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*ACCELERATORS WITH COLLIDING PARTICLE BEAMS**

G. I. BUDKER

Institute of Nuclear Physics, Siberian Division, Academy of Sciences, U.S.S.R.

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CHARGED-PARTICLE accelerators are the microscopes of modern physics. Just as with an ordinary microscope, we can evaluate the structure of the observed object from the picture produced when a stream of particles is scattered by it—light quanta in an optical microscope, and high-energy particles in an accelerator. In this sense the electron microscope is also an accelerator.

The theoretical resolution limit of any microscope is, as is well known, the wavelength of the light or the de Broglie wavelength of the employed particle stream. The higher the particle energy, the shorter the wavelength. By using particles of extremely small wavelength, Rutherford discovered the structure of the atom and observed the finite dimension of its nucleus. To study the electromagnetic structure of the proton and neutron, Hofstadter used a beam of electrons of energy up to 1 GeV.

The main objects investigated in contemporary high-energy physics are elementary particles. The accelerators are used not only to investigate their structure, but also to generate these particles. The number of known particles increases each year with increasing growth of the ultimate accelerator energy. The end purpose of this research is to develop a theory of nuclear forces and elementary particles. The significance of such a theory for science and practice cannot be overestimated.

A number of physicists hold to the opinion, which I believe to be wrong, that this theory can be constructed by reasoning, from some general principles. Physical experience shows that this happens very seldom. Thus, quantum mechanics and atomic theory could be developed only from Rutherford's experiments, a thorough study of the hydrogen spectrum, and the availability of Mendeleev's table. There are many logically noncontradictory theories, but only one truth. Relativistic gravitation theory—general relativity—is the very rare exception confirming this rule. The presently available experimental factual material is apparently insufficient for the creation of a theory of elementary particles, and experiments are needed at energies exceeding the present-day capabilities.

The particle energies obtainable with accelerators has been increasing during the past decades in a geometric progression, from tens of MeV with the first postwar cyclotrons to 30 GeV at CERN and Brookhaven, 70 GeV with the accelerator under construction in Serpukhov, and 1000 GeV with the accelerators now planned. But this splendid trend has encountered two major difficulties.

The first is technical and economic, connected with the fact that modern accelerators have attained tremendous sizes, and the cost of the largest of them is appreciable even for the budget of a large country. Thus, the cost of the 1000-GeV accelerator now under construction in the USA, with an orbit length of about 20 km, is almost one billion bollars.

The second difficulty, which aggravates the first, is of fundamental character. When the energy of the incident particle exceeds the rest energy of the investigated one, then the greater part of the energy is lost to moving the common center of mass of the two particles, and only a small fraction goes to their relative motion. But it is precisely this fraction which determines the ultimate masses of the created new particles and the possibility of investigating their structure. All the processes occur in the c.m.s.; the motion of the system as a whole, naturally, does not enter into the picture.

The desire to avoid such an excessive (from the point of view of both energy and money) transition from the laboratory frame to the c.m.s., brings automatically to mind the idea of combining the two frames, by directing the particles with equal momenta towards each other. Even in the nonrelativistic case, the collision energy is increased fourfold if the two particles are identical. For relativistic particles the effect increases sharply, yielding in the limit the relation

$$E_{\mathrm{lab}}=\frac{2E^2}{mc^2},$$

where E_{lab} and E are the particle energy in the lab and c.m.s., and mc^2 is its rest energy.

In Fig. 1 the ordinates and abscissas correspond to the particle energies in colliding-beam installations and in accelerators with stationary targets, at the same collision energy. The collision effect becomes noticeable first for light particles. Thus, for the study of electron-electron scattering, which we carried out with the VÉP installation (radius 43 cm, maximum electron energy 130 MeV), the required stationary-target accelerator would have to produce 70-GeV electrons. It is impossible in practice to construct a 2000-GeV accelerator with which to perform *the*

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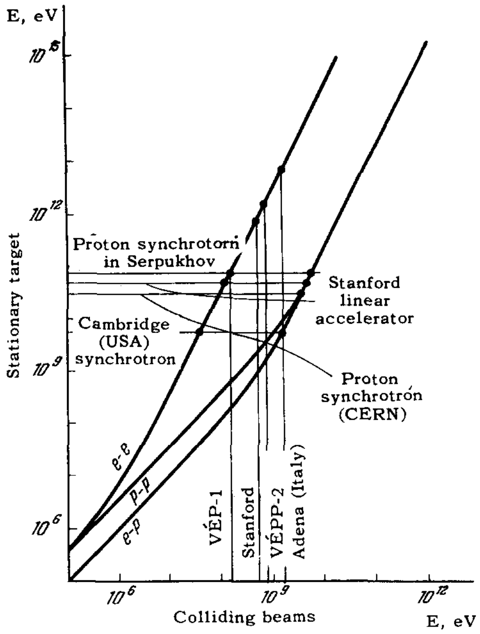

FIG. 1. Relation between the particle energies in installations with colliding beams and in accelerators with stationary targets, for equal collision energy.

electron-positron interaction experiments now being organized in Novosibirsk with the 1.5-meter VÉPP-2 colliding-beam apparatus.

