Accelerator and detector prospects of elementary particle physics

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This review treats the progressive changes in the field of physics and technology of accelerators, and in part, of detectors, which have exerted and will in the near future exert a fundamental influence on the development of elementary-particle physics. In particular, it discusses the possibilities of generation of beams of elementary particles and the prospects of performing experiments with colliding beams involving the development of methods of cooling charged-particle beams, designing superconducting systems, and developing superlinacs.

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INTRODUCTION

The development of accelerator physics and technology is a very important condition for the development of nuclear physics and elementary-particle physics. In this article, whose content corresponds to a considerable extent[1)] to a paper read at the 20th International Conference on High-Energy Physics,[1] I shall try to treat briefly the advances in the accelerator, and in part the detector fields, that have (as I see it) facilitated the progress of elementary-particle physics in recent years and will do so in the near future.

In preparation I shall make just two remarks, which are common today both to the accelerator and detector fields.

To solve all the complicated problems of elementary-particle physics compels one to proceed to ever larger scales of all the systems, both accelerators and detectors. This transition has been made possible, in particular, by the widespread use of the modular principle of all the systems with a maximal uniformity of the modules. This enables one substantially to reduce the cost of the system and improve its reliability.

The deep and many-sided employment of the briskly developing electronics, and especially computer technology, is of just as great importance. In modern high-energy-physics systems, computer systems have become just as widespread and necessary as magnets or counters. They perform the functions of complete and continuous information collection from apparatus and processes occurring in them, of system control, and data processing.

Section 1 examines the general problems involved in the most important physical and technological developments in the accelerator field: development and widespread application of the colliding-beam method, development of methods of cooling charged-particle beams, preparation for serious application of superconducting systems, and the beginning development of superlinacs.

Section 2 treats very briefly the most essential progressive changes occurring in the field of systems for detecting the end products of reactions under study and for processing the experimental data.

Section 3 is devoted to evaluating the current possibilities for generating beams of all high-energy particles, both primary accelerated particles and secondary particles, and tries to evaluate the longer-range prospects in this field. Especial attention is paid to obtaining high-quality beams-pure, as intense as possible, with as small an emittance as possible, and polarized as needed.

Section 4 treats the prospects of designing systems of colliding beams with as broad as possible a selection of particles, including polarized particles and those as monochromatic as possible. The possibility is stressed of obtaining a sufficient luminosity with the participation also of unstable particles.

Sections 5 and 6 are especially concrete in character and involve a field that has been developing for the past

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[1)] Sections 1 to 4 inclusive overlap with Ref. 1. Sections 5 and 6 are new. (Ed. note).

10 years in the Institute of Nuclear Physics of the Siberian Division of the Academy of Sciences of the USSR (Novosibirsk)—the development of superlinacs, which was begun on the initiative of A. M. Budker.

Section 5 describes the so-called proton klystron, which enables one to employ contemporary and future proton accelerators at extremely high energies to generate pure, intense beams of particles for which no other ways of production have yet been apparent. The aim of this section is to "jog" the major proton centers into developing concrete projects in this field.

Finally, Sec. 6 describes the project developed in the Institute of Nuclear Physics of a system with linear colliding electron-positron beams (VLÉPP). If realized on a full scale, it will enable one to obtain an energy of electron-positron interaction up to 1 TeV.

I note that the inclusion in the article of the last two sections of special character has led to a greater representation in the reference list of studies from the Institute of Nuclear Physics of the Siberian Division of the Academy of Sciences of the USSR.

1. PROGRESS IN THE PHYSICS AND TECHNOLOGY OF ACCELERATORS

a) The major event in the area under consideration is the exploration of the colliding-beam method. Colliding-beam experiments starting with electron-electron beams in Stanford and Novosibirsk, electron-positron in Novosibirsk, Orsay and Frascati and proton-proton at CERN have become one of the main sources of fundamental information in elementary particle physics, and their significance will only increase in future. (The results of development in this field and its prospects are treated, in particular, in Ref. 2.)

b) It is well-known how important for implementation of electron-positron colliding beams was the existence of *radiation cooling* for light particles, even at low energies. Radiation cooling has enabled one to stack intense positron beams, to compress transverse dimensions of e^+e^- colliding beams down to small sizes (to a few microns already) and to maintain the beams compressed despite strong perturbations of particle motion caused by the field of the counterbeam, that, in turn, permits achieving high luminosity.

Cooling will have the same fundamental importance also for implementation of the proton-antiproton colliding-beam experiments. Cooling of heavy-particle beams became accessible after development of *electron cooling* in Novosibirsk[3,4] and *stochastic cooling* at CERN.[5] These methods complement each other substantially in their possibilities. Stochastic cooling is especially effective for beams of low density with large emittance (i.e. at small 6-dimensional phase density). Electron cooling is most effective particularly for getting low-temperature ("narrow") beams of heavy charged particles (protons, antiprotons, ions). It is not ruled out that cooling with the circulating electron beam will turn out to be useful for suppressing the diffusional beam cross-section growth with time of proton-antiproton colliding beams of high energies. Let me note that at energies $\gtrsim 10$ TeV an important and positive role will be played by radiation cooling for increasing luminosity of proton-antiproton colliding beams. The use of *ionization cooling*[4,5] can open up very interesting possibilities in getting intense muon beams of high energy including implementation of muon colliding beams of sufficiently high luminosity.

Continuous cooling of the particle beam in a storage ring offers an important possibility for carrying out experiments with a superthin internal target[6] wherein diffusional growth of the beam size (because of multiple scattering in the target substance and due to fluctuations of ionization losses) is suppressed by intensive cooling. Thus, fine "spectrometric" experiments become possible with the *ultimate high luminosity* which is only determined by the injector productivity and the cross-section for single-scattered particle loss in the target substance, which are impossible to achieve in the ordinary set-up of experiments. Experiments of this kind—electro-excitation of nuclei—for a few years have been performed on electron storage ring VÉPP-2.[6]

Another application of the superthin target mode of operation is generation of secondary beams with good tagging (of the type of generated particle and its momentum) using registration of accompanying particles. Such a mode gives 100% duty cycle, the relative intensity of the secondary beam is determined by the ratio of the interaction cross-section of the process being used to the total cross-section for loss of circulating particles by collision with the particles of the target, while the beam emittance is determined only by the characteristics of the interaction process used for generation and the dimensions of the primary circulating beam (continuously cooled) in the interaction section. Naturally, there is no attenuation of the flux of secondary particles by absorption in the target.

Similar set up of experiments with continuous cooling is reasonable even under conditions when the target cannot practically be made so dense that the lifetime of a particle in the storage ring would be determined by the collision with target and not by residual gas in the vacuum chamber (another possible restriction on increase of luminosity can be diffuculty of achieving of high enough stored currents). Correspondingly, although the ultimate luminosity is not attained here, it is for higher, than in the single-flight mode with the same target and accelerator, and beam qualities are the best.

Such a situation is characteristic of experiments with the polarized gas-targets which nowadays permit one to have (even for hydrogen or deuterium) up to 10^{12} atom/cm^2 only, which corresponds to an average vacuum in a storage ring better than 10^{-9} Torr. Naturally, the most interesting work with a polarized target is in a storage ring with polarized beams.

Another interesting example of this kind is the target of free neutrons which is especially promising for detailed study of $\bar{p}n$ interaction at low and medium energies.[4]

c) Nowadays we are at the stage when important improvements in accelerator technology are being implemented.

First of all, wide use of superconductivity has started. The use of superconducting magnetic systems, which has been advanced further by the studies at the Fermilab, already permits increasing the maximum guiding field from 20 kG to 45 kG (using Nb, Ti alloys) and correspondingly gaining in energy for proton and antiproton beams (at a given scale of accelerator facility). There is a possibility of reaching 100 kG in the near future (use of Nb, Sn alloys). An important fact is the significant reduction in energy consumption which is especially high in the storage ring case.

I would like to draw attention to the fact that also at small fields up to 20 kG (with ferromagnetic formation of a magnetic field in a storage ring or a slow accelerator) the use of superconducting coils permits construction of extremely miniature magnet systems (design works of the High Energy Laboratory, JINR, Dubna). However, superconducting magnet systems have yet to demonstrate prolonged operation with the intense beams which are planned for most projects; that longevity requires special care, especially when operating in an accelerator regime.

The use of high magnetic guide fields enables one to increase the energy of heavy-particle beams, but this way is ruled out for electrons and positrons because of excessive increase of synchrotron radiation losses. However, the use of superconducting magnetic structures turns out to be efficient for reaching higher luminosity for electron-positron colliding beams at low and average energies[2] and also for producing irradiating structures for various applications of synchrotron radiation.

The use of superconducting resonators in RF accelerating structures will be essential for accelerator progress. Up to now it is not clear whether an increase of accelerating gradient of these systems higher than 5 or 10 MeV/m will be achieved, but, at any rate, such systems will permit increasing noticeably (by a factor of 1.5–2) the energy of cyclic electron-positron storage rings.[7,8]

d) One can achieve a sharp increase in acceleration rate in linear accelerating structures (up to 100 MeV/m and maybe somewhat higher) in a pulsed mode (with normal conductivity of the resonators). Such accelerators could be called superlinacs. We can consider the problem of achieving an appropriate surface strength with respect to high voltage break-down, as well as the problem of developing accelerating structures for relativistic particles with minimum overvoltage, as solved in principle.[9,10] The basis of possible progress in this field is the development of pulsed short-wave generators of a fundamentally new level of pulsed power (of the order of a gigawatt). Two directions in the development of pumping systems seem to be most promising.

One of these directions is connected with the fast progress in the technology of high-power pulsed relativistic electron beams.[9] Already now in solving controlled fusion problems, a pulsed power of electron beams of a few gigawatts is achieved for durations of the order of a microsecond, with transformation of a substantial part of the beam energy into the energy of the RF electromagnetic field. The present day task is to make these generators more efficient, more sensitive in control of amplitude and phase and to develop them for a regime of comparatively high repetition rates.

Another direction[11] is connected with the fact that modern big proton accelerators (not even mentioning future accelerators) have an energy stored in the beam of millions of joules and powers of hundred of gigawatts in a single-turn extraction. The very good properties of high energy proton beams (small energy spread-only tens of MeV at an energy of 500 GeV and a small emittance) permit rather easily (with the help of a bending modulator) deep bunching along the beam with the required wave length of the order of one centimeter. With the beam passing through the appropriate diaphragmed waveguide, one can efficiently transfer the energy of a proton beam to the electromagnetic field of this linear accelerating structure with an accelerating rate up to 100 GeV/km. Let us call such a mode of operation the proton klystron mode (see Sec. 5). By injecting particles to be accelerated after the exciting proton bunch one can obtain a wide range of particles of high energies.

So, it is possible to transfer nearly the total energy of the basic proton accelerator to accelerating particles with the beam intensities constituting an appreciable fraction of the initial beam intensity. By lengthening the accelerating structure and exciting consecutive sections with different proton superbunches one can proportionally raise the energy of accelerating particles with the corresponding loss in their intensity.

2. PROGRESS IN THE FIELD OF DETECTORS[2)]

a) The progress in detector systems is strongly connected with the continuously proceeding revolution in electronics. Namely the "electronic revolution" enables one to create modern fast track devices and to handle large flows of information. A very rought upper estimate of information on an individual event in a big detector (10^7 resolvable elements of space $\times 10^2$ resolvable elements) shows that the number of elements is large, so that computer image of an event is quite informative—or as it is said sometimes now—is quite pictorial. As a rule, thousands of these events should be registered in a second i.e., the full information flows are very large.

Therefore, development of faster processors is very important. Apparently the "Fast-bus system" developed at Brookhaven is the record-holding one which provides a processing rate up to Gigabits per second.[12] But even this rate is insufficient for processing the full information flow if the information is considered as totally uncorrelated and of equal value.

[2)] The references to the literature in this section are mainly made to material presented at the 20th International Conference on High-Energy Physics.

The wide use of parallel collection and processing of information is of great significance, as well as the use for this purpose of ever more perfect programmable microprocessors, that enable one to record and then to use for analysis only potentially interesting information. There could be several levels of decision on the subsequent more detailed recording and processing of the information and even several levels of triggering of the detector devices.

b) Detector systems already can be huge in size. Especially large are neutrino detectors[13] and the multikiloton detectors for the study of proton stability.[14]

But of extreme importance also is the line of development of microdetectors when for achieving the necessary information one uses the ultimate high spatial, time and amplitude resolutions (either separately or combined). The International Symposium in Italy (September, 1980) will be specially devoted to microdetectors.

c) Let us consider now the progress and prospects in some concrete detecting methods.

