LINEAR COLLIDERS

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Abstract

The report treats the role of colliding beam experiments which involve the electrons and photons as the necessary part of elementary-particle physics (the relationship between the possibilities and the field of interest). It is shown that linear colliding beams is the only and real way to ultrahigh energies of electrons and positrons. The fundamental physical and technical problems on the creation of linear colliders are considered. Estimations are made of the achievable luminosities for e^+e^-, $e\gamma$, $\gamma\gamma$, ep, γp and pp polarized colliding beams at total energies of up to 1 TeV. The status of the VLEPP project is described.

1. First of all, we would like to make a few, evident today remarks.

In the last 10 - 15 years the electron-positron colliding-beam experiments have become one of the main sources of fundamental information in elementary particle physics, and their significance will only increase in future[1].

There are several direction in the development of this method. To study narrow resonances (quarkonia) it will be very useful a sharp increase in monochromaticity (by one order of magnitude and higher in the VEPP-4M project[2]). Production of polarized beams in storage rings already bear fruit, in particular, offering the possibility for a sharp raise of the accuracy of the masses of quarkonia[3]. Of special significance will be the experiments with longitudinally-polarized colliding beams[4] whose set up opens up new possibilities in a study of fundamental interactions. There are the possibilities for a sharp increase in the luminosity of electron-positron storage rings in the 'old' energy ranges: from $3\cdot10^{32}$ cm^{-2} s^{-1} at $\sqrt{s}$ = 1 GeV up to $3\cdot10^{33}$ cm^{-2} s^{-1} at $\sqrt{s}$ = 10 GeV.

However, the main line of development remains, no doubt, an increase of the achievable reaction energies. With the use of traditional now cyclic storage rings, in comparison with proton-antiproton storage rings, the basic obstacle for further increase is a catastrophic growth of energy losses because of synchrotron radiation. This circumstance makes the overall dimensions of the facilities to the quadratically increased with increasing their ultimate energy. The prospects of this direction were discussed in detail by B. Richter in 1978[5]. It is likely that the LEP, which is being constructed at CERN, is the terminal point on this path.

The transition to linear colliding electron-positron beams seems to be natural under these conditions. As far as we know, linear colliders as a means of the transition to energies of hundreds of GeV and higher have been first discussed in the Novosibirsk report at the International Seminar on High Energy Physics Prospects in Morges (Switzerland) in 1971[6]. Two possible schemes of such colliders were treated.

The first version was to use two pulsed linear accelerators at full energy. These accelerators 'fire' short bunches towards each other which focus into as small as size as possible at the collision point and are then used for generation of the electrons and positrons involved in the following cycle. The $e^{\pm}$ produced are injected into storage rings and are radiation-cooled down to as low emittances as possible.

The second version was to use superconducting linear continuous-operation accelerators; in this case, the particles accelerated in the first accelerator give off, while slowing down, their energy to the accelerating structure of the second linac and vice versa. Thus, RF power is consumed, mainly, to maintain the field in the unloaded structure. The decelerated $e^{\pm}$ are injected, just as in the first version, into the storage rings and are prepared for the next cycle. The scheme, which includes the superconducting linear accelerators with energy recuperation using injection from electron guns, was suggested by M. Tigner[7] in 1965 as an alternative for the electronelectron beams at an energy of few GeV on the basis of cyclic storage rings and then was extensively discussed in CERN, Cornell, and Hamburg[8,9].

The Novosibirsk group has concentrated its efforts on the development of the first approach, and our already self-consistent project of an electron-positron colliding-beam installation, the VLEPP project, was presented in 1978[10].

The versions of linear colliders in comparison with storage rings and the relevant problems have been treated actively at the international level: ICFA-I (1978), INFA-II (1979), etc. One can say that these discussions have confirmed the fact that the cyclic electron-positron storage rings at an energy higher than 2 × 150 GeV are likely to have no prospects from an economical point of view. As far as the comparison of the versions of linear colliders is concerned, with the use of superconducting continuous-operation linacs, at least at the today's level of technology in this field, the facilities are obtained too long, consume too high power for refrigeration and, hence, the cost of these systems is too high. In view of this, on recent years attention has been paid to the development of pulsed linear colliders.

At present, the project rather close to linear colliders - the SLC project - is in construction at SLAC. A lay-out of the facility is shown in Fig. 1. The now existing linac will be employed, after its modification, as an accelerator, and two bunches accelerated one after another will collide while turning them by magnetic arches. Solution of a variety of the problems connected with the formation of bunches with the required parameters, their 'safe' acceleration, and with organization of collision will become an important stage of the development of singlepass colliding beams. At the same time, an increase in the energy of facilities of this kind higher than 2 × 70 GeV planned for the SLC is practically impossible.

2. Let us treat the specific features, effects, problems and potentialities of linear colliders. We will consider the VLEPP project as a reference. A lay-out of the installation is depicted in Fig. 2. In the basic VLEPP mode of operation, two superlinacs, which are several kilometers long with an energy gain of about 100 GeV per 1 km, fed by high-power RF generators set 10 m apart, 'fire' single 0.5-cm long bunches towards on another, each containing 10^{12} polarized electrons or positrons, with a cycle frequency of the order of 10 Hz. After collision at the interaction point with a very strong focusing (β_z = 0.5 cm) providing the 10 mkm^2 effective beam area, the bunches are slightly deflected with a pulsed magnetic field from the acceleration line and are directed into conversion systems. Each of these systems consists of a long helical magnetic undulator. While passing through the latter, the particles emit about 1% their energy in the form of circularly-polarized photons with an energy of about 15 MeV.

The remaining polarized beams are then removed from the photon propagation line, and are directed either for the stationary target experiments or to the beam dumping. The photon beam enters a target-converter. The upper part of the spectrum of the produced $e^{\pm}$ will be longitudinally-polarized. These particles are collected with a short-focus lithium lens, 'captured' by the superlinac section, and accelerated at a high gain to an energy of 1 GeV with the effective conversion coefficient equal to 1. The beam is then lengthened to 10 cm with a bending expander, and the energy gradient along the bunch is compensated by means of an appropriate accelerating section. Simultaneously, this method allows proportionally to ease the requirements on the energy acceptance of the coolers. The polarization of particles is then transformed into the transverse (vertical), and the particle are injected, correspondingly, into the electron and positron storage rings-coolers. In these storage rings the beams are cooled down to the required, very small emittances (the required emittance in the vertical direction is about 300 m·rad at an energy of 1 GeV). The cooled beam is directed into a bending buncher, the bunches are shortened from 10 cm to 0.5 cm, the $e^{\pm}$ polarization is transformed as required in the given experiment, and the bunches are injected into the main superlinacs of the VLEPP installation. And the cycle is then repeated 10 times for a second. In this case, the luminosity will attain 10^{32} cm^{-2} s^{-1}. All the components of the VLEPP are capable of operating up to 100 cycles second. In view of this, one can increase the luminosity of the collider, utilizing additional power.

3. In the VLEPP installation, the RF generators initially 'pump' energy into the sectioned 1-m long structure with the necessary shift in the times of excitation of each section with correct phasing, so that the bunch being accelerated travels all the time at full amplitude and in the required phase. Then the bunch being accelerated is injected.

The longitudinal bunch dynamics in a superlinac is determined by an accelerating field excited in the structure with an external generator and by a radiation field of the bunch being accelerated. The intrinsic field of an ultrarelativistic bunch has no practical influence on the motion of the 'own' particles. The radiation field in an accelerating waveguide having the azimuthal symmetry can be represented in cylindrical coordinates as a sum over azimuthal harmonics; for example, for $\vec{E}$:

$$\vec{E} = \sum_{m=0}^{\infty} \vec{E}_m \cos m\phi$$

In this case, the harmonics of the longitudinal electric radiation field E_{Hm}, which determines the longitudinal dynamics of the particles being accelerated, are proportional to $r^m\delta^m$, where δ is the deflection from the symmetry axis of the bunch or its part exciting the field, and r is a coordinate of the observation point. It is seen immediately that the longitudinal motion (i.e. the acceleration itself) is mainly influenced by the azimuthal-symmetric harmonic (m = 0).

The calculations [10,12,13], which have been made by solving directly the Maxwell equations for a diaphragmed axisymmetric waveguide excited by the given motion of an ultrarelativistic beam with a smooth longitudinal charge density distribution, have shown that one can transfer to the particles being accelerated a substantial fraction of the energy stored in the accelerating structure, and simultaneously to provide a sufficiently high monochromaticity of the bunch after acceleration, by selecting, in a consistent way, the amplitude of the accelerating field and its wavelength, the passage phase of a single bunch, the length of the bunch, and the number of particles in it. Figure 3 illustrates the distribution of the averaged accelerating field along the length of the bunch in the design project, $N = 10^{12}$ and $\sigma = 4.6$ mm, with an amplitude of the mean external field of 100 MV/m. In this case, the energy gain is 80 MeV/m with a monochromaticity of ±1%; the beam carries away about 30% of the stored energy, and several per cent are converted into the residual energy of the higher harmonics of the field.

4. The transverse motion of intense bunches in a linac proves to be much more complicated and rich[10,12,14], and the solution of the problems of conserving the very small value of the transverse normalized emittance during acceleration gives rise to a considerable complication of the installations. Let us discuss in somewhat greater detail this problem.

The transverse dynamics is determined by the radiation fields of a bunch, the fields of quadrupole lenses, and by the field excited by the external generator. Emphasize once more that the internal field has no influence on the 'own' particles, just as in case of the longitudinal motion.