The idea of colliding beams is not new, and is a trivial consequence of general relativity. Insofar as I know, the first to advance it was Academician Zel'dovich, albeit in a very pessimistic tone. The pessimism is perfectly understandable. In this case the target is a second beam, whose density is smaller by 17 orders of magnitude than the density of the condensed medium used in the target of an ordinary accelerator. However, this tremendous number can be greatly decreased by allowing the beams to pass one through the other a large number of times. Recognizing that in ordinary accelerators there are limitations on the target thickness, and taking measures aimed at increasing the beam current and decreasing their transverse dimensions (both parameters give a quadratic effect), we can hope to obtain with colliding-beam installations counting rates that are comparable with those obtained with usual accelerators. Experience shows this to be an attainable goal.

Before we describe our installations, I wish to dwell more on the relation between colliding-beam installations and accelerators with stationary targets, in order to avoid doubts and misunderstandings. For studies of interactions between stable particles and of the creation of new particles, the colliding-beam installations have an absolute advantage over stationary-target accelerators. In addition to the main advantage—high interaction energy, beyond that attainable with ordinary accelerators—colliding-beam installations have also the advantage that the experimenter works in the c.m.s., which theoreticians have been using for many years and in which the reaction products are scattered through large angles and are easily identified. In a stationary-target accelerator for highly relativistic particles, all the secondary particles move forward together with the c.m.s. in a very narrow angle and are difficult to distinguish, owing to the high energy.

This shortcoming of the stationary-target accelerator is simultaneously its main advantage for another group of experiments. When the secondary particles move with the c.m.s. in a narrow angle, they acquire a high energy, comparable with that of the incoming particles. Thus, a stationary-target accelerator is a generator of beams of high-energy secondary particles. There is a sufficiently large group of investigations for which such beams are necessary.

At the present time stationary-target accelerators have one more major advantage over colliding-beam installations: they are common and we are used to them. Historically developed traditions, operating experiments, ready-made laboratories, and well developed apparatus undoubtedly make this research method preferable. I believe, however, that this advantage is not so large as to justify the almost hundredfold ratio of expenditures on the construction of new stationary-target accelerators and installations with colliding beams, which prevails in the whole world and particularly here in the Soviet Union. To be sure, most recent reports indicate that in the nearest future this ratio will take a turn for the better.

When choosing a research trend, each country, institute, or laboratory should start from the available material means, equipment, and operating experience. At the time of its founding, our institute was not burdened with either money, old equipment, or traditions. We therefore chose colliding beams.

Work on colliding electron beams was started at the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Science (then the Laboratory for New Acceleration Methods of the Kurchatov Atomic Energy Institute) at the end of 1956, after the Geneva conference, where the feasibility of the colliding-beam idea was first discussed. At that time we already had experience with obtaining large electron currents with apparatus of the betatron type. To accumulate large currents in the developing colliding-beam installations, we chose the method of multiple external injection, which is made possible by the presence of synchrotron-radiation damping.

The first colliding-beam installations were single-purpose devices. They were intended to check the limits of applicability of quantum electrodynamics at small distances by studying the angular distribution of elastic (Møller) scattering of electrons by electrons. As is well known, in quantum electrodynamics the electron is regarded as a point. However, not all methods of quantum electrodynamics are completely correct, something always considered as evidence that the theory is not fully consistent. This inconsistency could be eliminated by introducing some minimal length. At that time, it was tempting, as is even now, to ascribe this length to the structure of space and time. This could serve as a basis of creating not only a correct theory of quantum electrodynamics, but also a theory of elementary particles. The available experimental data suggest for this characteristic length a value in the region of 10^{-14} cm (the corresponding time interval is 3×10^{-25} sec). At a measurement accuracy of 10%, this calls for the study of particle scattering with a momentum transfer on the order of 1 GeV.

When planning the colliding beam installations, however, we aimed at a much wider scope than this experiment alone. Our main purpose was to develop and realize a colliding-beam method which could be used in the future for a broader class of particles and experiments.

The initial proposal was to construct two installations, VÉP-1 with energy 2 × 130 MeV and VÉP-2 with energy 2 × 500 MeV. The VÉP-1 installation was regarded as an operating mock-up for the colliding-beam accelerator and was intended for adjustment of apparatus and performance of the first experiments at low energies. The VÉP-2 was to be used to check the applicability of quantum electrodynamics at small distances.