Discharge track devices are improving greatly. The revolution in electronics enables one to use ever finer properties of the electric discharge in various media. Already now the spatial resolution in a liquid-argon chamber is $\sigma_x = 8$ μm[15], in a gas chamber –20 μm[16] and the time resolution achieved is $\sigma_t = 20$ picoseconds.[17] One can confidently predict that further improvement and miniaturization of electronic components (as well as their lower cost) and, maybe, the use of integrated manufective of sensitive and electronic processing components will further facilitate progress in track detectors.

d) The approach is quite promising of "active targets" with fast (electronic) information collections which is direct outgrowth of the bubble chambers and high pressure gas chambers.[18] One of the versions of such a target is a set of successive fine semiconductor counters[19] with a longitudinal resolution of 10 μm, designed, in particular, for measuring the life-time of D-mesons generated in the substance of the target itself. The possibilities of this device are expanded especially by the addition of the transverse resolution for each counter (the prototype of the device is already manufactured providing transverse resolution $\sigma_x = 10$ μm). But with the use of technological means of modern microelectronics—thin silicon—plate production, ion implantation, molecular epitaxy, lasers, and in the not too distant future, X-ray lithography using synchrotron radiation of electron storage rings, the use of integrated circuits in production of the whole channel up to transfer of information into the processor—the prospects open up for a real revolution in this whole field. The latter remark is valid also for the system of information read-out, optical, in particular, for detectors of any kind.

e) Quite interesting possibilities appear when using thin-wire scintillation hodoscopes.[20] Good results have been obtained for information read-out when using avalanche photodiodes and microchannel electron multipliers. It looks realistic today to have hodoscopes with a spatial resolution up to 100 μm, a length along the filaments of 1 m and event rate up to 10^7/Hz.

f) Interesting prospects open up for small bubble chambers operating with very small bubbles[21]—the resolution already achieved is 10 μm. Especially attractive in this case is the use of holographic information collection, which enables one (maintaining the same resolution) to, increase sharply the image optical depth (a 10 cm image depth is already achieved). The main efforts in this case are put on the subsequent information processing. Note, the holographic way of collecting information is apparently feasible for streamer chambers, as shown by developments at the Leningrad Institute of Nuclear Physics. Actually, for holographic detection in real detectors it is reasonable to tend to use the filmless way of taking information, i.e. microchannel multiplier plates, large-area semiconductor counters with the necessary spatial resolution, and perhaps some other methods.

g) Hybrid emulsion and rapid-cycle buble chambers with counter detection of the interesting events and addition of high time resolution are still of interest, especially for operation with very high multiplicities and complex unknown events.

In particular, hybrid bubble chambers can be adequate to the work with linear electron-positron colliding beams at super high energies[9] when at an average repetition rate of tens of Hz the luminosity at a single interaction should be very high.

h) In closing the detector section let me note the quite extensively developing methods of direct measurements (or at least estimates) of relativistic γ-factors of particles under study. With energy growth this problem becomes more and more complicated and important. Among these methods I would note the gas Čherenkov counters (especially those with microchannel measurements of the Čherenkov radiation circle[22]), detectors of transition radiation,[23] the use of relativistic dependence of ionization loss (at high energies in gases), radiation in channeling in single crystals, which is most successfully applied for positive particles, and magnetic-braking synchrotron radiation. For various cases the optimal methods can be different and sometimes their combination may be optimal. Some methods, for instance, registration during channeling, are mostly applicable for tagging the secondary particles striking the target when the directions of their motion are sufficiently collinear.

3. POSSIBILITIES OF GENERATING CHARGED-PARTICLE BEAMS

Let us consider now the possibilities for generating high-quality beams of as wide as possible a set of particles, both primary accelerated and secondary. Progress in this direction determines to a significant extent the development of elementary particle physics.

Among the characteristics of beams significant from the point of view of their information content for elementary particle physics, energy and intensity have obvious importance. An increase in the energy E of the projectile particles leads to an increase in reaction energy for fundamental processes under study. In ultrarelativistic case this energy increases as $\sqrt{E}$ in the experiments with stationary target and as E in colliding beams. An increase in intensity makes possible both the observation of rarer processes and higher accuracy of experimental data, which frequently supplies qualitatively new information of fundamental importance. A bright illustration of the latter may be the discovery in laser experiments of parity violation in atomic transitions and, consequently, the discovery of electron-nucleon weak interaction due to neutral currents.[24]

In addition to energy and intensity, the following qualities of beams are of a very great importance: smallness of their emittance, monochromaticity and optimal time structure. The smallness of emittance permits minimizing the transverse size of the interaction region between particles of the beam and the substance of the target, which improves, say, the momentum analysis of reaction product. Concerning the time structure of the beams, it is worth mentioning that it is sometimes beneficial to have the shortest intense bunches separated by long vacant sections (for helping to eliminate, for example, homogeneous cosmic background, for the use of preliminarily triggered detectors like bubble chambers, and for velocity selection); in other cases it is beneficial to have the beams, continuously distributed in time, loading optimally the detecting electronics and getting the possibility of "tagging" each interesting particle with the products accompanying its production.

In recent years, obtaining polarized beams has become more and more important. The opinion prevalent earlier that spin effects, for strong interactions at any rate, become weaker and weaker at higher energy turned out to be absolutely incorrect. More than that, one can say that it is impossible to develop a quantitative theory of elementary particles without experimental study of spin properties.

Let us consider now, very schematically, the possibilities of generation of beams of all known sufficiently stable particles.

The secondary beam generation is often a multi-step and complex process. And at many stages the use of super-thin target mode with suitable cooling is effective.

a) Protons

Proton accelerators continue to grow in energy and intensity, being the basis for a vast class of experiments, including colliding beams.

Even now energies up to 500 GeV are accessible; in the not so distant future the DOUBLER at 1 TeV will be put into operation; the UNK project at 3 TeV is under way.[25] The subject of consideration if ICFA (International Committee on Future Accelerators) was an accelerator at an energy of 20 TeV.

The current intensity of proton beams of the highest energy is 10^{13} p/sec; further increase of their intensity is connected with solving the problem of further sharp improvement in the "beam hygiene", which is of particular importance for accelerators using superconductivity, which is used in every project for proton accelerators at super high energy. The use of superlinacs with proton klystrons opens up interesting possibilities for getting protons of higher energies.

Naturally, the record intensities for medium energies belong to meson factories (up to 10^{16} p/sec). Further increase in intensity will be permitted by the growth in power of RF generators and by solution of radiation problems.

In the field of lower energies, electrostatic tandem generators ensure excellent beam properties. The biggest tandem generator, for 60 MeV protons, is nearing completion in Daresbury. However, many corresponding experiments, e.g. spectrometric, appear to be feasible (and without sharp energy limit) with the help of storage rings with electron cooling in the super-thin target operation mode.[4]

Obtaining intense polarized proton beams is connected with the design of intense sources of polarized protons and, in the case of cyclic accelerators at high energies, with overcoming the depolarizing effects of spin resonances. The experience of Argonne laboratory has shown experimentally the possibility (and usefulness) of acceleration of polarized protons up to rather high energies.

New possibilities are already seen now for filling cyclic proton accelerators with polarized particles up to the total intensity of the given accelerator. The main way is to use proton polarized H^--beams, which may have almost the same intensity as polarized H^+-beams, and to use charge-exchange injection into the accelerator, which permits one to increase by several thousands the current circulating in the accelerator compared to the current of the H^--source.[26] Additional increase in injection multiplicity and improvement in the stored beam emittance can be achieved by introducing electron cooling during the injection process. Only for meson factories are there yet no possibilities for bringing the intensity of polarized proton beams to approach the intensities of ordinary beams.

Acceleration up to very high energies in cyclic accelerators is accompanied by numerous spin resonances. This question as been thoroughly studied theoretically and ways were found for overcoming the detrimental effect of resonances, including producing magnetic structures which eliminate these resonances completely.[27]

The problem of obtaining polarized protons of high energies after initial charge-exchange stacking in a booster is especially simplified with use of superlinacs, in particular, with the use of proton klystrons.[11]

Since presently there are no pure polarized targets of condensed substances, an especially important role could be played by experiments in storage rings with an internal gas target, which enable one to operate with nearly pure initial spin states. One should pay attention to the fact that even a longitudinal polarization of the circulating beam near the target can be made stable[28] for achieving initial states with given helicities.

b) Nuclei

"Relativistic nuclear physics" turned out to be more interesting than has expected earlier ("porridge on porridge"). Such experiments give both ideas on supercompressed nuclear substance and supply data on fundamental interactions (study of inclusive processes). Already nowadays accelerated uranium nuclei are obtained with energy up to 10 MeV/nucleon and intensity up to 10^9 U/s and nuclei up to carbon with 5 GeV/nucleon energy and up to 10^7 C/s intensity. An implementation of projects is under way which will sharply raise the ceiling of available energies and intensities. In some cases coherent methods of acceleration could be used, including "smoketron" devices.

Table I represents the expected maximum parameters (energy and intensity) of the nuclear beams for one of the biggest projects, BENUS (Berkeley):

This project also envisages operation in the colliding-beam mode.

Obtaining beams of polarized deuterons of high energies is even simpler than for the case of protons (because of smallness of the anaomalous magnetic moment).

I note that, if one must store heavy-ion beams, and especially, keep them in a compressed state for a long time, it is most reasonable to employ cooling with a proton beam, which in turn is cooled with electrons ("proton cooling"[41]).

c) Neutrons

Neutron fluxes with an energy up to tens of MeV are obtained mainly with nuclear reactors (including pulsed reactors) and in deuteron and proton accelerators. For monochromatization of reaction energy fast separators and time-of-flight methods of detection are used. I cannot help but draw attention to the fact that it is a very attractive possibility for the energy range from tens of eV to hundreds of keV to use very powerful and highly collimated synchrotron radiation (with quantum energy higher than 1.6 MeV) from electron storage rings at an energy $\gtrsim 10$ GeV irradiating a beryllium target. Small transverse dimensions of the effective neutron source (achievable dimensions are down to 10 μm × 1 mm), short pulse (fractions of 2 nanosecond) and a very low duty factor ($\lesssim 10^{-5}$) at high average intensity better conditions (up to 10^{14} ns) ensure by many orders of magnitude for the study of neutron reactions using the time-of-flight method. In the lower part of the mentioned energy range the small transverse dimensions of the source make very effective the use of Bragg monochromatization employing bent crystals, and also make effective the obtaining of polarized neutrons with the help of magnetic mirrors.

TABLE I. Ultimate parameters of beams of nuclei in the VENUS project, s^{-1}.

	1 GeV/nucleon	20 GeV/nucleon
Ne	$0.8\cdot10^{12}$	$1.2\cdot10^{11}$
Kr	$2\cdot10^{11}$	$3\cdot10^{10}$
U	$0.7\cdot10^{11}$	$1\cdot10^{10}$

At higher energies an interesting pulsed source of neutrons can be obtained at meson factories with the use of charge-exchange ($H^- \to H^+, D^- \to D^+$) stacking of accelerated protons or deuterons in a cyclic storage ring, and using fast extraction onto the target.

At energies $\gtrsim 100$ MeV an optimal method for obtaining quite monochromatic and well directed neutrons is the use of the decay reaction for accelerated deuterons having the required energy per nucleon. In the superthin-target mode an intensity for a well collimated and quite monochromatic neutron flux can be achieved close to that for the deuterons and also good tagging with the remaining proton of the same energy. The use of polarized deuterons enables one to obtain neutrons with a good degree of polarization.

The use of the charge-exchange reaction $pZ \to n\,(Z+1)$ permits doubling the energy for neutrons obtained at a given cyclic accelerator but the beam quality in this case is worse. The cross-section for elastic charge-exchange declines rapidly with proton energy increase ($\sigma_{ex} \approx 2/E^2_{Gev}$ mb, $\sigma_{ex}/\sigma_{tot} \approx 0.04\ E^{-2}_{GeV}$ mb). At energies higher than tens of GeV one has to use the reaction $pp \to n\pi^+p$ with the useful cross-section of 0.2 mb, with proton accelerators up to 0.5% efficiency of transforming while obtaining protons into neutrons.

d) Antiprotons

Development of electron and stochastic cooling gives the possibility of obtaining high-intensity, absolutely pure, monochromatic and small-emittance antiproton beams. The first projects of antiproton storage rings under implementation and under preparation[30-34] will give $(1-5)\cdot10^7\ \bar{p}$/s. The first experiments at CERN have already obtained a satisfactory stacking rate.[31] The ways are now visible for increasing the production efficiency to $10^9\ \bar{p}$/s.[4,33,34]

The stacking will be performed at an energy 0.5 – 5 GeV. The antiprotons can be decelerated to very low energies[4,35] or be accelerated up to energies of the available proton accelerators (or even higher when using proton klystrons). Of special interest are the studies with antiprotons at low energies with continuous electron cooling in obtaining intense and long-life protonium fluxes—$p\bar{p}$-electromagnetically—bound states.[4,35]

When using antiproton beams continuously cooled with electrons, which interact with a longitudinally polarized gas target in the storage-ring section with stable longitudinal polarization of the circulating beam, one can achieve polarized antiproton beams with intensity up to 10% of the intensity of the initial antiprotons[4] with their subsequent acceleration (or deceleration) up (or down) to the energy required.

e) Antideuterons

With the same storage rings being designed for obtaining antiprotons one can get absolutely pure beams of antideuterons with intensity only 3–4 orders of magnitude lower than that for antiprotons.[4] At these low energies it becomes optimal to use stochastic cooling in the storage system, which allows one to cool beams with a large energy spread and large emittance directly at the energy of creation of the antideuterons. Such beams can turn out to be interesting for the study of nuclear states consisting of nucleons and two antinucleons.

f) Antineutrons

At energies up to tens of GeV the most profitable way is to obtain antineutrons by the elastic charge-exchange reaction $\bar{p}p \to \bar{n}n$ [the cross-section at high energies is about $\sigma_{ex} = 15/E^2(\mathrm{GeV})$ mb] with tagging, if possible, by the remaining low-energy neutron. The intensity of antineutrons will be up to $\sigma_{ex}/\sigma_{tot} \approx 0.3\ E_{\mathrm{GeV}}^{-2}$ of the system efficiency for antiprotons. The use of polarized antiprotons will enable mainly the obtaining of beams of polarized antineutrons with an intensity one more order of magnitude lower (because of losses during antiproton polarization).

