ELECTRON-POSITRON LINEAR COLLIDERS

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The electron-positron colliding beam installations where the experiments have been first started at the Institute of Nuclear Physics of the Siberian Branch of Russian Academy of Science (INP SB RAS) at VEPP-2 became by now conventional and made the basis of the world high energy physics programs.

In spite of the fact that the energy of electron-positron colliders is more than the order of magnitude lower than that of the proton storage rings including proton colliders, a major part of experimental data is supplied by the electron-positron colliding beam machines. This is related to the fact that at the initial stage, there are actually elementary particles - leptons with a zeroth total charge and fixed energy.

However, soon after the construction of the first installations it became clear that their intrinsic property -the presence of synchrotron radiation of particles in a storage ring, which plays a positive role in damping the transverse oscillation motion of particles providing the storage and thereby the luminosity, with an energy growth it becomes to be negative effect limiting an attainable energy of particles.

Therefore, at the end of 1960's , INP started to search for the ways to solve this problem aiming at the development of the lepton colliding beams at energies of 100 GeV and higher. One of the way to solve the problem was an intensely discussed possibility of the developent of μ-meson colliding beams. An ultimate version enabling one to overcome the problem of synchrotron radiation is the use of electron - positron colliding beams based on linear colliders. A study of such a possibility was started by G.I.Budker, A.N.Skrinsky, and the author at the end of 1960's.

This work was first reported by A.N.Skrinsky in 1971 at the International Conference at Mourge (Switzerland). Even the first consideration has shown that for the succes of the technique suggested it was necessary to solve two main problems as obtaining the required energy at acceptable dimensions of the facility and obtaining the required luminosity at a reasonable consumption of electric power from the mains.

The work conducted first in the group and later in the laboratory headed by the author allowed in 1978 to arrive at the conclusion on the feasibility to develop the electron-positron storage rings at super high energies based on linear colliders.[2]

However, the realization of this possibility required a large amount of the technical-engineering and technological studies. Among the problems to be solved it is worth mentioning those as an increase in accelerating gradient by an order of magnitude, an increase in RF power of sources by two-three orders of magnitude, an improvement of alignment accuracy of storage ring components by two-three orders, as well as the improvement by the same order of the sensitivity to the displacement of the beam position probes, the reduction of price by several times of the RF-sources of high voltage power supply, etc.

In the work presented here the ways to solve the above mentioned problems are shown and the parameters close to the required ones were achieved for all the main problems. It is worth mentioning that soon after our publication in 1978, the proposal on updating the available linear accelerator for the work with colliding beams appeared in the USA and at the end of 1980's, the development of the linear colliding beam technique acquired its international character. Following Russia such countries as the USA, Japan, Germany, Switzerland (CERN) took an active part in the work in this direction.

In spite of the fact that the economic and political situation in Russia does not offer the hope for the feasibility of the VLEPP project by our own efforts, nevertheless the basic ideas and achievements realized in the process of work on the VLEPP project are now used both in the SLC accelerator and in the other projects. In case of realization of the VLEPP International project, Russia could take a qualified part in the project.

The present work is devoted to the physics fundamentals of this novel technique in accelerator physics - the method of linear colliding beams.

1 Obtainig energy

1.1 Accelerating structures

In the beginning of the work, quite common and well acceptable value of accelerating gradient for the high frequency for electron linacs was the value of 10 Mev/m meaning that for attaining an energy of colliding beams of a few hundred GeV the total required length of accelerator should be of tens kilometers.

Such a value was considered as hardly acceptable from the economic point of view. Therefore, one of the first problems to be solved was an attainment of acceleration rate to be by an order of magnitude higher that those conventional i.e., of 100 MeV/m.

At the same time, the experience obtained in the development of microtron has shown that the required intensities of electric field could be achieved in single cavities of microtrons. However, it was difficult to use directly the microtron cavity operation because of the bad reproducibility : high intensities occured due to several reassamblies and cleanings of cavities.

It is clear that in case of linac accelerating cavities comprising a few tens of cavities, where the structure strength is determined by the strength of the weakest cavity, one has to provide high reproducibility of an electric strength.

A series of experiments on the specially constructed stand has been conducted for studying this problem.[2]

The schematic diagram of the experiment is given in Fig.1. A standard powerful pulse klystron at a wave length of 10 cm excited an individual (sectionized) cavity of a special shape. Due to special cavity shape it was produced such a distribution of RF electric field to attain its maximum value in the center of removable disk.

The flat surface of the disk was a test surface. The advantage of such an approach is a possibility of multiple use of the same cavity, an ease in processing and preparation of the test flat surface. For the measurement of the electric field value attained on the test copper surface, the magnetic spectrometer with the detection of particles by scintillation counter was used. For these measurements, the

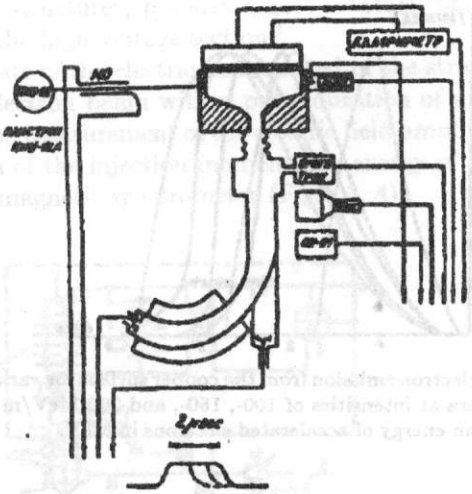


Figure 1: Schematic of experiment on measurement of an ultimate electric intensity on the copper surface An energy of electrons emitted by a flat surface are measured by the magnetic spectrometer. The breakdowns in a cavity are detected by the shape of reflected RF wave, by luminescence in the cavity , by gamma-radiation , and by a decrease in vacuum.

electrons were used emitted from the copper surface due to autoelectron emission. The high sensitivity of the scintillation counter detecting even single electrons enabled the reliable measurement of electric fields beginning from intensity value of 50 MeV/m.

As a result of the work the technology was developed to provide attaining electric strength on the copper surface of 450-200 MeV/m that with an account for overvoltage in the real structure enables one to attain accelerating gradient of 100 MeV/m.

High electric strength was achieved in a reproducible way by providing the following conditions:

a) high accuracy treatment of the oxygen-free copper surface by a diamond cutter;

b) upon the treatment the surface is subjected to ultrasonic cleaning with the use of surface active substances and deionized water;

c) after cleaning, the surface is transported in a dustless tare;

d) the installation vacuum is provided by oilless pumping.

Fig.2 shows some samples of electron spectra obtained for various samples demonstrating a feasibility to attain the above mentioned values of the field intensity.

These results allowed us to arrive at the conclusion of a feasibility in principle to attain the reproducible results on obtaining ultimate electric strength of 100 MeV/m in high frequency accelerating structures. These results based the choice of parameters of our first proposal in 1978. [1, 2]

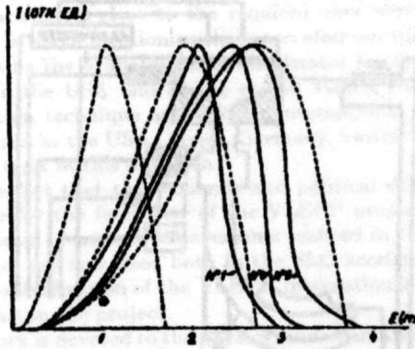


Figure 2: Spectra of autoelectron emission from the copper surface for various test samples (solid line) and calculated spectra at intensities of 100-, 150-, and 200 MeV/m, respectively (dashed line). Horizontal scale is an energy of accelerated electrons in MeV.