After Professor Panofsky reported in 1958 similar work aimed at checking quantum electrodynamics with colliding beams, carried out in his laboratory at Stanford in collaboration with Princeton University, we abandoned the construction of the 500-MeV storage tracks and continued working on the VÉP-1 only. Unlike Stanford, we had to build not only the storage rings, but also the accelerator. In addition, we were faced with the move to Novosibirsk, which, in spite of most favorable conditions, could not fail to delay the work.

We decided to construct, in lieu of VÉP-2, the VÉPP-2 installation with colliding electron-positron beams and with maximum energy 2 × 700 MeV. Its construction was a much more complicated problem, since 100,000 electrons are needed to obtain a single positron; on the other hand, this installation offered many more experimental capabilities. In addition to checking quantum electrodynamics, which can be done by studying elastic scattering and annihilation into two γ quanta, the installation can be used to observe the creation of pairs of μ, π, and K mesons and to study their interaction with their own antiparticles. It was proposed to investigate in the first experiments processes in which there are two particles in the initial and final states. This does not exhaust the possibilities afforded by the VÉPP-2 installation. The availability of spark chambers has greatly extended the range of possible experiments by eliminating the condition that two particles exist in the final state.

In 1960 the Italian scientists at Frascati reported initial work with electron-positron colliding beams, following approximately the same program, which they carried out subsequently in collaboration with a group of French physicists at Orsay.

We delivered our own papers on colliding beams in 1963 at the international conference in Dubna, when a beam was already accumulated in the VÉP-1 installation, and the VÉPP-2 installation was erected. By that time a beam was also working at Stanford and in the experimental ''Ada'' installation of the Italian-French group.

During the last three years all three groups carried out experiments on instabilities and other processes observed after a prolonged existence of large electron currents. These investigations were made in very close collaboration. It suffices to say that during that time, besides two large international conferences on high-energy accelerators, several smaller conferences devoted exclusively to colliding beams were convened, two of them in Novosibirsk.

Splendid experiments on the so-called Ada-effect were made by the Italians. The Americans discovered and investigated the transverse beam instability, while in Siberia they discovered the longitudinal instability connected with the interaction between the beam and the resonator.

The most harmful and dangerous was the instability connected with the so-called beam-beam interaction. When beam met beam, the stronger mutilated and eventually destroyed the weaker one. An experimental study of this phenomenon was made here and at Stanford. The young Novosibirsk physicist A. N. Skrinskiĭ explained this phenomenon as being a manifestation of many equilibrium orbits of the particles of the weak beam in the highly nonlinear field of the stronger colliding beam. By understanding the phenomenon, it became possible to find means of combatting it.

In the summer of 1965, the Stanford-Princeton and the Novosibirsk groups reported at the Frascati international conference on the first colliding-beam large-angle electron-electron scattering experiments. From the methodological point of view the results were practically the same—the same electron currents, and approximately the same number of registered scattering events. From the point of view of checking the validity of quantum electrodynamics, the American results are undoubtedly of great interest, since they were made at higher energy.

At the same time, we reported the startup of a positron-electron colliding-beam installation with maximum energy 2 × 700 MeV and the study of beam interaction with this installation.

The Italian-French group was split in two. At present two positron-electron installations are under con-

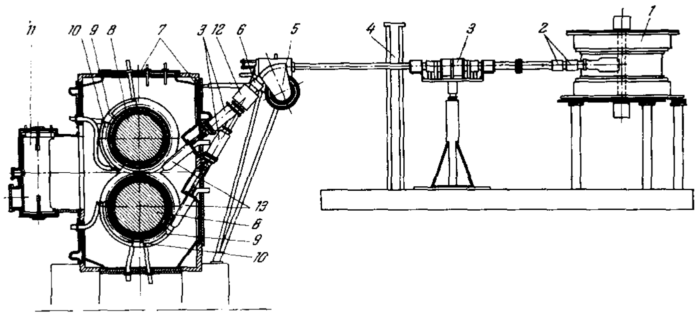

FIG. 2. General arrangement of the VÉP-1 installation. 1 – Injector-synchrotron B-2S, 2 – correcting magnets, 3 – quadrupole lenses, 4 – radiation and magnetic screen, 5 – turning magnet, 6 – correcting coil, 7 – external vacuum chamber, 8 – storage-ring magnets, 9 – resonators, 10 – inflectors, 11 – titanium pump, 12 – switching magnet, 13 – compensating magnets.

struction: at Orsay (France) for 2 × 500 MeV and at Frascati (Italy) for 2 × 1500 MeV. The French installation started operation at the end of 1965; the Italian one is scheduled to start at the end of 1966. Their joint experimental model was dismantled.

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Allow me to proceed to a description of the Siberian installations. Each consists of the following main elements:

1. Cyclic electron accelerator with its own injector.
2. Magnetic storage track.
3. High-vacuum system.
4. High-power high-frequency supply to accelerate the particles in the accelerator and to maintain their energy in the storage ring.
5. Single-turn system for extraction from the accelerator and entrance to the track.
6. Beam focusing and transporting system.
7. Beam observation system.
8. System of counters and spark chambers for the experiments.

