A SUPERHIGH ENERGY COLLIDING ELECTRON-POSITRON BEAM FACILITY (VLEPP)*)

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ABSTRACT

The feasibility of creating accelerators with colliding linear electron-positron beams (VLEPP) at energies of the order of several hundreds of GeV is analysed. In special storage rings-injectors the single bunches containing 10^{12} particles of electrons and positrons are "cooled" by synchrotron radiation down to small emittance and then the bunches are accelerated by a 100 GeV/km gradient with no increase in the emittance. At the collision region the beams are focused to the dimensions of the order of one micron. After collision the beams are deflected into the conversion system where recuperation of polarized particles occurs. Then upon pre-acceleration, the particles are injected into storage rings. This cycle is repeated tens of times per second. In the work presented here the bunch-collision effects and main problems of creating such accelerators are also considered.

1. At the International Seminar on the Prospects for High-Energy Physics in Morges (Switzerland, 1971) our paper discussed ways of producing colliding electron-positron beams at energies of hundreds of GeV without the restrictions associated with catastrophically growing synchrotron radiation. There we viewed with greater optimism the variant utilizing superconducting accelerating structures. It was proposed to have a very long straight section with a superconducting system in a special storage device turning particles at a moderate energy of a few GeV. In the first half of this system the stacked particles should be accelerated, acquiring the energy stored in the accelerating structure, and in the second half they should be decelerated, transferring energy to the electromagnetic field of the cavities. The colliding particles should be accelerated in the second part and decelerated in the first part of the accelerating system. Total energy recovery thus is effected and in the first approximation there is no power consumption from the RF system. However, hopes of rapid progress in the attainable acceleration rates in superconducting structures are not yet justified. This makes such devices exceedingly large. Furthermore, in the period since then there has been experience in working with colliding beams with very small dimensions at the collision point -- down to a few microns /2/. Another method, also

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*) The main results of this work were reported at the International Seminar "Problems of High Energy Physics and Controlled Nuclear Fusion" devoted to the 60th anniversary of Professor G.I.Budker's birth (April, 1978, Novosibirsk).

The results of this work were reported in more detail at the 6th All-Union Accelerator Conference (October, 1978, Dubna)/1/.

considered in our paper, using two linear accelerators that "fire" at each other and into which intense electron and positron beams with an extremely small phase volume are injected therefore now seems more promising to us. The present paper is devoted to a review of this variant, the problems that arise in it, and ways of solving them.

The general idea of creating VLEPP (Colliding Linear Electron-Positron Beams) consists in obtaining colliding beams by using two linear accelerators with electrons or positrons of energy that accelerate towards each other single bunches with a large number of particles.

The luminosity L of such a unit is roughly

$$L = \frac{N^2}{S} f$$

where N is the number of particles in the colliding bunches,

S is the effective beam cross section at the collision point,

f is the acceleration cycle frequency.

It is easy to see the loss in luminosity in comparison with a cyclic accelerator, where the rotation frequency acts as the cycle repetition frequency f. As will be seen from what follows, the frequency f has the scale 10-100 Hz, while the rotation frequency for an accelerator with an orbital length of tens of kilometres is of the order of 10^4 Hz.

Two or three orders of magnitude of the loss can be compensated in practice only by reducing the effective cross section of the beams at the collision point. For example, taking $N = 10^{12}$ and $f = 10$ Hz hereinafter, we will find that for a luminosity of 10^{32} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ we should have an effective beam radius r_0 at the collision point of order 1 micron. This beam size should be preserved over the entire collision length; assuming the bunch length to be about 1 cm, we find that the angular spread of the particles at the collision point should not exceed $\Delta\theta = \pm 10^{-4}$ radians. Hence the phase volume of an accelerated bunch is $\frac{\Omega}{\pi} = 10^{-8}$ rad·cm. This is a serious requirement, which nonetheless can be satisfied, as will be seen from what follows. But increasing the number of particles substantially beyond 10^{12} runs up against major difficulties, particularly energy difficulties, since even at $E = 100$ GeV, $2N = 2 \times 10^{12}$ particles have an energy of 30 kJ. In the accelerating structure the stored energy must be severalfold greater, i.e. over 100 kJ.

