IDEAS IN THE FIELD OF ACCELERATORS

A. A. KOLOMENSKIĬ

P. N. Lebedev Physics Institute, USSR Academy of Sciences

Usp. Fiz. Nauk 93, 593–610 (December, 1967)

V. I. Veksler's basic papers paved the way towards a rapid and extensive development of modern accelerators. Prior to the publication of these papers, in the early forties, there were already in operation betatrons for electron acceleration, cyclotrons for heavy-particle acceleration, and linear accelerators. The latter were at that time at the initial primitive level. No appreciable increase in the particle energy could be attained with either cyclotrons or betatrons. New ways had to be found for further progress. They were indicated in 1944 by V. I. Veksler [1], who proposed a number of new types of accelerators based on the phase stability principle developed by him. This principle, which by now is widely known, can be interpreted in different ways, for example, by considering the effective accelerating wave of a longitudinal electric field and a particle interacting with this wave. The wave and the particle can propagate along a straight line (Linear accelerator) or execute periodic motion (cyclic accelerator). In general, there exists a certain preferred particle motion, called resonant or equilibrium. In this motion, the particle maintains in a definite equilibrium phase relative to the wave, moves in exact synchronism with this wave, and acquires energy from it in a resonant fashion. The phase stability principle states that, when certain not too stringent requirements are satisfied, the deviation of the motion conditions from equilibrium does not upset the mechanism whereby the particle energy is increased. Exact synchronism is replaced by synchronism in the mean, and different characteristics of the particle motion, such as the phase, the energy, or the radius, oscillate in stable fashion about equilibrium values.

The discovery of phase stability has made it possible to develop and then construct numerous accelerators of different types: synchrocyclotrons - accelerators with a constant magnetic field of the cyclotron type and with an accelerating electric field of variable frequency; proton synchrotrons - ring accelerators with variable accelerating-field frequency and with time-varying magnetic field; synchrotrons - accelerators with time-varying magnetic field and constant accelerating-field frequency; microtrons - accelerators with time-constant magnetic field and alternating

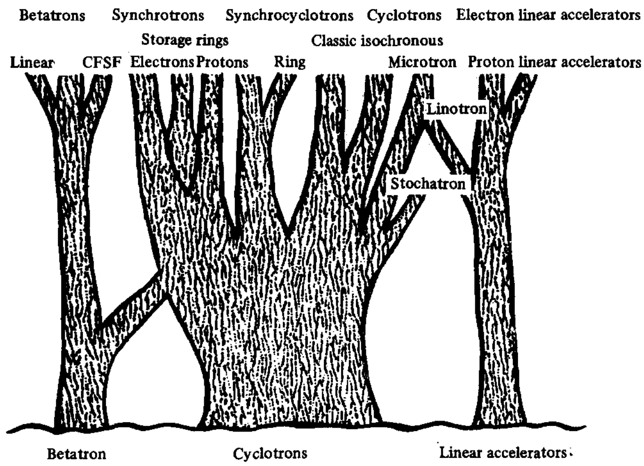

FIG. 1. "Family tree" of accelerators. (CFSF - constant field, strong focusing or ring-type synchrocyclotrons.)

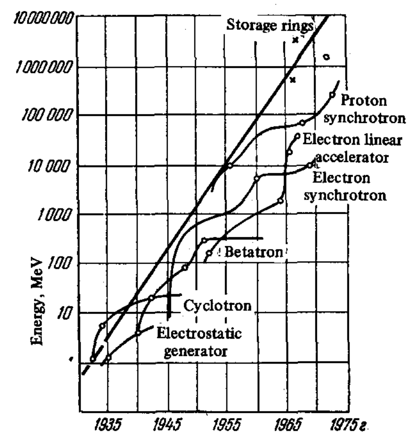

FIG. 2. Maximum particle energy attained in accelerators of different types during different years.

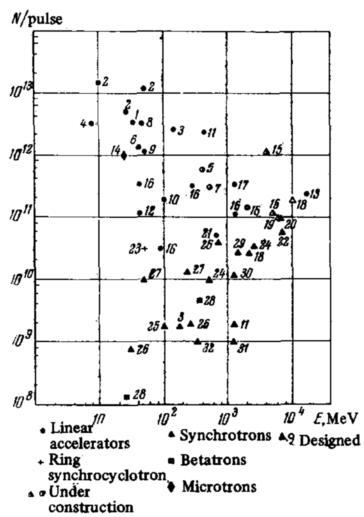

FIG. 3. Distribution of electron accelerators by energy and intensity (pulsed).

For the linear accelerators, the intensity is referred to an energy scatter with half-width ±0.5%. The energy of the linear accelerators is assumed to be the one for which the values of intensity are cited in the literature.

1. Toronto University (Canada). 2. Accelerators constructed by the General Dynamics Corporation (USA). 3. National Bureau of Standards (Gaithersburg, Md.) 4. Osaka (Japan) Radiation Center. 5. Massachusetts Institute of Technology (Cambridge, USA). 6. Yale University (New Haven). 7. National Institute of Nuclear Physics and Technology (Sarclay, France). 8. Rennselaer Polytechnic Institute (Troy, USA). 9. Institute of Technical Nuclear Physics (Darmstadt, West Germany). 10. Saskatchewan University (Saskatoon, Canada). 11. National Laboratory in Frascati (Italy). 12. Naval Research Laboratory (Washington). 13. SLAC–Stanford Linear Accelerator Center (Stanford, USA). 14. Joint Institute for Nuclear Research (Dubna, USSR). 15. NINR–National Institute of Nuclear Research (Dursbury, Great Britain). 16. Accelerators of the Physico-technical Institute of the Ukrainian Academy of Sciences (Khar'kov, USSR). 17. Laboratory of the Linear Accelerator of the Paris University (Orsay, France). 18. Accelerators of Cornell University (Ithaca, USA). 19. Physics Institute (Erevan, USSR). 20. CEA–Cambridge Electron Accelerator, Massachusetts Institute of Technology and Harvard University (Cambridge, USA). 21. Stanford University (USA). 22. DEZI–German Electron Synchrotron (Hamburg, West Germany). 23. Midwest University Association (Madison, USA). 24. Accelerators of the Bonn University (Bonn, West Germany). 25. Turin University (Italy). 26. Accelerators of the P. N. Lebedev Physics Institute of the USSR Academy of Sciences (Moscow, USSR). 27. Injector synchrotrons of the Storage rings of the Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences (Novosibirsk, USSR). 28. Illinois University (Urbana, USA). 29. California Institute of Technology (Pasadena, USA). 30. Scientific Research Institute of Nuclear Physics of the Tomsk Polytechnic Institute (Tomsk, USSR). 31. Lund University (Sweden). 32. Glasgow University (Great Britain).