We are the only laboratory using cyclic accelerators for the injection of particles into the storage rings; the other laboratories use linear accelerators, which are much more expensive and which at the initial time were practically unobtainable by our laboratory.

The use of cyclic accelerators was made possible by the single-turn extraction system developed by us and the special focusing of the beam. In spite of the fact that they have at Frascati one of the best electron synchrotrons in the world, the lack of such a system has prevented the Italian physicists from using their available synchrotron, and they were forced to buy from the Americans a linear accelerator, thus increasing the cost and delaying the work.

A distinct feature of our cyclic injector-accelerators is that they use no iron and are pulsed; this greatly simplifies the construction and makes them cheaper. Most focusing elements are also pulsed.

Important elements of the installations are the high-power nanosecond pulse generator developed at our laboratory and used in the extraction-injection system. At a power exceeding 100 MW, they deliver a pulse with a front shorter than one-billionth of a second and are synchronized with the same accuracy. This makes it possible to vary the magnetic field on the orbit within less than one revolution and to transfer the beam from one magnet to another with practically no losses.

The general arrangement of the VÉP-1 installation is shown in Fig. 2. A photograph of the storage ring is shown in Fig. 3. The magnetic tracks of the storage ring have a radius of 43 cm. Slots are provided in the common part of the magnet poles, opposite the point of tangency of the orbits, for the extraction of the electrons scattered at the place of beam encounter. The installation is so arranged that the median plane of the storage rings is vertical and one ring is under the other.

The energy of the electrons injected in the storage ring is 43 MeV. The energy limit is 2 × 130 MeV. The injector is a special iron-free B-2S synchrotron with helical electron accumulation. The beam current extracted from the synchrotron in a pulse shorter than 5 nsec is about 300 mA (more than 10^{10} particles). The energy scatter does not exceed 0.2%. The acceleration-pulse repetition frequency is once every 15 sec. The beam transportation system contains a pulsed switching magnet which makes it possible to guide the beam to either of the tracks of the storage ring.

A general view of the VÉPP-2 installation is shown in Fig. 4, and a photograph of the storage ring is shown in Fig. 5. The storage track is a weak-focusing racetrack of 150 cm radius with four identical straight line intervals. Two are used for the injection of the electrons and positrons; the third contains the high-frequency resonator; the interval opposite the resonator

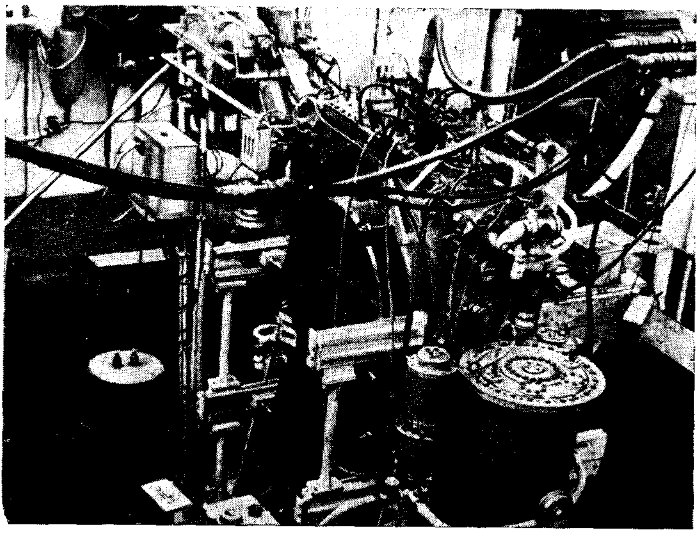

FIG. 3. Storage ring of the VÉP-1 installation (spark chambers removed).

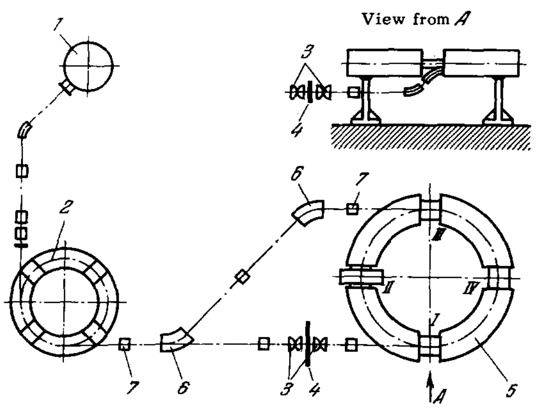

FIG. 4. General arrangement of the VÉPP-2 installation. 1 – Injector, 2 – B-3M synchrotron, 3 – parabolic lenses, 4 – converter, 5 – storage track, 6 – turning magnets, 7 – quadrupole lenses.

is intended for the experiments. The energy limit is 2 × 700 MeV.