This energy must be transferred from the SHF power sources in times significantly shorter than the damping time of the accelerating structure cavities. For example, for cavities with $\lambda = 5$ cm this time is 10^{-7} sec. Thus, sources with a total SHF power of over 10^5 J/10^{-7} sec = 10^{12} W are required. Assuming that the number of "klystron" sources is 200, we will find that the power of a single source must be 5×10^9 W.

The desire to have the shortest possible accelerator length forces us to strive for the maximum possible acceleration rate. Studies have shown that we may hope to have an acceleration rate of 100 MeV/m, giving a length of 2 x 1 km for a 2 x 100 GeV accelerator.

The required total storage of electromagnetic field energy at the attainable field strength makes it possible to select the working frequency, or wavelength, of the accelerator. For our example we then will obtain $\lambda = 5$ cm.

The task of creating a VLEPP, thus, consists in creating an accelerating structure with an acceleration rate of 100 MeV/m that is capable of accelerating 10^{12} particles in a single bunch, monochromatically if possible, with an extremely small bunch phase volume at the exit, and in creating SHF sources with a pulse power of a few gigawatts. The total average power of the sources must be at the level of 3-30 MW for repetition frequencies of 10-100 Hz at an efficiency of about 30%. Electron and positron injectors handling 10^{12} particles with a small phase volume, a bunch length no greater than 1 cm, and a repetition frequency of 10-100 Hz must be built. The most important task is to preserve this small bunch emittance during acceleration in a long accelerating structure.

A nonessential but nonetheless desirable property of the facility is the possibility of using the entire length of the accelerator to carry out experiments with doubled-energy particles.

2. The general layout of the facility may be represented as follows (Fig.1). Two linear accelerators 2 x 1 km long, fed by high-power SHF sources installed about 5-10 m apart, "fire" at each other single bunches of electrons and positrons at a repetition rate of order 10 Hz. Following the collision, at the collision point the bunches are slightly deflected by a pulsed field into a small-angle analyzing system that makes it possible to measure the energy spectrum of the colliding particles. From the analyzer the bunch enters a special conversion system /3/ using the helical undulator which enables one to obtain electrons and positrons polarized in longitudinal direction of an energy of a few MeV with the conversion coefficient being not less than unity.

After preacceleration in the linear accelerator up to an energy of the order of 1 GeV the particle spin is turned vertically by the special magnetic structure and in the debuncher (Fig.1) the bunch length is increased up to about 10 cm. Such a beam is injected into the precooling storage ring with a large transverse and energetic acceptance. After radiation cooling the particles are transferred into the next focusing storage ring where the particles are cooled down to the required (quite a small) emittance determined by quantum fluctuations and the effect of internal particle scattering in the beam (naturally on the assumption that coherent beam instabilities can be suppressed). In this case the bunch length during the cooling process may be much greater than final length needed (say, $\sim$10 cm) to reduce the contribution of internal scattering and ease the problem of coherent stability. Then the particles are released and transported over the entire length of the accelerator from the collision region, where the storage devices are installed, to the injection point. For injec-