Let us first examine the action of radiation fields. The azimuthal harmonics of the transverse constituents of these fields $E_{\perp m}$ and $H_{\perp m}$ are proportional to $mr^{m-1}\delta^m$. Correspondingly, the first harmonic turns out to be a determinant one. Therefore, the appearance of transverse forces in a first approximation proves to be connected with the presence of the coherent shifts of the segments of the bunch relative to the symmetry axis of the waveguide (and proportional to them) and is uniform near the beam axis.

The radiation fields of an ultrarelativistic bunch in the diaphragmed waveguide having an influence on a short single bunch can be considered as a result of the diffraction on the diaphragms of the intrinsic, almost plane field of the bunch. The field, which yields the transverse forces, appears upon deviation from the symmetry axis of the bunches' element exciting them. Such a diffracted field, excited by an infinitely short element of the bunch, can reach this element in a free space on the length γr_d, where r_d is the radius of a hole in the diaphragm. It is clear that in our case this field will be already infinitely small because of its attenuation when passing through a large number of diaphragms. For this reason, the self-action of the bunch's element is equal to zero. The actions extented by all the parts of the bunch that follow closely the exciting element is also incomplete because of the mutual compensation of the transverse forces from the electric and magnetic fields of a wave that follows the relativistic particle at a small angle to its velocity. The effective transverse field averaged over the pass between the diaphragms will be maximal for the particles which are left behind at a distance of the order of $2r_d$ from the exciting element. Figure 4 gives the ratio $\bar{G}$ of the averaged effective field acting on the particles of the bunch travelling with a steady shift relative to the symmetry axis of the linac's waveguide to the magnitude of this shift. The quantity $\bar{G}$ is given as a function of the position inside the bunch for the standard parameters of the VLEPP. The action of this field is directed along the shift causing it, i.e. strives to increase to an even larger extent the deviation of the tail elements of the bunch shifted as a whole.

It is evident that such a structure of radiation fields gives rise to the appearance of the instability of transverse coherent oscillations of the bunch traveling in the diaphragmed waveguide. This instability manifests itself in an unlimited growth of the oscillation amplitude raising from the unchanged initial amplitude for the head particle up to the maximum for a tail one. The process of development of this instability is demonstrated in Fig. 5-1 for the standard bunch with $N = 10^{12}$ traveling in the VLEPP waveguide with a constant energy of 10 GeV and with a 12-m wavelength of transverse oscillations of particles (upon focusing with quadrupole lenses).

Figure 5-2 shows the phase picture of the bunch after passage through a 250-m long section. This instability leads to a completely inadmissible increase in the emittance of the beam after acceleration. The measures taken in conventional linacs against similar phenomena fail in acceleration of single bunches. In Novosibirsk it has been found most effective to overcome this obstacle by introducing a large energy gradient of the particles along the bunch. This leads to the frequency gradient of individual transverse oscillations of the elements of the bunch along the latter, thereby introducing a certain similarity of the Landau damping. Since the force acting on the tail elements upon oscillation of the bunch as a whole is directed along their displacement, preferable would be the sign such that this additional force is compensated by an increase of the focusing action of quadrupole lenses. Therefore, the particles of the bunch's head should have a higher and the particles of the tail a lower energy compared with a mean one. The relative difference in the energies of the particles in the beam, which corresponds to such a situation, can be estimated according to the formula

$$\frac{E_{head}-\bar{E}}{\bar{E}} = \frac{\beta_F^2 \, e \, G_{max}}{2E} \qquad (1)$$

where $G_{max} \sim N$; β_F is the beta-function of the transverse oscillations of particles at the given stage of acceleration.

Figures 5-3 ∿ 5-6 demonstrate, similar to Figs. 5-1 and 5-2, the behavior of the standard bunch at different values of $\Delta E/E$. Figure 6 shows the dependence of the effective emittance of the bunch, whose ellipse on the phase plane includes 70% of the particles, at the exit of the 250-m long section as a function of the energy gradient along the bunch. Curve I gives the emittance relative to the accelerator axis, and curve II with respect to the centre of gravity of the beam (i.e. with the exclusion of coherent oscillations). Figure 7 presents the dependence of the emittance on the number of particles in the bunch in a similar situation for a fixed value of $\Delta E/E$.

Similar computer simulations, which have been performed for the complete process of acceleration in the VLEPP accelerators, have shown that in order to suppress this instability at the standard parameters it is sufficient to introduce the energy gradient of the particles along the bunch such that the head's and tail's energies differ by ±10% from the mean at an initial energy of 1 GeV; this gradient can be gradually decreased during acceleration according to formula (1).

The needed gradient can be imparted to the bunch by a correct choice of its phase in the first accelerating sections with respect to the field excited by an external generator, and controlled, in the same way, in the further process of acceleration.

5. The action of a variety of factors which perturb the transverse motion of a bunch, and connected with various errors in the position of the focusing elements and accelerating sections (in our case, highly-intense bunches with a large gradient of transverse frequencies with the stringent requirements on the resultant emittance of a beam) needs to be considered in very detail[12,15)]

Let us quote the main sources of such stochastic perturbations and make very rough estimations under the assumption that there is no feed-back beam position correction yet, and the perturbations of individual acting elements are independent. Production of colliding beams with such energy, luminosity and polarization meets with extreme difficulties.

Of interest are also the experiments which become accessible at the above laser conversion of electrons travelling towards the protons.

The possibility of producing the full-energy polarized protons may make interesting even the performing of the experiments with colliding proton beams.

1) Let us evaluate the influence of random shifts of the optical axes of quadrupole lenses. We will assume that the focusing is made with quadrupole lenses of constant length and with constant gradient. For simplicity, these lenses are set at equal distances apart. At a low energy, the polarities of the lenses alternate, thereby providing the focusing in the centre of the stability domain. As the energy and focal length of particular lenses increases, these are first joined in the samepolarity pairs with alteration of pair polarity, then form the sets with three lenses in each, and so on. If the transverse shifts of individual lenses are completely independent, the resultant mean square of the transverse momentum $(\overline{\Delta\rho_Z})^1$ will be approximately equal to the rms momentum $(\Delta\rho_Z)^2$ due to one lens kick multiplied by half the number of lenses $1/2\ N_L = L/2L_1$, where L is the length of an accelerator, and L_1 is the distance between the neighbour lenses (1/2 takes into account the

unequal effectiveness of a single strike at different phases of transverse oscillations). The corresponding mean-square value of the angle at the accelerator exit will be equal to $\bar{\theta}^2 = (\overline{\Delta p_Z})^2 \, c^2/E^2 fin$. If β_F^{fin} stands for the beta-functions of the accelerator focusing system at the exit, we obtain for the low intensity bunch that the particle at the accelerator exit will be, in average, on the phase ellipse whose area is $\beta_F^{fin} \, \bar{\theta}^2$. If the errors in the lenses are constant in time and the energy of particles slightly varies, the particle at the exit will then trace around the entire boundary of this ellipse. In the case when the energy spread in the beam is so large that such 'scatterings' over the phase of the transverse oscillations occur several times in the process of acceleration - namely such a situation is planned for VLEPP in order to eliminate the coherent instability - then the particles in the bunch occupy completely the finite ellipse on the phase plane. Hence, the emittance of the beam at the linac exit is estimated as follows:

$$\varepsilon = \frac{\delta_L^2 \, \beta_F^{fin}}{2F_{in}^2} \cdot \left(\frac{E_{in}}{E_{fin}}\right)^2 \cdot \frac{L}{L_1} \qquad (2)$$

where δ_L is the rms error in the position of the optical axis of lenses, and Fin is their initial focal length.

This emittance can be somewhat decreased if we switch off the end lenses in long series (the end lenses mutually compensate with those of neighbour series). As a consequence of the fact that the oscillations acquired on the last section of the accelerator have no time to dephase, the real emittance with respect to the centre of the beam will be a little less; note that the coherent part of the oscillations should be taken into account when the colliding bunches are aimed at each other.

Of course, the correct estimations can be made in computer calculations with due regard for the forces acting from the side of radiation fields (see the foregoing section).

2) Misalignment of the accelerating sections, occuring because of the errors δ_{str} in their adjustment relative to the optical axis of the focusing system, also results in the appearance of the nearly uniform transverse momenta (on account of the transverse component of the accelerating field in the misaligned section). The final effect is similar to that taking place

because of the errors in the position of the lenses. From this point of view, the statistically independent errors in the position of the ends of the sections will be equivalent to those of the lenses, which satisfy the condition

$$\delta_{str}^{eq} = \frac{E}{F_L \cdot \frac{dE}{dL}} \cdot \delta_L$$

Correspondingly, the allowable errors, referring to this effect, in the position of the sections for VLEPP, will be more than one order of magnitude larger compared with those in the position of the lenses.

3) With the shift of the axes of the sections, the particles in the bunch acquire a strike, connected with the radiation fields, in the direction opposite to the section shift (the strike is zero for the 'head' particles, and is maximal for the 'tail' ones). The acquired transverse momentum, in its average value, will be equivalent to that from the shifted lens if the relation

$$\delta_{str} = \frac{4E}{e\, G_{max} L_1 F_L} \delta_L$$

is satisfied. Since the strikes are not equal for different particles along the bunch, the phase ellipse is filled considerably more rapidly than in the preceding cases.