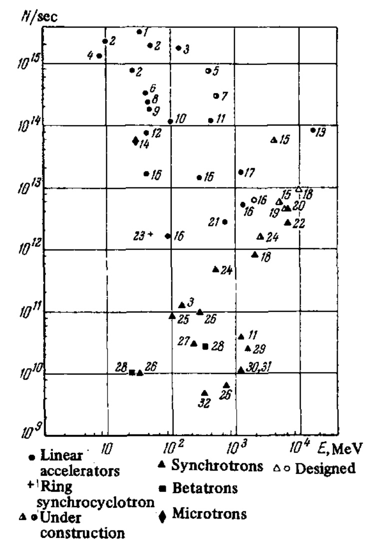

FIG. 4. Distribution of electron accelerators by energy and intensity (average).

multiplicity (ratio of the revolution frequency to the constant frequency of the accelerating field). The appearance of these machines started the modern stage of accelerator development, which led in final analysis to the blossoming of the new basic field of science - high-energy physics.

The creation and development of the family of modern accelerators of different types and scales can be illustrated, for example, with the aid of the accelerator "family tree" (Fig. 1). We note that Veksler's work made also possible a new approach, from the point of view of phase stability, to the "old" accelerators, such as the cyclotron and the linear accelerators. They also progressed greatly during the elapsed twenty years.

What main accomplishment can be pointed out at present, compared with the period when Veksler and his co-workers laid the ground work for the modern phase-stability machines?

The first striking result is the increase of the particle energy, by 3–4 orders of magnitude. Maximum particle energies were attained in different years with

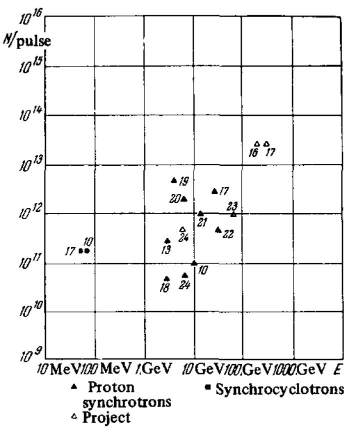

FIG. 5. Distribution of large proton accelerators by energy and intensity (pulsed).

1. Birmingham University (Great Britain). 2. Amersham (Great Britain). 3. Prototype of the adjustable-energy cyclotrons of the Philips Company (Eindhoven, Netherlands). 4. Michigan University (East Lansing' USA). 5. University of California (Berkeley, USA). 6. Isotope production cyclotron of the Philips firm (Einhoven, Netherlands). 7. Rutherford High Energy Laboratory (Harwell, Great Britain). 8. Oak Ridge National Laboratory (Oak Ridge, USA). 9. Cyclotron for the acceleration of negative hydrogen ions, University of California (Los Angeles, USA). 10. Joint Institute for Nuclear Research (Dubna, USSR). 11. Nuclear Research Center (Karlsruhe, West Germany). 12. Milan University (Italy). 13. National Institute of Nuclear Physics and Technology (Sarclay, France). 14. University of Manitoba (Winnipeg, Canada). 15. Swiss Federal Technological Institute (Zurich, Switzerland). 16. 200-MeV proton synchrotron (Weston, USA). 17. European Center of Nuclear Research (CERN) (Geneva, Switzerland). 18. Princeton-Pennsylvania proton synchrotron (Princeton, USA). 19. Bevatron, University of California (Berkeley, USA). 20. NIMROD, High Energy Laboratory (Chilton, Great Britain). 21. Zero-gradient synchrotron, Argonne National Laboratory (Argonne, USA). 22. Brookhaven National Laboratory (Upton, USA). 23. Institute of High Energy Physics (Sepukhov, USSR). 24. Institute of Theoretical and Experimental Physics (Moscow, USSR). 25. "Saturn" (Sarclay, France).

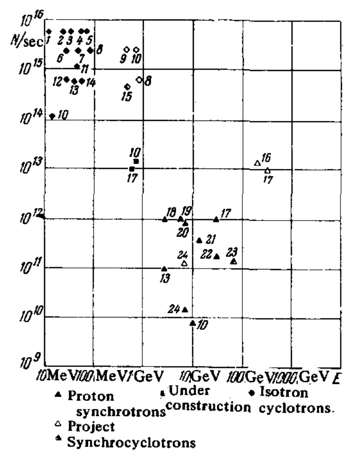

FIG. 6. Distribution of large proton accelerators by energy and intensity (average).

machines of different types. This can be illustrated by a special graph (Fig. 2) covering the last 30—40 years, starting with the appearance of the cyclotron. It is curious that the maximum particle energy obtained with accelerators has increased by one order of magnitude approximately every 6—7 years. Only recently did the growth begin to slow down. However, if account is taken of the colliding-beam installations which have already been started or are under construction, and take the equivalent energy for one beam, which to be sure is somewhat arbitrary, then it turns out that the same growth rate is still being maintained and will be maintained for the next few years.

Another most important accomplishment characterizing the present stage of development is the appearance of strong-current accelerators and storage rings. The increased intensities become manifest in three different aspects. First, the experiment time is shortened and the accuracy is increased, making it possible to study rare events and reactions with small cross sections, hitherto inaccessible to investigation. All this, in final analysis, raises the physics of high energies (and not only high energies alone) to a new level. Second, questions of shielding against radiation, radiation damage, the influence of the background, remote control, beam extraction, which must meet very stringent requirements in strong-current machinery, must again be reviewed quite thoroughly. Third, the acceleration process becomes more complicated, new effects due to particle interaction appear, and different instabilities arise, making it necessary to introduce special devices for the suppression of undesirable and dangerous effects. We shall return to this question later.

A general idea of the modern status of accelerators can be obtained by considering the position of the individual installations on plots with energy and intensity as coordinates. The overwhelming majority of the now operating accelerators (both cyclic and linear) produces particles in short pulses separated by relatively long pauses. It is therefore necessary to distinguish between the intensity in the pulse from the average intensity (the number of particles accelerated per second). Figures 3–6 show separately the distribution of the electron and large proton accelerators with respect to the average and pulsed intensities (at different energies). The plots show (especially for the electron accelerators) a great variety of types and of the main characteristics. Thus, the electron accelerators differ by approximately six orders of magnitude in average intensity and by almost four orders in energy.*

We shall not here touch upon investigations connected with acceleration of bunches of electron-ion plasma or with acceleration of particles with the aid of a plasma, which are interesting from the physical point of view. Veksler was one of the pioneers in this field[2], which so far has not yet emerged from the stage of initial explorations, the realization of the existing ideas encountering serious difficulties. In the future, however, the use of plasma in accelerator physics may turn out to be effective. It is possible that it will become an alternative for the forced giant-size mania distinguishing this field.