At still higher energies one must obtain antineutrons in the reaction $\bar{p}p \to \bar{n}\pi^- p$ with a cross-section of fractions of mb with worsened quality of the resulting beam (even with tagging). The antineutron intensity can reach a fraction of a percent of the antiproton intensity.

An antineutron beam of excellent quality, intensity up to 10^{-3} that for antiprotons and with ideal tagging by the remaining $\bar{p}$ can be obtained with stored and accelerated antideuterons: $\bar{d}p \to \bar{n}\bar{p}p$.

g) Pions

Obtaining beams of charged pions is the most explored procedure among second-particle beam production at high energies. Here, I would like to draw attention only to the tempting prospects for obtaining pure, rather monochromatic and well-collimated pion beams by their acceleration in superlinacs with an acceleration rate higher than $2m_\pi c/\tau_\pi = 0.4$ MeV/cm; in this case, the most natural way is to use a proton klystron.[11] When using optimal conversion systems, for each ten protons with energy $\gtrsim 100$ GeV one can have one pion, either positive and/or negative, with energy of a few GeV which is fit for further acceleration. In order to decrease the number of muons accompanying the beam of accelerated pions one should seek the maximum acceleration rate.

Let me note here that, at energies higher than hundreds of GeV, the number of events with full cross-section induced by neutral pions in a condensed target becomes substantial. So, at initial proton energy of 1 TeV with intensity 10^{13} p/s more than 10^5 events will be caused by neutral pions having an average flight length of 20 μm. But, of course, the problem of identification of these events is extremely difficult.

h) Kaons

Unfortunately, for acceleration of charged kaons accelerating gradients higher than 3 MeV/cm are required; that is still far from realization. There is some hope of achieving such gradients using special modification of the proton klystron: all the protons occupying the whole circumference of a big proton accelerator should be compressed into one (or several, with long distances in-between) bunch about 1 cm long and injected into a special linear waveguide structure[37] (see Sec. 5e). In this case, inside the bunch a very strong longitudinal electric field will appear, bracking (decelerating) the protons of the bunch. Consequently, negative particles travelling together with protons inside the bunch will be accelerated, in this case K^-. Neutral kaons could be produced then, as desired, with great efficiency by charge transfer, with removal of all charged particles with a magnetic field. However, the development and design of sufficiently damage-resistant systems of this kind is, of course, a task for the future.

But up to now at high energies an optimal method for setting up experiments on kaon-nucleon interaction may turn out to be the use of the thin-target mode (and at energies and intensities enabling effective cooling—the superthin-target mode) in a proton storage ring with the best available tagging (correspondingly with a very versatile complicated trigger). Since the total cross-section for generation of every kind of kaons in p-p reactions is large (fractions of mb), there are many kaons generated in this target. Naturally, for making a more pure experiment one will have to use the whole arsenal of the charge, momentum, velocity and gamma factor selection techniques, and, recording products of KN in reaction, one should most carefully take into accound the quantum numbers of particles produced.

i) Hyperons

A new circumstance at superhigh energies is the long life-time for hyperons. Eben at 100 GeV the long-lived hyperons live for distances of tens of meters. Nevertheless, for separation of the primary beam from the beam of produced hyperons one should use strong magnetic fields, but this problem becomes linearly easier with energy growth. All the rest that I have said on carrying out experiments with kaons remains valid even in this case (inclusive cross-sections, in particular, are of the same order).

j) Antihyperons

At not very high energies (mostly, to hundreds of GeV) the use of elastic charge-exchange reactions $\bar{p}p \to \bar{Y}Y$ ($\sigma_{ex}/\sigma_{tot} \approx 10^{-2}/E_{\mathrm{GeV}}^2$) with tagging with the by-product hyperons (being nearly at rest) in the (super) thin target mode in an antiproton storage ring seems optimal for obtaining antihyperon beams. Apparently, antihyperons produced in such a process by polarized antiprotons will preserve a noticeable polarization level.

At higher energies one will have to proceed in the same way as in the case of hyperons; the inclusive cross-section for antihyperon production in pp collisions is by only one order of magnitude lower than that for hyperons.

k) Electrons

Electron accelerators and storage rings currently play a very essential role both in experiments in elementary-particle physics and in various application (in particular, for generation of synchrotron radiation).

The record in electron accelerators belongs to SLAC; the available energy there is in excess of 30 GeV and in the near future will attain 50 GeV at intensity up to 10^{14} e^-/s.

Both electrons and positrons of higher energies are obtained at present on proton accelerators by the process $pZ \rightarrow \pi^0 X$; $\pi^0 \rightarrow 2\gamma$; $\gamma Z \rightarrow e^+e^- Z$. Nowadays it is possible to obtain electron beams of quite good quality with energy up to 300 GeV at intensity up to 10^8 $e^\pm$/s (separation with synchrotron radiation, for example[37]).

A sharp increase in intensity (up to 10^{13} e^-/s) of electron beams with energy of hundreds GeV will become feasible after design of superlinacs for linear electron-positron colliding beams (see Sec. 31).

Intensities of polarized electron beams have reached 10^{11} e^-/s at SLAC. Intense polarized circulating beams are obtained by radiative polarization in storage rings.[38-42] Using intense circularly-polarized radiation (e.g. laser beam) travelling against the electron beam, it is possible to achieve a much higher polarization rate of the circulating electrons (and positrons).[43,44] One can obtain a satisfactory degree of e^- polarization at energies above 100 GeV with a single passage through magnetic fields of hundreds of kilogauss by using the dependence of the synchrotron losses on the orientation of the spins of the emitting particles with respect to the magnetic field.[45]

l) Positrons

In the field of energies of electron accelerators, the presently available intensity of positron beams at practically the full energy reaches 1% of the electron intensity with worse beam quality. The use of intermediate storage rings with radiation cooling can essentially improve the quality of positron beams and increase their intensity. Obtaining beams of polarized positrons experimentally so far has been necessarily connected with radiative polarization in storage rings. At energies higher than 100 GeV, as mentioned above, possibilities for positron beams, including polarized beams, are the same as those for electrons.

m) Photons

Intensities and energies of beams of high-energy gamma quanta obtained as bremsstrahlung in electron accelerators and also by decay of neutral pions at proton accelerators are quite high. However, an important problem is beam separation and energy tagging for quanta hitting the targets. The latter is especially complicated for proton accelerators, and even so complicated that first of all one has to obtain $e^\pm$ beams of known energy, and only after that, following the ordinary procedure of measuring the energy of the remaining $e^\pm$, can the energy of the bremsstrahlung quantum be tagged. The same technique of tagging energies of photons obtained in internal (superthin) targets is also convenient for obtaining intense fluxes of gamma-quanta in electron storage rings.

Interesting prospects in obtaining intense, monochromatic and, at the same time, appropriately polarized beams of gamma-quanta of high energies is the inverse Compton-effect on electrons travelling in cyclic storage rings at high energies. For obtaining such quanta with energy E, one should have electrons with energy E and polarized photons with energy higher than $(m_e c^2)^2/E$. Under these conditions, zero-angle scattered photons will have full energy the E (almost independently on the initial photon energy). At scattering angles greater than $m_e c^2/E$ the photon energy will be much less. So, for effective monochromatization one needs to measure the direction of their travel to the points of interaction with the target, while the electron beam should have as small an angular spread as possible. It is useful, additionally, to measure the energy of the simultaneously scattered electron for tagging the quantum energy. Inside the angle $m_e c^2/E$, the photons will have the energy E with the spread $\Delta E/E = (mc^2)^2/EE_\gamma$, where E_γ is the energy of the primary photons. A fraction of the total flux of scattered photons of the order of $\ln^{-1}(E/\Delta E)$ will be concentrated within this angle.

At energies up to 50 GeV it is reasonable to employ synchrotron radiation from spiral undulators. In this case, it is necessary to ensure that the colliding electrons interact exclusively with photons, emitted inside the angle $1/\gamma$ (γ is the relativistic factor of the electrons radiating in the undulator). The radiating particles can travel either in the same storage ring (e^+e^- colliding beams) or in a special storage ring at a substantially lower energy.

Some interesting possibilities can arise if one employs scattering of the radiation of short-wave intense electron-beam lasers (without mirrors).[46] At energies higher than 50 GeV one can use photons of high-power short-wave lasers of usual type.

The intensity of such beams of gamma-quanta corresponds to transfer of all stored electrons to these quanta with a life-time due to this process of thousands of seconds (up to 10^8 γ/s), while using synchrotron radiation as the primary radiation. The flux intensity of high-energy quanta can be sharply elevated if one possesses suitable lasers.

Especially intense fluxes of γ-quanta can be obtained in installations like VLÉPP (see Sec. 6).

For quanta of low energies (up to several MeV; in the future up to 20 MeV), the record-setting sources in intensity (and especially in luminosity) are electron storage rings at the high energies of 10–100 GeV (see also Ref. 47).

For energies of tens and hundreds of MeV, interesting prospects are opened up by using the radiation from the channeled motion of electrons in single crystals.[48,49] The intensity of these well collimated beams can be tens of times larger than the bremsstrahlung of electron beams in this same region of the spectrum.

n) Muons

In order to have completely pure, high energy and most intense muon beams with a very small emittance and good monochromaticity, it is reasonable to proceed as follows[4,5,11,50]:

a) to obtain as many as possible pions with energy of about 1 GeV on the target, with strong focusing, in a nuclear cascade using proton beams of energy $\gtrsim 100$ GeV;

b) to let the pions decay in a channel with as strong focusing as possible;

c) to cool the muons (with ionization cooling) in a special ring with targets placed in the sections with very strong focusing;

d) to accelerate the muons up to the required energy in a short-pulse cyclic accelerator or (better) in a superlinac.

The intensity of the muon beam can reach up to 10% of the intensity of the basic proton synchrotron (with use of the proton klystron mode).

In order to obtain polarized muon beams of high energy it seems most profitable to use monochromatic pion beams accelerated in a superlinac by injecting them into a special storage ring with a strong magnetic field (pulsed or superconducting). The structure of the ring should be designed so as to have dynamically stable longitudinal polarization[28] of the circulating muons (at injection energy, at any rate) that is equal in both long straight sections, which occupy, say, 3/4 of the circumference of the ring. The muons produced in the forward hemisphere with respect to the momentum of the pions in their rest frame will have a momentum very close to that of the pions and almost the same helicity in the laboratory frame; muons of inverse helicity (moving backward in the rest frame of the pions) deviate strongly in momentum and can be easily removed from the ring. Polarization of the produced muon beams can be quite high (approaching the ratio of length of the straight sections to the circumference).

o) *Neutrinos*

Beams of muon neutrinos of high energies, well-directed and of useful intensity of a few percent of the intensity of the basic proton synchrotron, can be obtained with beams of accelerated pions. In order to decrease the neutrino beam diameter near the detecting facilities, which are naturally located behind shielding of required thickness, it is profitable to carry out the pion decay in a special storage ring with relatively long straight sections. Both muon and electron neutrinos of the same intensity can be obtained in a track of this kind by injecting into the track the accelerated cooled muons. Thus, combination: "superlinac special race-track" can be a multipurpose installation.

As to the beams of ν_τ—neutrinos connected with a heavy lepton, it might turn out that their main source will be decay of τ—leptons of $\tau^\pm$—pairs produced by γ—quanta in the target nuclei.[51] γ-quanta one can obtain both with the help of proton and electron beams of high energy. More specifically one can evaluate the flux of τ-neutrinos coming from electrons. In a thick target the order of number of produced $\tau^\pm$ pairs will be the number of produced $\tau^\pm$ pairs will be of the order of $(m_e/m_\tau)^2 = 10^{-7}$ with respect to the number of incident electrons, since, at a high enough energy, the form factor of the nucleus no longer affects the cross-section for τ-pair creation (see Sec. 6i).