It is clear that for continuing the work with accelerating structures at high gradient in this range it was necessary to develop RF sources of sufficient power of the frequency range required. In RF energetics, it is common that difficulties in the development of RF power sources grow with a decrease in the wavelength as a square of wavelength therefore, we have chosen the wavelength of 4 cm as compromise solution.

In this range, the number of sources of an amplifier type with a power ranging from 20 to 50 mW have been developed. With their use the experiments on a study of high frequency structures with a wavelength of 4 cm have been done.

The choice of a type of high frequency accelerating structure for a storage ring should satisfy a number of contradictory requirements. So, in order to reduce the load of accelerating structure by the beam one should have maximum large amount of the stored energy in the structure meanwhile a large amount of energy leads to a large energy loss for heat in the period of oscillation therefore, it requires large power for the excitation of oscillations.

The transverse fields excited by an accelerated bunch passage are especially dangerous since they cause the transverse instability of a beam. In order to reduce these forces one has to increase the diameter of holes in diaphragms separating single cavities of accelerating structures. But an increase in the diameters of holes (connection holes) increases the group velocity in a structure which also increases the power required for the structure excitation.

The situation is facilitated with the use of accelerating structures with a standing wave, where the wave passed the structure is reflected from its ends and it is then used for exciting the accelerating field.

In the INP workshop, it was developed the production of the structure components and also the technique of soldering with the use of (to a major extent discovered earlier) technology providing high electric strength.

The high power test of the structure required the production of a special stand including the powerful source of RF oscillations, wave guide proving the transfer of the power to structures, powerful phase rotators, branchers, loads, and other components of the high voltage section.[3]

Measurements of the electric field excited in the structure was made with the help of a test electron beam with a pulse duration of a few tens of nonoseconds thus enabling the measurement of the electric field amplitude as a function of time by the variation of the injection moment. An energy of accelerated electrons was measured by a magnetic spectrometer (Figs. 3, 4).

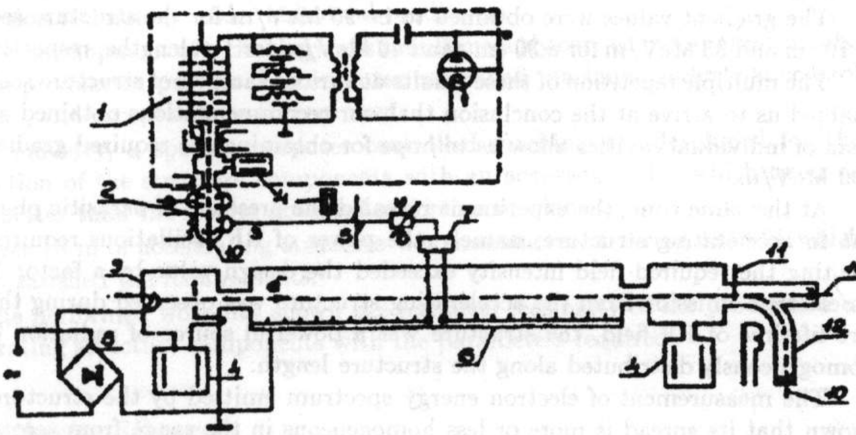


Figure 3: Test stand schematic diagram
1- electron beam generator for gyrocon; 2- gyrocon; 3-wave guide ; 4-magnetodischarge pump; 5- directed brancher; 6-phase rotator; 7-wave type transformer; 8,9-generator of a "trial" beam; 10- Faradey cup; 11-current probe; 12-magnetic spectrometer; 13-tested section .

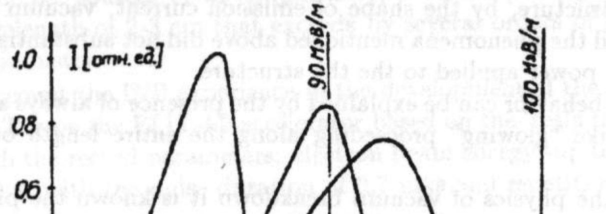


Figure 4: "Test" beam spectrum for vatious power levels applied to structures. It is seen that at maximum available power, an intensity of accelerating electric field is over 90 MeV/m.

As a result of a series of experiments conducted in the beginning of 1980's a number of devices have been simultaneously developed for further realization of accelerator project as the high voltage source for an electron beam of RF generator, various kinds of RF generators, other components of the powerful RF section, the technology for producing and soldering accelerator structures, and finally, the test on the highest level of power.

The structure components were made by a diamond cutter of a special profile providing the required surface quality close to the mirror surface with further cleaning of the surface and an assembly with precaution against dust and soldering in vacuum oven which was filled with dustless medium (nitrogen) during its opening.

The gradient values were obtained to be 90 MeV/m for the structure section of 10 cm and 35 MeV/m for a 30 cm , and 40 MeV/m for 1 m lengths, respectively.[3]

The multiple repetition of these results at various samples of structure scetions enabled us to arrive at the conclusion that our recommendations obtained at the tests of individual cavities allow us to hope for obtaining the required gradient of 100 MeV/m.

At the same time, the experiment revealed the presence of parasitic phenomena in accelerating structure, namely, the power of RF oscillations required for exciting the required field intensity exceeded the design value by a factor 1.5-2, an electron emission from the accelerating structure was observed during the entire lifetime of RF field, the structure was a powerful source of radiation being homogeneously distributed along the structure length.

The measurement of electron energy spectrum emitted by the structure has shown that its spread is more or less homogeneous in the range from zero to its maximum value. It has to be stressed that all these phenomena were observed with the absence of clear breaksowns in the accelerating structure and they were reliably detected by the shape of envelopes of the incident and reflected waves from the structure, by the shape of emission current, vacuum behavior, etc. In addition, all the phenomena mentioned above did not substantially depend on the level of RF power applied to the the structure.

Such a behavior can be explained by the presence of always available discharge processes like "glowing" proceeding along the entire length of the accelerating structure.

From the physics of vacuum breakdown it is known the phenomenon of the secondary-emission discharge in RF field having the properties enabling the explantion of the phenomena observed.

Usually, the secondary emission discharge is observed in the field of weak electric fields and the large amplitude of RF magnetic field facilitates this also.

In order to find out the discharge location, the following way was used: an organic vapor (spiritus) was filled into the vacuum cavity aiming at the vapor decomposition by an occurred discharge and then, after cutting the accelerating structure along the discharge traces one can localize the secondary emission discharge.

This idea was realized and the experiment has shown that the secondary emission discharge occurred in the region of connection holes on a surface of complex shape.

Therefore, the cardinal decision was made to shift from the standing wave structure to the well studied structure with traveling wave like the diaphragmed wave guide.

Meanwhile, the experience accumulated in the development of power sources of RF oscillations allowed the hope for obtaining the required power with further reduction of the wavelength down to 2 cm that seems to be preferable from the viewpoint of beam dynamics.

During the development of the traveling wave accelerating structure at a wave length of 2 cm it was decided to carry out simultaneously the work on the serial production technology under industrial conditions.

The development of technology was simultaneously carried out at three plants. For the production process the computer controlled machines, industrial control systems , and acceptance tests were used.

In industry, a special computer controlled machine was developed for the production of the structure components with an accuracy of 1.. which twice as much better than the results obtained at foreign machines.