The influence of the transverse strikes on the total emittance can be decreased sharply if the centre of gravity of the bunch is matched with the optical centres of the lenses on the whole length of an accelerator. The admissible errors of such a matching exceed more than by one order of magnitude the allowable deflections of the lenses in the case of their uncorrelated position errors.

Such a correction of the beam and lenses can be made-only during many operation cycles of a collider by successive approximations. For the shorter periods of time, stabilization of the position of the lenses should be provided to much higher accuracy required for the case of the completely uncorrelated perturbations.

If the shift of the lenses is caused by the transverse (vertical) seismic waves, their influence will be noticeable if only their effective wavelength is of the same order of magnitude or less that the wavelength of the transverse oscillations of the beam. Otherwise, their influence is not significant.

The other kinds of perturbations (turns of the lenses, non-linearities in the lenses of the accelerator, instability of their gradients, etc.) look not so dangerous as those considered above.

For the VLEPP, in working with flat beams, the required uncorrelated stability of the optical centres of the lenses constitutes fractions of a micron.

6. Let us examine now what happens in the collisions of such dense bunches[10, 1,12,16]. The electric and magnetic fields of bunches, of the intensity under discussion and micron transverse sizes, attain megagauss magnitudes. 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 action on the particles of the counterbeam add up, and the maximum effective field is doubled:

$$|\vec{H}_{eff}| = |\vec{H}| + |\vec{E}| = \frac{4N_e}{\ell_e(\sigma_x+\sigma_z)}$$

Here σ_x and σ_z are the transverse halfdimensions of the beam at the collision point, and ℓ_e 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 of the total energy loss proves to be very small:

$$\ell_{Rod} = \frac{mc^2}{Z_e^2\ \gamma H_{eff}}$$

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 multitute of $e\gamma$ and $\gamma\gamma$ collisions. Therefore one must resort to flat bunches, while conserving the cross-sectional area to maintain the luminosity. As we have seen, the fields here decreases in proportion to the increase in the width of the bunch. The reaction energy spread will correspond here to the energy spread in the beam

$$\frac{\Delta E}{E} = \pm \frac{2Z_e^3 N_\gamma^2}{\ell_e(\sigma_x+\sigma_z)^2}$$

The maximum dimension is determined by the required monochromaticity.

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 occur in head-on collisions for bunches having a smooth density distribution in all directions (there is even a small contraction). It has been shown by computer simulation of the self-consistent collision that the plasma type instability develops if the number of oscillations over small (vertical) size is more than 2. This boundary determines the ultimate density of the bunches. 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

$$\theta_{allow} \approx \frac{1}{3} \cdot \frac{g_o}{\gamma g^1} = \frac{0.15}{E_{GeV}}$$

In order to fulfil this condition for horizontal direction (in the case of longitudinal polarization), we must have

$$\alpha \cdot Z_e \cdot \frac{N}{\sigma_x+\sigma_z} \lesssim 1, \qquad \alpha = \frac{1}{137}$$

Going over to flat beams solves this problem as well.

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 directions. 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 point, then their coherent fields mutually compensate to the accuracy of the matching of the bunches and superimposing them. Therefore all the effects of the collision are sharply weakened (the radiation is decreased even quadratically) and cease to play a deleterious role. Here the singleness of the collision of the bunches prevents the development of instabilities that were faced in the DCI storage rings in working in a four-bunch regime. It is the logically simplest way 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.

If small emittances prove to be accessible, one can gain by one order of magnitude in the luminosity of a collider (compensation regime), by making as strong a focusing as possible ($\beta_x \to \beta_z = 0.5$ cm).

Note that in this regime half of the total luminosity will be due to e^+e^- reactions, while the other half is divided equally between e^-e^- and e^+e^+ collisions.

The energy of the second pair of e^+e^- bunches can be several times lower compared with the ultimate energy of the collider. In addition to the gain in the cost, this offers the possibility of measuring the charge asymmetry of the processes under study.

7. One of the basic problems in achievement of a high luminosity in linear colliders is to obtain an ultimately strong focusing at the collision point. Here one of the main difficulties is to eliminate the deleterious action of chromatic aberration. This is of great significance because the energy spread in the beam will be not less than 1% in the main regime.

The standard way to compensate the chromaticity by excitation of the energy dispersion, by means of the bending magnets and with the use of sextupole correction, turns out to be practically unsuitable for the $e^\pm$ of such high energy. As the most promising for VLEPP, the variant has been chosen of using, at the final stage of focusing, two very strong quadrupole lenses, and of compensating their relatively small chromatic aberration with the remaining lenses in the collision straight section. (Despite very high gradients, the smallness of the beam dimensions in these lenses provides the smallness of the synchrotron radiation losses in them). These lenses are placed inside a detector at a very short distance from the collision point, and their (very small) aperture should be sufficient to transmit both the particles of the main beam whose emittance raises after its strong perturbing interaction with the counterbeam, and the flux of photons of synchrotron radiation on this bunch, as well as the various secondary particles emitting from the collision point at small angles.

Employment of short-focus lenses solves to a considerable extent the problem of chromatic aberration. However, without special measures, even in this case, the increase in the beam dimensions at the collision point will constitute 1.5-2 times because of the chromatic aberration for the energy spread ±.5%. In order to eliminate completely the chromatic aberration in a first approximation, the decision has been made to build the VLEPP optics in its final part in a way such that the chromaticity of the last lens is compensated by the chromaticity of the remaining lenses of the straight sections.

Below, an example is given of the optics performing the achromatic focusing in the linear over $\Delta E/E$ approximation at the collision point in the vertical direction for an energy of 150 GeV (the sequence of distances starts from the collision point, and '+' stands for the horizontal focusing polarity):

Length (cm)	Gradient (kG/cm)
20	0
100	-122.8
70	0
80	46.74
510	0
80	-75.65
180	0
100	27.70
80	0
100	-18.19
40	0
100	11.86
400	0
100	-14.29
400	0
100	18.20
400	0
100	-27.74

For E = 150 GeV this scheme ensures the following parameters of the focusing: β_z = 0.5 cm and β_x 100 cm.

Figure 8 shows the diagram of the chromaticity of the focusing (to be precise, of the function $dw/d(\Delta E/E)$ where w is the Floke function for vertical direction) along the collision section, calculated for the above example.

After compensation of the linear part of chromaticity, the increase of the vertical dimension because of the contribution from the higher-order terms over $\Delta E/E$ has become equal to less than 10% for $\Delta E/E = \pm 1\%$. This can be considered already as a satisfactory result.

The most serious technical difficulty which arises in realizing the optical scheme, described above, of the final section of VLEPP is the development of miniature short-focus lenses with the gradients of 100–1000 kG/cm. Today we consider two kinds of such lenses. These are the permanent lenses made of $SmCo_5$ with the gradient of 100–200 kG/cm for relatively low 100-200 GeV energies (a sufficient energy variation requires the replacement of these lenses), and the pulsed lenses with the gradients up to 1000 kG/cm for an energy of up to 500 GeV. With the small apertures being planned, the fields in these lenses will not exceed to technically realistic ones.

8. The necessity to focus the beams at the collision point into very small sizes compels one to impose stringent requirements on the preparation of bunches for their injection into the linacs. So, in the VLEPP project[10,12], the bunches of $e^{\pm}$, each containing 10^{12} particles, 0.5 cm long and with the very small vertical emittance of $3 \cdot 10^{-8}$ cm·rad, must be injected into the linacs at an energy of 1 GeV. It is extremely difficult to prepare such bunches directly in storage rings-coolers and, therefore, the bunch before its injection into linacs is subjected to a 20-fold longitudinal compression (see Section 2). This offers the possibility of working in coolers with the bunches of 10 cm long. This substantially simplifies the 'struggle' with the coherent instabilities of different nature, and helps to suppress to the needed level the diffusions caused by a multiple intrabeam scattering.

With an energy of 1 GeV and the required parameters of a bunch, this diffusion proves to be considerably more intensive in comparison with that caused by the quantum fluctuations of synchrotron radiation. The ratio of the diffusion rate to the rate of radiation cooling determines the equilibrium emittance (first of all, energy spread and radial betatron emittance). The equilibrium vertical emittance is mainly determined by the coupling of the vertical motion with a radial one. As our experience shows, such a coupling between the amplitudes of vertical and radial oscillations can be made equal to 0.04. If this relation is considered as a given one, then from the required vertical emittance we obtain the requirements on the radial. It is possible to show that, using sufficiently high bending magnetic fields (20 kG) and assigning a sufficient rigidness to the focusing structure of a strong ring (dimensionless frequency of transverse oscillations is about 10) and preventing the emittance from increasing due to the coherent effects, one can achieve the parameters of the bunches necessary for VLEPP.

To the very important requirements on storage rings are referred a sufficient magnitude of the acceptance to receive the $e^{\pm}$ newly generated by the method described above (see Section 2), and the capability of conserving, at the initial level, the degree of polarization of the injected particles with vertical spins. Note that the system of primary stacking of electron bunches can be useful also for stabilization of the intensity of the VLEPP beams.

An important stage in handling the generation of short intense bunches will be the experience on operation of the storage rings of this purpose at Stanford for the SLC project.

9. Let us treat now some questions and problems associated with the design of superlinacs for linear colliders. The choice of the parameters of superlinacs has a decisive influence on the whole view of an installation. In addition to physical aspects, a great deal of the other, technological, economical and social factors should be taken into consideration. I can dwell upon only a few points, and present a variant of their solution in the VLEPP project.