So, one can hardly expect that the neutrino beam quality will be higher in the case of protons. It is not excluded, that in a 100% duty-cycle mode it would be possible to design the trigger system for τ-lepton production and similar events, for facilitating selection of ν_τ events.

4. COLLIDING BEAMS

Colliding beam experiments have become the main supplier of fundamental data in physics of elementary particles. Many electron-positron storage rings are in operation now (see Table II and Figure 1). Colliding-beam experiments are essentially needed at the highest energies.

a) However, this method will necessarily be developed and advanced not only at the highest energies. In particular, the necessity of this is connected with the fact that detailed study of quark-gluon systems in the field of low and average energies is of primary importance at present since it permits quantitative study of quantum chromodynamic effects, in particular, connected with the transition from asymptotic freedom to confinement. Such experiments are especially suitable for electron-positron colliding beams, but to this end a sharp increase in luminosity of installations is requited. The possibility and usefulness of this were proved by experience of VÉPP-2M designed spefically for increased luminosity and, correspondingly, yielding increased accuracy of experimental data in the energy range up to 1.5 GeV. Already now the possibilities are seen for constructing installations with luminosity up to 10^{33} cm^{-2}s^{-1} at full energy of 4–5 GeV.

TABLE II. Electron-electron and electron-positron installations.

Storage ring (laboratory)	Particles	$\sqrt{s}$, GeV	L, cm^{-2} s^{-1}	Start of operation
VÉP-2 (Novosibirsk)	e^-e^-	0.32	$5\cdot10^{27}$	1965, closed
Stanford	e^-e^-	1	$2\cdot10^{28}$	1965, closed
VÉPP-2 (Novosibirsk)	e^+e^-	1.4	$3\cdot10^{28}$	1966, closed
ACO (Orsay)	e^+e^-	1.1	$1\cdot10^{29}$	1967, closed
ADONE (Frascati)	e^+e^-	3	$6\cdot10^{29}$	1970
CEA (Cambridge)	e^+e^-	4	$3\cdot10^{28}$	1971, closed
SPEAR (Stanford)	e^+e^-	8.2	$2\cdot10^{31}$	1972
VÉPP-2M (Novosibirsk)	e^+e^-	1.4	$3\cdot10^{30}$	1974
DORIS (Hamburg)	e^+e^-	11	$1\cdot10^{30}$ (10^{31})	1976
DCI (Orsay)	e^+e^-	4	$1\cdot10^{30}$	1976
VÉPP-4 (Novosibirsk)	e^+e^-	11	$1,5\cdot10^{30}$	1979
PETRA (Hamburg)	e^+e^-	38	$2\cdot10^{31}$ (10^{32})	1979
CESR (Cornell)	e^+e^-	11 (16)	$3\cdot10^{30}$ (10^{32})	1979
PEP (Stanford)	e^+e^-	28 (36)	$0.7\cdot10^{31}$ (10^{32})	1980

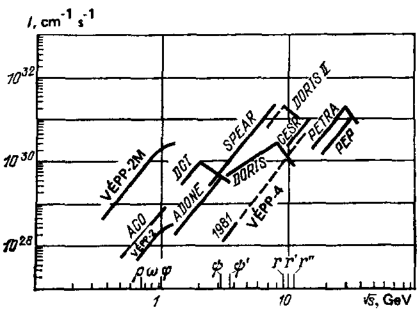

FIG. 1. Relationship of the luminosity of installations with colliding electron-positron beams to the reaction energy $\sqrt{s}$. (At present energies and luminosities have been obtained on VÉPP-4 corresponding to the full range of the presented graph).

Other lines of improvement of electron-positron installations also promise to give important results. The possibility of working with polarized beams is very useful. In addition to a sharp increase in absolute accuracy of measurements of masses of created particles[52,53] (see Table III), even working with transversely polarized colliding beams helps in understanding more cleanly the quantum numbers of the formations being created. Implementation of experiments with longitudinally polarized beams enables one to have a pure spin state of the intermediate formations and the final particles, and this permits obtaining qualitatively new information on the spin-dependent strong interactions, and studying, for instance, weak interactions of b-quarks in the region of Υ-mesons and the decay properties of heavy leptons. We note that in many cases it is sufficient to have only one of the beams longitudinally polarized at the point of collision.

The possible sharp increase (higher than one order of magnitude) in monochromaticity of electron-positron reactions opens up interesting possibilities.[54] Thus, one can proportionally raise the fraction of resonance reactions, which is of special importance Υ-mesons, and study the inner structure of ψ-mesons (even for the purpose of proving that they do not exist). Note, that even higher monochromaticity can be achieved with $p\bar{p}$-colliding beams under continuous electron cooling.[4]

b) But the main trend in the field of electron-positron colliding beams remains the tendency to higher energies, which is a problem of cardinal importance.

Already now total energies up to 40 GeV have become accessible (PETRA, PEP). An intensive development of the LEP project is under way (first stage-up to $\sqrt{s}$ = 100 GeV, second—up to 250 GeV), the project of the new storage ring at Cornell and also the HERA project enables, in principle, obtaining e^+e^- energies up to 100 GeV (see Table IV). Note, that even at these high energies (despite the overlapping of spin resonances), implementation of e^+e^- polarized colliding beams is feasible.[55] A new and interesting feature is the project of quasilinear single-pass e^+e^- colliding beams at SLAC[56] (Fig. 2) at an energy up to $\sqrt{s}$ = 100–140 GeV.

TABLE III. Masses of several particles obtained by the resonance-depolarization method.

	Old table value of the mass, MeV	Value of the mass obtained in VÉPP-2M and VÉPP-4, MeV
$m_{K^+} - m_{K^-}$ (CPT test)	—0.032±0.090	—0.009±0.054 *)
m_{K°	497.67±0.13	497.618±0.085 **)
m_φ	1019.62±0.24	1019.53±0.09
m_ψ	3097.1±0.9	3096.93±0.09
$m_{\psi'}$	3685.3±1.2	3686.00±0.10
m_Υ	9458±6	9459.7±0.6

*Result obtained with use of data of studies of another type.
**Preliminary result.

TABLE IV. Projected ultrahigh-energy electron-positron installations.

Project		$\sqrt{s}$, GeV	L, cm^{-2} s^{-1}	Planned starting date
LEP (CERN)	1st stage	100	10^{32}	1986
	Complete project	250		
New Cornell Ring		100	$3\cdot10^{31}$	1986 (?)
Stanford Single Pass Collider (SLC)		100	$1\cdot10^{30}$	1985 (?)
VLÉPP	1st stage	300	$1\cdot10^{32}$	1989 (?)
	Complete project	1000	$1\cdot10^{32}$	

Further increase in energy of electron-positron colliding beams in cyclic storage rings (now conventional) is almost unrealistic because of the catastrophic rise in loss by synchrotron radiation that forces one to enlarge the installation both in dimensions and power consumption as the square of energy. Therefore, the main direction in development becomes linear colliding beams.[9]

In the plans for linear colliders at super-high energies, even in the initial stage, the possibilities are considered of using long superconducting structures with recovery of accelerated particle energy and of using pulsed superlinacs.[43] Several projects of linear e^+e^- superconducting colliders are being developed now-Cornell, CERN, Hamburg.[58,60] The collider project VLÉPP based on superlinacs is being developed in Novosibirsk[9,10,61,62] (see Sec. 6).

c) The first proton colliding beam facility (ISR) has been operating at CERN since 1971. Its maximum energy is 2 ×33 GeV, the maximum number of stored particles is up to 10^{14} in each beam, ultimate luminosity is $0.7\cdot10^{32}$ cm^{-2}s^{-1}. During this period a number of important experiments have been conducted which provided valuable information.

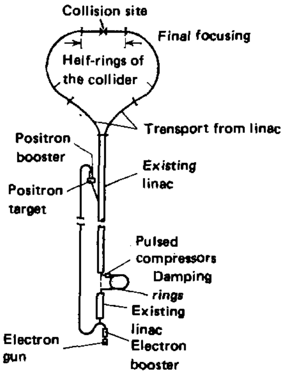

FIG. 2. General diagram of the Single Pass Collider at SLC.

Construction of big superconducting storage rings is being carried out at Brookhaven with proton-proton colliding beams at energy $\sqrt{s} = 800$ GeV—ISABELLE—with bery high design luminosity (10^{33} cm^{-2}s^{-1}). Implementation of proton-proton experiments on the Main Ring-Doubler facility is under consideration at Fermilab at an energy $\sqrt{s} = 1100$ GeV (300 GeV on 1000 GeV). Proton-proton colliding beams are envisaged in the accelerating facility at Serpukhov (UNK) at an energy up to 2×3 TeV. So, we see, colliding-beam energies will increase rather rapidly. But experimental feasibility of reactions, now of intense interest, with energy of 0.1 megajoule in an elementary event (10^{15} GeV in rest frame beloved of theoretically!)- is a question for the not so near future.

d) the first installations with colliding proton-proton beams have begun to operate. The installation ISR and the proton synchrotron SPS (CERN) have been converted to this regime.[30,31] Energies have been obtained in the SPS up to $\sqrt{s} = 600$ GeV. The luminosity of 5×10^{27} cm^{-2}s^{-1} attained in 1971 in each of the installations has already enabled the start therein of experiments involving the cross-sections of ordinary nuclear interactions. Intensive work is being done on raising the luminosity.

Next will be the commissioning of the proton-antiproton installation at an energy up to $\sqrt{s} = 2000$ GeV based on the superconducting proton syndhrotron Doubler (Tevatron, Phase I) being built at Fermilab.[32] The $p\bar{p}$ project is designed for UNK (Novosibirsk-Serpukhov collaboration) at energy up to $\sqrt{s} = 6$ TeV.[33,34]

In the first years after announcing the first proton-antiporton colliding beam project (1966 VAPP-NAP, Novosibirsk),[63,64] proton-antiproton experiments at maximum accessible energy were considered by many physicists as an exceedingly complicated addition to proton-proton experiments at the same energies. Even then, of course, it was evident that this addition is rather important.

In addition to the need for testing the fundamental theorem on the equality of the overall pp and $p\bar{p}$ cross-sections, two classes of experiments were considered that are specific to proton-antiproton colliding beams: first, the study of hadron annihilation, second, the study of two-particle charge-exchange reactions, i.e.. reactions with conservation of baryon charge of each colliding particle. The annihilation cross-section apparently decreases only inversely as the energy of the colliding beams and even at an energy of 2×1000 GeV the cross-section will be of the order of 10^{-30} cm^2. So, the main problem will be the separation of annihilation processes from the vast majority of "total cross-section" events. At the same time, the cross-section of processes like $p\bar{p} - \bar{Y}Y$ decreases (in the energy region presently known) as E^{-4} and only with a luminosity of the order 10^{32} cm^{-2}s^{-1} one can manage to get some data about these processes at energies above 100 GeV.

In recent years the attitude of the physics community toward proton-antiproton colliding beams has changed greatly. The quark model is acquiring more and more dynamical content and more and ever more grounds arise for considering hadrons as consisting of quarks interacting as point-like particles. Accordingly, processes with very large momentum transfer will occur through the interaction of quarks, the components of the colliding hadrons. Here proton-proton collisions give quark-quark reactions, while proton-antiproton collisions give quark-antiquark reactions. In this sense one can say that in experiments in colliding proton-antiproton beams in particular in Drell-Yalle processes, it is possible to obtain in first approximation the same fundamental information as in colliding electron-positron beams of the same luminosity and with an energy of the order of one-sixth of the energy of the baryons (although in the hadron collisions the energy of the reactors is completely "smested out"). Similarly, proton-proton colliding beams are equivalent to electron-electron collisions. Of course, for strongly interacting particles such as protons and antiprotons we cannot say that they consist only of quarks of one "polarity". However, according to contemporary data the content of antiquarks in a proton is about 5% (this is also the estimate of the content of quarks in the antiproton). Therefore, in proton-proton collisions, quark-antiquark interactions provide only a small admixture. For proton-antiproton collisions the ratio will be the reverse. In addition, the average energy of quark-antiquark reactions in proton-proton collisions will be substantially lower than in proton-antiproton collisions.

Thus, for example, the extremely interesting reactions

$$p\bar{p} \to \begin{pmatrix} u\bar{u} \\ d\bar{d} \end{pmatrix} + X \to Z^0 + X,$$

$$p\bar{p} \to \begin{pmatrix} u\bar{d} \\ d\bar{u} \end{pmatrix} + X \to W^\pm + X$$

will occur with relatively high cross-sections of the order of 10^{-34} cm^2 in $p\bar{p}$ colliding beams with energies of hundreds of GeV.