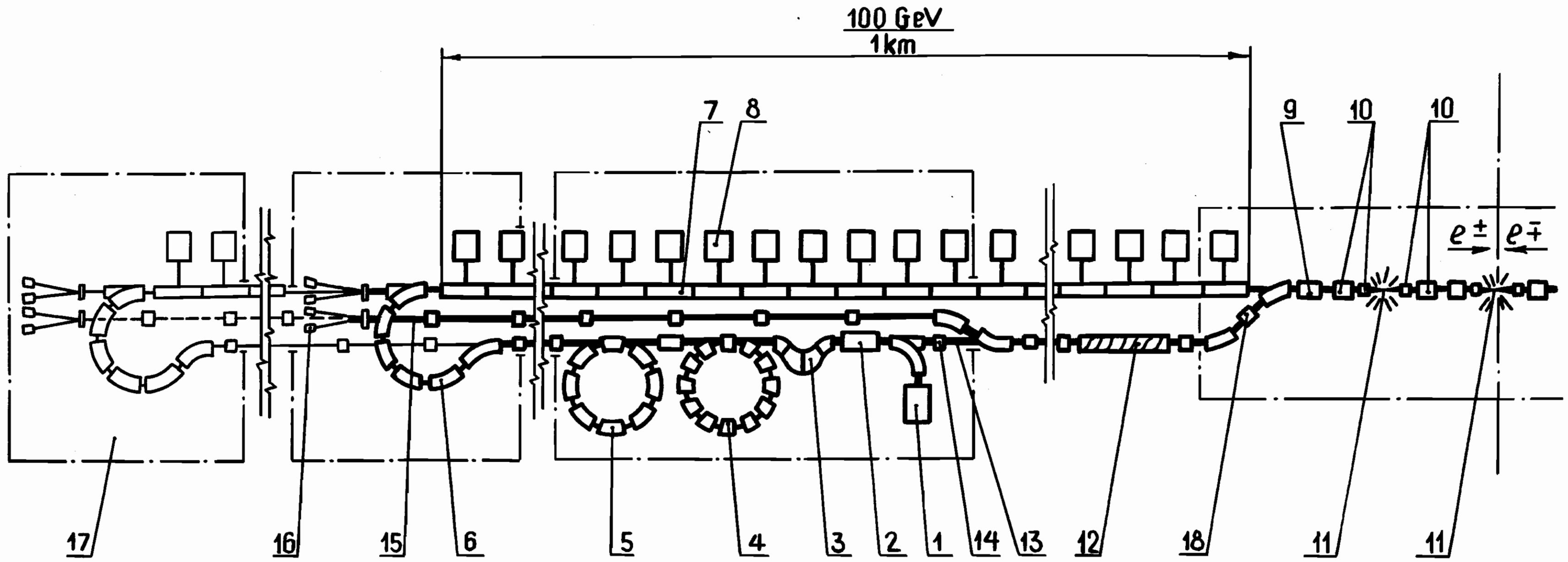

Fig.1

1. INITIAL INJECTOR
2. INTERMEDIATE ACCELERATOR
3. DEBUNCHER
4. STORAGE RING
5. COOLER -INJECTOR
6. BUNCHER
7. ACCELERATING SECTIONS
8. SHF SOURCE
9. PULSE DEFLECTOR
10. FOCUSING LENSES
11. COLLISION POINTS
12. HELICAL ONDULATOR
13. THE BEAM OF γ-QUANTA
14. CONVERSION TARGET
15. RESIDUAL ELECTRON BEAM
16. ELECTRON (POSITRON) BEAM EXPERIMENTS WITH STATIONARY TARGET
17. THE SECOND STEP
18. SPECTROMETER

tion into a linear accelerator the particles are rotated 180° by means of a special nonaberrational magnet system and the bunch length is reduced down to required value ∿ 1 cm in the buncher, as it was done in the scheme /4/. The particle spin can also be turned in the longitudinal or transversal direction. This arrangement of the storage devices makes it possible easily to increase the accelerator length without reinstalling the conversion system and storage device-injectors.

A colliding beam facility based on the scheme described has the pleasant feature that it is possible to increase the length and consequently the energy of the accelerator. For example, initially an accelerator with a maximum energy of 2 x 100 GeV may be placed in operation. While experiments are being conducted in this energy range accelerator sections that raise the energy to 2 x 200 GeV are built, and so forth.

3. Let us consider in greater detail some problems of the electrodynamics of the accelerating structure and the acceleration process. In our case operation in a stored-energy mode is a feature of the accelerating system, i.e. the SHF generator energises the accelerating system over a comparatively long time, and then the charge acquires in a very short time part of the energy in the cavity. The power extraction by the charge during acceleration consists in the fact that the charge, on traversing the cavity, emits a wave that damps the field present in the cavity. True, when this occurs other modes of oscillations also are emitted, decreasing the energy extracted from the cavity. This process has been studied in detail numerically. It was found that a π-type structure is optimal from this standpoint.

A nontrivial result of the analysis of the acceleration process lies in the fact that by selecting the shape of the bunch distribution and the phase of entry into the cavity for each charge value it is possible to obtain a monochromatic particle beam at the exit. Here the bunch carries from the cavity a significant fraction of the energy -- up to 0.5 of the stored energy /5/ (Fig.2). Fig.2 from Ref./5/ represents the picture of electric field at various moments during the beam passing along the axis of cylindrical accelerating system. This fact is extremely valuable for obtaining colliding bunches of well-defined energy and markedly simplifies the problem of beam focusing at the collision point.