Over 10 m of accelerating structure was manufactured during 1988-91 which mainly satisfied the requirements.[4]

The performed work has shown the technical feasibility of the production of accelerating structure components with the parameters required.

1.2 Attaining RF power

As already mentioned above, there is no production of RF oscillation generators of required power therefore, the development of linear collider technology requires the development of RF sources of an amplifier type with a pulse power of 50-100 MW at a wavelength of 2-3 cm that exceeds by several orders of magnitude those available in industry.

Taking into account the INP experience in the development of the pulse electron source of ELIT-type the ELIT-L2 accelerator based on the Tesla transformer was developed with the record parameters: electron beam energy -up to 1.2 MeV, pulse current=200 A with the pulse duration of 0.7 mks and repetition rate of a few Hz.[5]

The accelerator made a good base for further work on RF power generation. A few principles of the conversion of electron beam energy have been tested.

In addition to the well known klystron method some new techniques as a "separator" , a multi- cavity gyrocon with frequency doubling, and flat gyrocon have been tested.

With these devices of an amplifier type, the power values within the range of 20-60 MW were obtained at a wave length of 4 cm and efficiency of about 20-40%. RF power generated by these devices was used for studying the accelerating structures and other components of the wave guide conduit.[6]

In the experiments with these devices, a number of parasitic phenomena like a multipact discharge in regions with low electric fields , various kinds of instabilities, and breakdowns were found out.

The experience in solving these problems as well as the results obtained enabled us to propose a new concept of the system of RF power supply for linear collider.

The proposed concept differs from the existing conventional approach to the power supply of linear accelerators by three main points:

- Quite low capital investment for the production of the RF power supply system for linear colliders.
- Quite low standard consumption of electric power because of high efficiency of the system.
- The system compactness which reduces expenditure for the accelerator construction since the required underground space for housing equipment is reduced.

Because of the limited scope of the report we will only briefly outline the main points of the concept which enable the solution of the abovementioned problems.[7]

For the better understanding of the idea we will outline the sequence of the energy conversion process from the mains to the final high energy beam of electrons or positrons.

A 50 Hz mains voltage is converted into the 1000 Hz voltage in order to reduce the space for future equipment.

Then, an alternate voltage is converted into direct voltage of 1.15 MV in the high voltage source located in the underground tunnel.

Capacitances of the storage line formed by the gaps between metal pipes are charged by this voltage.

In order to increase an electric strength all the high voltage cavities are filled with SF6 pressurized gas.

The storage line is connected to the cathode grid unit of the klystron electronic optical system.

However, there is no current in the klystron since on the govern electrode ("grid") there is a negative potential with respect to the cathode.

At an appropriate instant, the positive potential is applied to the "grid" from the control unit being at high voltage and the cathode starts to emit current to be accelerated in the gaps of a multisectional accelerating tube and then, it is applied to the klystron high voltage system where it is converted into RF oscillation energy similarly to that as in the conventional klystron .

The beam focusing in klystron is provided by a sign varying focusing system with permanent magnets. General layout of the klystron is given in Fig.5

During the electron pulse, the klystron cathode voltage is "reduced" down to 1 MV. For the time between pulses the voltage is restored to its maximum value.

As is seen, such a scheme does not envisage the powerful energy commutator, pulse transformer, expensive capacitors of the storage line.

The source of constant high voltage necessary for the operation of this system can supply over 10 klystrons simultaneously thus reducing the cost of the project. The sizes of storage line (0.5 m in diameter) and high voltage source enable their location in the tunnel together with the accelerator equipment.

Of course, these advantages are not free of charge. So, the presence of governing electrode in the electron optical system requires an increase in the cathode

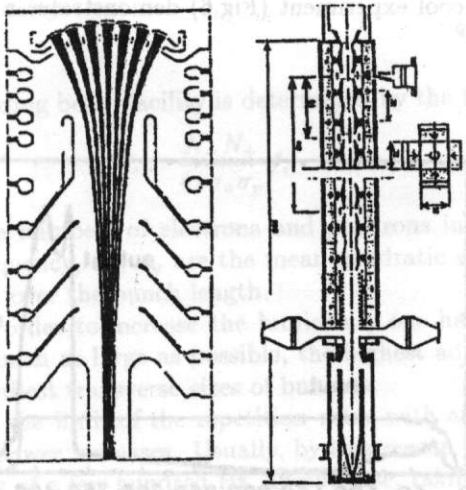


Figure 5: Layout of klystron with a multicell cathode, current free grid control, multigap accelerating tube (a), focusing system with permanent magnets, and traveling wave output system (b). A large number of cavities (8) enables the record large amplification (80 dB).

size and its special cell structure which complicates the problem of further beam focusing. The system of time varying focusing on permanent magnets complicates also the problem of beam transport in klystrons.

The use of constant high voltage (1 MV instead of 0.5 MV pulse voltage) complicates the design of accelerating tube though it enables one, in principle, to get higher efficiency due to small perveance of the beam.

The RF-power pulse with duration of 500 ns is applied to the so-called power multiplier which stores high frequency energy during the first 400 ns and then, after reswitching the phase of RF signal by 180°, it is applied to the accelerating system during the 100 ns pulse and a power 4 times higher than the initial value.

The idea of such a conversion of a pulse and appropriate devices have been proposed at SLAC, USA and used there in the linear accelerator at a wavelength of 10 cm.

With the shift to shorter waves of 2 cm the time constant of cavities drops more than 10 times therefore, the existing principles of energy storage are not applicable.

In order to overcome this difficult, the author suggested [8] a new type of RF device based on the use of the so-called "open" cavities having high duty factor ($Q = 3 \cdot 10^5$). Special way of excitation of these cavities which provides the generation of one mode as well as the use of two connected cavities enabled one to obtain the pulse shape close to rectangular instead of the exponential one as it was done at SLAC.

The results of cool experiment (Fig.6) demonstrates a very good agreement with calculations .[9]

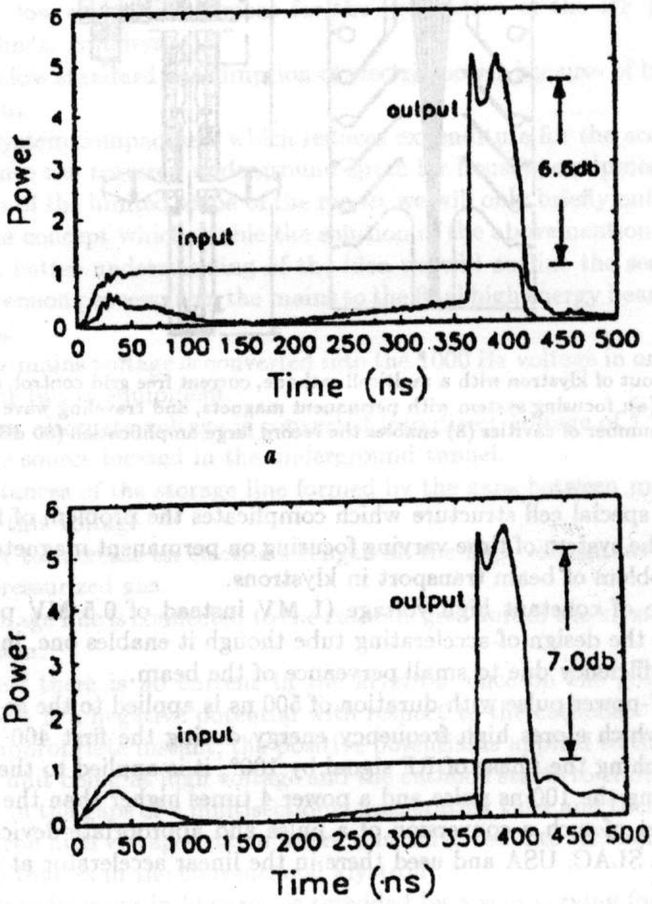


Figure 6: Results of "cool" tests of the power multiplying system with the use of "open" cavities. The upper part -experiment; the lower part-the design.