In this project we direct our attention to a high rate of acceleration, about 100 MeV/m. This rate allows a proportional decrease in the length of the installation, and a proportional increase in the energetically admissible number of particles in a short bunch (of a length of the order of 10% of the wavelength of the linac). The possibility of attaining the required gradient of about $1.5 \sim 1.8$ MV/cm on the most tense parts of the surface of a diaphragmed waveguide was preliminarily demonstrated and tested in experiments with a single resonator[17]. So far, in Novosibirsk, the rate of electron acceleration achieved on the many-cell section with a wavelength of about 5 cm is 75 MeV/m. At stanford, the tests have been performed of a section at a wavelength of 10 cm; the gradient obtained should give the possibility to accelerate the electrons at a rate of 65 MeV/m. It is important to emphasize that no breakdown limitations occured in the regular parts of the accelerating structure at such gradients.

A high rate of acceleration[10,17] is reasonable to obtain in the waveguides wherein the distance between the diaphragms is equal to half of the wavelength (naturally, the phases of oscillations of the adjucent resonator cells must be shifted in phase by 180° - the so-called π-structure). The needed coupling between the cells is performed with concentric, side coupling resonators, and a section of about 1 m long will be filled with an electromagnetic field during the wave propagation from the centre to the end and backward. This duration is much shorter than the time of dissipation in the waveguide's walls (about 0.3 s). Here after the reflected wave returns to the place of power input, almost the total energy proves to be concentrated in the main waveguide (only a small fraction of it remains in the coupling resonators), while a considerable fraction of it can be carried away by the short bunch. An important advantage of such a scheme is the fact that in case of a breakdown in one of the cells, only an insignificant fraction of all the power applied to this section is dissipated in the breakdown zone, while the remaining is reflected from the breakdown-closed cell whose impedance is of reactive nature. Therefore, in such a structure the breakdowns improve the surface quality rather than damage it.

An important advantage of the developed structure of the linac for the VELPP is a relatively small exceeding of the maximum strength of an electric field cn the metal's surface compared with the mean energy gain (the ratio is about 1.6) with a sufficiently large hole in the diaphragm for beam passage.

The choice of the high rate of acceleration does not lead to the growth of the mean power consumed by linacs from the mains: the $e^{\pm}$ bunches in the planned regime take away about 30% of the energy stored in the accelerating section, that constitutes about 30 J/m. However, the high rate of acceleration requires to generate a very high pulsed power of the RF generators (over 200 MW/m). In view of this, the major technical problem associated with the creation of a linear collider is the development of RF cm-range generators of completely new level of peak power (the total peak RF power of the full VLEPP project is about 4.000 GW for 2E = 1 TeV). At present, the commercially available generators are far from providing the operation of linear colliders. Our main hopes are connected with the fast developing field of high-power electron relativistic beams. I would like to stress that merely the level of generated RF power close to the required has already been achieved. However, it is necessary to develop the technology of powerful RF generators in the amplifying regime with a fine control and stabilization of the frequency, amplitude and phase of the generation at a considerably high (10 Hz and higher) repetition rate and a long working time.

At Stanford, an interesting variant to simplify the problem of peak power being discussed has recently been suggested and is being developed. The point is a sharp increase of the dissipation time (and, correspondingly, a proportional increase of the admissible time of RF-pumping and the same increase in the required peak RF power) by using the superconducting accelerating structures in the pulse regime. There are reasons to hope, and this has been shown in the experiments, that one will be able, in the pulsed regime, to raise the operating accelerating gradient by several times in comparison with that in the continuous regime, while conserving a high enough quality factor of the waveguides. The estimates show that it is possible to lengthen the operating pulses approximately by one order of magnitude and, consequently, to reduce the required total pulse power to RF generators, while keeping the total energy consumption (including the power consumed for refrigeration). However, with the use of pure niobium, it is apparently impossible to have the gradients over 50 MeV/m. Therefore, the search for more promising materials acquires an especial significance. Also, an important problem is to extract completely, from the structure, the higher harmonics excited by the bunch being accelerated, otherwise these harmonics can increase substantially the energy consumption for refrigeration.

In conclusion, I would like to mention the possibility of using the proton-klystron regime in linear colliders with the application of the intense beams of modern and future proton accelerators at superhigh energies[18].

10. The spectra of the reactions obtained can be expanded further on single-pass colliders. Laser technology is approaching the stage that enables one to create highly effective photon targets (at least, of small transverse cross

section). Owing to the inverse Compton effect, they allow one to convert, for one pass, the major fraction of the electrons immediately before collision into γ-quanta having an energy close to the total energy of the accelerated particles. Therefore the possibility arises of attaining real photon-photon colliding beams at superhigh energies.

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

At an energy of the primary photons of $E_{\gamma 1} \gtrsim m_2 c^2/\gamma$ (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 $\lambda \ell_e$, 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_z^{Phot} in the photon pulse will be

$$E_z^{Phot} \gtrsim \frac{2\varkappa\, m_e c^2\, \ell 2}{d\ell_2}$$

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

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. With a sufficient productivity of the system of primary stacking of electrons, the mode of operation is possible without their recycling, by conversion.

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

$$L_{\gamma\gamma} = \frac{N_\gamma^2}{S_{eff}^{\gamma\gamma}} \cdot f = \frac{\varkappa^2 N_e^2 \gamma^2 f}{2\pi L_o^2}$$

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

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

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

Note that while the conditions of the e^+e^- collisions in an uncompensated regime must be chosen so as to keep the filed in the bunches from being too large, this restriction does not exist for γγ- and eγ-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 γγ- and eγ-colliding beams in the VLEPP, with the luminosities

$$L_{\gamma\gamma} \geq 3 \cdot 10^{31}\ cm^{-2}\ s^{-1},$$

$$L_{e\gamma} \geq 1 \cdot 10^{31}\ cm^{-2}\ s^{-1}.$$

We emphasize that one can obtain a luminosity of photon-photon collisions of full energy approaching that of electron-positron (or electron) colliding beams only in the installations with single collisions of the bunches of accelerated particles. Cyclic storage rings do not have this potentiality.

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

With regard to the main bulk of events involving production of hadrons, $\gamma\gamma$-collisions will resemble hadron-hadron collisions of 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 the production of hadrons in $\gamma\gamma$-collisions will apparently be very large - of the order of 0.3 microbarn. The major fraction of such events will yield hadrons travelling at very small angles from the direction of photons. Hence it will be difficult of access to study, although in principle one can separate the primary γ-beams and the produced charged hadrons with a magnetic field.

It is more promising to study the electromagnetic production of quark (antiquark) jets. Here, for all types of quarks having a mass much smaller than the energy of 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 have a radical advantage over pp- and $p\bar{p}$-colliding beams, whose quark composition sharply favors the creations of jets containing u, d, $\bar{u}$, and d-quarks. Moreover, $\gamma\gamma$-collisions efficiently yield gluon jets as well. 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 on the VLEPP.

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 does not decline with energy in the first approximation (in contract, e.g., to e^+e^- W^+W^-). The study of this process allows one to get information on the completely unstudied now γW^+W^- vertex (anomalous magnetic moment of W, electromagnetic form factor of W, etc.).

The same vertex can be studied in the reaction

$$\gamma e^{\pm} \rightarrow W^{\pm}\nu$$

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

11. Linear colliders exhibit important additional possibilities while making changes, comparatively cheap, in the injection part of the installations: starting with an energy of about 10 GeV, the proton acceleration, in the regular structure of the VLEPP, with an almost full rate of acceleration up to the full finite energy becomes possible. In order to provide high luminosity, the same as for e^+e^- collisions, it is necessary to accelerate the proton beams which have the same intensity and the same small emittance.

The possibility is already seen now to prepare the bunches of polarized protons with necessary parameters. The sources of hydrogen negative ions, with polarized protons, are being developed. The charge exchange storing of protons has been developed and it is worth mentioning that one manages to accumulate circulating currents thousands times higher in comparison with the current of the source. The extremely small emittance of the polarized proton beam is possible to be completely formed using the cooling by an intense 'magnetized' electron flux (rapid electron cooling).

Performing of the ep, γp experiments with the electrons and protons polarized in a required manner may be referred to the basic application of this regime.

12. Now let us analyze some features of the performance of experiments on the VLEPP-type installation. VLEPP differs from usual colliding-beam systems in that the collisions of bunches occur very rarely - tens of times per second - with a very high integrated luminosity per collision. This situation complicates the distinguishing of events, including the problems of cutting off the background reactions.

The most principal restriction of the useful luminosity per collision of bunches is the fact that the total cross section for electrodynamical processes of the type

$$e^+e^- \rightarrow e^+e^- + X$$

increasing rapidly with decreasing the momentum transferred 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, search, and analysis of interesting events. Naturally, one can make the probability of superposition of two interesting events in a given experiments negligibly small by an appropriate decrease in 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 colliding beam. As I have said above, these fields must be made small enough so 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 basic background processes of this origin will be the production of electron and muon pairs. One can combat against this background by the methods mentioned above. When one employs the 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 do exist. So, strongly deflected particles can accompany the bunch of electrons, which has extremely small rms dimensions in the installations being discussed. Such particles arise, e.g., due to single scattering by the nuclei of the residual gas in the cooling storage ring '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 storage rings and linacs, and installing of special diaphragms far from the collidion point.