The π -structure thus has turned out to be most appropriate for work in the stored-energy mode. This is quite a general assertion. It is independent of the details of the structure's geometry. Qualitative physical arguments that confirm this conclusion also can be cited. At the same time, yet another important requirement is satisfied, namely the possibility of accelerating particles in two directions.

4. The problem of transverse forces has turned out to be much more complicated.

It is well known that in linear electron accelerators an instability associated with the excitation of nonsymmetric modes is present. Its es-

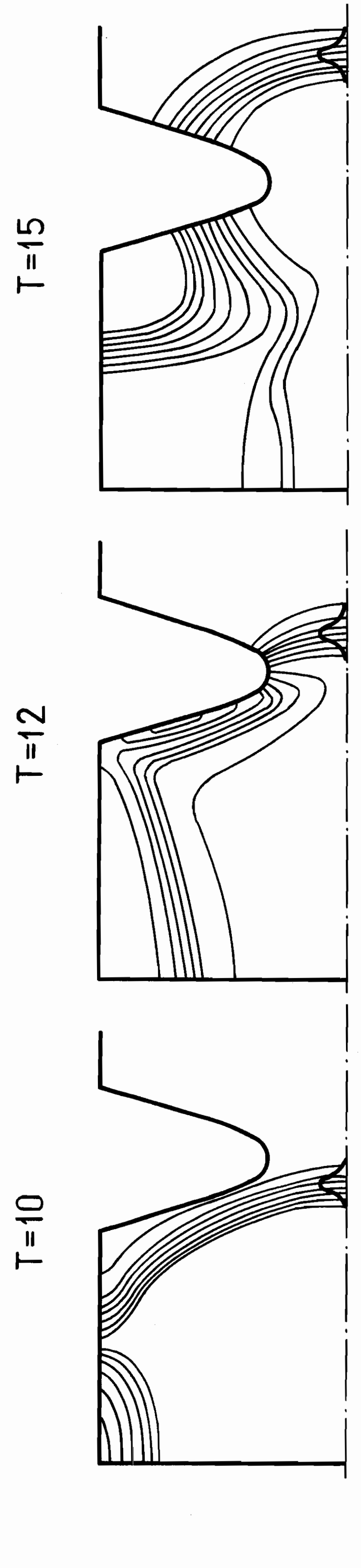

Fig.2

sence lies in the fact that the particles of the first bunch entering the accelerating system, traveling not strictly at the centre of the structure, radiate nonsymmetric modes of oscillations with an amplitude proportional to the displacement from the centre of the system. The magnetic and radial electric fields of the nonsymmetric mode deflect the second particle bunch. After acquiring an angle, this bunch, on traversing some distance in the structure, acquires a large lateral displacement which exceeds that of the first bunch. When this occurs it in turn excites a nonsymmetric wave of increased amplitude that deflects the third bunch, and so forth. This instability leads to a situation in which the "tail" of a current pulse containing a large number of particles, after taking on large enough angles, ultimately may strike the walls of the accelerating structure. And in any case the effective transverse dimensions of the beam are increased.

In our case just one bunch is accelerated, but this does not eliminate the problem since instead of the words "the first, second, and succeeding bunches" we need only insert the words "the first, second, and succeeding particles in a bunch", and everything else formally will remain valid. In other words, when even a single bunch is accelerated an instability of the "head-tail" type is possible. This consideration has long been known to us and the lack of a radical method of controlling this instability long was an obstacle to developing the work. The fact of the matter is that even after increasing the precision of beam tracking through the centre of the accelerating system, increasing the hardness of the focusing system, and raising the acceleration rate it was possible to pass an intense beam through the accelerating system, but the phase volume of the bunch increased so much when this was done that the entire system has no meaning as a colliding-beam facility because of its negligibly low luminosity.

We may cite a somewhat different picture of the development of the instability -- a picture that suggests a method of suppressing the instability.

Let us mentally divide the bunch into two parts -- the "head" and the "tail". On passing through the RF system and having some initial deflection from the accelerator axis, the "head" undergoes oscillations relative to this axis because of the action of the focusing lenses, simultaneously exciting a nonsymmetric wave in the accelerating structure. It is easy to understand that for the "tail" the force of the nonsymmetric wave is in resonance with the transverse motion in the focusing-lens fields, which causes the instability to develop.