As seen from Fig. 2, the maximum particle energy is attained with proton synchrotrons. The history of their development began at the Physics Institute of the USSR Academy of Sciences (FIAN), where this type of accelerators was first conceived twenty years ago. In 1948–1950, a group of physicists headed by V. I. Veksler[3,4] developed the physical principles and the theory of particle motion, which served as the basis for the design of the hitherto unprecedented 10-GeV proton accelerator. The choice of the energy was dictated by different considerations, particularly the desire to exceed the threshold for the production of a nucleon-antinucleon pair on a nucleon (5.6 GeV), and at the same time to exceed greatly the value 6 GeV attainable by the Berkeley (California) bevatron accelerator which was to go into construction at approximately the same time.

A special 180-MeV setup was constructed at FIAN

*Details concerning the present status of electron accelerators are found in [20].

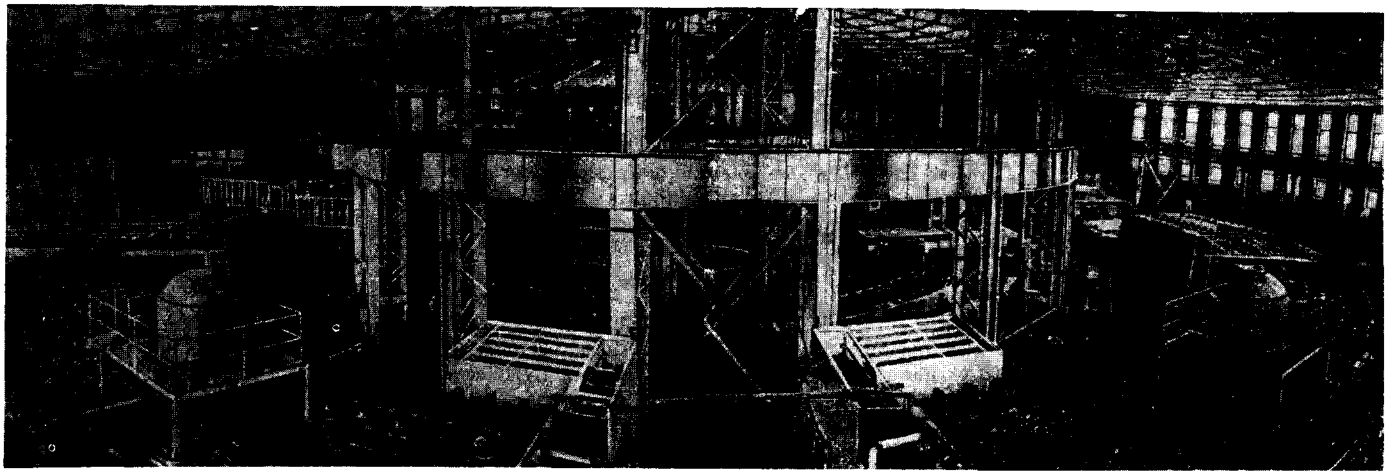

FIG. 7. Over-all view of the 10-GeV proton synchrotron in Dubna.

and went into operation in 1953 for an experimental verification and development of the most important conclusions of the theory.* For a number of years, during the course of the design and construction of the 10-GeV proton synchrotron at Dubna, many difficult physical, electrotechnical, radiotechnical, vacuum, structural, and other problems were solved; this called for intense work on the part of many major scientific, engineering, and production staffs. The entire work was under the direct supervision of V. I. Veksler, who proved himself in this case to be not only an outstanding physicist but also a talented engineer and organizer. In 1957–1958 the Dubna proton synchrotron delivered the rated values of the energy and proton-beam intensity.

The history of the creation of the unique Dubna installation and its main features and parameters are well known. An overall view is shown in Fig. 7. The significance of this installation, of course, is not limited to the fact that it delivered and still delivers high energies for the physicists. As a result of this construction and start-up, physical and technical foundations were laid for an entire new trend, and the ground work was laid for the next stage - the creation of strong-focusing proton synchrotrons, first the 7 GeV unit of the Institute of Theoretical and Experimental Physics in Moscow [5], and then the 70-GeV unit in Serpukhov [6]. The latter accelerator, for which the start-up and adjustment recently began, is presently the largest in the world and will remain so for a number of years.

Let us discuss briefly the prospects of the Dubna accelerator. It was started ten years ago, and the 10 GeV energy, which at that time was a record, was subsequently exceeded in a number of later large-scale machines. However, the Dubna installation has tremendous unexploited potential in the sense of increasing the proton-beam intensity. It must be stated that the corresponding work was already performed in connection with its competitor - the American 6-Gev bevatron - and is under way on a number of later-generation machines.

Certain features of the cyclic high-intensity machines will be discussed later. For the time being it should be noted that the present level of the understanding of the problem makes it possible to assert that there are favorable possibilities of increasing the intensity in this machine. The Dubna proton synchrtron can and should be made into a strong-current machine - a powerful generator of secondary-particle beams, especially K mesons. To this end it is necessary to increase the energy and intensity of the linear injector-accelerator, increase the shield, and ensure effective beam extraction. An important role may be played in this case by the realization of a proposal, submitted by the present author earlier, of using a special storage ring for injection [7]. The numerous particle pulses, which a linear accelerator is capable of producing within ~10 sec between injection periods, should be accumulated in the storage ring. The intense stored beam, accelerated to the required energy, is then introduced into the main machine using multiturn injection. Recent progress in storage rings gives grounds for expecting this method, various modifications of which have been attracting increasing attention recently, to be quite effective (see the Transactions of the Fifth International Conference on Accelerators, Frascati, 1965).

The modernization of the Dubna machine will greatly strengthen the work done on high-energy physics in our country. At the same time, this will honor the memory of V. I. Veksler, who devoted so many efforts to this machine.

The history of the construction of the most widely used high-energy electron accelerators - synchrotrons - also began with the development and starting of the first machines of this type by Veksler's staff at FIAN in 1946–1949. The first phase-stability accelerator in our country - a 30-MeV electron synchrotron - was developed and constructed in 1945–1947. It is still in operation, being the main instrument of the photonuclear laboratory. Inasmuch as an induction acceleration mode is used during the initial stage of the acceleration, this installation is at the same time also

*This installation was subsequently reconstructed into the 680-MeV electron synchrotron [10].

the first betatron launched in the USSR (for a description of this machine see [8]). During the subsequent years, synchrotrons of ever increasing size were developed and constructed at FIAN. In 1947, work began on the design of a 250-MeV synchrotron, with an energy sufficient for pion photoproduction. Owing to the experience gained during the construction of the first synchrotron, this accelerator was constructed within a short time and started in October 1949 (the electron energy was subsequently increased to 280 MeV). This synchrotron (for a description see [9]), which produces an electron beam of larger average intensity, served as the basis for the photomeson laboratory, which assumed, as a result of its investigations, a leading position in its field.