Another source of technical background can be the entering into the detector region of the products of interaction of beam-beam synchrotron radiation with the matter of the vacuum chamber, lenses, etc. This compels one to take measure to keep the site of entering these photons into matter sufficiently far removed from the collision point. In this case, the moment of arriving at the detector of the background particles will be strongly shifted with 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 backgroung of this origin 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 produced with an energy consisting a considerable fraction of the energy of the initial particles will entail no difficulties. This type of processes includes two-particle reactions (electrodynamical, weak, and mixed) and the production 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. Note that the physical background in studying $\gamma\gamma$- and $e\gamma$-reactions in the VLEPP will be far lower.

The pulsed nature of the luminosity of the VLEPP, the high resultant multiplicity 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 sections. It is not rouled out that one of the possible solutions might be to use hybrid, fast cycling bubble chambers with electronic hit detection.

We stress that the mean luminosity of the VLEPP can be distributed among several independent experiments. Here only one collision point is involved in a given cycle; the sequence of this involvement can be assigned arbitrarily.

13. The linear colliders under discussion can be employed in a regime parallel to the colliding-beam regime as an accelerator that yields 10^{13} electrons and positrons per second with any required polarization having the full energy E. Also, if one employs the 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} s^{-1} for experiments with stationary targets.

We also mention that one can obtain very intense, well collimated fluxes of high-energy neutrinos of all types by directing the electron, or even better the photon, beams of the VLEPP onto a target. Especially interesting, these fluxes will be sharply enriched in $\nu\tau$-neutrinos from the decay of photo-produced τ-leptons (and if they exist, in neutrinos from heavier leptons). Here the flux can be as great as 10^6 $\nu\tau$/s in an angle $M_{\tau c}2/5$ 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 VLEPP with intense source of charged pions and cooled muons, one can also use it to accelerate them.

Of special interest is the version in which the first 100 GeV are used for the acceleration of protons, then a highly-effective conversion into the charged pions is made (the coefficient is close to unity), and finally, the $\pi^{\pm}$ are accelerated up to a nearly full energy, 2E = 1000 GeV. With a planned 100 MeV/m rate of acceleration, only an insignificant fraction of pions decays. Then, these π may be used, in particular, for generation of very intense highly-collimated fluxed ν_{μ}, $\bar{\nu}_{\mu}$ at an energy of about 0.7 E.

14. Finally, the Table of the basic parameters of the VLEPP installation is presented.

This report is prepared together with my Novosibirsk colleagues; T.A. Vsevolozhskaya, A.A. Zholents, I.A. Koop, A.V. Novokhatsky, I.Ya. Protopopov, Yu.A. Pupkov, G.I. Silvestrov and V.P. Smirnov.

Table

	First stage		Full 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 points		5	
Frequency of cycles		10 Hz	
Number of particles per bunch		10^{12}	
Mean beam power	2×250 kW		2×900 kW
Peak RF supply power	1.000 GW		4.000 GW
Total consumed power from the supply mains	15 MW		40 MW

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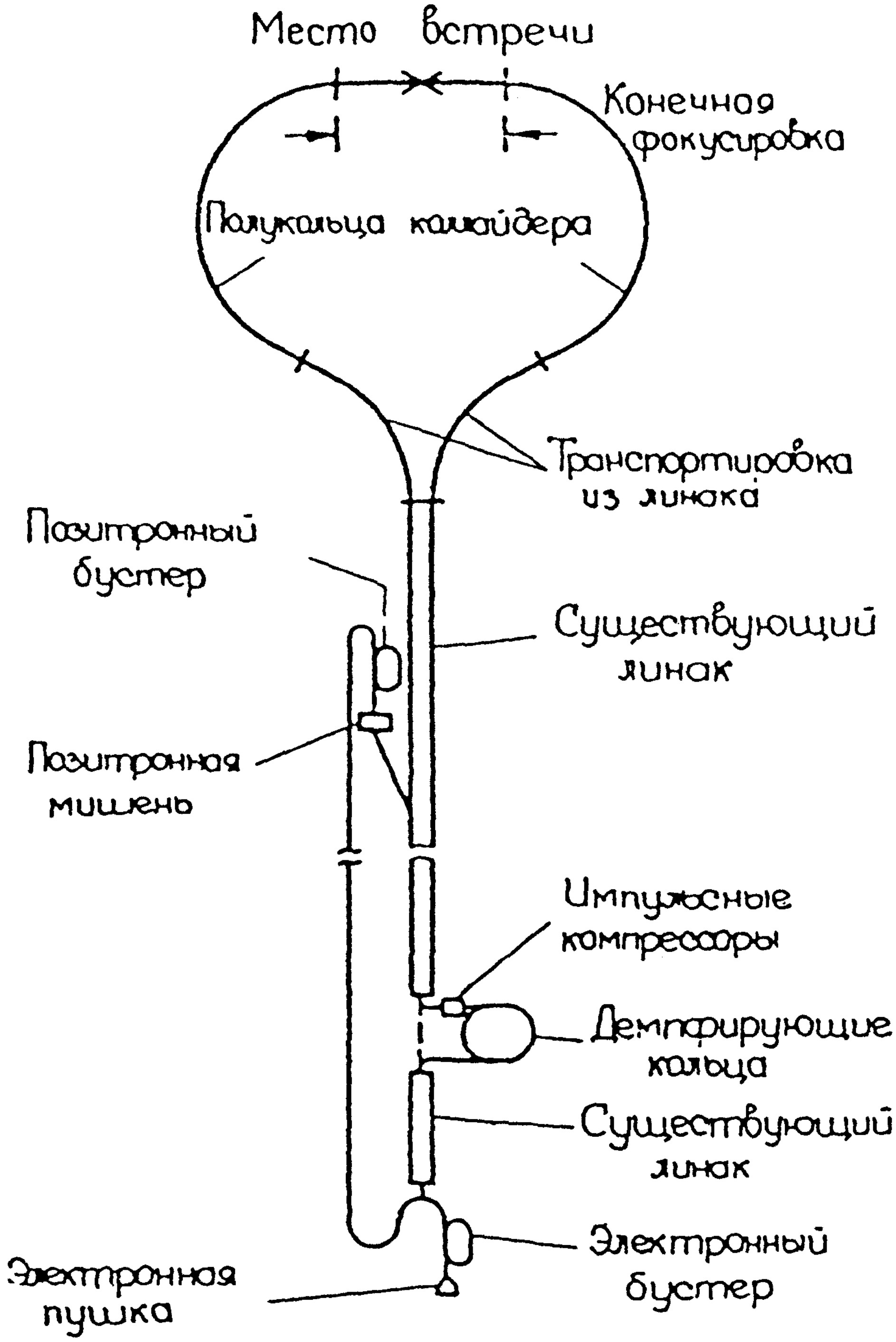

Место встречи
Конечная фокусировка
Полукольца коллайдера
Транспортировка из линака
Позитронный бустер
Существующий линак
Позитронная мишень
Импульсные компрессоры
Демпфирующие кольца
Существующий линак
Электронный бустер
Электронная пушка

Fig. 1.

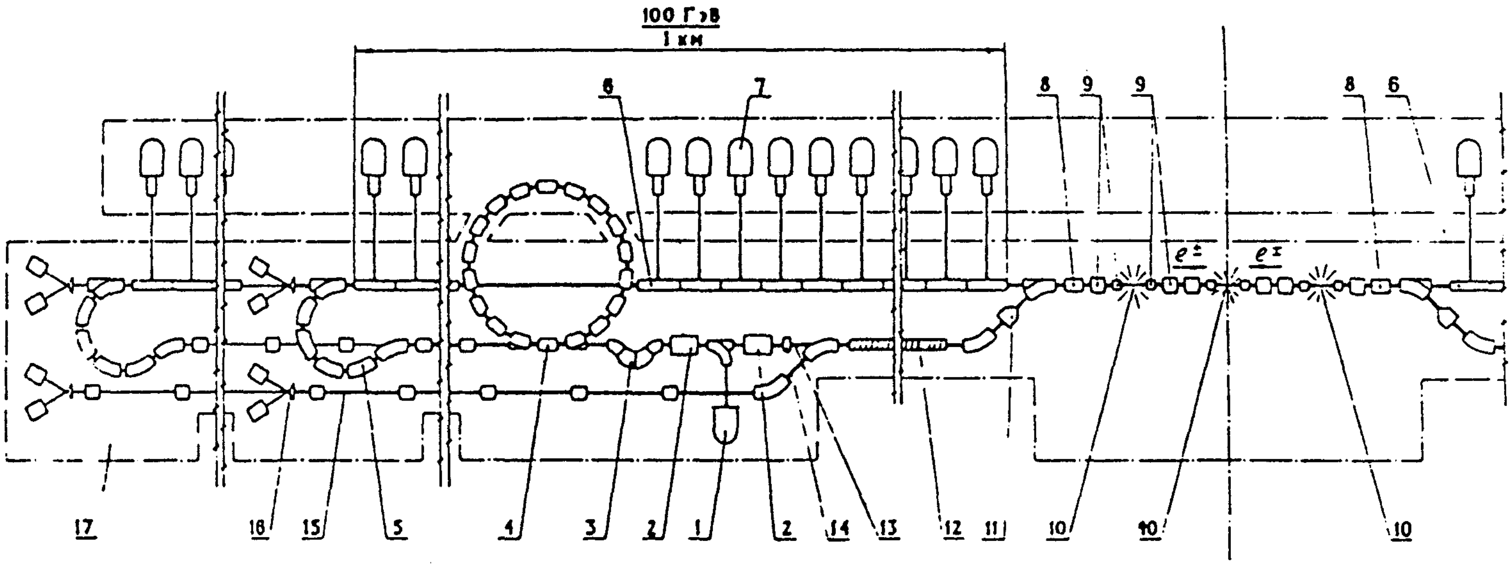


Fig. 2: 1 - initial injector, 2 - intermediate accelerator, 3 - debuncher-monochromator, 4 - storage ring, 5 - buncher, 6 - accelerating sections, 7 - RF supply, 8 - pulsed deflector, 9 - focusing lenses, 10 - collision points, 11 - spiral undulator, 12 - beam of γ-quanta, 13 - conversion target, 14 - electron beam, 15 - experiments with electron (positron) beams with a stationary target, 16 - second stage.