The pulse power of 60 MW at a wavelength of 2 cm at the record amplification factor of 8 dB was achieved on the klystron experimental sample.

At the same time, in order to achieve all the design parameters, it is necessary to work out the design.

2 Obtaining luminosity

2.1 Collision effects

The luminosity of colliding beam facility is determined by the formula:

$$L = \frac{N_- N_+}{4\pi\sigma_x\sigma_y} f,$$

where N_-, N_+ are numbers of electrons and positrons in a bunch, f is the collision repetition frequency, σ_x, σ_y are the mean quadratic sizes of the beams, respectively , averaged over the bunch length.

It is clear that in order to increase the luminosity one has to use the number of particles in a bunch as large as possible, the highest admissible repetition frequency, and the smallest transverse sizes of bunches.

The most vivid is the limit of the repetition rate: with an increase in repetitions the consumed power increases. Usually, by this reason the repetition rate in linacs is of the order of a few hundred Hz. In our case, taking into account the higher efficiency of the power supply system one can expect to get the repetition rate of 150-300 Hz.

The number of particles N_- and N_+ cannot be taken arbitrary large, namely: an energy taken away by a bunch from the accelerating structure should amount a small part of the energy stored in electromagnetic field of the structure.

Thus, the only arbitrary parameter seems to be the beam size σ_x, σ_y and it would seem to be able to attain any high luminosity if one could achieve the beam size sufficiently small.

The first limit to the beam diameter was discovered during the considerations of particle bremmstrahlung effects in the collective field of an encountered bunch. As it turned out, this effect limits substantially an admissible luminosity of the device but without overcoming this obstacle this makes the linear colliding beam device beyond the interest.

In order to overcome this limitation, the author suggested to use the flat beams. In this case, the transverse magnetic field is equal to:

$$H \sim \frac{N}{4\sigma(\sigma_x + \sigma_y)},$$

As is seen from this equation, with a decrease in one of the beam sizes, σ_x, for example, the magnetic field becomes only 2 times higher but at the same time, the luminosity $1/\sigma_x$ can be arbitrarily high.

Since the sum of the electric and magnetic fields of the encountered beam produces the focusing force, one could expect that during collision, particles will oscillate with respect to the center of the encountered bunch.

An analytic consideration under assumption of the strong encountered bunch proves this [10] and gives the following value for the number of transverse oscillations in a flat bunch

$$\nu_x \simeq \left(\frac{N\sigma_z}{\gamma\sigma_x^2}\right)^{\frac{1}{2}},$$

$$\nu_x \simeq \left(\frac{N\sigma_z}{\gamma\sigma_x^2\sigma_y^2}\right)^{\frac{1}{2}},$$

It is evident that in order to keep the bunch flat it is necessary to have the number of transverse oscillations Υ much less than unity: $\nu_y << 1$, otherwise the field of an encountered bunch increases and meets the abovementioned limitation of the bremmstrahlung effect.

For the smaller size of a bunch i.e. along the X-direction, the analytic estimate gives $\nu_x > 1$. This means that we should consider the self-matched motion of particles colliding in bunches.

The numerical simulation of the bunch collision dynamics[7] proved the analytic estimate but the limitation for the minimum size of the bunch was discovered σ_x, namely, the beam size cannot exceed the value at which the number of transverse oscillations ν_x becomes larger than 2.

This limitation is related to the onset of the fast two-beam transverse instability of colliding beams with the start of which the effective transverse size of a beam increases and consequently the luminosity decreases.

At the same time, the idea given in our first paper in 1978 [1] on the use of transverse forces of the encountered bunch for producing the "pinch" effect, i.e. the use of focusing properties of the beam seems to be quite attractive.

The numerical calculations [10] have shown that in reality, at quite a small number of particles (to be more exact, at a small number of transverse oscillations $\nu_x = 0.25 - 0.5$) the focusing effect is observed with an increase in luminosity by a factor 1.5 compared to the purely geometric luminosity but with increase in ν_x up to its optimum value about 2 the focusing effect vanished (Fig.7).

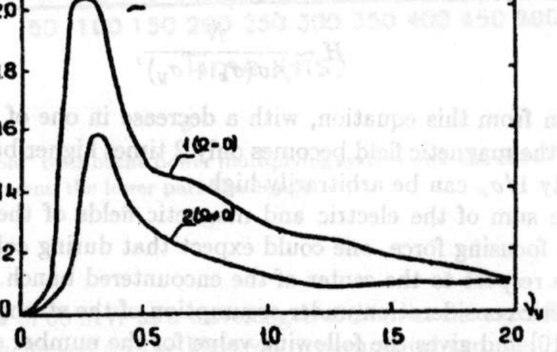


Figure 7: Relative luminosity $K = \frac{L}{L_o}$ as a function of ν_y for the collision of similar bunches with homogeneous distribution of discharge density (L_o is the luminosity calculated geometrically with no account for collision effects). *1– The bunch phase volume* $\Sigma = 0$. *2– The phase volume* $\neq 0$; $\beta = \sigma_x$.

Recently [11], the author has found out the beam focusing technique the so-called "running focus". For obtaining the "running focus" effect one has to provide the following conditions:

1. beam focusing at the point of collision should be sufficiently strong, namely, $\beta << \sigma_z$;

2. focusing system should have the given chromatism;

3. inside the bunch, an energy should be specially distributed: the bunch "head" energy should be higher than the tail "energy" by the given value, for example, by 0.5-1%;

4. the largest effect is observed at the density distribution in a bunch closer to rectangular one.

By following these conditions, the "heads" of colliding beams are focused to small sizes and then they keep the small size because of focusing forces of the encountered beam (Fig.8).

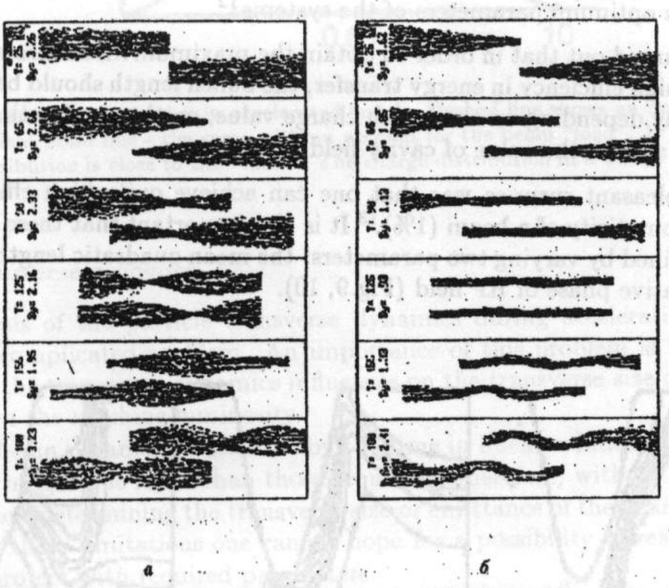


Figure 8: a. Simulation results of collision of two oppositely charged bunches . An additional focusing by the field of encountered bunch is seen (the central collision on the image is artificially displaced for better viewing).
b. The same as given in Fig. 7a during the operation of focusing system in the regime of "running focus". The onset of transverse instability is seen.