The special B-3M synchrotron, used as the injector-accelerator, operates at present at energies up to 200 MeV. The external injector of the synchrotron, called the "amplitude accelerator," produces a beam of electrons with energy about 3 MeV. The current extracted from the synchrotron in a pulse of duration shorter than 20 nsec reaches 300 mA (more than 3×10^{10} particles). The energy spread does not exceed 0.2%. The acceleration pulse repetition frequency reaches 3 cps.

The "preparation" of the positrons occurs in a converter block consisting of a tungsten plate 1 mm thick and two special short-focusing parabolic pulsed lenses, in which a field stronger than 100 kG is developed within several microseconds. The inclusion of this lens block increases the current of accumulated positrons by one order of magnitude.

It should be noted that all our installations were developed and constructed wholly by the staff of our institute.

In addition to the conventional methods of observing the accelerator beams (probes, pickup electrodes, etc. a method was employed for direct visual observation of the beam in the storage tracks, using the light emitted by the beam in the magnetic field. The radiation power amounts to several kilowatts, and the spectrum is continuous and has a maximum that depends on the particle energy, which can be readily shifted from the infrared to the ultraviolet region. The light is concentrated in a narrow angle and is directed tangentially to the beam. During the time of operation, the form of the beam is observed with a televisor and can be readily photographed. By deflecting the beam away from the circle with the aid of a special electron-optical converter synchronized with the revolution frequency, we can view it stroboscopically, as it were, in a direction perpendicular to the plane of the orbit, and we can see the position and distribution of the intensity in azimuth. It would be extremely difficult to adjust the beam encounter, with allowance for the beam interaction, without a continuous visual display of the transverse and longitudinal distributions of the particles in the beams.

I wish to stop and discuss one beautiful phenomenon used by us to measure the beam current. The point is that the amount of light from one revolving electron or positron is enough to be seen with the unaided eye, and all the more with an instrument. After the beam is stored, its intensity decreases gradually as a result of the particle scattering by the gas. At low beam intensity, the light is decreased in strictly equal batches, each corresponding to the loss of one particle (Fig. 6). By counting the number of steps, we can calibrate our instrument as if we were to count the number of electrons. When only one step is left, we are certain that the track contains a single electron, which can be seen, as already mentioned, with the unaided eye. If the vacuum is good, the lifetime of the particles in the track is several dozen hours, and you can, when you get to work in the morning, see the same electron or positron that you left the preceding evening.

At full intensity, not only the electron beam, but also the positron beam produces bright glow that hurts the eyes. We have already said that this light not only serves to show the beam, but is also the basis of the method of multiple accumulation, since it is this light which ensures attenuation of the transverse and longitudinal oscillations. The motion picture photograph of Fig. 7 shows the decrease of the transverse dimensions of the beam after it is captured in the track.

The photograph of Fig. 8 shows the suppression of a weak positron beam by a strong electron beam (the light from the latter goes in the opposite direction and is not seen in the photograph) and the results of combatting this suppression in the VÉPP-2 installation. In

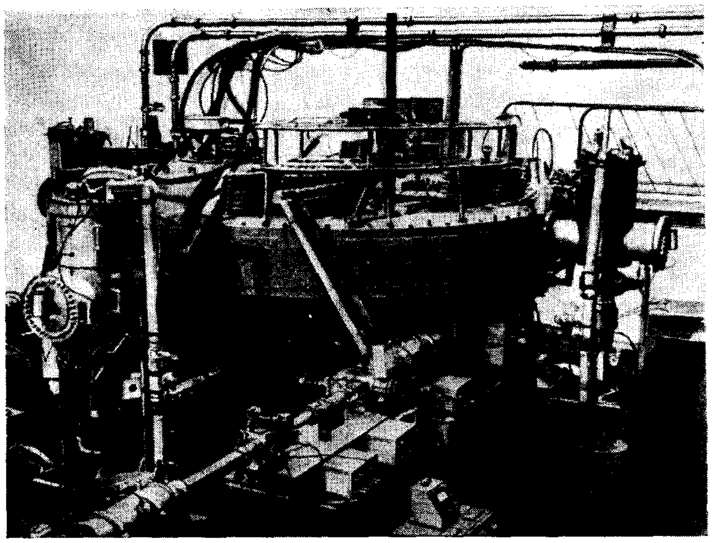

FIG. 5. Storage ring of VÉPP-2 installation.