A way out of this situation lies in altering the frequency of the transverse oscillations for the "tail" as compared with the frequency of the oscillations of the "head". We may imagine, for example, that focusing is accomplished by RF lenses that manage to change strength during the transit time of a centimetre-long bunch.

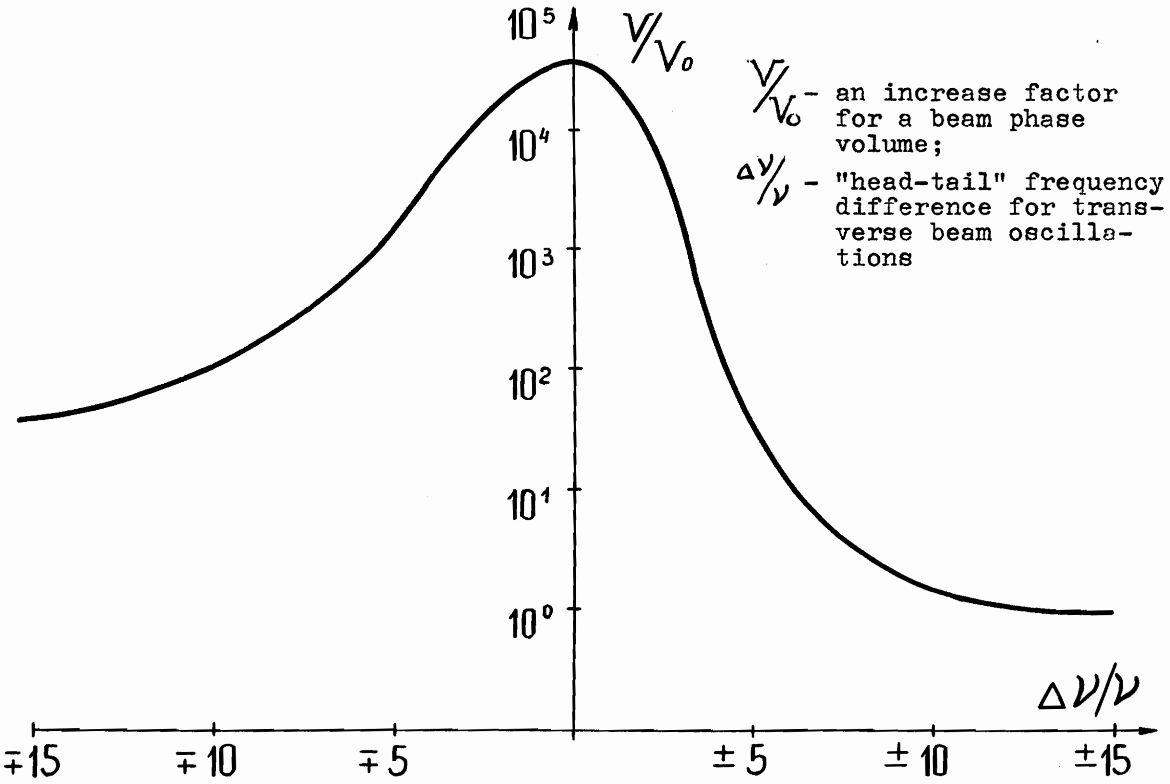

Fig.3

Much more accessible is another method of changing the frequency of transverse oscillations by varying the particle energy along the bunch. This can be easily achieved by injecting the bunch into a phase-shifted accelerating structure. As the particles are accelerated the role of the transverse forces decreases and the energy spread can be reduced. Computer simulation of the particle motion in this accelerating system with some comparatively reasonable selection of the magnet structure shows that to suppress the instability an initial energy spread of ±10% along the bunch is needed. By the end of acceleration this spread can be smoothly reduced to ±3% /5/ (Fig.3).

Naturally, there must be a system for complete monochromatization to a level no worse than a percent in the final section so that there is a well-defined energy, and also for reducing the chromatic aberration of the particle focusing at the collision point.