Note (see Sec. 3) that it is feasible to obtain proton-proton *polarized* beams with full luminosity and also proton-antiproton beams with luminosity one order of magnitude lower than that for unpolarized $p\bar{p}$ beams, including experiments with given helicities of initial particles. We note that many interesting experiments can be set up if only the proton beam is longitudinally polarized (with controlled helicity) at the collision site. In this regime one can realize the ultimate luminosity of the proton-antiproton installation.

Some interesting possibilities will open up when the cooling of high energy colliding $p\bar{p}$ beams with a circulating electron beam[4,65-67] will be developed. For high-luminosity colliding beams (correspondingly, with a relatively high emittance of the $p\bar{p}$ beams) achievement of effective cooling requires solution of very complicated technical problems and it is not so easy to estimate correctly the prospects of this method. But at a luminocity of about 10^{28} cm^{-2}s^{-1} such electron cooling looks like a not an extremely difficult problem. But with very small equilibrium sizes of the colliding beams, one shall have the possibility of measuring precisely the differential cross-section of $p\bar{p}$ elastic scattering in the region of effective interference of strong and Coulomb interactions. Such measurement will give information about the behavior of total proton-antiproton cross-section at energies an order of magnitude higher than the energy of $p\bar{p}$ collisions.

e) A few words about the "strategy" of advancing to the ultra-high energies. One can distinguish (quite schematically) three stages of exploring new regions at energies of hundreds GeV and higher.

In the first stage one must be able to study interactions of any pointlike objects (nowadays—leptons, quarks), which enable one to produce as large as possible momentum transfer both in scattering and in production of massive objects (space- and time-like momentum transfers). In the first stage it is not too important for which pairs it will be done. The question of primary importance is the question of having colliding beams available for the first-stage experiments. Colliding beams of particles and antiparticles seem to give more experimental information, as systems having fewer quantum-number prohibitions for generation of massive objects. From this standpoint the most advantageous variant for the experiments will be proton-antiproton colliding beams.

Of course, when we are talking now and later about studying fundamental interactions of different types, it is just a way of classifying the experiments in terms of the initial states. Each certain class of experiments will also provide vast additional information on other interactions.

At the second stage one can consider experiments which cover the interactions of all fundamental particles (leptons and quarks) i.e. the study of lepton-lepton, lepton-antilepton, quark-lepton, quark-antilepton, quark-quark and quark-antiquark interactions and also intersections involving real photons. In this case, the choice of concrete particles is also determined by which experiment is the most likely to be realized.

These problems will be solved most probably, in the following colliding-beam experiments:

1) lepton-lepton and lepton-antilepton—$e^- + e^-$ and $e^- + e^+$ (and also γe and $\gamma\gamma$ in installations like VLÉPP);

2) lepton-quark and antilepton-quark—$e^- + p$ and $e^+ + p$; experiments of this kind are already planned at the installations at superhigh energies which are being built and designed[68,71] (see Table V);

3) quark- and antiquark interactions will primarily be studied in pp and $p\bar{p}$ experiments.

TABLE V. Installations with colliding pp-, $p\bar{p}$, and ep-beams.

Project, Laboratory	Particles	$\sqrt{s}$, GeV	L, $cm^{-2}\,s^{-1}$	Start of operation
ISR (CERN)	pp	62	$0,7\cdot 10^{32}$	1971
ISABELLE (Brookhaven)	pp	800	$2\cdot 10^{32}$ $(1\cdot 10^{33})$	1986
Main Ring-Doubler (Fermilab)	pp	1100		
UNK (Serpukhov)	pp	6000		
ISR (CERN)	$\bar{p}p$	62	$1\cdot 10^{27}$	1981
SPS (CERN)	$\bar{p}p$	600	$1\cdot 10^{27}$ $(1\cdot 10^{30})$	1981
Tevatron, phase I (Fermilab)	$\bar{p}p$	2000	$1\cdot 10^{30}$	1984
UNK (Serpukhov-Novosibirsk)	$\bar{p}p$	6000	$3\cdot 10^{30}$	1990
Pentavac (Fermilab)	$\bar{p}p$	10000		
HERA (Hamburg)	$e^{\pm}p$	300 $(30_e \times 800_p)$	$4\cdot 10^{31}$	1988
CHEER (Fermilab)	e^-p	200 $(10_e \times 1000_p)$	$5\cdot 10^{31}$	1985 (?)
TRISTAN (KEK)	e^-p	170 $(25_e \times 300_p)$	$1\cdot 10^{31}$	1988

In the next stage it will apparently be important to obtain as complete as possible a set of pairs of fundamental particles in the initial state. And finally, for an advance in understanding of fundamental interactions at ultimate high energies it will become necessary to have colliding beams of all elementary particles and apparently also of nuclei.

f) In this connection, it is worth paying attention to the fact that many of those experiments which now seem exotic and unreal will become available in the not too distant future.

Thus, quite soon after exploring proton-antiproton colliding beams deuteron-antideuteron experiments will also become accessible (for studying neutron-antineutron interactions): for the effectiveness of stacking antideuterons is only four orders of magnitude lower than that for antiprotons, so that a luminosity of the order of 10^{27} $cm^{-2}s^{-1}$ will be achieved in the immediate future and one should not have to wait too long for progress in this field.

With time, colliding beam experiments involving real photons (see Sec. 6) and unstable particles (see Sec. 5) will become accessible. Good prospects for carrying out such experiments involving muons and pions are opened up with the use of intense beams from presently available and future proton accelerators for exciting linear accelerators.[11]

5. THE "PROTON KLYSTRON"

a) As I have already mentioned above, interesting prospects are opened up by using large proton ring accelerators as stores of large amounts of energy in a form excellently adapted for conversion into the electromagnetic energy of excitation of a linear accelerating structure.[11] The energy stored in the proton beams has already reached a level of 3 MJ in the SPS and Main Ring accelerators, while far higher energies and intensities are being projected. Only proton (but not electron) ring accelerators are envisioned because only in these is the HF supply power transferred to the beam, rather than being spent on compensating the losses in synchrotron radiation. I note that, when one employs superconducting magnet and HF systems, the conversion coefficient of the power in the circuit into proton-beam power can be relatively high.

A stored energy of 3 MJ suffices for exciting the accelerating structure with a wavelength, e.g., of 5 cm at a rate of acceleration of 100 MeV/m and length 50 km. In the limit, this makes it possible to accelerate a wide selection of charged particles ($p^{\pm}, e^{\pm}, \mu^{\pm}, \pi^{\pm}$) to an energy of 5 TeV. I emphasize that the energy of the particles of the basis accelerator can be far lower here. In principle one can transfer up to half the energy stored in the beam of the basis accelerator to the particles being accelerated. However, in this limiting case the energy of the accelerated particles will be substantially lower than the limit attainable in the chosen scheme. The HG pumping power (even without longitudinal compression of the exciting proton beam) can reach 100 GW in modern accelerators; longitudinal compression allows one to increase this value sharply in addition.

b) Now we shall treat the problem of how to make a proton beam having a large stored energy capable of transferring this energy to a linear accelerating structure, i.e., to an appropriately selected diaphragmed waveguide.

First of all, one must convert a proton beam homogeneous in time into a density-modulated beam with the necessary wavelength (of the order of a centimeter). Here it is desirable that the amplitude of the needed harmonic of the current I_λ should be close to the maximum possible, i.e., $I_\lambda \approx 2I$, where I is the proton current before modulation. One can carry out this modulation in two stages. First the homogeneous beam is modulated in terms of the energy of transmission through the accelerating structure, which is excited at the needed wavelength, and which gives rise to a modulation of the energy of the proton beam considerably exceeding the energy spread of the primary proton beam (this spread in SPS is less than 50 MeV). In order to improve the impending bunching, it is useful to add modulation at the higher harmonics as well. The subsequent conversion of the energy modulation of the beam into density modulation for ultrarelativistic particles such as high-energy protons is optimally performed with a bending modulator. With a correct choice of the radius of bending and focusing structure of the modulator, the path length will depend on the energy of the protons (in the "normal" case the path length increases with increasing energy, and correspondingly, protons of lower energy will overtake protons of higher energy along the bend). Let bending be interrupted at the instant when protons of all energies within the limit of one wavelength are aligned in one azimuth to the accuracy of the intrinsic energy spread of the beam and the degree of approximation of the effective energy modulation to a sawtooth distribution. Then the beam emerging from the modulator will have the maximum content of the required harmonic of the current. After this operation the proton beam is directed into the appropriate linear accelerating structure having the necessary magnetic quadrupole focusing to keep the protons within the apertures of the diaphragms of the waveguide. There are no longer any further relative longitudinal displacements of the ultrarelativistic particles during their rectilinear motion.

One can employ as the bending modulator either a special magnetic tract, through which the emitted proton beam is passed after energy modulation, or the ring of the basis proton accelerator. In the latter case one can set up a linear accelerator (of energy of the order of 100 MeV) in one of the rectilinear sections of the basis ring accelerator outside the working aperture. After finishing the accelerating cycle, the beam is "ejected" at a single time into this modulating linac, while the required density modulation of the beam arises in the subsequent motion in the bending region.

c) Let us pass such a density-modulated beam of ultrarelativistic protons through a linear accelerating structure tuned to the wavelength λ corresponding to the first modulation harmonic. A high-frequency field will be excited in this structure that decelerates the protons, which will transfer their energy to the electromagnetic field. At first the amplitude E_0 of this field will increase in proportion to the total charge eN of the protons that have passed through the given cross-section:

$$E_0 \approx 10^2 \frac{eN}{\lambda^2} = 1.5 \cdot 10^{-11} \frac{N}{\lambda^2_{\text{cm}}} \, (\text{MV/cm}).$$

This increase will continue up to the intrinsic decay time τ_d in the system, which is proportional to $\lambda^{3/2}$. For $\lambda = 1$ cm it amounts to about 20 ns in a copper waveguide. Yet if the time of passage of the proton current is much larger than τ_d, an amplitude of the electric field is established in the structure that is proportional to the mean proton current I:

$$E_0 = 2IR \approx 3 \frac{I_{\text{A}}}{\sqrt{\lambda_{\text{cm}}}} \, (\text{MV/cm}).$$

In the latter formula R is the lineal impedance of the structure and I_A is the proton current in amperes. Here we have assumed that the electron loading arising from cold emission caused by the large excited elastic field is still negligibly small.

If one directly employs the proton current of the contemporary record-setting high-energy accelerators, one can obtain in a structure having $\lambda = 1$ cm an established (within the time of rotation in these accelerators, which amounts to about 20 μs) field amplitude of about 0.6 MV/cm. Even a relatively small preliminary bunching of the proton beam will enable one to obtain an effective field up to 1.5 MV/cm in the accelerating structure, which is at the limit for the electric strength of the surface. The total time of existence of this field will be proportionally smaller than without this bunching. If one injects any type of ultrarelativistic particles into the accelerating phase (for the given sign of charge of the particles) along with the exciting proton beam, one can accelerate them at a rate of 60–150 GeV/km, respectively.

Thus one can accelerate particles up to an energy approaching the limiting energy of the basis accelerator. The limiting intensity of the accelerated beam will amount here to about 10% of the intensity of the basis accelerator (with a monochromaticity of the order of a percent).

Upon dividing the primary beam into several bunches of sufficient length and passing them separately (with the correct time shift) through consecutive linear accelerating structures, each of which brings about almost complete braking of the primary beam, one can make the particles being accelerated pass successively through all the accelerating structures, while proportionally elevating the energy of the accelerated particles as compared with the energy of the basis accelerator. Naturally, the limiting intensity of the beam of accelerated particles will be proportionally lower.

The needed redistribution in time of the individual parts of the exciting beam—the spent and the "fresh" bunches must arrive simultaneously at each new section—can be carried out with different schemes. Logically the simplest is to install in the tunnel of the main accelerator some additional pulsed magnetic small-aperture full-energy tracks having somewhat different periods of reversal for particles with a given momentum, and to admit each bunch, which occupies its corresponding fraction of the perimeter of the accelerator, into its own track. When all the bunches coincide in azimuthal position one must, after the operation of short-wavelength modulation of the density of each of the bunches, release them and direct them toward the corresponding sections of the linear accelerating structure. This same operation can also be performed with long delays in channels, although this requires additional tunnels.

d) In order to confine the particles of both the exciting and the accelerated beams within the apertures in the diaphragmed waveguide of the linear accelerating structure, one requires sufficiently hard focusing. Here one must attain simultaneous stability of the transverse oscillations of particles with sharply differing momenta. Estimates show that the beams of modern proton accelerators will pass through almost without losses when one attains the optimal quadrupole focusing for accelerated particles having a momentum of several GeV/c, even for waveguides in the centimeter range.