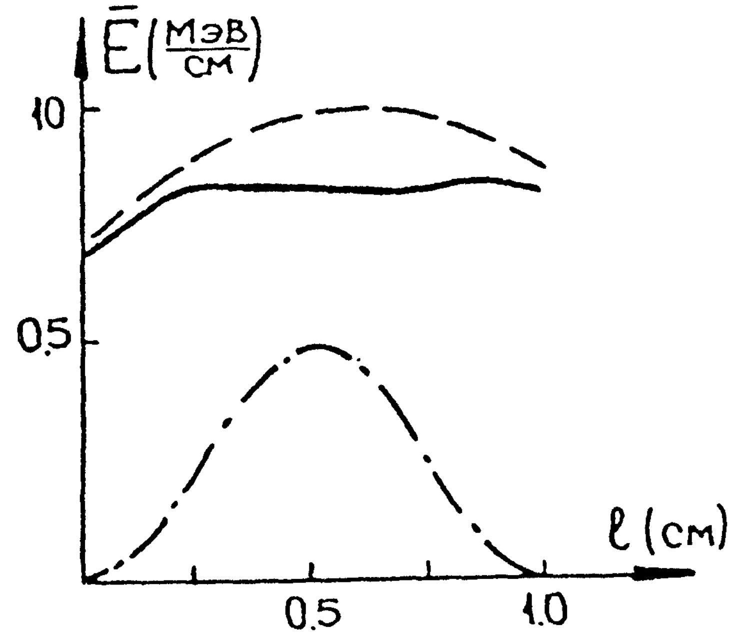


Fig. 3.

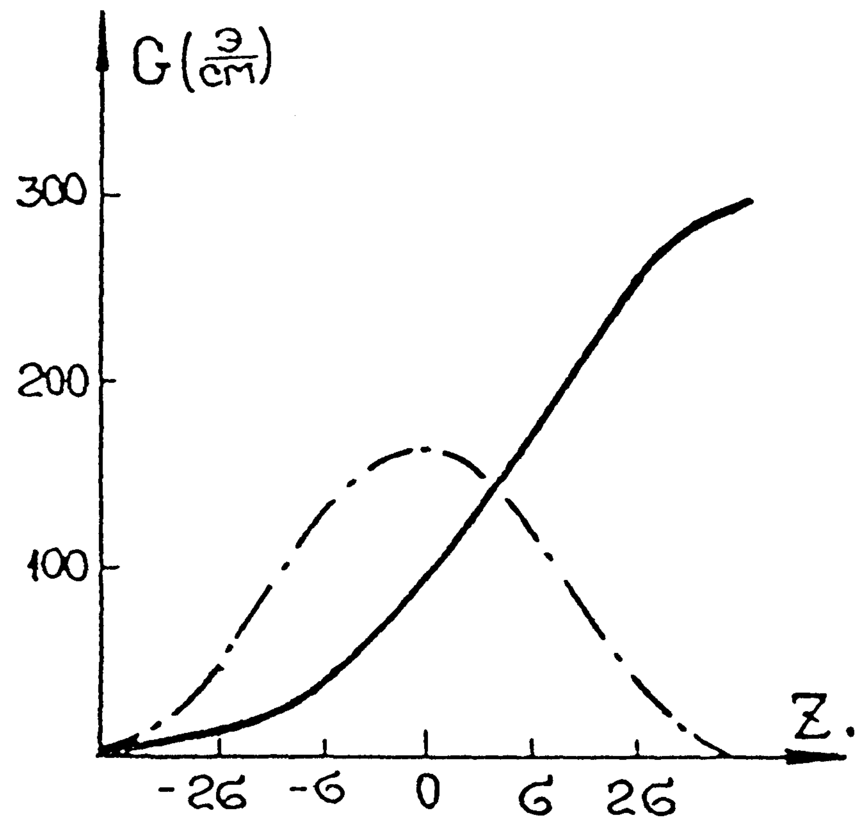
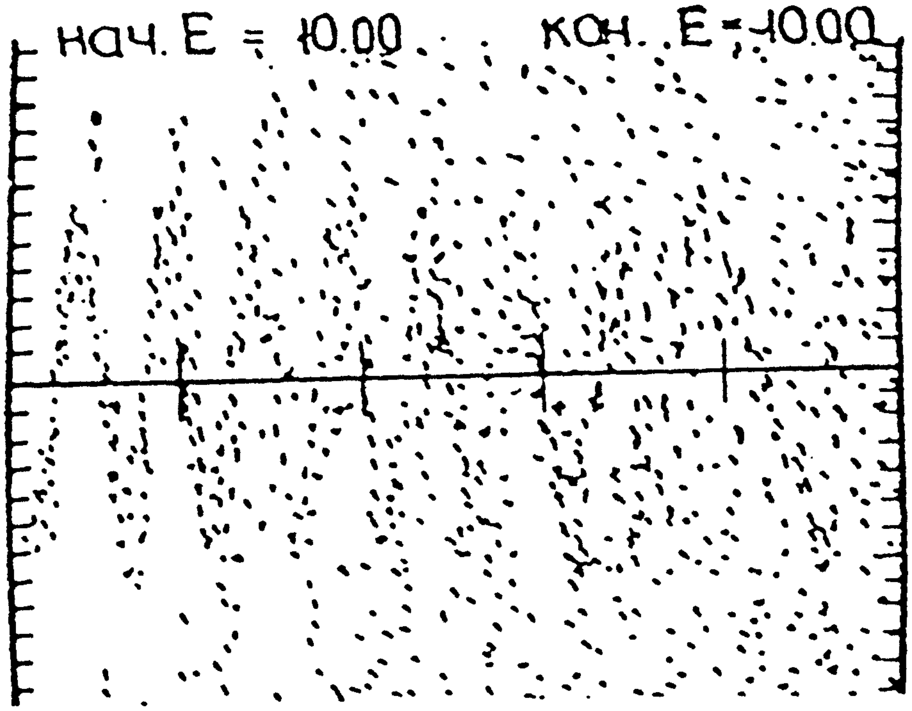
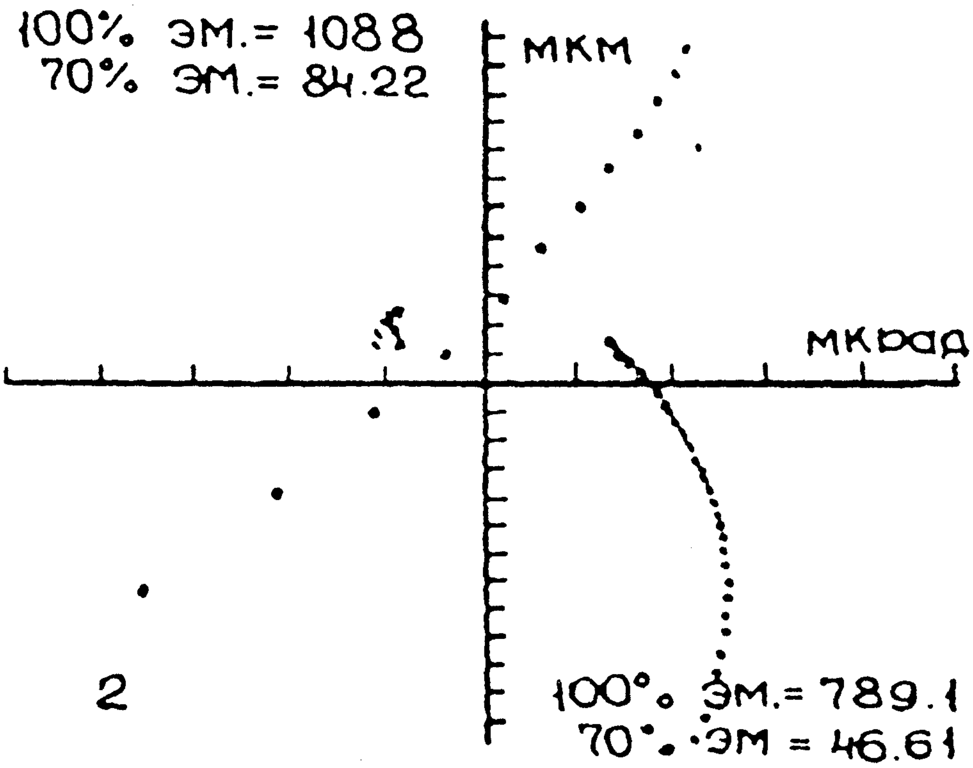


Fig. 4.