Subsequent development of the synchrotrons is inseparably connected with progress in the understanding of the dynamics of electrons in the presence of synchrotron radiation. Veksler was interested in this phenomenon from the very beginning, and back in 1946 he proposed, together with a group of co-workers, a method for generating millimeter waves, based on the use of the coherent part of the synchrotron radiation [11]. It must be stated that the synchrotron radiation in itself is a most interesting physical phenomenon, which is encountered in various branches of science, but it is exceedingly important for electron synchrotrons, especially those of high energy. This not due solely to the fact that the radiation losses reach large values and require a powerful high-frequency system for their compensation. Incidentally, phase stability reveals here, too, its remarkable properties, by ensuring automatic compensation of the losses (within the limits of available power). The most important feature is that synchrotron radiation is decisive for the entire dynamics of the electrons, both for focusing and for the acceleration process. We cannot stop here to discuss the corresponding theory developed at FIAN as a result of the investigations initially connected with the first relatively small synchrotrons. This theory, initially developed by the author together with A. N. Lebedev [12,13], demonstrated the existence of the so-called radiation friction (positive or negative). It turned out that the radiation, together with the electromagnetic field of the accelerating system, can produce either damping or growth of betatron and synchrotron oscillations, depending on the structure of the magnetic system of the accelerator or of the storage ring. These notions are the basis of the large modern strong-focusing synchrotrons, in which the electrons are accelerated to energies on the order of 5—10 GeV. The radiation-friction concept is particularly important for the development and construction of electron and electron-positron storage rings. This friction ensures the very possibility of accumulating sufficiently dense circulating beams, for without it, according to the Liouville theorem, it is impossible to increase the density above the density of the introduced beams. On the other hand, this friction ensures a sufficiently long lifetime of the particles with respect to various disturbing phenomena - scattering and bremsstrahlung from the residual gas, different Coulomb instabilities, and also with respect to quantum statistical fluctuations of the radiation itself, the importance of which was first noted in [14]. This long lifetime is essential for accelerators and especially for storage rings.

What are the prospects of the synchrotrons in the sense of obtained larger energy and intensity? Further progress in both respects is hindered by radiation losses, the power of which increases in proportion to the fourth power of the energy. At the same time, the loss per revolution is inversely proportional to the radius of curvature of the orbit. Therefore, in principle, they can always be reduced to reasonable level at the expense of suitably increasing the synchrotron radius. This is the path followed recently. In addition, great prospects can be uncovered by going over to superconducting resonators. In such resonators there are practically no wall losses and the entire high-frequency power goes to raise the energy of the beam. In the nearest future synchrotrons will apparently deliver electrons with energies 20—25 GeV, and perhaps even higher.

Now a few words concerning the microtron or, as initially called by Veksler, the multiple-resonance accelerator. This was one of the first phase-stability accelerators proposed by him [1]. It is interesting that the microtron, with respect to some of its properties, is an exception among all other accelerators. Theory shows [15] that motion on the plane that serves as the phase plane occurs in the microtron, generally speaking, in abrupt jumps and not smoothly as in others. Among the different microtron modifications, a variant with a so-called slotted magnet capable of housing a sufficiently powerful accelerating system was under consideration back in 1947 at FIAN. The microtron did not find wide acceptance for quite some time, in spite of the simplicity of its construction. In the sixties, following experimental investigations at the Institute of Physics Problems, and later also at FIAN, certain effective improvements were introduced into the microtron construction [16,17]. As a result, low-energy microtrons (5—30 MeV) were made to deliver electron beams with good pulse intensity and found a number of applications. At the present time we are witnessing the start of a new stage in the development of the microtron which, possibly, will lead in final analysis to the creation of installations providing a continuous accelerated electron beam with energy on the order of several hundred MeV, and maybe even higher. In such a microtron the accelerating system should be a superconducting resonator or a linear accelerator. Although there are many proposed modifications of the magnetic system of the microtron, aimed at producing focusing, only the already mentioned simple variant with a slotted magnet [18,19] is presently under serious discussion. It must be stated that, in spite of the principle simplicity of the system, its practical realization calls for great efforts to ensure phase and vertical stability.

In addition to the already considered known methods of particle acceleration, we must dwell briefly on one less known unique method, proposed by É. L. Burshteĭn, V. I. Veksler, and the author. Although it has not been widely used, it is interesting from the fundamental point of view and is encountered also in various physical phenomena not directly connected with accelerators. We are speaking here of the so-called stochastic method, first proposed in 1948 but reported later [21]. Its distinguishing feature is the use of a probability (stochastic) acceleration mechanism, which can be realized, in general, in both linear and cyclic acceleration. Let us consider the simplest scheme, in which the particle, revolving in a time-constant magnetic field, passes many times a gap with an alternative voltage. Let this voltage be able to assume, with equal probability, two values +V and −V. The probability that the particle will fall k times in succession into an accelerating field and will acquire an energy E_k (keV) is equal to 2^{-k} and is exceedingly small if k is appreciable. However, the acceleration efficiency will be determined not by this probability, but by the fraction w_k of the number of particles reaching an energy E_k after an arbitrary number of revolutions, i.e., following different random successions of accelerations and decelerations. Calculations show that w_k is of the order of $1/2k$, corresponding to an appreciable beam intensity at the output of such an accelerator - stochatron - since in principle the particles flow here continuously and not in pulses. The average number of revolutions is of course, larger than k and its order of magnitude is k^2. The subsequently developed theory of the stochastic mode [22] has shown that its efficiency is in the general case strongly dependent on the spectrum of the accelerating "noise" V(t). The stochastic mode can be useful when combined with other acceleration methods: to facilitate the injection conditions in a synchrocyclotron [23a], to go through the critical energy [23b], and also to accumulate particles on a definite orbit [22]. A mechanism similar to the considered stochastic mode is responsible to a certain degree for the acceleration of electrons in interaction between beams and a plasma (see, e.g., p 750).

The variety of accelerator types makes it possible, using the language of genetics, to cross-breed different types of accelerators in order to obtain new more effective or more economical accelerators. Projects and proposals of this type were made already twenty years ago, with Veksler taking part. The first example is the synchrobetatron, i.e., a combination of a synchrotron and a betatron. This was the name given at one time to synchrotrons with betatrons as first stages, such as the first FIAN machines. Another example is the already-mentioned proton synchrotron, which combines a synchrotron and a synchrocyclotron.