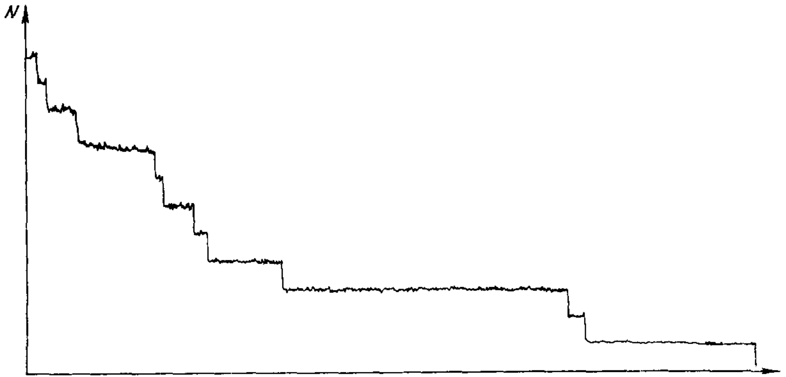

FIG. 6. Curve showing decrease of intensity of synchrotron radiation of an electron beam.

this case the experimenter, who is made of ordinary matter, must render aid to antimatter particles (positrons) against their closest relatives, matter particles (electrons).

We were able to accumulate electron currents up to 0.5 A in both installations. This exceeds by one order of magnitude the current allowed by the instability arising when the beams collide. The work is carried out in practice at currents of about 50 mA. The velocity of light in the VÉP installation is such that the time of the experiment is already determined by the rate of processing of the results. Unfortunately, the rate of development of appropriate techniques for this purpose in our laboratory leaves something to be desired.

In the middle of last year we accumulated 0.4 mA of positron current. This is already enough for the first experiments. However, to increase the counting rate we have deemed it advisable to carry out some additional work aimed at increasing the positron current, and we hope to raise it soon to 3 mA. At this current the productivity of our first experiments will apparently also be governed by the rate of processing of the results.

We are preparing a positron injector in the synchrotron. At the end of this year, after carrying out the first series of experiments, we propose to transfer the B-3M synchrotron to the positron mode, thus obtaining in the storage ring positron currents equal to the electron currents.

The final adjustment of the apparatus and control over the collision efficiency will be effected by registering the small-angle electron-electron scattering. The large cross section of this process makes it possible to find, without appreciable loss of time, the optimal operating conditions by varying numerous parameters of the installation. A system of scintillation counters registers electron pairs experiencing scattering through ~ 1.5°. The number of counts produced by this system in the VÉP-1 installation reached 30 per second. Figure 9 shows the results of measurements with the aid of this system of the value of the "collision efficiency" as a function of the displacement of the beams in the radial (Fig. 9a) and axial (Fig. 9b) directions, and also on the phase separation of the bunches (Fig. 9c); the form of the curves agrees well with data on the bunch dimensions.

A measure of the efficiency of the encounter process is the number of counts produced by the described system of counters, normalized to the integral of the products of the currents of the two beams over the measurement time. A convenient unit for the measurement of this integral is the coulam (short for coulomb-ampere). The installation can yield up to 10 coulams in one hour of operation. The luminosity, defined as the observed counting rate divided by the effective cross section of the process, is on the order of 10^{27} cm^{-2} sec^{-1}. At a process cross section ~ 10^{-29} cm^2 this yields 10^3 counts per day.

Figure 10 shows the arrangement of the experiment aimed at measurement the angular distribution of electron-electron scattering in the angle range 45–135°. The recording system consists of four cylindrical spark chambers whose vertical axes pass through the location of the beam encounter. The lens of the camera lies on the same axis; the employed prism system has axial symmetry. The second coordinate of the track is measured with the aid of inclined mirrors mounted under

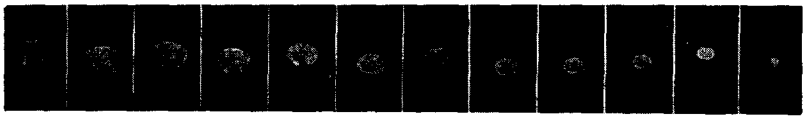

FIG. 7. Damping of transverse oscillations of an electron beam in a storage ring after injection.

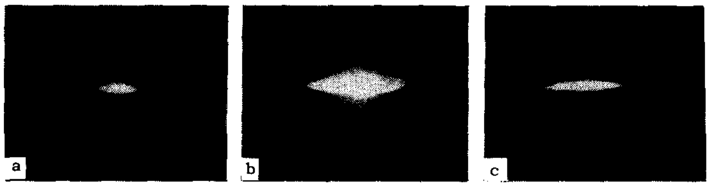

FIG. 8. Transverse cross section of the positron beam in the absence of an electron beam (a), in the presence of an electron current of 20 mA (b), and the same with suppression of the collision effects (c).

the spark chambers. The spark chambers are triggered by a coincidence circuit connected between two groups of five scintillation counters each.

In the first experiments, performed with 43-MeV electrons, the system of spark chambers operated more than 200 times per coulam; approximately 10 photographs corresponded to registration of the electron-electron scattering, and this does not disagree with our notions concerning the luminosity of the installation. Control measurements in which the electron bunches were separated in phase and in the axial direction have shown that the background does not exceed 20%.