It can be inderstood that the requirement of having an energy spread does not deprive of value the first result of the calculations -- the possibility of accelerating a large-charge monochromatic bunch. Furthermore, only in this case will we be able, by adjusting the phase, to obtain for an extended bunch the linear energy variation along the beam that we require. This subsequently can be fully compensated by shifting a phase of different sign.

Beam instability is not the only cause of the increase in phase volume during acceleration. The next important aspect is the increase in phase volume due to the nonideally precise placement of lenses relative to the system's axis.

The lateral movement of one lens by some amount thus causes beam oscillations relative to the axis with an amplitude of the same order. Because of beam nonmonochromaticity, these oscillations enter the beam size. Any transverse impulses thus "heat up" the beam.

This fact imposes the requirement that the precision of adjustment of all accelerator systems be no worse than a few microns. It seems rational to us to use the beam itself for final positioning the system. When this is done the adjustment procedure can be completely automated and can be performed with the accelerator in operation. This reduces the requirements for long-term stability of the accelerator foundation, soil, etc.

5. Finally, yet another parameter must be taken into consideration in panning the structure. To reduce the overall length of the accelerator it is desirable to use the highest possible accelerating field gradient, which is limited by vacuum breakdown and autoemission loading. From this standpoint the accelerating structure can be characterized by the parameter κ :

$$\kappa = \frac{E_{max}}{E_{av}}$$

where E_{max} is the maximum field intensity at the surface of the accelerating structure and E_{av} is the average energy acquired by a unit ultrarelativistic charge per unit length of the structure.

A calculation shows that by selecting the optimal profile of the cavities it is possible to obtain κ quite close to unity; here it turns out that the requirements of having a large aperture in the slit and a small κ are contradictory. There has been success /6/ in selecting a compromise profile for a cavity with length $\lambda = 5$ cm and slit radius $a = 1$ cm at $\kappa = 1.4$.

The oscillations in adjacent accelerating cavities are phase-shifted by π . The structure is excited by means of ring coupling cavities.

Of course, this cavity profile is not optimal from the standpoint of active losses, but in our case this fact is not fundamental.

Preliminary experiments have shown that field intensities of about 150 MeV/m, which do not cause vacuum breakdown, are tolerable on the surface of well-machined copper. This makes it possible actually to have an acceleration rate of about 100 MeV/m in the accelerating structure.

6. Let us address the problem of supplying SHF power to the accelerating structure.

The SHF sources developed in industry have a power two orders of magnitude less than needed to supply a system with a reasonable number of such sources.

At the same time, in recent years the rapidly developing field of the technology of high-power relativistic beams has demonstrated the feasibility of using SHF power at the required level of the order of gigawatts, although this is in single-pulse operation.

One possible way of exciting the accelerating structure is to use the intense beams of large proton accelerators /7/.

7. It is quite curious to consider the effects of the collision, i.e. the effects of coherent interaction in bunches of colliding particles. In cyclic storage devices collisional effects are known to play a significant part and generally limit the luminosity.

An estimate of the electric and magnetic fields of a bunch at the collision point give a value of order 10^6 oersteds at the planned luminosity. These fields do not act on particles of "their own" bunch since the effects of the electric and magnetic fields are mutually compensated, but for a colliding particle the effects of the electric and magnetic fields are combined:

$$H = E = \frac{2Ne}{\ell(\sigma_x + \sigma_y)}$$

In this coherent field of a colliding bunch the electrons and positrons lose energy to radiation (the energy loss length is about $\ell_{rad} = mc^2/\gamma r_e^2 H^2$, and instead of colliding beams of defined energy we therefore will obtain a continuous spectrum. If monochromaticity at the level of a few percent is required, the attainable luminosity per pulse given a circular beam cross section turns out to be of order 10^{31} cm^2 for 100 GeV.

Changing to flat beams at the collision point while preserving the beam cross section area ($\sigma_x \gg \sigma_y$, $\sigma_x \cdot \sigma_y$ = const) is a radical method of reducing the effects of synchrotron radiation.

The second important effect is the influence of the coherent fields of the colliding bunches on particle motion at the collision point. For the case of collision of bunches of opposite sign, the fields of a colliding bunch are focusing fields. At the planned densities in the bunches a particle will succeed in undergoing a few oscillations in a bunch's field during its transit time.