The use of "running focus" provides the gain in luminosity by a factor 2-2.5 at a beam emittance about 5 times higher.

2.2 *Longitudinal dynamics*

The feature of the colliding beam mode operation of the linear collider is the accelerating structure operation in the mode of stored energy. At this operation run, in the accelerating structure, the electromagnetic field energy is stored during quite a long period of time (a few thousand periods of oscillation) and then, during a fraction of a period it is transferred to the accelerated bunch.

It is clear that the process should proceed at high efficiency in order to achieve maximum use of field energy for the particle acceleration. On the other hand, it is evident that if one would achieve the full energy transfer to the bunch it would also cause a 100% energy spread in a bunch since the last particles in a bunch would be moved in zeroth field thus having zeroth energy.

For the analysis of the process in the laboratory headed by the author the numerical methods of analysis of these processes have been developed enabling us to select the optimum parameters of the systems.[12]

So, it turned out that in order to obtain the maximum monochromaticity of a bunch and high efficiency in energy transfer, the bunch length should be selected in a special way depending on the bunch charge value, on the accelerating structure wavelength and on the value of cavity field intensity.

Quite pleasant surprise was that one can achieve quite high efficiency, say, 25monochromaticity of a beam (1%).[13] It is also important that these parameters can be obtained by varying two parameters: the mean quadratic length of a bunch and the relative phase of RF field (Fig.9, 10).

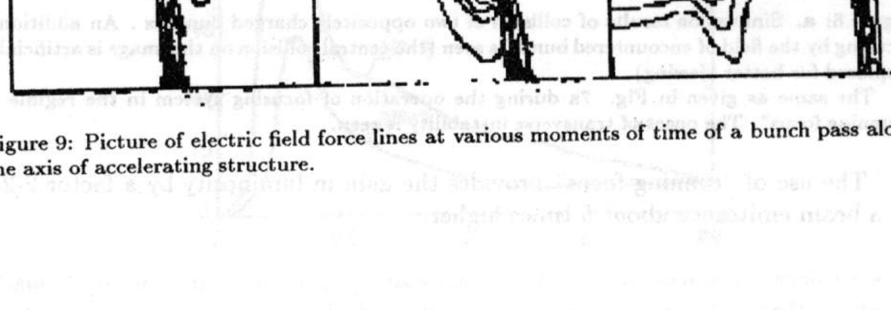


Figure 9: Picture of electric field force lines at various moments of time of a bunch pass along the axis of accelerating structure.

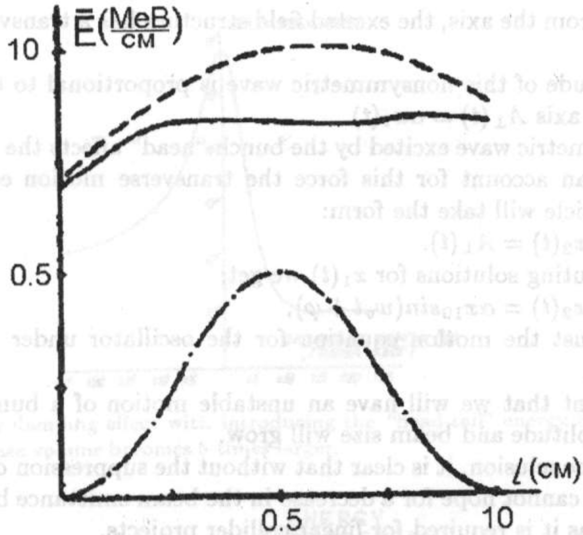


Figure 10: Energy distribution in accelerated bunch. Dashed line shows an amplitude of high frequency field, solid line - the same with an account for the beam "load". It is seen that the energy distribution is close to the "table". The charge distribution in a bunch is shown by the dashed line.

2.3 Transverse dynamics

An analysis of the particle transverse dynamics during acceleration turned by be more complicated problem. An importance of this problem is related to the fact that the transverse dynamics influences on the transverse size of a beam and thereby on the machine luminosity.

The beam parameters attained by the time in linear colliders were by several orders of magnitude lower than those required. Therefore, without an analysis of mechanisms determining the transverse size or emittance of the beam and without removing these limitations one cannot hope for a possibility to realize the linear collider project with required parameters.

The first problem encountered in an analysis of the transverse dynamics of a single bunch was the transverse instability of a single bunch.[1]

In order to consider this instability let us take the simplest model of a bunch with in the form of two particles with the transverse coordinates x_1(t) and x_2(t), respectively, traveling in a continuous focusing field.

The equation of motion for the first particle (bunch "head')' will have $\ddot{x}_1(t) + w_\circ^2 x_1(t) = 0$ with the solution $x_1(t) = x_{10} sin(w_\circ t + \varphi)$, i.e. the oscillatory motion with respect to the axis of accelerating system.

In order to find out the dynamics of the second particle (bunch "tail") following the first particle one has to take into account that the first particle passing the accelerating structure excites there an electromagnetic wave. In this case, if there is a deviation from the axis, the excited field structure has a transverse component $A_\perp(t)$.

An amplitude of this nonsymmetric wave is proportional to the deviation of $x_1(t)$ from the axis $A_\perp(t) = \alpha x_1(t)$.

A nonsymmetric wave excited by the bunch "head" affects the following bunch "tail". With an account for this force the transverse motion equation for the secondary particle will take the form:

$\ddot{x}_2(t) + w_\circ^2 x_2(t) = A_\perp(t)$.

By substituting solutions for $x_1(t)$ we get:

$\ddot{x}_2(t) + w_\circ^2 x_2(t) = \alpha x_{10} sin(w_\circ t + \varphi)$,

which is just the motion equation for the oscillator under the action of a resonant force.

It is evident that we will have an unstable motion of a bunch and the tail oscillation amplitude and beam size will grow.

After this conclusion, it is clear that without the suppression of the instability discovered one cannot hope for a decrease in the beam emittance by several orders of magnitude as it is required for linear collider projects.

The methods developed for suppressing "current break" do not work in the case of a single bunch instability.

The solution turned to be surprisingly simple and it could also be found in the simplest two- particle model, namely, in order to avoid the resonant instability, it is necessary to have the resonant frequencies of transverse oscillations different for the first and second particles.

In practice, it could be achieved by the phase shift between the instant of a bunch pass and RF oscillation phase in cavities of accelerating voltage. With such a shift, the difference in longitudinal energies occurs in the accelerated bunch leading to frequency variation of transverse oscillations that is required for suppressing instability.

This conclusion was also proved by numerical calculation [14] for a multiparticle bunch model (Fig.11) and in 1988, it was proved experimentally during commissioning the SLC linear collider. [a]

At present, this technique is widely accepted and used in the majority of linear collider projects suggested.

Unfortunately, the technique suggested for suppressing the instability has some negative features, namely, during the particle motion in the real accelerator , due to unavoidable mistakes in alignment of accelerator components the transverse oscillations are excited leading to an increase in the beam transverse size with the presence of the beam nonchromaticity. Fig.12 shows all the said above.