The result of prior processing of the obtained photographs is shown in Fig. 11. We see that the deviation from the calculated curve of Mǿller electron-electron scattering does not exceed the statistical error. At the present time experiments are under way with 135-MeV electrons.

To adjust the encounter of the beams in the VÉPP-2 storage ring, and to measure and monitor the luminosity during the operation, use is made of a system for the measurement of small-angle positron-electron scattering, similar to that used with the VÉP-1 installation.

A system of spark chambers, subtending a solid angle 2 × 0.7 sr near the vertical direction, has been prepared for experiments on the interaction between positrons and electrons. The arrangement of the chambers is shown in Fig. 12. Scattered particles first strike thin-plate spark chambers used to determine the particle-emission angles and the coordinates of the point of interaction. The magnetic field directed along the line of beam encounter makes it possible to determine the sign of the charge of the registered particles. The particle species is identified by the character of the interaction with the material of plates of "cascade" and "range" spark chambers. A rather complicated system of mirrors makes possible the use of a single camera.

The entire system of spark chambers is triggered by four 40 × 40 cm spark chambers connected for coincidence. For protection against cosmic radiation, an anticoincidence counter measuring 120 × 120 cm is used. A layer of lead 20 cm thick is placed between these counters and the chambers. We propose to carry out this year three experiments with the VÉPP installation. They will be connected with elastic scattering of electrons, annihilation with pion pair production, and annihilation with production of a pair of K mesons. Owing to the small cross section of muon pair production, and because γ quanta are more difficult to observe

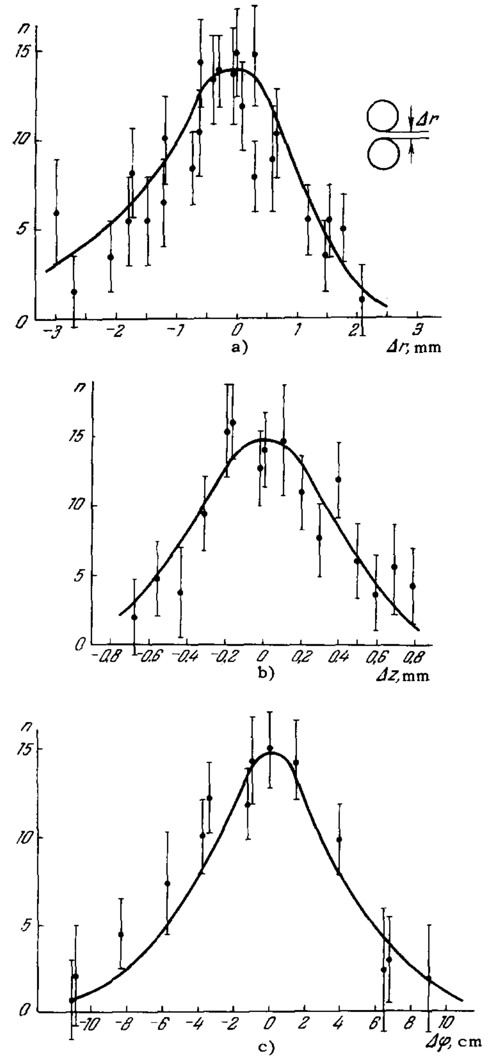

FIG. 9. Dependence of the collission efficiency on the separation of the beams in radial (a) and axial (b) directions, and also on the phase separation of the bunches. The ordinates show the bunber of counts per millicoulam. The measurements were made at currents on the order of 15 mA in each beam; solid lines – calculated curves; normalization is to the maximum count.

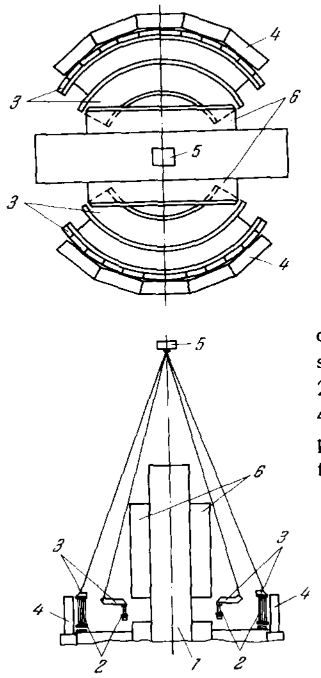

FIG. 10. Arrangement of the recording system on the VÉP-1 installation. 1 – Vacuum chamber, 2 – spark chambers, 3 – prisms, 4 – scintillation counters, 5 – photographic camera, 6 – upper-track magnet.

than charged particles, no measurements pertaining to the latter two processes are planned for the time being.