For some time we had the hope that focusing fields would lead to a sort of beam "collapse" and to an increase in luminosity. But numerical simulation of the self-consistent motion of cylindrical beams showed that an increase in beam size a severalfold decrease in luminosity (the "overtightening" effects) more likely should be expected. For the flat-beam case these effects of increasing transverse beam size are significantly attenuated.

Reduction of the vertical emittance of beams, which is required to obtain flat bunches, may happen to be a very complicated problem. In this case, one will, apparently, have to accelerate two bunches (electron and positron) in both directions. Both these bunches have the same number of particles (a half of their maximum possible number). Naturally, the electrons and positrons are accelerated with the shift by a half of the wave length. By changing the trajectory the front bunch is delayed on this length prior to its arrival at the collision point. After that the bunches superimpose each other exactly, the coherent fields are mutually compensated, and all the collision effects are eliminated. For this one-flight case, there is no compensation stability problem, which is probably an obstacle in attaining high luminosity in the four-beam storage ring DCI (see Ref. 8). One half of luminosity value will be gained from electron-positron collisions and another half - from the electron-electron and positron-positron collisions.

Maybe the simplest way for working in the régime of compensation is the acceleration of electron and positron bunches in each direction by means of independent accelerating structures (four-linac system). One may have the same luminosity and spend the same average power by choosing the corresponding wavelength and repetition frequency. The régime of compensation is needed absolutely for preservation of polarization at energies larger than 2 × 300 GeV. It should also be noted that the power of the beam-beam synchrotron radiation decreases as the square of the compensation parameter.

In the case of a collision of bunches carrying the same charge, i.e. in attempting to produce pure electron-electron and positron-positron beams, we will encounter a very strong repulsion effect which in this case apparently will reduce the maximum attainable luminosity by one or two orders of magnitude.

For the case of electron-positron collisions the strong attractive fields of the beams can facilitate the procedure for "aiming" beams at the collision point, and also will reduce somewhat the required focusing precision.

8. Finally, let us discuss the most pleasant part of the report: the specific features of setting up experiments with VLEPP.

There is no doubt as to the feasibility of detecting processes involving muon production - testing quantum electrodynamics or producing heavy leptons or $W^\pm$ or Z^0 bosons that decay into muons. By using high-power showers it obviously is easy to identify processes involving the creation of high-energy electrons and positrons, as well as γ -quanta. These processes include purely electromagnetic processes at large angles (scattering and annihilation) and hadron processes involving the creation of high energy π^0 mesons.

The situation is not so evident in experiments involving hadron detection.

The pulsed character of the luminosity degrades the signal-noise ratio in comparison with cyclic storage devices. Estimates show that the main source of the backgroundthat leads to the emission of soft quanta at large angles is the double electroproduction process /9/:

$$e^+ + e^- \to e^+ + e^- + e^+ + e^- + \gamma$$

which gives 10^2-10^3 photons per pulse. The energy of these photons basically does not exceed 0.5 MeV. Even a small absorber can appreciably attenuate this radiation flux at large angles, and it therefore is clear that the physical background does not pose an insurmountable obstacle to the detection of hadron events.

The background associated with particles striking the accelerator walls can be reduced, at least in principle, to the required extent by placing protective screens.

It is interesting to note that pulsed luminosity in principle makes it possible to use for event detection such devices as bubble chambers, preferably of the hybrid type (especially as the "inner", geometric part of the detector).

Finally, let us recall that a VLEPP can be used as a conventional double-energy accelerator with rather high average current polarized in any direction. This in itself is quite interesting, and the acceleration rate of 100 MeV/m also makes it possible to accelerate unstable mesons ($\pi^+\pi^-$) and, of course, muons.

In conclusion we present a rough table of the parameters of an accelerator at energies of 2 x 100 and 2 x 300 GeV.

Energy, GeV	2 x 100	2 x 300
Length	2 x 1 km	2 x 3 km
Luminosity	10^{32} cm^{-1}sec^{-1}	10^{32} cm^{-2} sec^{-1}
Average beam power	2 x 160 kW	2 x 480 kW
Number of particles in beam	10^{12}	10^{12}
Average power from mains	7-10MW	20-30 MW
Repetition frequency	10 Hz	10 Hz

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