Similar mechanism of size increase was considered during an analysis of the proton accelerator operation. However, in the case of linear colliders, where the length is large and the number of transverse oscillations is also large due to strong

[a] Foreign authors called this method "BNS-damping" by the first letters of the authors' names. In addition to the author, A.V.Novokhatsky and V.P.Smirnov participated in the work by making the numerical simultation for a multiparticle model of a bunch.

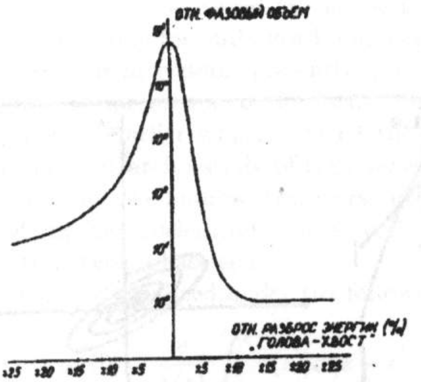


Figure 11: Instability damping effect with introducing the "head-tail" energy difference. At zeroth spread, the phase volume becomes 5 times larger.

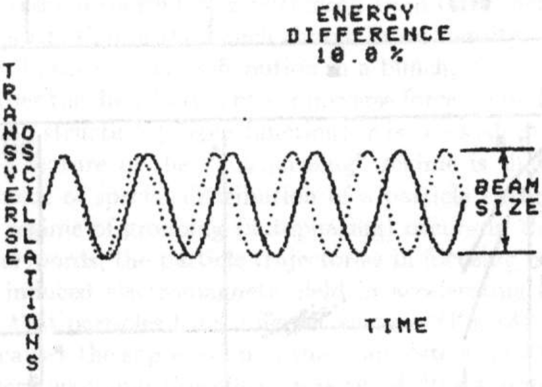


Figure 12: "Stochastic heating" of a beam. An increase in a beam phase volume with the presence of nonchromaticity and faults in component alignment.

focusing, a special regime of beam expansion occurs - the so-called "stochastic heating."[14]

The "stochastic heating" regime starts under the following condition :

$$2\pi \frac{\Delta E}{E} N > 1,$$

where $\frac{\Delta E}{E}$ is an energy spread in a beam necessary for instability damping, N is the number of transverse oscillations in a focusing system.

If the condition is satisfied, the beam expansion in transverse direction has diffusion character with a normal distribution of a beam density with respect to the center and the beam halo is formed, etc. [15]

This mechanism is only operated if the mistakes were made in the alignment of accelerator components thereby posing limits to the required alignment accuracy.

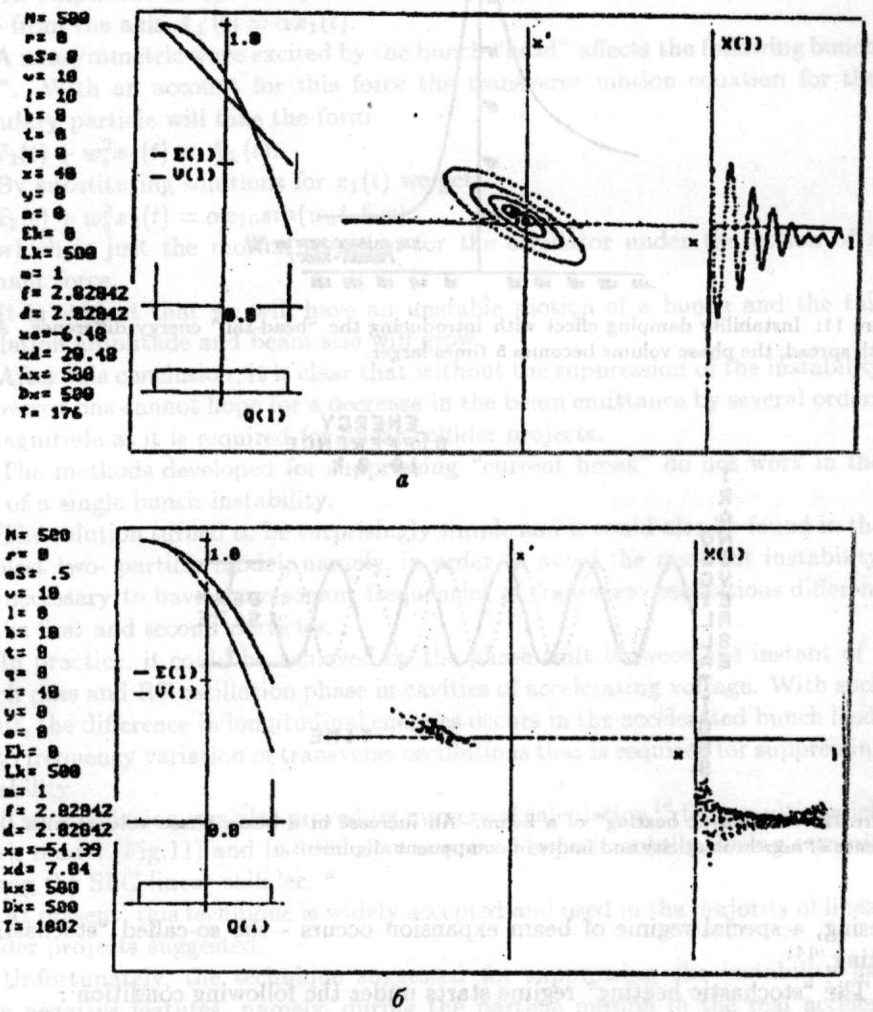


Figure 13: a - calculation of beam dynamics with an account for induced transverse fields with introducing the "head-tail" energy difference ("BNS"-damping). Energy distribution along the bunch *E(I)* and transverse force of residual field *V(I)* are given in the upper left-hand part, the charge distribution in a bunch (rectangular) is given in the lower left-hand part, in the right-hand side of the central part the transverse coordinate of particles along the bunch in the particle bunch distribution on the transverse phase plane ("head" - to the left);
b - the same as *(a)* but the particle energy distribution corresponds to the regime of "autophasing". The reduction of area occupied by the beam on the phase plane is noticeable and the size of the beam is substantially smaller.

Even in our earlier papers [1] we perceived the necessity of alignment of components with an accuracy of 1 mkm for quite low luminosity that is by 1-2 orders of magnitude stronger than that in systems presently available.

In order to reduce the requirements to the beam emittance, the "running focus" technique was proposed earlier which reduced the requirements at fixed luminosity of about five times[7]. Careful study of transverse dynamics of nonchromatic beam with an account for the induced transverse fields enabled the author to discover new regime of particle acceleration - the so-called regime of "autophasing" for particles in the transverse phase space

The "autophasing" regime is realized under the following condition:

$$w^2(z) = w^2(0) + \frac{c}{\gamma(z)} \int_0^z r(z')\alpha(z-z')dz'.$$

Here

$w(z)$ – is the frequency of transverse oscillations of bunch particles as a function of the longitudinal coordinate z referenced from the bunch "head",

$\gamma(z)$– the distribution of the bunch charge linear density,

$r(z)$ –charge linear density disfribution in a bunch,

$\alpha(z)$– describes the distribution of a transverse force excited by singular charge in the accelerating structure (Green function), c is the scale constant.

A surprising feature of the "autophasing" regime is that, if it is followed, i.e. with the choice of special distribution of a particle energy along the bunch a quite specific regime of grouping (autophasing) occurs in the transverse phase space or, in other words, the particle trajectories in focusing magnetic field (with an account for induced electromagnetic field in accelerating structure) coincide despite the fact that particles have different energies (Fig.13).