Lately, already without Veksler's participation, the family of accelerators has continued and continues to acquire new members representing combinations of different types. Let us consider several examples. We start with the linotron, which was proposed by us [24]. We note first that the dimensions of the synchrotrons and of the linear accelerators used to obtain high-energy electrons are very large: the lengths of the linear accelerators reach several kilometers, and the diameters of synchrotrons several hundred meters. The synchrotron dimensions are made as large as possible since it is necessary to decrease the loss to the already mentioned synchrotron radiation and reduce the power and the size of the high-frequency system. We note that the average intensity of the beam in the synchrotron is at least two orders of magnitude smaller than in a linear accelerator. This difference becomes even larger when cryogenic continuously-operating linear accelerators are used, but the loss per unit length is much larger in a cryogenic installation than in an ordinary one. At the same time, analysis of the

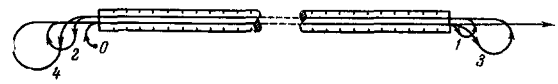

FIG. 8. Diagram of linotron: O – Injection channel, 1,2,3,4 – magnetic channels (reflectors).

dynamics of relativistic particles in a linear accelerator shows that there are several favorable properties, to which due attention was not paid. First, it is possible to accelerate simultaneously particles having different relativistic energies. Second, it is possible to accelerate particles in both directions, either alternately in a traveling wave or simultaneously by exciting a standing wave which represents the sum of waves traveling in opposite directions.

The foregoing properties make it possible to create a new effective system, in which it is possible to obtain in a given linear accelerator an energy which is several times larger (in principle, many times) than the original rating of the accelerator. We have called this system, for brevity, a linotron. To realize this system it is necessary to place at the ends of the linear accelerator "reflectors," i.e., rotating and focusing channels with a time-constant magnetic field. After each passage through the linear accelerator, the bunch of particles reenters the linear accelerator in the opposite direction, etc. (Fig. 8). The acceleration process in the linotron is a resonant mode with variable multiplicity, analogous in principle; to the mode used in the microtron [15]. Assume, for example, that we have a standing-wave linear accelerator for an energy $E_l = 1$ GeV and we wish to obtain $E_m = 3$ GeV, i.e., triple the electron energy. In this case we must add two ring magnets with respective radii $R_1 \approx 3$ m and $R_2 \approx 6$ m, assuming for the magnetic field intensity the moderate value H = 10 kOe. These magnets are relatively small compared with the linear accelerator itself, the length of which is ~200 m.

We note that it is also possible to effect the linotron mode of multiple acceleration in a traveling-wave linear accelerator. In this case the particle acceleration can occur with motion in both directions - with alternating propagation of the wave in the forward and backward directions. In principle it is possible to accelerate a particle many times in one direction, too, in the direction of the specified wave propagation, the particle energy remaining practically unchanged during the motion in the opposite direction - opposite to the wave.

In a linotron designed for a specified energy, the

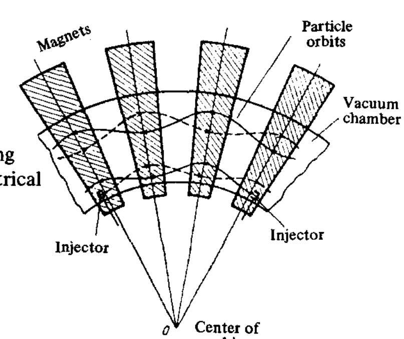

FIG. 9. Diagram showing particle motion in a symmetrical accelerator [26].

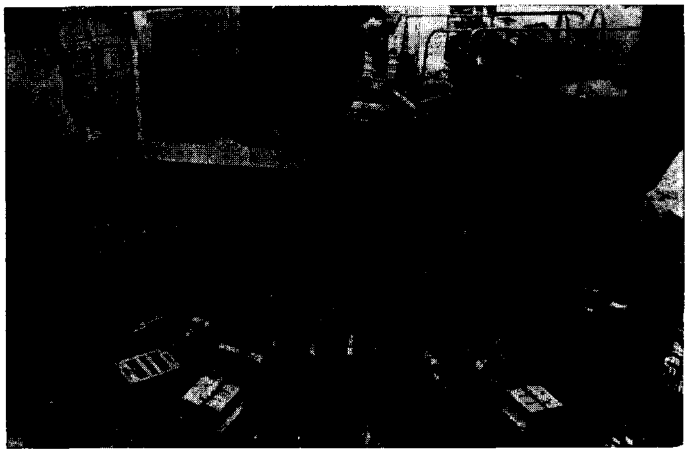

FIG. 10. Over-all view of symmetrical ring synchrocyclotron, FIAN[28]. (The ring magnet, the accelerating resonator, the betatron course, and the pulsed injector supplies).

length and the size of the supply system can be greatly decreased compared with the linear accelerator of the same rating. The linotron retains here the advantage from the point of view of intensity, and also from the point of view of simplicity of injection and extraction of the particles. It is also important that the synchrotron radiation of the electrons does not play as important a role in a linotron as in synchrotrons, since the number of passages through the magnetic field is limited, and the energy gain is large. For the same reason, it is possible to use strong magnetic fields and by the same token decrease the dimensions of the channels.

As a second example, let us consider particle storage rings intended either to realize the colliding-beam method or, in principle, to produce new or better experimental conditions in which the beams are used in the usual manner. Storage rings are usually constructed as separate special installations - in the form of two rings (figure-eight) for electron-electron collisions or a single ring for electron-positron collisions (for a description of such installations, see, e.g.[25]). The particles enter through special injector-accelerators. This path was followed by the laboratories at Stanford, Frascati, Novosibirsk, and Orsay, It must be taken into account, however, that modern storage rings are complicated and expensive installations, no less difficult to construct than large accelerators. This circumstance has stimulated work along a different path, which is followed at FIAN, and consists combining in a single installation the functions of acceleration, storage, and head-on collisions of particles.