Another problem involving the passage through the same structure of ultrarelativistic particles having sharply varying γ-factors, and hence somewhat differing velocities, is to effect the correct relative phasing of these particles. In order to remove the consequences of the gradual lag of the particles having lower velocity, after each section of length $\lambda\gamma^2_{\min}/2$ one must separate the exciting beam and the beam being accelerated and retard one beam with respect to the other by about $3\lambda/4$ via a difference in the path lengths to the entrance to the next accelerating section. This method allows one simultaneously to rid the beam being accelerated of particles having different masses.

e) As I already pointed out, the obtaining in linear accelerators of a rate of energy gain of the order of 100 MeV/m enables one to accelerate even unstable, but relatively long-lived particles—muons and charged pions. However, the acceleration of charged kaons requires a rate of acceleration greater than 300 MeV/m. Apparently such gradients unavoidably cause a complete shunting of the structure by cold-emission electrons. Correspondingly, one cannot obtain such a field by the gradual growth of energy stored in the waveguide.

An interesting possibility of obtaining gradients at the needed level based on the proton klystron has been proposed in Ref. 36. If one collects the number N of protons formally necessary for obtaining the gradient of interest in one short bunch of length equal to the distance between the diaphragms of the accelerator waveguide, then a maximum of the decelerating field will be attained within the proton bunch of the approximately equivalent quantity

$$E_{\max} \approx 10^{-12} \frac{N}{a^2_{\mathrm{cm}}} \,(\mathrm{MV/cm}).$$

Here a is the distance between the diaphragms of the waveguide and the diameter of their apertures.

In the language of eigenmodes of the waveguide, we can say that a solitary bunch simultaneously excites several (azimuthally symmetric) harmonics whose amplitudes add up within the limits of the length of the exciting bunch.

The electric field intensity at the surface of the diaphragms attains the same magnitude as in the center of the bunch, though for a very short time. Therefore a large shunting electron current necessarily arises. However, this no longer necessarily succeeds in substantially affecting the magnitude of the retarding field inside the bunch. One must only take care that the residual electromagnetic field excited by the bunch does not release its energy at the surface of the diaphragms. In order to do this, one can leave the diaphragms open on the outside, and place a strongly absorbing material at a sufficiently great distance from the diaphragms instead of the outer coaxial waveguide.

The method that I have just described enables one to accelerate even shorter bunches of particles of the opposite sign (i.e., negative particles inside a bunch of protons) inside a bunch of the exciting particles. In order to obtain a rate of acceleration of the order of 300 MeV/m, which constitutes the necessary minimum for accelerating negative kaons, one must form half-centimeter bunches of ultrarelativistic protons with 10^{12} protons per bunch. In the metnioned large proton accelerators, this number of protons occupies 3×10^{-3} of the perimeter of the accelerator (with account taken of the bunching coefficient). This amounts to about 20 meters. In obtaining the needed bunch, the energy spread (about 50 MeV) existing in the accelerator must increase owing to the pure longitudinal compression, at least up to 200 GeV (almost 50% of the total quantity). Apparently, technically, this operation can hardly be performed.

The realization of the method can be facilitated by employing the smallness of the transverse emittance of the proton beam and increasing the lineal density of the beam by transverse combination of individual segments of the proton beam, which initially extends along the entire perimeter of the basis accelerator. For example, one can do this by releasing part of the beam from the accelerator and subsequently reinjecting it with the necessary time lag, including use of additional tracks (see Sec. 5c). A multiple compression of this type can be carried out somewhat more chearply if the complex already contains two rings at full energy (Main Ring-Doubler, ISABELLE, UNK).

f) Now let us examine in somewhat greater detail the potentialities of the variant of acceleration described in Sec. 5.

If the conditions given above are satisfied, the acceleration of stable charged particles (if their velocity is close enough to the speed of light at the outset) gives rise to no difficulties, independently of the type of particles. It is of interest both to increase the energy of protons (with injection of a fraction of the primary protons in the accelerating phase of the hf potential) and to accelerate preliminarily stored and cooled antiprotons and ions, or to accelerate electrons and positrons without the restrictions associated with the catastrophic growth of synchrotron radiation characteristic of ring accelerators (in linear acceleration the losses in noncoherent radiation are negligibly small). It is of especial interest to accelerate polarized particles of all types—since with linear acceleration the depolarizing effects can be made very small.

Accelerators based on proton klystrons can be of greatest interest for accelerating unstable particles. The required rate of acceleration $\mathrm{d}E/\mathrm{d}S|_0$ from the energy E_i to the energy E_f while the number of particles in the beam being accelerated is decreased by decay from N_i to N_f is given by the formula

$$\frac{\mathrm{d}E}{\mathrm{d}S}=\frac{mc}{\tau_0}\,\frac{\ln(E_f/E_i)}{\ln(N_i/N_f)}\,.$$

Here m and τ_0 are the mass and lifetime of the particles in their own frame of reference.

For muons the quantity mc/τ_0 amounts to 1.6 keV/cm, and 0.18 MeV/cm for pions. We see directly from this that a linear accelerator with a rate of gain of energy of about 1 MeV/cm enables one to accelerate both muons and pions to the limiting energy with small intensity losses.

As I have already said above, it is rational to cool a muon beam before acceleration by ionization cooling, and to bunch the muons into regions close to the maxima of the accelerating voltage with a bending modulator prior to injection. It is desirable to perform the needed bunching of pion beams to be injected into the superlinac by bunching the high-quality primary proton beam used for generating the pions.

In the method being discussed, kaons can be accelerated only by using the technique described in Sec. 5e.

g) The use of superlinacs with proton klystrons allows one in principle to perform many experiments with the colliding beams described in Sec. 4 on the basis of existing superhigh-energy proton accelerators, or those under construction or in planning, if one can achieve the required luminosity.

In order to create $\pi^+\pi^-$ colliding beams, after one has accelerated the pions in a superlinac, one must inject them into a magnetic track with an extremely high value of the magnetic field (in order to increase the number of collisions per lifetime). In this case the limiting mean luminosity $L_\Sigma^{\pi\pi}$ will be

$$L_\Sigma^{\pi\pi}=\frac{\zeta\dot{N}_\mathrm{p}}{l_\mathrm{t}^{\mathrm{eff}}}\,\frac{N_\pi}{l_\pi}\,\frac{p_\pi p}{(m_\pi c)^2}\,\frac{eH\tau_\pi}{2\pi m_\pi c}\,.$$

Here ζ is the efficiency of proton-pion conversion; $\dot{N}_\mathrm{p}$ is the number of protons supplied by the basis accelerator per second; N_π is the number of pions in one superbunch; $l_\mathrm{t}^{\mathrm{eff}}$ is the effective length of the optimized conversion target; l_π is the length of a pion superbunch in the magnetic track, and at the same time, the value of the beta-function at the collision site; p_π is the momentum of the pions after conversion, p is the momentum of the accelerated pions; H is the value of the magnetic field in the track where the collisions occur; and τ_π is the intrinsic lifetime of a pion.

If we assume that $\dot{N}_\mathrm{p}=10^{13}$ p/sec, $N_\pi=10^{11}$, $\zeta=10^{-1}$, $p_\pi=5$ GeV/c, $p=500$ GeV/c, $H=100$ kG, $l_\mathrm{t}^{\mathrm{eff}}=1$ cm, and $l_\pi=1$ m, then we obtain the following limiting luminosity:

$$L_\Sigma^{\pi\pi}=3\cdot10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,.$$

In principle, this suffices for experiments to study the fundamental properties of the strong pion-pion interaction.

When one employs the same system for pion-proton experiments with substitution of protons for the positive pions, the limiting mean luminosity is

$$L_\Sigma^{\pi\mathrm{p}}=L_\Sigma^{\pi\pi}\,\frac{N_\mathrm{p}^1}{N_\pi}\,.$$

With a number of particles $N_\mathrm{p}^1=10^{12}$ in one proton bunch and with the other parameters as before, this gives

$$L_\Sigma^{\pi\mathrm{p}}=3\cdot10^{28}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,.$$

If we utilize the system being discussed to perform muon-nuon experiments with colliding beams while using muon beams with ionization cooling (under the condition of keeping the normalized emittance of the muons at collision equal to their emittance immediately after the ultimate ionization cooling), then we obtain the following limiting mean luminosity;

$$L_\Sigma^{\mu\mu}=\frac{\zeta\dot{N}_\mathrm{p}}{l_\mathrm{c}}\,\frac{N_\mu}{l_\mu}\,\frac{p}{2m_\mathrm{e}c}\,\frac{eH\tau_\mu}{2\pi m_\mu c}\,.$$

Here l_c is the length of the ionization-cooling target, which is equal to the value of the beta-function of the cooling agent in the region of the target; m_e is the mass of an electron. Upon assuming that $l_\mathrm{c}=1$ cm and $l_\mu=5$ cm, with the rest of the parameters as given above, we obtain an estimate for the limiting luminosity:

$$L_\Sigma^{\mu\mu}=3\cdot10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,.$$

Superlinacs excited by proton klystrons can be used also for performing experiments with electron-positron linear colliding beams. If one employs the approach and estimates described in Sec. 6, then with the "standard" productivity of the proton accelerator of $\dot{N}_\mathrm{p}=10^{13}$ p/sec, the limiting electron-positron luminosity will be

$$L_\Sigma^{e^+e^-}=10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,.$$

A luminosity at this level is already of interest; moreover, the productivity of synchrotrons is expected to increase even further.

6. THE VLÉPP PROJECT

Finally I want to say something in greater detail about the VLÉPP project, which has already been reported several times at conferences and meetings, but is still insufficiently well known to the physics community.

a) First a bit of history. The Novosibirsk report at the International Seminar on Perspectives in High Energy Physics (Morges, Switzerland, 1971)[57] said the following:

"Perhaps the most interesting topic in high-energy physics is lepton-lepton interactions at energies as high as possible...

One of the ways of studying these reactions at energies of hundreds of GeV is to build two ordinary electron (or positron) linear accelerators with as high as possible a power of the generated beams and to learn to compress the transverse dimensions of the beams to about ten microns, while attaining the same degree of accuracy of converging them. If this is successful, one can obtain a luminosity of 10^{31} cm^{-2} s^{-1} for a beam power of 10 MW.

Another way of studying electron-positron reactions at these energies will be opened up by developing and gaining experience with superconducting linear accelerators.[3)] In this case the opportunity arises of dispensing with storage of a large active power in the beam. Here one of the beams is accelerated in the first half of the accelerator and decelerated in the second half, while the other beam, which is moving in the opposite direction, is accelerated in the same accelerating structure in the second half of the accelerator and decelerated in the first half (thereby the beams exchange their energy, while the HF generators must only maintain the accelerating field in the unloaded accelerating structure). In this case no HF power is expended, and a maximum energy of reaction will occur at the midpoint of the whole accelerator. In this variant of colliding beams it is very complicated to estimate the luminocity at all definitely. Yet it seems that it can be higher (and even much higher) than in the former case." In the latter variant one plans to carry out the bending of the electron and positron beams at an energy of several GeV. This does not lead to extreme losses by synchrotron radiation, and at the same time, ensures an effective radiation cooling, which allows one to store and compress the beams.

As we see from the above quotation, we then estimated the prospects more optimistically for superconducting linear colliding beams. However, the subsequent advances in obtaining and working with colliding electron-positron beams with a transverse dimension at the collision site of several microns (VÉPP-2M), together with the difficulties in attaining a high rate of acceleration in superconducting structures, which makes super-high-energy linear accelerators based on them extremely unwieldy, compelled us to concentrate our efforts on developing colliding linear electron-positron beams based on pulsed linear accelerators with a maximal rate of acceleration.

As a result, at the International Seminar "Problems of High-Energy Physics and Controlled Thermonuclear Fusion", which was held in Novosibirsk in April 1978 and was devoted to the 60th birthday of Academician A. M. Budker, who unfortunately did not survive to this jubilee, we were able to present the first relatively detailed project of electron-positron colliding beams at an energy of reaction of 200–500 GeV—the VLÉPP project, which has subsequently been reported at many conferences and meetings.[9]

Let us briefly discuss this project in the form in which we visualize it today.

b) As I have already said, the general idea of VLÉPP consists of employing two linear accelerators "shooting" bunches of electrons and positrons at one another. In this form the idea looks trivial. However, an analysis of the potentialities of modern linear accelerators shows that their parameters fail by several orders of magnitude from satisfying the requirements for having a sufficiently high luminosity (one must have very intense bunches with extremely small emittance), satisfactory energetics and dimensions of the installation.

Evidently the luminosity of such an installation is estimated to be

$$L=\frac{N^2}{4\pi\sigma_x\sigma_z}f.$$

Here N is the number of particles in each of the colliding single bunches, $4\pi\sigma_x\sigma_z$ is the effective area of the cross-section of the beams at the collision site; and f is the frequency of repetition of the cycles.