$\frac{\Delta E}{E} = 0$

Fig. 5-1



$\frac{\Delta E}{E} = 0$

Fig. 5-2

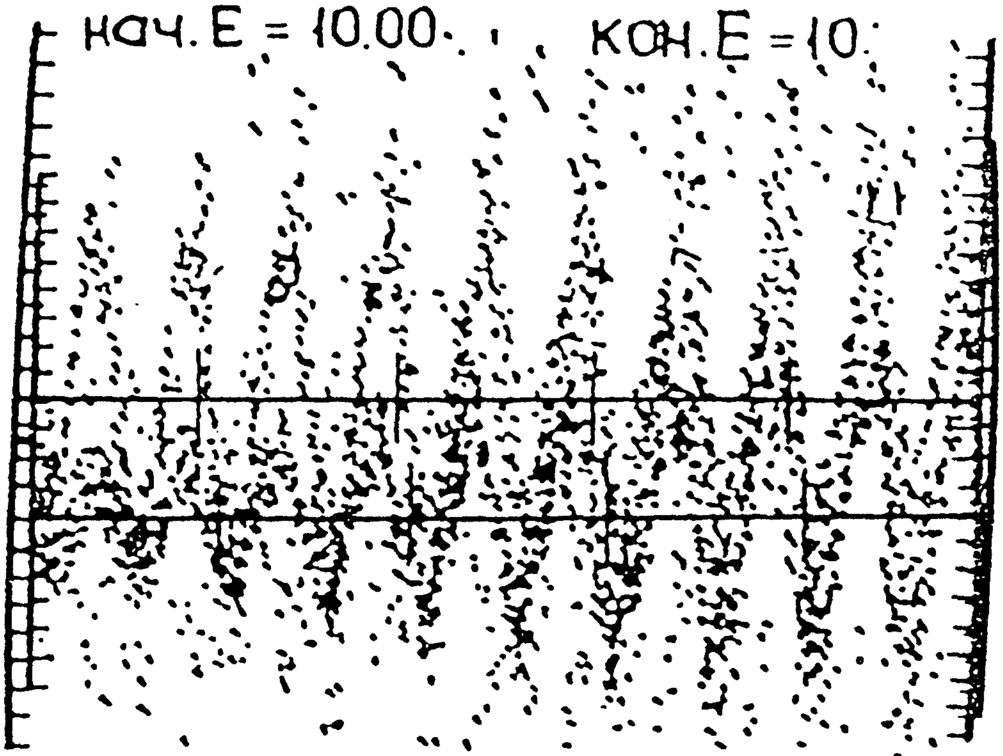


Fig. 5-3 $\frac{\Delta E}{E} = +4\%$

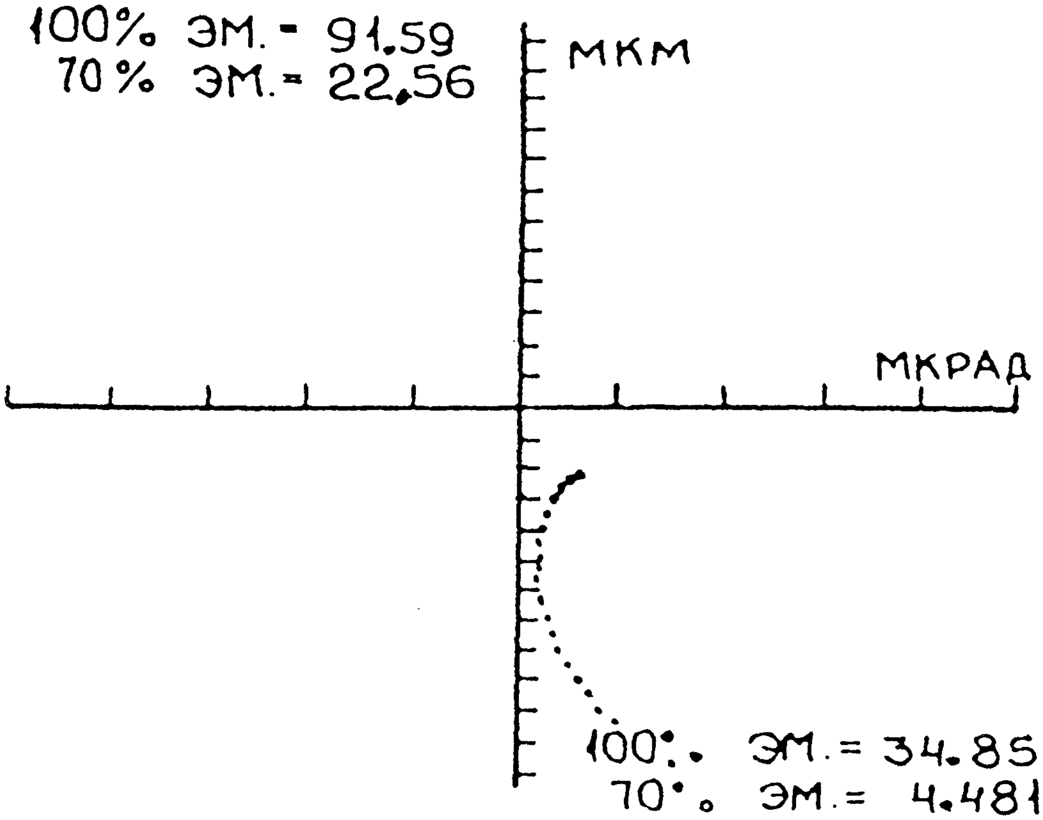


Fig. 5-4 $\frac{\Delta E}{E} = +4\%$

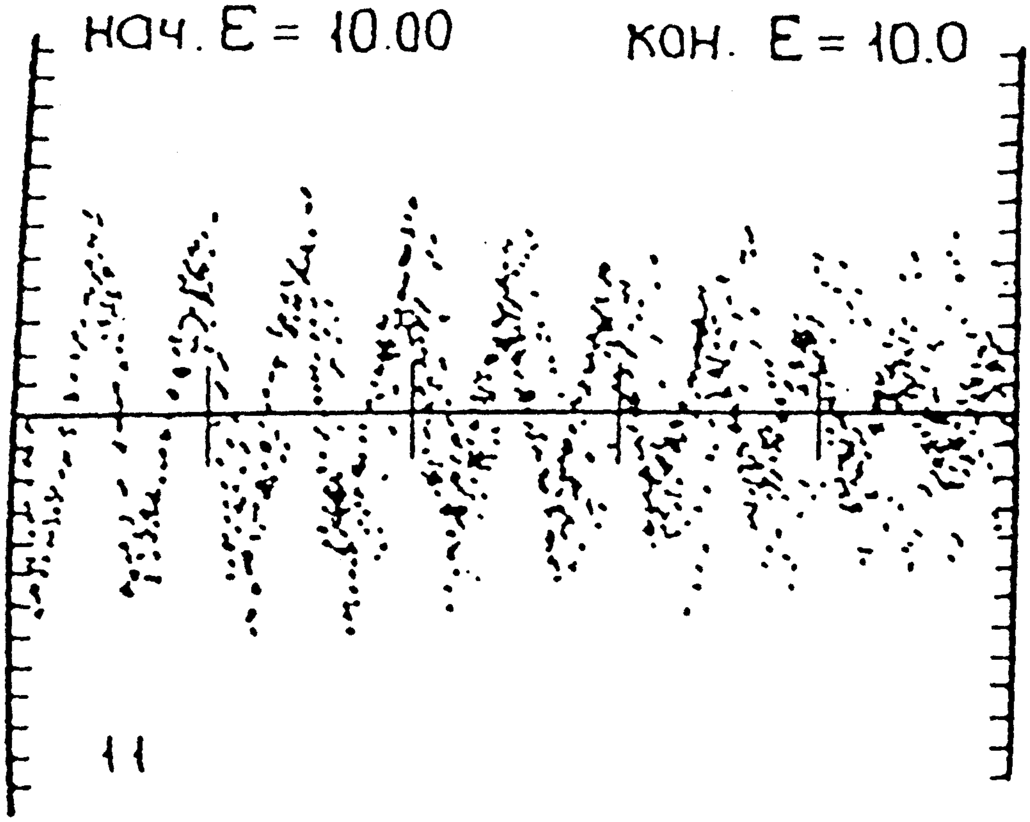
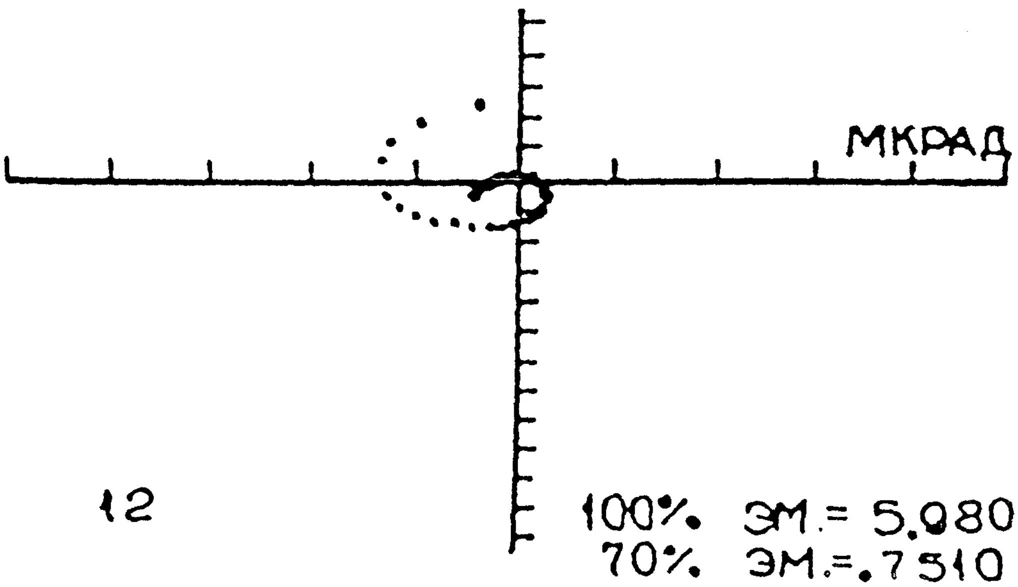
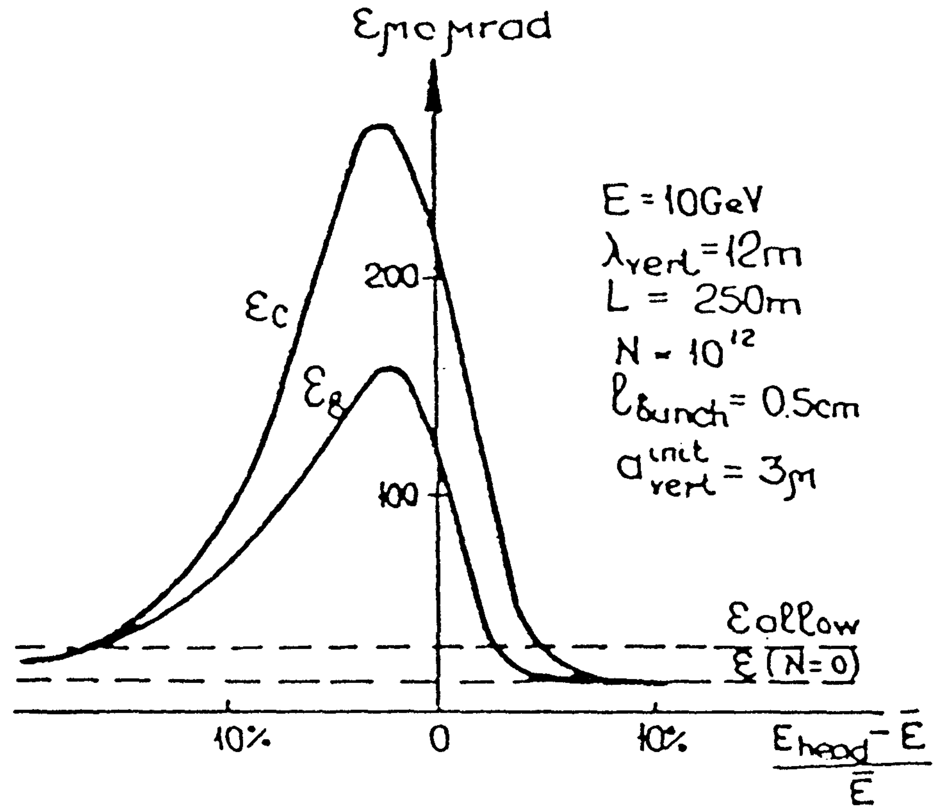