From the cross-section curves, in which only pointlike electromagnetic interaction is taken into account, it follows that the cross section for pion production, and especially K-meson production, is much smaller than the muon-production cross section. However, while we were working on the construction of VÉPP-2, two new mesons, ρ and φ, were discovered. At summary electron and positron energies 2 × 380 MeV and 2 × 510 MeV, the particles annihilate to form ρ and φ mesons, which decay instantaneously into two pions or K mesons. Two resonant peaks appear on the production curves. The φ-meson resonance on the K-meson production curve is especially sharp and high. It increases the K-meson production cross section by five orders of magnitude. The width of this resonance is very low, about 3 MeV, but the energy spread in our beams is even smaller. At the maxima of the ρ- and φ-meson resonances the π- and K-meson production cross sections become larger than the cross section for large-angle elastic electron-positron scattering.

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Thus, colliding-beam experiments in high-energy physics have already been started. The main result of the many years' labor by the Siberian physicists and our foreign colleagues is not the obtained concrete electron-electron scattering curves. The emphasis is on the accelerator results. This research has dispelled the concealed and sometimes open lack of faith and skepticism with respect to the colliding-beam method, the use of which uncovers a new region of energy in elementary-particle physics.

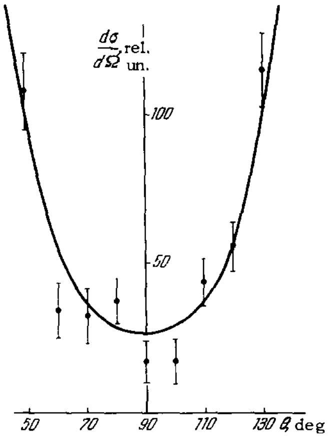

FIG. 11. Angular distribution of electron-electron scattering; the curve shows the calculated Møller cross section.

Whereas at present modern technical and experimental capabilities are limited to 1000 GeV accelerators, which amounts to not little more than 2 × 20 GeV in the c.m.s., the application of the colliding-beam principle would make it possible, at the same cost, to effect a collision with energy 2 × 1000 GeV, which in terms of stationary-target accelerators amounts to 2×10^{15} eV. Both theoretical and experimental physicists should prepare now for the mastery of this new field.

In fact, this preparation has already begun. In Stanford, Novosibirsk, Cambridge, Khar'kov, Hamburg, and elsewhere, electron-positron storage rings for energies up to 2 × 5 GeV are already being designed. At the same time, a radical advance was made in the design of colliding-beam installations for heavy particles. Eighty million dollars have been earmarked at CERN for the construction of colliding proton-proton beams

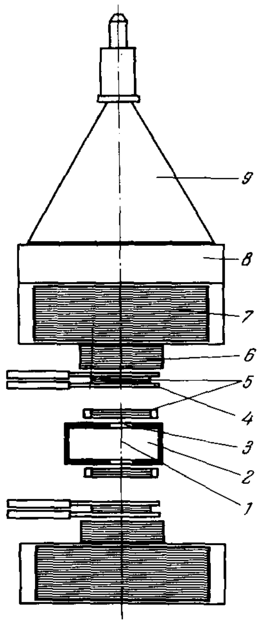

FIG. 12. Vertical section through the encounter region and the recording system of the VÉPP-2 installation. 1 – Colliding beams, 2 – vacuum chamber, 3 – "window," 4 – scintillation counter, 5 – "thin" spark chambers, 6 – cascade chamber, 7 – range chamber, 8 – lead shield, 9 – scintillation chamber.

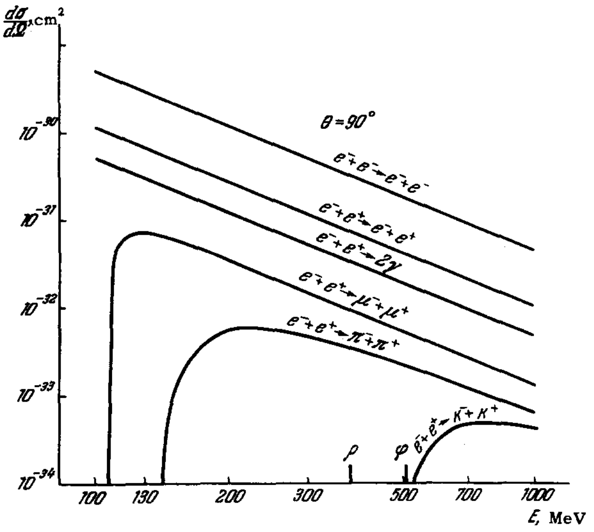

FIG. 13. Energy dependence of the cross sections of Møller scattering and of two particle processes occurring during the interaction of positrons with electrons.

for 2 × 30 GeV energy, corresponding to a stationary-target accelerator rated 2000 GeV.

Work is going on at our institute towards construction of installations for colliding proton-antiproton beams. We hope to obtain a large circulating current of antiprotons by using an effective method, proposed by the author of this paper, for suppressing the transverse ion oscillations in an accelerator with an electron beam. An experimental check on this method is now in preparation, and a whole set of installations with colliding proton-antiproton beams is being developed.

Translated by J. G. Adashko