A system of this type - symmetrical or bilateral accelerator and storage ring - was first proposed by us approximately ten years ago[26]. This is an annular strong-focusing installation with constant magnetic field, representing a special modification of the so-called ring-type synchrocyclotron[27]. It consists of magnetic blocks with poles of alternating signs, increasing rapidly in absolute magnitude with increasing radius. The ratio of the fields in the neighboring blocks is close to unity, so that two beams of identical particles, revolving in opposite directions, can be simultaneously accelerated, and the beams can be accumulated and made to collide in the same installation (Fig. 9). An accelerator and storage ring of this type was developed, constructed, and started at FIAN for an electron energy up to 30 MeV[28]. With the aid of this installation (Fig. 10), which had a very unique magnetic-field form, it was possible to realize two accelerating modes - inductive (betatron) and resonant (synchrocyclotron), both having large capabilities in the sense of beam intensity compared with ordinary electron betatrons and synchrotrons of the same scale. The idea of aiming beams of identical particles in opposite directions in a single ring with a magnetic field that is modulated in sign (or magnitude) has subsequently gained recognition. In particular, it serves as a basis for the unique storage ring for head-on collisions of protons of 25-GeV energy[29]. This installation is being constructed at CERN (International European Center of Nuclear Research) in Geneva, Switzerland, using as an injector the powerful proton synchrotron now in operation there (Fig. 11).

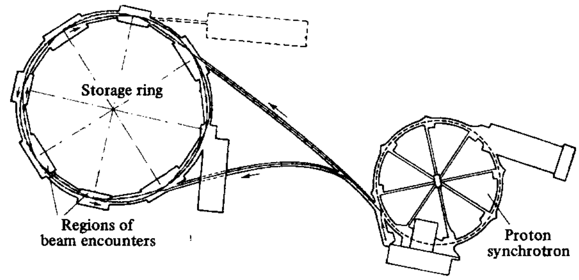

FIG. 11. Plan of the proton storage ring constructed at CERN[29].

Yu. M. Ado of FIAN also proposed a method for accumulating opposing electron-positron beams directly in a synchrotron[30]. Unlike ordinary storage rings, in this case an alternating magnetic field of single polarity is used instead of a constant field. This means that a dc component is superimposed on a sinusoidally varying magnetic field. The particle injection is near the minimum of the magnetic field, and the radiation damping of the betatron and of the synchrotron oscillations occurs essentially in the region of the field maximum. Because of this damping, room is "freed" in phase space for the next batch of injected particles after each acceleration and deceleration cycle. Experiments on the storage of electrons and positrons in a synchrotron were performed with the 280-Mev synchrotron. The results of these experiments confirmed that if certain definite conditions are satisfied (vacuum, injection) the efficiency of such a method of particle storage is quite high.

A design was recently developed at FIAN for electron-positron cascade acceleration and storage, using two storage synchrotrons: a booster (~300 MeV), where preliminary particle storage takes place, and the main synchrotron, where the particle energy is raised to maximum value ~1.2 GeV[31]. Such a system makes it possible to dispense with the expensive linear accelerator and at the same time provides the required rate of accumulation in the colliding-beam mode. A general diagram of the proposed setup and a schedule of its operation are shown in Figs. 12 and 13.

The favorable results of the first experiments have stimulated the development of such a storage method as applied to the high-energy range. This is reflected

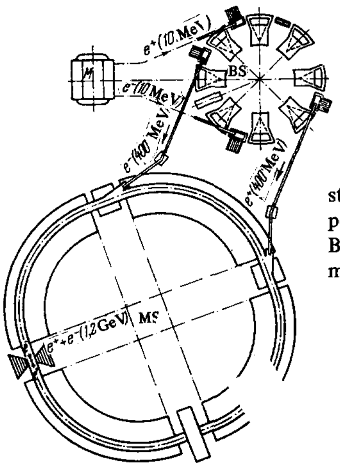

FIG. 12. Cascade acceleration-storage system for electrons and positrons[31]. M – microtron, BS – booster synchrotron, MS – main synchrotron.

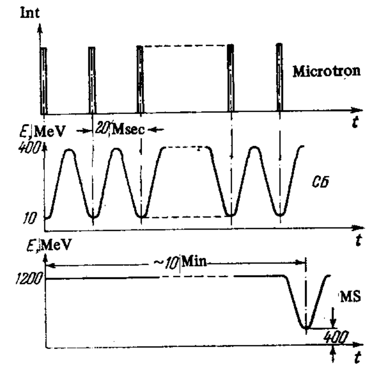

FIG. 13. Time schedule of system of cascade acceleration and storage[31].

in a project wherein it is proposed to realize the electron-positron colliding beam method with the Cambridge (USA) 6-GeV synchrotron using the so-called spare path method[22]. In this method, the storage of particles with energy ~3 GeV occurs in the synchrotron itself, and the collisions occur in a region situated in a supplementary specially equipped magnetic channel with a constant field. After the required intensity is attained, the particles are transferred to a ring consisting of this channel and the remaining larger part of the synchrotron, where the constant magnetic field corresponding to the storage energy is maintained.

Our description of the present status of the development of accelerators would be incomplete if we did not stop to discuss several physical problems connected with the large beam intensity. We note that Veksler did much work aimed at obtaining large accelerator-particle currents, and saw the greatest promise not in accelerators of the synchrotron type, but in accelerators of plasma or plasma-like charged bunches[2,33]. Real progress in this direction, however, has been made so far only in the development and improvement of cyclic and linear accelerators of the usual types.

There was a time when the notion of single-particle motion or motion of a system of non-interacting particles could be used both in theory and in practice of accelerators. Now, however, the space charge of the accelerated or stored beam frequently reaches such large magnitude that allowance for interaction between the particles, and also for the interaction with the surrounding walls, the pole pieces, and the accelerating system becomes obligatory. Different effects connected with space charge and occurring when particles move in accelerating systems have been investigated in a large number of papers, especially recently. Therefore even a brief review of these papers should be the subject of a separate larger article. Here we touch upon this question briefly and mainly from the point of view of those phenomena that become manifest in phase stability (for concreteness we shall consider motion in a synchrotron). The influence of the space charge on the longitudinal (azimuthal) motion of the particles is determined essentially by the form of the dependence of the revolution frequency ω on the energy E, or in first approximation by the derivative $\partial\omega/\partial E$ and especially its sign. The energy at which $\partial\omega/\partial E = 0$ is called critical, E_{cr}. Phase stability vanishes in this case, the phase motion fades out, and the particle becomes strongly influenced by the action of different disturbances. Below E_{cr}, i.e., when $E < E_{cr}$, the quantity $\partial\omega/\partial E$ is positive. Above E_{cr} we have $\partial\omega/\partial E < 0$. There exist synchrotrons in which $\partial\omega/\partial E > 0$ all the time (the 7-GeV proton synchrotron of the Institute of Theoretical and Experimental Physics), and also those in which, to the contrary, $\partial\omega/\partial E < 0$ all the time (the JINR 10-GeV proton synchrotron, the Erevan 6-GeV electron synchrotron). Finally, there are synchrotrons in which during the course of acceleration first $E < E_{cr}$ and then automatic frequency control causes T to go through $E = E_{cr}$ and then into the region $E > E_{cr}$ (the 28-GeV proton synchrotron at CERN and the 33-GeV proton synchrotron in Brookhaven, USA).