This effect causes the suppression of the beam "stochastic heating" effect and therefore [15], where we found this effect, was titled "the suppression of the beam stochastic heating in linear colliders".

2.4 Adaptive alignment

Further efforts were aimed at a study of the problem of precise alignment of the accelerator components and a search for ways to improve the accuracy.

An analysis of data on the stability of the available accelerator components, data on the seismic vibration of the ground, and an estimate of the thermal deformation of components at air temperature fluctuations shows that under assumption of an accuracy of tens and hundreds fractions of a micron, one should give up the conventional approach to the component alignment (static alignment) based on the solid stable supports, rigid fixing of components, etc.

Instead of static alignment the author suggested a new approach called an "adaptive alignment" [16]

General idea of the method is that the beam position probes are placed into the focusing quadrupole lenses required the most precise alignment and by the data provided by the probes the element position is corrected. One can say that we are using the beam for laying out the direct line and all the accelerator components are further set up with respect to the line, whereas at conventional approach (static alignment) the accelerator components are aligned with the special system of alignment (geodesic way with the laser beam, etc.) and then, with the help of correcting magnets they try to run the beam through elements set up with errors.

The correction of elements with an adaptive alignment can be achieved in the dynamic mode of operation at a rate of ten times per second. With such a correction frequency the effects related to seismic oscillations of low frequency (0.1 Hz) with large amplitudes ($\sim 1mkm$) are suppressed as well as the slow drift of elements related to the variation of temperature, pressure, humidity, etc.

The realization of the idea of adaptive alignment requires the solution of three basically important problems:

1. the development of beam position probes with a sensitivity by 2-3 orders of magnitude higher than that presently available;

2. the development of a system of mechanical drives for moving accelerator elements with an accuracy level of hundred fractions of a micron and with a frequency transparency band of a few Hz;

3. an algorithm should be found out providing the stable operation of the adaptive aligment system of a few thousand elements at a set-up frequency about ten times per second with an appropriate computer support.

The currently attainable accuracy for the beam position probes is of the order of 10 mkm. Recently, at SLAC, the probe with an ultimate accuracy of 1 mkm was developed for the linear collider program but we suggested the concept of a probe with an accuracy of $10^{-2} - 10^{-3}\mu km$.[17]

For the solution of the problem it is suggested to use a single cavity where the running bunch of particles generates an electromagnetic field whose analysis enables one to judge of the bunch flight coordinate.

The idea itself is not new but the novelty is the technique of signal processing which allows to achieve the required sensitivity to the beam displacement with respect to the cavity axis.

The main difficulty is that the useful signal power of an asymmetric wave is weaker than background signal of symmetric wave in a cavity by 100-200 dB ($10^{10} - 10^{12}$ times). Therefore, the main efforts are concentrated on the ways to separate the weak useful signal.

In reality, an analysis of excitation dynamics for an asymmetric wave shows that in the real cavity with an account for errors in manufacture sizes , nonideal cylindricity, etc. The nonsymmetric wave is always excited. In other words, an accuracy in defining "axis", i.e. the zeroth coordinate, does not exceed the mechanical accuracy of probe manufacture which is of the order of 1 mkm.

In order to overcome this problem, it was suggested to measure an amplitude and additionally the phase of induced signal, i.e. the phase of nonsymmetric wave with respect to the instant of the bunch flight.

Technically simplest way to solve the problem is to add one more "reference" cavity whose main mode frequency is the same as a frequency of nonsymmetric mode of measuring cavity.

Signals from measuring cavity (after their additional processing) and reference cavity signals are applied to the phase detection circuit on whose output we will have the signal proportional to the bunch coordinate displacement with respect to some code cavity axis.

In order to achieve the above mentioned level of useful signal filtration , a few levels of signal selection are used each providing the level of 30-40 dB in order to achieve the required resulting level of signal separation.

The first level of selection is a spatial filtration using different structure of fields of the symmetric and nonsymmetric wave.

In other words, the device for signal extraction from the cavity is made in such a way that symmetric mode signals are subtracted and nonsymmetric mode signals are added.

This is achieved with a passive device decreasing the power level of symmetric wave down to the value at which one can further use the active devices.

The next level of selection is time filtration. The matter is that the structure of a current exciting the cavity is of a σ–function character, i.e. its spectrum comprises all the frequencies and therefore, in spite of a large difference in frequencies of the symmetric and nonsymmetric waves in a cavity we will always have signal mixing. In order to suppress this effect, or for damping a continuous part of the σ–function signal spectrum there are two techniques:

- the cavity duty factor for symmetric mode is made much lower than that for the nonsymmetric wave;
- unless the symmetric mode signal attenuated substantially in the cavity, the receiving system is disconnected from the measuring cavity and only in some time (of the order of a few attenuation times for symmetric mode), the receiving system is smoothly switched on. The smoothness of connection is also necessary to avoid the noise signal excitation in the spectrum.

The third level of selection is a frequency selection. It is achieved by the standard technique of frequency filtration after which the small separated signal of nonsymmetric mode is applied to (as was explained above) to the phase detector.

On the basis of this concept an experimental sample of the system was manufactured[18] and it was shown that in "cool" experiments it was possible to reach an accuracy level of 10^{-3}mkm (see Fig.14).

So, having the signal of beam displacement with respect to the probe "axis" one has to correct positions of accelerator elements in order to eliminate the appeared displacements.

As to quadrupole lenses, the positions of their magnetic centers can be displaced with additional dipole windings but for the displacement of accelerating structures it is necessary to have mechanical drives capable to move objects of a few tens of kilograms with an accuracy of 10^{-2}mkm and transparency band (displacement speed) of a few Hz and they should be simple and cheap.

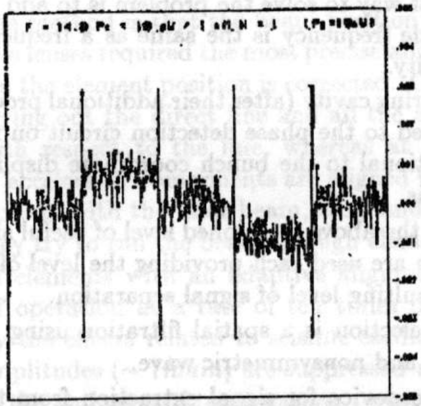


Figure 14: Results of tests of the beam position measuring electronics. First readings prior to vertical line correspond to a "zeroth" position of a beam, in the section up to the next vertical line, the "beam" is displaced "up" and then again returned to zero, displaced down and returned again. In all the cases, the displacement value is 10^{-3} mkm. It is seen that the signal corresponding to this displacement is separated on the noise level.

Such drives have been developed, designed, and manufactured.[19] The test results obtained satisfy with a large margin the posed requirements (Fig.15).

In reality, there is a possibility of averaging a few tens of readings and thus making the signal/noise ratio better.

Thus, if we have sufficiently sensitive probes of beam displacement and executing drives for moving accelerator elements, it would seem that by introducing them into back coupling system one could realize the idea of "adaptive" alignment.

In order to solve the problem, the author managed to find out an algorithm providing the stable operation of the back coupling system and does not require a complex system for the collection and transfer data to central computer, does not require complex computational operations and electronics, and, in principle, it could be realized even with no processors at all, just based on the analog components.