To attain satisfactory energy characteristics, a linear accelerator must operate at a frequency of repetition of 10–100 Hz. For the same reasons, and also because of the growth of complexity of the "large-current" problems, the number of particles being accelerated cannot be raised substantially above 10^{12} particles per bunch. Therefore, in order to attain the necessary luminosity of the order of 10^{32} cm^{-2}s^{-1}, the area S of the cross-section at the collision site must be very small—of the order of several square micrometers. Correspondingly, one must know how to make the emittance of the beams (for the case of a circular cross-section) unprocedentedly small, even with optimal focusing and length of the bunches of only about 1 cm. This quantity is of the order of

$$\frac{\Omega}{\pi}=\frac{S}{l}\approx 10^{-8}\ \text{cm}\cdot\text{radian}\,.$$

Both the obtaining of intense bunches of such a small emittance and the maintaining of the latter during the acceleration process are extremely complicated problems. Yet it has been possible to show them to be solvable.

In order to accelerate 2×10^{12} particles to 100 GeV, one must provide an energy of about 30 kJ; here the total energy stored in the accelerating structure must be no smaller than 150 kJ. It must be transmitted to the accelerating structure from the UHF generators in a time smaller than the decay time of the electromagnetic field in the structure. For a wavelength $\lambda=5$ cm, this amounts to about 2×10^{-7} s. This implies that the total power of the UHF generators must be of the order of

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[3)] We note that a similar scheme for electron-electron colliding beams with direct injection was first considered, so far as we have since found out, by M. Tigner in 1965.[72]

10^{12} W, while the needed power of one generator, assuming one generator for each GeV of the accelerator, will reach 5 GW. This exceeds by two orders of magnitude the record power of commercially available generators with a wavelength of the order of 10 cm. However, as I have said above, the progress in developing high-power electron beams offers real grounds for assurance of the solution of this problem in the near future.

The quest to have the dimensions of the installation as small as possible, as well as to simplify the solution of the problem of conserving the emittance of the beams during acceleration, compels one to resort to superlinacs with a rate of acceleration about 100 MeV/m. The analysis that has been performed and experiments have shown this problem also to be solvable.[9,10]

Thus the problem of building the VLÉPP consists in developing linear accelerators with a rate of acceleration of about 100 MeV/m, which would make it possible to accelerate single bunches of electrons and positrons about 1 cm long with 10^{12} particles per bunch. This should make it possible to have a very small emittance of the beams at the output with adequate monochromaticity. One must also build highly efficient UHF generators that are finely controllable in amplitude and phase with a wavelength of about 5 cm, and with a power per pulse of several gigawatts at a repetition frequency of tens of hertz. It is also extremely desirable to have the possibility of operating with polarized colliding beams of electrons and positrons.

c) One can represent the overall scheme of the apparatus as follows (Fig. 3).[9] Two superlinacs of energy, say, 100 GeV, each 1 km long, fed by high-power UHF supplies set 10 m apart, "fire" single bunches 1-cm long toward one another, each containing 10^{12} polarized electrons or positrons, with a cycle frequency of the order of 10 Hz. After collision at the collision site, the bunches are slightly deflected with a pulsed field into a small-angle analyzing system, which enables one to measure the energy spectrum of the colliding particles. After the analyzer, the bunch enters a conversion system, which amounts to a long, helical magnetic undulator. While passing through the latter the particles emit about 1% of their energy in the form of circularly polarized photons with an energy about 10 MeV.[62] Then the remaining polarized beam is slightly deflected and is directed, e.g., into special shambers for performing experiments with stationary polarized targets, while the photons enter a converter. The longitudinally polarized particles of the required sign generated in the target (the upper part of the spectrum is taken) are collected and accelerated at a high rate to an energy of about 1 GeV. Then the polarization of the particles is converted to transverse (vertical), the length of the bunch is increased by an order of magnitude, and the particles, after preliminary radiation cooling in a storage ring having a large acceptance, are transferred to a special ring cooler, where the emittance of the beam "decays" to the necessary very small value (which is not at all simple to attain for 10^{12} particles per bunch). After complete cooling, the beam is transported without aberrations to the injector end of the superlinac. Before injection the beam is shortened to 1 cm, while the polarization of the particles is converted as desired. Next follows the acceleration at the limiting high rate of acceleration and special measures are taken to prevent an increase in the emittance. After acceleration, the bunches are focused at the collision site in an ellipse with an effective area about 10 μm^2 and the cycle is then repeated.

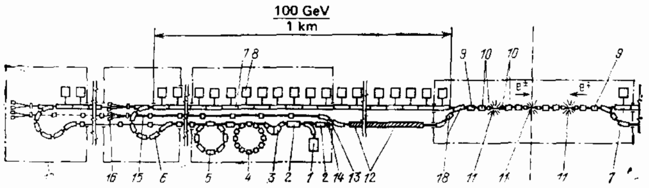

FIG. 3. General diagram of the VLÉPP installation. 1—initial injector, 2—intermediate accelerator, 3—debuncher-monochromator, 4—storage ring, 5—cooler-injector, 6—buncher, 7—accelerating sections, 8—UHF supply, 9—pulsed deflector, 10—focusing lenses, 11—collision sites, 12—spiral undulator, 13—beam of γ-quanta, 14—conversion target, 15—residual electron beam, 16—experiments with electron (positron) beams with a stationary target, 17—second stage, 18—spectrometer.

d) Let us discuss in somewhat greater detail the electrodynamics of the accelerating structure and the acceleration process. In our case the UHF generators initially "pump" energy into the sectioned structure with the necessary shift in the times of excitation of each section with the correct phasing so that the bunch being accelerated travels all the time at full amplitude and in the required phase. Then a bunch to be accelerated having a length much smaller than the wavelength of the accelerator is injected.

A nontrivial result of analyzing the acceleration process[61] consists of the fact that, if one selects the length of the bunch containing the necessary number of particles, one can obtain after acceleration a high monochromaticity by transferring to the electrons a considerable fraction of the energy stored in the structure. Thus, an ultrarelativistic 1-cm-long bunch containing 10^{12} electrons carries away 20% of the stored electromagnetic energy upon passing through an accelerating structure with a wavelength of 5 cm with an effective rate of acceleration of 100 MeV/m (another 20% will be converted into the parasitic energy of the higher modes of excitation of the structure). Here the energy spread after acceleration will be about 1% and the particles will be accelerated up to 80% of the limiting energy. We note that the so-called π-structure, in which adjacent resonators are excited in counterphase, is optimal for working in a stored-energy regime. Moreover, such a structure allows one to accelerate particles in both directions.

e) The problem of conserving the small value of the emittance of the beam during acceleration has proved to be considerably more complicated.[61]

When a bunch is moving strictly along the axis of an accelerating structure that amounts to a periodically constricted waveguide, the particles are practically not subject to transverse forces exerted by the overall HF field. Upon deviating from the axis, each particle emits an asymmetrical mode whose field, as formed at a diaphragm of the waveguide, gradually overtakes the bunch. In ultrarelativistics, this field cannot overtake the segment of the bunch that gave rise to it, but it exerts its full transverse action on all the parts of the bunch that follow it. A segment of the bunch that has undergone this action will deviate ever more from the axis, thus giving rise to an ever stronger perturbing action on the following regions. The sum of the actions of all the diaphragms of the accelerating system, even if installed to an accuracy of a micrometer, leads at the required intensities to a completely inadmissible increase in the effective emittance of the beam, and thus to a catastrophic decline in the luminosity.

It has proved possible to overcome this unpleasantness by introducing into the acceleration process a large energy gradient of the particles along the bunch with sufficiently strong focusing with quadrupole lenses. Under these conditions the frequencies of the transverse oscillations of the successive regions of a bunch will differ sufficiently, and the described instability will not develop. Figure 4 shows the results of a numerical modeling of this effect that confirmed the possibility of eliminating the increase in emittance. Indeed, stringent requirements appear in this case on the accuracy of alignment of the focusing lenses (of the order of 1–10 μm in a length of the order of that of the transverse oscillations of the particles). The final alignment of the lenses and stabilization of their positions will be performed directly by measuring the transverse motion of the bunches.

Toward the end of acceleration, the difference in the energies of the particles along a bunch declines from the initial ±10% to the required spread of 1%.

f) Let us examine now what happens in the collisions of such dense bunches.[51]

The electric and magnetic fields of bunches of the intensity under discussion attain megagauss magnitudes for dimensions of μm. For the particles of "their own" bunch the forces exerted by the electric and magnetic fields mutually compensate and exert no influence on the behavior of the particles. At the same time, their actions on the particles of the counterbeam add up, and the maximum effective field is doubled:

$$|\mathbf{H}_{\mathrm{eff}}| = |\mathbf{H}| + |\mathbf{E}| = \frac{4N_e}{l(\sigma_x+\sigma_z)}.$$

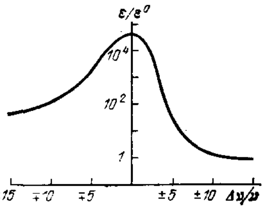

FIG. 4. Results of numerical modeling. $\varepsilon/\varepsilon^0$ is the ratio of the emittance of the accelerated beam to the initial emittance; $\Delta\nu/\nu$ is the frequency difference in the transverse oscillations of the particles at the beginning (or end) and the middle of the bunch.

Here σ_x and σ_z are the transverse half-dimensions of the beam at the collision site, and l is the length of a bunch.

Let us examine briefly three aspects of the influence of these fields.

First, in this field the particles emit synchrotron radiation, and here the distance for total energy loss proves to be very small:

$$l_{\mathrm{rad}} = \frac{mc^2}{r_e^2\gamma H_{\mathrm{eff}}^2}.$$

The energy spread of the reactions will correspond here to the energy spread in the beam

$$\frac{\Delta E}{E} \approx \pm\frac{1}{8}\frac{l}{l_{\mathrm{rad}}} = \pm\frac{2r_e^3N^2\gamma}{l(\sigma_x+\sigma_z)^2}.$$

Consequently, instead of collision of monochromatic electron-positron bunches, we obtain for $\sigma_x=\sigma_z$ a diffuse spectrum of e^+e^- reactions, together with a multitude of *γe and $\gamma\gamma$ collisions. Therefore one must resort* to planar bunches, while conserving the cross-sectional area to maintain the luminosity. As we have seen, the fields here decrease in proportion to the increase in the width of the bunch.

Second, the field of the counterbeam of particles of the opposite sign exerts a strong focusing action. Consequently, during the time of collision of the bunches, the particles execute several oscillations. Here no increase in the effective dimensions occurs in head-on collisions for bunches having a smooth density distribution in all directions (there is even a small constriction). This has been shown by numerical modeling of the self-consistent collision. We note that the effect being discussed sharply diminishes the attainable luminosity of electron-electron (or e^+e^+) colliding beams (defocusing!).

The third important effect of the coherent fields of the counterbunch is their action on the behavior of the spins of polarized colliding beams. The rotation of the spin with respect to the velocity of the particles that arises from the anomalous magnetic moment when the angles of the transverse oscillations of the particles in the field of the counterbunch are too large completely depolarizes the electrons and positrons in the process of collision. The allowable angles in the beam here amount to

$$\theta_{\mathrm{all}} \approx \frac{1}{3}\frac{g_0}{g'\gamma} = \frac{0{,}15}{E_{\mathrm{GeV}}}.$$

In order to fulfill this condition (in the case of longitudinal polarization), we must have

$$\alpha r_e\frac{N}{\sigma_x+\sigma_z} \lessdot 1,\ \alpha=\frac{1}{137}.$$

Going over to plane beams solves this problem as well.

However, the decrease in one of the dimensions of the bunches to such small magnitudes requires a quadratic decrease in the emittance of the beam in this direction. If this requirement proves too difficult to satisfy technically, one can resort to the variant of collision having four bunches in each collision—an electron and a positron bunch each side. If the bunches moving from each side are superimposed on one another up to the collision site, then their coherent fields mutually compensate (to the accuracy of the matching of the bunches and of superposing them). Therefore all the effects of the collision are sharply weakened and cease to play a deleterious role. Here the singleness of the collision of the bunches prevents the instabilities from developing that one faces in the DCI storage ring in working in a four-bunch regime. It is logically simplest of all to obtain four bunches by employing four independent accelerators, but one can also simultaneously accelerate electron and positron bunches in a single accelerating structure with a shift of one-half wavelength between them, with a subsequent delay in the leading bunch.

Perhaps the use of a regime of compensated bunches will allow a substantial increase in the luminocity of VLÉPP. We note that in this regime half of the total luminosity will be due to e^+e^- reaction, while the other half is divided equally between e^-e^- and e^+e^+collisions. A defect of this regime of operation is the impossibility of measuring the charge asymmetry of the processes being studied.

g) It has been recently acknowledged that the spectrum of obtainable reactions on the VLÉPP can be expanded further.[73] Laser technology is approaching the stage that enables one to create highly effective photon targets (in any case of small transverse cross-section). Owing to the inverse Compton effect, they allow one to convert the major fraction of the electrons immediately before collision into γ-quanta having an energy close to the total energy of the particles being accelerated. Therefore the possibility arises of attaining real photon-photon colliding beams at superhigh energies.