Let us assume that a beam of particles subject to Coulomb interaction revolves in a magnetic field and that this revolution is free, in the absence of an alternating accelerating field. The longitudinal (azimuthal) stability of such a beam was considered by A. N. Lebedev and the author in 1959[34], who observed a phenomenon called the negative-mass effect. This phenomenon consists in the fact that if $\partial\omega/\partial E < 0$, i.e., $E > E_{cr}$, and the energy scatter (meaning also the radial scatter) in the beam is sufficiently small, then the azimuthal distribution of the beam turns out to be unstable. This can be qualitatively explained in the following manner. Positive density fluctuation at a given point gives rise to the appearance of azimuthally directed forces which repel the neighboring particles. As a result, the energy of the particle moving ahead of the fluctuations increases, leading, owing to the condition $\partial\omega/\partial E < 0$, to a decrease of ω, i.e., to a lag of the particle during its revolution. Thus, the neighboring particles are drawn, as it were, into the region of the fluctuation, causing the latter to increase. It can be stated that the azimuthal motion of particles neighboring on the fluctuation proceeds as if the particles were to have a negative mass. The acceleration is directed opposite to the force. Hence the name the negative-mass effect; this phenomenon can play an important role, in particular, during the injection period. To the contrary, if the opposite condition $\partial\omega/\partial E > 0$ is satisfied, the circulating beam is stable, the resultant fluctuation does not grow, but produces density oscillations - a positive-mass effect, which incidentally takes place also for a charged beam moving in a straight line.

Let us consider now the azimuthal motion of a charged-particle beam in the presence of an alternating accelerating electric field, which produces phase sta-

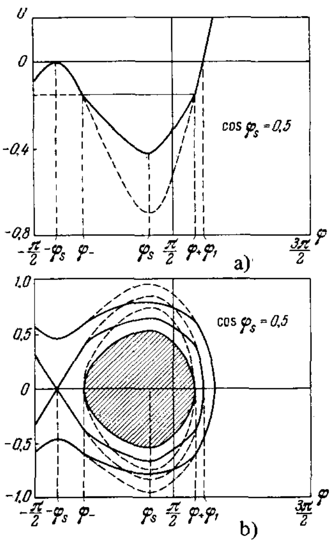

FIG. 14. Influence of space charge on the phase stability in the region $E < E_{cr}$[35]. a) Potential well for azimuthal motion. The dashed lines show the shape of the well without allowance for the space charge. b) Phase-plane pattern. The dashed lines show the phase trajectories without allowance for space charge. The shaded region is the one occupied by the beam.

bility of the particles. Owing to this phase stability, the stable motion of the particles relative to the equilibrium position, occurs within the limits of an azimuthally varying potential well bounded by a special curve - separatrix (on a plane with azimuth and radius as coordinates). When speaking of a single particle, there is no qualitative difference in principle between the action of a phase stability under conditions when $E < E_{cr}$ or to the contrary when $E > E_{cr}$. However, as shown by the theory developed in detail in[35], the situation can change radically in the presence of noticeable space charge. The influence of the space charge is manifest in different manners and in some sense its effect above the critical energy is the opposite of the effect below the critical energy, in analogy with the situation just illustrated for the freely revolving beam.

The foregoing can be illustrated by means of a phase-plane plot under the simplest assumption in which the charge density in the beam is constant.

When $E < E_{cr}$ (Fig. 14) the space charge becomes manifest as follows: a) The potential well becomes flatter within the limits of the plasmoid. b) The phase stability becomes worse, as is evidenced by a contraction of the separatrix, i.e., by a reduction of its radial dimensions, and by a decrease in the synchrotron-oscillation frequency. c) There exists a limiting charge N_{lim} corresponding to complete equalization (degeneracy) of the potential well and vanishing of the separatrix. We note that during the acceleration process, on approaching E_{cr}, strong damping of the phase oscillations takes place in the absence of the space charge. In the presence of space charge, the law governing the damping changes and unless special measures are taken large particle losses can occur. When $E > E_{cr}$ (Fig. 15) the effect of the space charge is quite different: a) The potential well becomes deeper and the result is at first glance paradoxical: the larger the number of the Coulomb-interacting particles in the plasmoid; the more room is freed for them. b) The phase stability improves - the separatrix broadens, i.e., its radial dimensions increase, and the frequency of the synchrotron oscillations decreases.

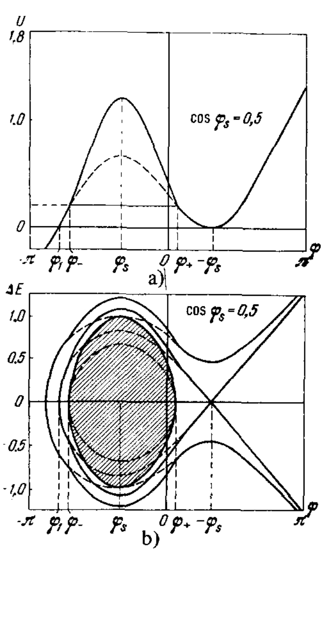

FIG. 15. Influence of space charge on phase stability in the region $E < E_{cr}$[35]. a) Potential well for azimuthal motion. The picture of the well in the vertical direction is inverted, in connection with the fact that the effective mass in the phase equation is in this case negative. b) Phase-plane pattern. The notation is the same as in Fig. 14.

When speaking of longitudinal particle motion there exists, besides the effect considered above, also effects such as longitudinal instability in resistance, existing on both sides of E_{cr} and due to the finite conductivity of the chamber walls, instability due to the interaction between the beam and the resonator, which is particularly important for electron synchrotrons, and other phenomena. Space charge is also important for transverse motion, i.e., for focusing. Its direct influence, and also the influence of the image forces, cause the betatron oscillation frequency to change. The tolerance for this displacement determines the limiting number of particles. The finite conductivity of the chamber walls also leads to a strong transverse instability, both for the case of a solid beam and for the case of individual bunches.

There are also other instabilities, longitudinal and transverse, which become manifest differently in different machines. In storage rings, there are additional specific instabilities connected with the beam-encounter effect. So far, the number of beam instabilities in accelerators is still not as large as in the case of magnetic plasma traps used in thermonuclear research, but their theoretically and experimentally observed number increases persistently. Naturally, method for their stabilization are under development. For example, coherent instabilities due to the resistance have been suppressed in a number of accelerators by applying voltages on special electrodes and using feedback. The instability of the negative-mass type can be suppressed, for example, with the aid of at least partially coating the chanber walls with a dielectric. It can be assumed that with further increase of the accelerator beam intensity, the vacuum chamber, provided with suitable devices, will in general become an increasingly active element of the accelerator, acting on the behavior of the beam to the same degree as the magnet and the accelerating system. It is interesting that at the new contemporary stage, characterized by strong-current accelerators, V. I. Veksler's phase stability, modified in suitable manner, again serves as the basis for the acceleration modes.