Fig. 5-5 $\frac{\Delta E}{E} = +10\%$



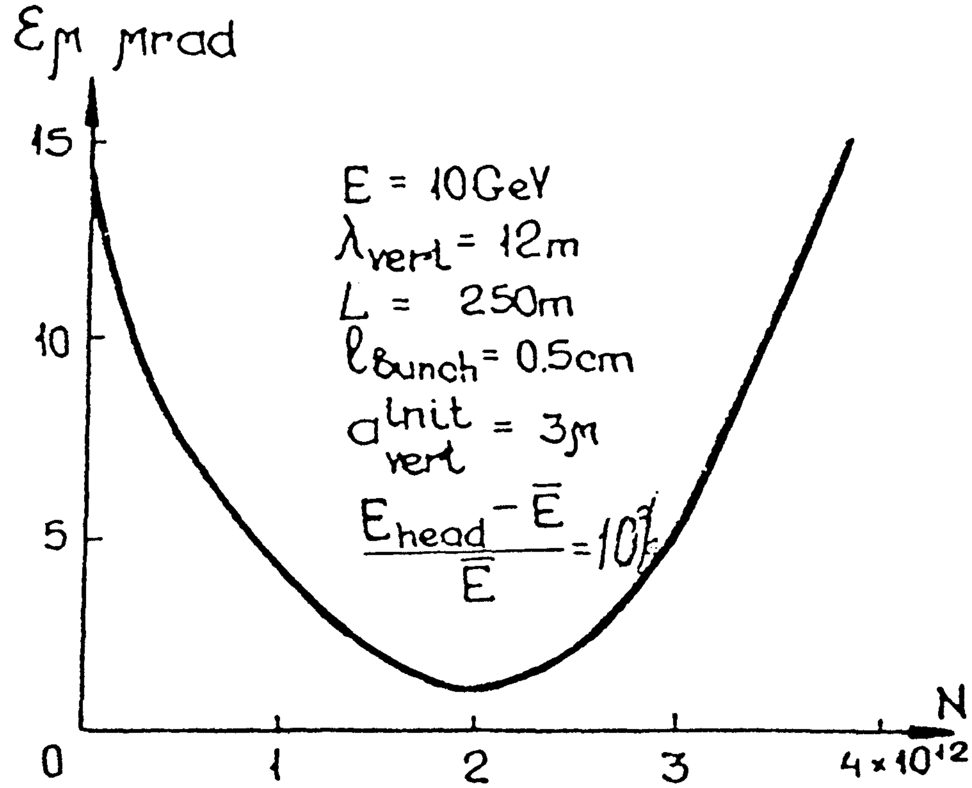
$\frac{\Delta E}{E} = +10\%$

Fig. 5-6



εμcμrad
200
100
εc
εg
E = 10GeV
λvert = 12m
L = 250m
N ~ 10^12
ℓbunch = 0.5cm
a^init_vert = 3μ
εallow
ε(N=0)
10%
0
10%
(Ehead − Ē)/Ē

Fig. 6.



εμ μrad
15
10
5
0
E = 10GeV
λvert = 12m
L = 250m
ℓbunch = 0.5cm
a^init_vert = 3μ
(Ehead − Ē)/Ē = 10%
N
1
2
3
4×10^12

Fig. 7.

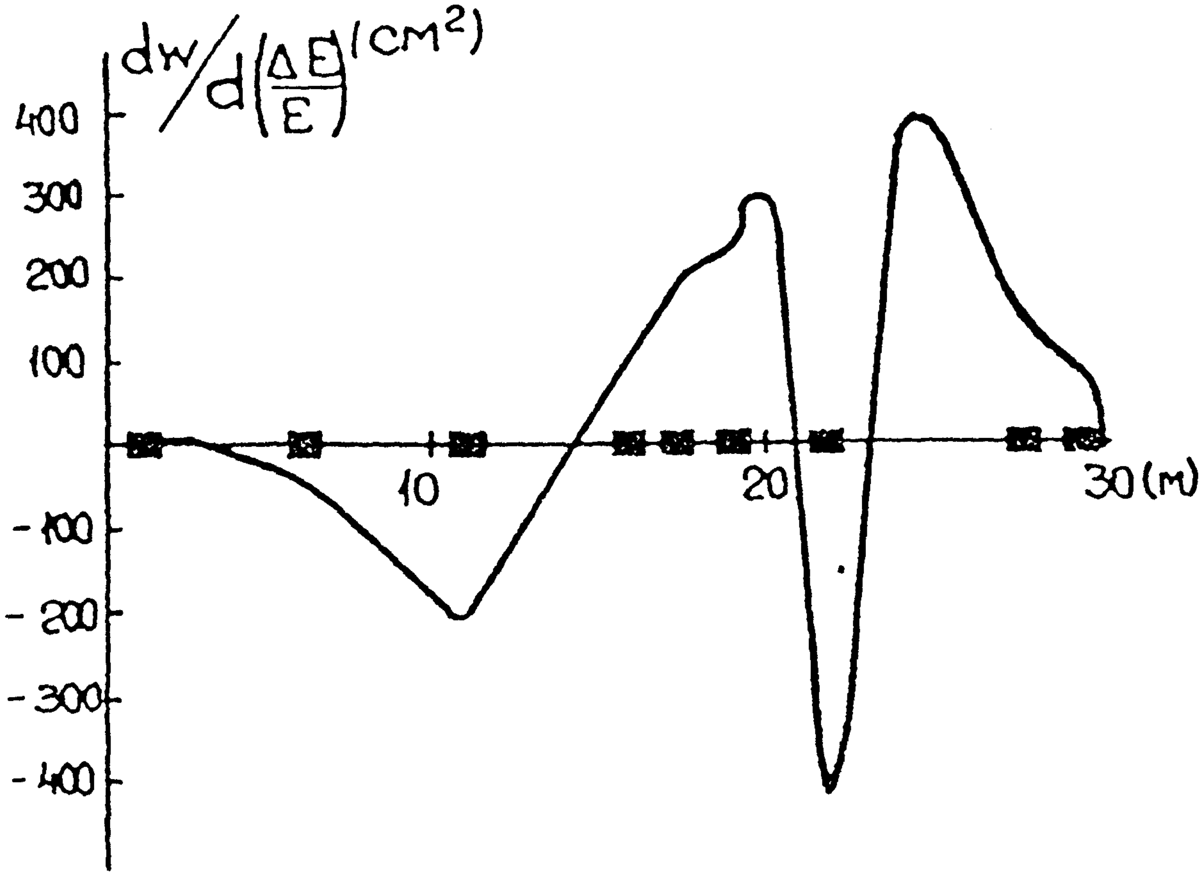


Fig. 8.