Let us examine briefly the fundamental problems involved in performing these experiments, while paying attention only to the points specific to the operation of VLÉPP in this special regime.

At an energy of the primary photons of $E_{\gamma 1} \approx mc^2/\gamma$ (and all the more so if higher), photons of almost the total energy E will travel at an angle $1/\gamma$ with respect to the direction of motion of the scattering electron. Let the effective length of the primary photon pulse be smaller than the length of the electron bunch l_e, while the light beam is focused to the diffraction limit with an area of λl_e, where λ is the wavelength of the primary photons, this area remaining larger than the area of the electron beam in this region. Then, in order to obtain an efficiency of conversion $\varkappa$, the required total energy E_Σ^{phot} in the photon pulse will be

$$E_\Sigma^{\text{phot}} \approx \frac{2\varkappa mc^2 l_e}{\alpha r_e}.$$

The most promising variant of generating such photon pulses is to use coherent radiation in the appropriate with self-bunching undulators/(mirror-free electron laser) of the electron beams by the VLÉPP installation itself[74]: for these beams will have a very high local density, very small emittance, and small local energy spread, while the emission spectrum in the technically suitable undulators with an electron energy of several GeV falls in the required range.

Of course, the parameters of the high-energy electron beams remaining after passing through the laser targets must make possible the recycling of the electrons for further cycles.

The angular spread (at the given point) of the electrons in the VLÉPP outside the collision site is much smaller than $1/\gamma$. Therefore, if one places the photon target in the convergent electron flux at the small distance L_0 from the collision point, then the useful photons of energy E will form a spot with the area $\pi\,(L_e/\gamma)^2$. One must introduce a magnetic field of moderate magnitude between the photon targets and the collision site in order to displace the electron beams at the collision site by an amount larger than the dimension of the electron spot (from this standpoint, it is favorable to operate precisely in the electron-electron regime). To do this, in particular, L_0 must be large enough. Then only γ-quanta of full energy will effectively collide, with a limiting luminosity of the order of

$$L_{\gamma\gamma} = \frac{N_\gamma^2}{S_{\text{eff}}^{\gamma\gamma}} f = \frac{\varkappa^2 N_e^2 \gamma^2 f}{2\pi L_0^2}.$$

The energy spread of the $\gamma\gamma$-reactions will be about 10% here. When necessary, the monochromaticity of the reactions can be improved by using lasers of shorter wavelength (with a proportional increase in the energy per laser pulse).

If only one electron beam is converted into photons, then one can obtain $e\gamma$ colliding beams of almost full energy with an even smaller energy spread, and with the luminosity

$$L_{e\gamma} = \frac{N_e N_\gamma}{S_{\text{eff}}^{\gamma}} f = \frac{\varkappa N_e^2 \gamma^2}{\pi L_0^2} f.$$

I note that, while the conditions of the e^+e^- collision in an uncompensated regime must be chosen so as to keep the field of the bunches from being too large, this restriction does not exist for $\gamma\gamma$- and $e\gamma$-collisions, and in principle, the luminosity can be even higher.

For an energy per laser pulse of the order of 10 J, one can relay, even at an energy of 2 × 100 GeV, on obtaining sufficiently monochromatic colliding $\gamma\gamma$- and $e\gamma$-beams in the VLÉPP, with the luminosities

$$L_{\gamma\gamma} \gg 3 \cdot 10^{30}\ \text{cm}^{-2}\ \text{s}^{-1},$$
$$L_{e\gamma} \gg 1 \cdot 10^{31}\ \text{cm}^{-2}\ \text{s}^{-1}.$$

I note that one can obtain a luminosity of photon-photon collisions approaching that of electron-positron (or electron) colliding beams only in instruments having single collisions of bunches of accelerated particles. Storage rings do not have this potentiality.

The study of $\gamma\gamma$- and $e\gamma$-interactions, with arbitrarily selected helicities of the interacting particles (by an appropriate choice of the polarization of the laser beam), can become an important expansion of the potentialities of the VLÉPP installation.

With regard to the main bulk of events involving creation of hadrons, $\gamma\gamma$-collisions will resemble hadron-hadron collisions at the same energy, while $e\gamma$-reactions will provide information close to that obtained in deep inelastic ep-reactions.

Here the total cross-section for creation of hadrons in $\gamma\gamma$-collisions will apparently be very large—of the order of 0.3 microbarn. The major fraction of these events will yield hadrons traveling at very small angles from the direction of the photons. Hence it will be difficulty accessible to study, although in principle one can separate the primary γ-beams and the created charged hadrons with a magnetic field.

It is more promising to study the electromagnetic creation of quark (and antiquark) jets. Here, for all types of quarks having a mass much smaller than the energy of the photons, the cross-sections for jet formation are the same (with account taken of the ratio of the squares of their charges). Here the photon-photon collisions will have a radical advantage over pp- and $p\bar{p}$-colliding beams, whose quark composition sharply favors the creation of jets containing u, $\bar{u}$-, d-, and $\bar{d}$-quarks. Moreover, $\gamma\gamma$-collisions efficiently yield also gluon jets. The partial cross-section of these processes at energies of hundreds of GeV is of the order of 10^{-35} cm^2. Hence it is accessible in principle to study in the VLÉPP.

In the electro-weak interaction region, it seems especially interesting to study the reactions

$$\gamma\gamma \to W^+W^-.$$

The cross-section of this process is of the order of 10^{-34} cm^2, and it does not decline with energy in the first approximation (in contrast, e.g., to $e^+e^- \to W^+W^-$). The study of this process allows one to get information on the as yet completely unstudied γW^+W^- vertex (anomalous magnetic moment of W, electromagnetic form factor of W, etc.).

The same vertex can be studied in the reaction

$$\gamma e^{\pm} \to W^{\pm}\nu,$$

whose cross-section is at the same level, while the threshold is somewhat lower. A feature of this reaction is the singleness of the W created, which enables one to deal very cleanly with the decay properties of these bosons. Moreover, the dependence of the $e\nu W$ vertex on the helicity of the electron is manifested very sharply here.

h) Now let us examine certain features of the performance of experiments in the VLÉPP installation. VLÉPP differs from the usual colliding-beam systems in that the collisions of the bunches occur very rarely—tens of times per second—with a high total luminosity per collision. This situation complicates the distinguishing of events, including tuning out of background reactions.

The most fundamental restriction of the useful luminosity per collision of bunches is the fact that the total cross-section for electrodynamic processes of the type

$$e^+e^- \to e^+e^- + X$$

increases rapidly with decreasing momentum imparted to X. Correspondingly, each collision of bunches and each interesting event is accompanied by a large number of charged particles and photons with energies much smaller than the total energy of the initial particles. Hence one must take measures including, e. g., setting an absorbing material in front of the detector, introducing a longitudinal magnetic field, preventing particles at small angles from recording, developing special variants of triggers, etc., in order to make possible the recording, singling out, and analysis of interesting events. Naturally, one can make the probability of superposition of two *interesting* events in a given experiment negligibly small by an appropriate decrease in the luminosity, while keeping the high rate of collection of the statistics of these events.

Another source of background is the photons of synchrotron radiation that accompany the collision, which are created in the coherent field of the counterbunch. As I have said above, these fields must be made small enough that the mean energy loss in synchrotron radiation does not exceed, say, 1%. Here each electron and positron emits several photons, which can interact with the photons and electrons coming head-on. The fundamental background processes of this origin will be the creation of electron and muon pairs. One can combat this background by the methods mentioned above. When one employs a four-beam regime with compensation of the coherent fields, this source of background can be practically completely eliminated.

Also other, more "technical" forms of background can exist. Thus, strongly deflected particles can accompany the bunch of electrons, which has extremely small rms dimensions in the instruments being discussed. Such particles arise, e.g., from single scattering by the nuclei of the residual gas in the last storage ring, or cooler ("halo" of the beam). The interaction of these particles with matter in the region of the detector gives rise to showers at the full energy. Therefore one requires a very high level of "beam hygiene", including a very good vacuum in the storage ring and the linac and installation of special diaphragms far from the collision site.

Another source of technical background can be the entrance into the detector region of the products of interaction of quanta of beam-beam synchrotron radiation with the matter of the vacuum chamber, lenses, etc. This compels one to take measures to keep the site of entrance of these photons into matter sufficiently far removed from the collision site. Then the instant of entrance into the detector of the background particles will be strongly shifted with respect to the events being studied. Moreover, one can by collimation sharply reduce the solid angle, and correspondingly, the total number of secondary particles entering the detector. Naturally, the background from this source disappears in the four-beam regime.

Thus we see that the study (at any rate, inclusive) of the events in which electrons, muons, and photons are created with an energy constituting a considerable fraction of the energy of the initial particles will entail no difficulties. This type of processes include two-particle reactions (electrodynamic, weak, and mixed) and the creation of intermediate bosons. It will also present no fundamental difficulties to study reactions that form hadron jets bearing a considerable fraction of the energy of the primary particles. At the same time, the study of *all* interesting processes will require solution of very complex background problems.

I note that the physical background in studying $\gamma\gamma$- and $e\gamma$-reactions in the VLÉPP will be far lower.

The pulsed nature of the luminosity in the VLÉPP, the high resultant multiplicity of most of the most interesting processes, and also the considerable number of relatively low-energy background particles, compel one to develop highly special detecting systems, especially in their inner, "geometric" track regions. It is not ruled out that one of the possible solutions might be to use hybrid, fast-cycling bubble chambers with electronic hit detection.

I stress that the lean luminosity of the VLÉPP can be distributed among several independent experiments. Here one turns on only one collision site in each given cycle; the sequence of these switchings can be assigned arbitrarily.

i) I recall that the VLÉPP can be employed in a regime parallel with the colliding beams as an accelerator that yields 10^{13} per second of electrons and positrons with any required polarization having the full energy E. Also, if one employs laser conversion of the processed $e^{\pm}$, one can use it as a source of polarized γ-quanta of almost the full energy with sufficient monochromaticity and an intensity of the order of 10^{12} cm^{-1} for experiments with stationary targets.

I also mention that one can obtain very intense, well collimated fluxes of high-energy neutrinos of all types by directing the electron, or especially the photon, beams of the VLÉPP onto a target. Especially interestingly, these fluxes will be sharply enriched in ν_τ-neutrinos from the decay of photocreated τ-leptons (and if they exist, in neutrinos from heavier leptons). Here the flux can be as great as 10^6 ν_τ/sec in an angle $M_\tau c^2/E$ with an energy of the order of $E/4$.

In a special regime one can obtain polarized electrons, positrons, and photons of twice the energy by making the $e^{\pm}$ pass successively through both linacs (the sections of the second linac in this case must operate with a time shift opposite to the normal).

If one supplements the VLÉPP with intense sources of charged pions and cooled nuons, one can then also use it to accelerate them.

TABLE VI. Fundamental parameters of the VLÉPP project.

	1st stage	Complete project
Energy	2×150 GeV	2×500 GeV
Length	2×1.5 km	2×5 km
Luminosity	10^{32} cm^{-2} s^{-1}	
Number of collision sites	5	
Frequency of cycles	10 Hz	
Number of particles per bunch	10^{12}	
Mean beam power	2×250 kW	2×900 kW
Pulsed HF supply power	1000 GW	4000 GW
Total consumed power from the supply mains	15 MW	40 MW

j) Finally, Table VI presents the fundamental parameters of the VLÉPP project.

CONCLUSION

The seventies were characterized by a brisk development of elementary-particle physics. Here the decisive factor was the sharp expansion of our experimental potentialities. The coming decade opens up even more captivating prospects (if only the character of development of science will not be deformed by external circumstances).

To an ever greater extent, it becomes a serious point to apply the developments, methods, and phenomena initially worked out in high-energy physics in quite different fields of science and technology. Important examples of this type are radiation (and especially radiation-chemical) technology, and the use of contemporary systems for charged-particle detection and for processing the experimental data that has begun, e.g., in medicine, and the highly varied applications of the synchrotron radiation of electron storage rings. This situation must facilitate the further attraction of attention to the development of high-energy physics.

In closing, I wish to express deep gratitude to my many associates at the Institute of Nuclear Physics (Novosibirsk), and also to our colleagues from the Institute of Theoretical and Experimental Physics (Moscow), and the Institute of Mathematics of the Siberian Division of the Academy of Sciences of the USSR, the Lenigrad Institute of Nuclear Physics, the Institute of High-Energy Physics, the Stanford Accelerator Center, the University of Wisconsin, the Fermi National Accelerator Laboratory, Cornell University, CERN, and the Hamburg Accelerator Center for numerous fruitful discussions with which they aided the development of the views and approach that have been reflected in this review.

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