As seen from our necessarily insufficiently complete review, the ideas and trends in the accelerator field, founded by V. I. Veksler, turned out to be exceedingly fruitful. They are being successfully developed and continue to exert a strong decisive influence on the progress of accelerator physics and engineering.

[1] V. I. Veksler, Dokl. Akad. Nauk SSSR 43, 346 and 44, 393 (1944).

[2] a) V. I. Veksler, Atomnaya énergiya 2, 427 (1957); b) V. I. Veksler et al., Proceedings, International Conference on Accelerators, Cambridge, 1967.

[3] V. I. Veksler, A. A. Kolmenskiĭ, V. A. Petukhov, and M. S. Rabinovich, Suppl. No. 4 to the journal "Atomnaya énergiya," 1957, p. 5.

[4] M. S. Rabinovich, Trudy, FIAN (Physics Institute, Academy of Sciences) 10, 23 (1958).

[5] Special issue of the journal PTÉ, No. 4 (1962).

[6] V. V. Vladimirskiĭ, E. G. Komar, A. L. Mintz, et al., Proc., Internat. Conf. on Accelerators, Dubna, Atomizdat, 1964, p. 197.

[7] A. A. Kolomenskiĭ, PTÉ, No. 1, 19 (1961).

[8] The 30-MeV FIAN Synchrotron, Trudy, FIAN 19, 98 (1963).

[9] A. Ya. Belyak, V. I. Veksler, V. N. Kanunnikov, P. A. Cerenkov, and B. N. Yabokov. Appendix No. 4 to the journal "Atomnaya énergiya, 1957, p. 57.

[10] Collection of articles: The 680-MeV Synchrotron, Atomizdat, 1962.

[11] B. V. Belousov, V. I. Veksler, I. Ya. Pomeranchuk, and M. E. Rabinovich, Report, FIAN, 1946.

[12] A. A. Kolomenskiĭ and A. N. Lebedev, Teoriya tsiklicheskikh uskoritelei (Theory of Cyclic Accelerators), Fizmatgiz, 1962, Ch. V.

[13] A. A. Kolomenskiĭ, Trudy FIAN 13, 3 (1960).

[14] A. A. Sokolov and I. M. Ternov, Zh. Eksp. Teor. Fiz. 28, 431 (1955) [Sov. Phys.-JETP 1, 227 (1955)].

[15] A. A. Kolomenskiĭ, Zh. Tekh. Fiz. 30, 1347 (1960) [Sov. Phys.-Tech. Phys. 5, 1278 (1961)].

[16] S. P. Kapitza, V. P. Bykov, and V. N. Melekhin, Zh. Eksp. Teor. Fiz. 41, 368 (1961) [Sov. Phys.-JETP 14, 266 (1962)].

[17] K. A. Belovintsev, Dissertation (FIAN, 1964).

[18] B. H. Week, H. A. Schwettman, and F. B. Wilson, Proceedings, XV-th Internat. Conf. on Accelerators, Frascati, 1965, p. 686.

[19] C. S. Robinson, Superconducting Microtron, Univ. of Illinois Report, January 1967.

[20] A. A. Kolomenskiĭ, Proceedings, Internat, Conf. on Electromagnetic Interactions at Low and Medium Energies, Dubna, 1967, p. 3.

[21] É. L. Burshteĭn, V. I. Veksler, and A. A. Kolomenskiĭ, in: Nekotorye voprosy teorii tsiklicheskikh uskoriteleĭ (Certain Problems in the Theory of Cyclic Accelerators), Moscow, AN SSSR, 1955, p. 3.

[22] A. A. Kolomenskiĭ and A. N. Lebedev, Proceedings, Internat. Conf. on Accelerators, CERN, Geneva, 1959, p. 184.

[23] a) R. Keller, see [22], p. 636; b) M. Barbier, see [22], p. 636.

[24] A. A. Kolomenskiĭ, ZhETF Pis. Red. 5, 204 (1967) [JETP Lett. 5, 164 (1967)]; see also [2b].

[25] A. I. Alikhanyan, S. K. Esin, and S. A. Kheifets, Usp. Fiz. Nauk 81, 7 (1963) [Sov. Phys.-Usp. 6, 614 (1964)]; G. I. Budker, ibid. 89, 533 (1966) [9, 534 (1967)]; see also [2b].

[26] A. A. Kolomenskiĭ, Zh. Eksp. Teor. Fiz. 33, 298 (1957) [Sov. Phys.-JETP 6, 231 (1958)].

[27] A. A. Kolomenskiĭ, V. A. Petukhov, and M. S. Rabinovich, see [21], p. 7; PTÉ No. 2, 26 (1956).

[28] A. A. Kolomenskiĭ, L. N. Kazanskiĭ, V. N. Kanunnikov, E. P. Ovchinnikova, V. A. Papadichev, S. S. Semenov, A. P. Fateev, and B. N. Yablokov, Atomnaya énergiya 20, 513 and 21, 166 (1966).

[29] K. Johnsen, W. C. Middelkoop, B. de Raad, L. Resegotti, A. Schoch, K. R. Symon, and C. J. Zilverschoon, Proceed. Internat. Conf. on Accelerators, 1963, Dubna, Atomizdat, 1964, p. 312.

[30] Yu. M. Ado, Atomnaya énergiya 12, 54 (1962); Yu. M. Ado, K. A. Belovintsev, A. Ya. Belyak, E. G. Bessonov, O. B. Dem'yanovskiĭ, V. A. Skorik, P. A. Cerenkov, and V. S. Shirchenko, ibid. p. 355.

[31] K. A. Belovintsev, A. Ya. Belyak, E. G. Bessonov, A. A. Kolomenskiĭ, A. N. Lebedev, A. P. Fateev, and P. A. Cerenkov, Cascade Storage System, FIAN Preprint No. 45, 1967; see also [2b].

[32] M. S. Lvingston, Cambridge Electron Accelerator, CEAL-1028, 1966.

[33] V. I. Veksler and V. N. Tsytovich, Proceed. Second Internat. Conf. on Accelerators, CERN, Geneva, 1959, p. 160.

[34] A. A. Kolomenskiĭ and A. N. Lebedev, Atomnaya énergiya 7, 549 (1959); see [33], p. 115.

[35] A. N. Lebedev and E. A. Zhil'kov, Nucl. Instr. 45, 238 (1966).

Translated by J. G. Adashko