The solution found for the problem is the following: displacement signals from three adjacent elements are applied to the circuit calculating by superposition of these signals the displacement value of the central element of the triade. The calculation algorithm has the following form:

$$dx_n = K_{N-1}X_{N-1} + K_N(\frac{\Delta E}{E})X_N + K_{N+1}X_N).$$

Here

K_{N-1}, K_N, K_{N+1} are the lens focal distance dependent coefficients, $\frac{\Delta E}{E}$ is a beam energy spread at the correction point, X_N beam coordinates measured by probes, dx_n is the necessary correction value for N element position.

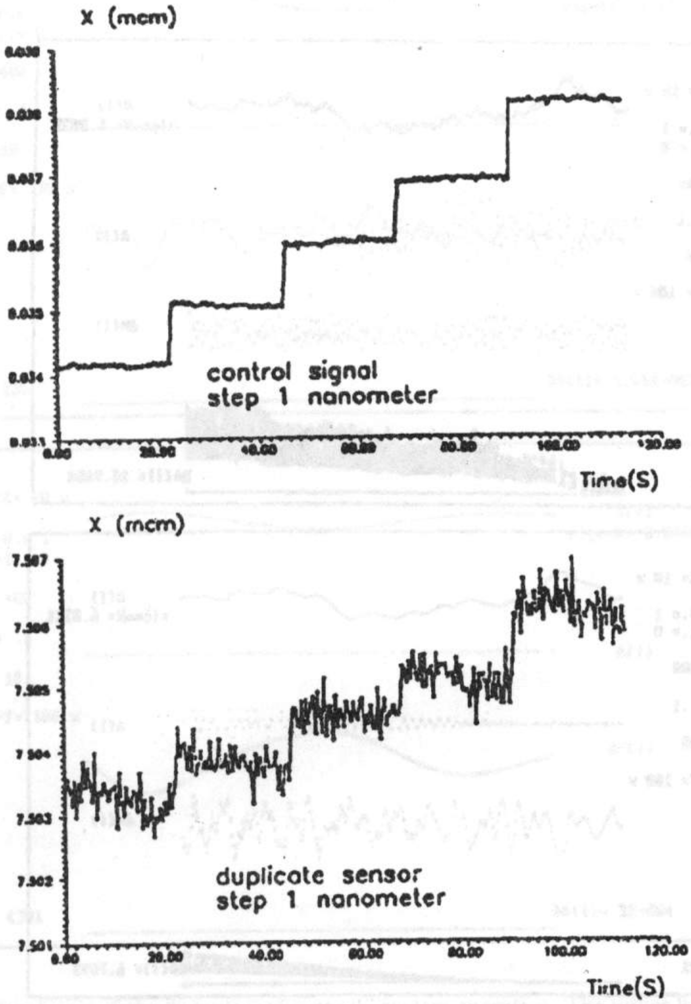
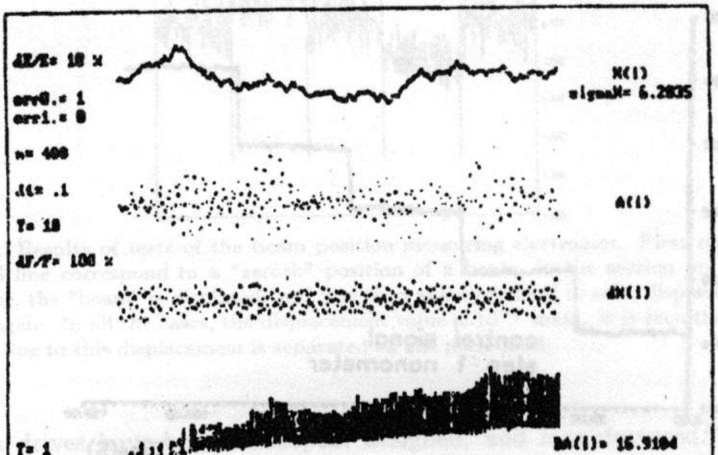


Figure 15: Demonstration of operation accuracy of mechanical drive for the system of adaptive alignment. The upper diagram is for the control voltage applied to the drive, the lower - drive displacement (a step = $10^{-3}\mu km$).



dX/X= 10 %
X(I)
sigmaX= 6.2835
n= 400
A(I)
T= 10
dY/Y= 100 %
dX(I)
T= 1
DA(I)= 15.9104
dX/X= 10 %
X(I)
sigmaX= 6.8321
n= 400
A(I)
T= 10
dY/Y= 100 %
dX(I)
T= 21
DA(I)= 6.7693

Figure 16:

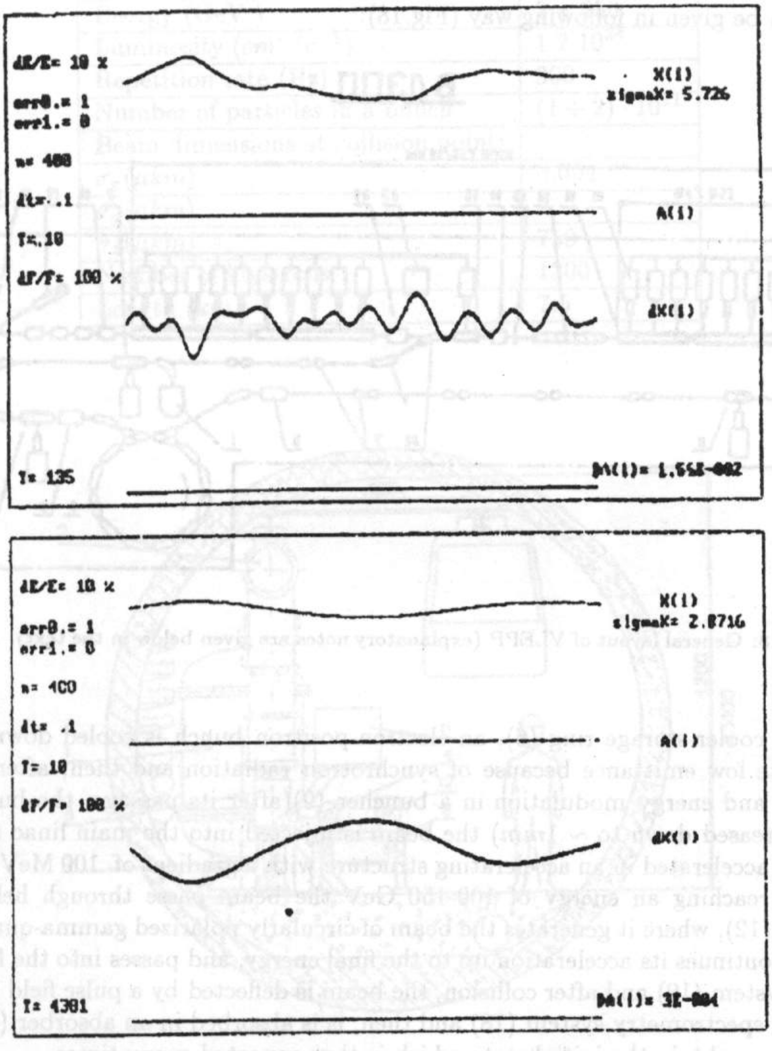


Figure 17: Simulation of the "adaptive alignment" system operation. The upper line in Figures shows the focusing lens positions. In the lower part of the diagram, the beam size is shown for the beam passing the accelerator. At an instant T=1 the accelerator is roughly adjusted with a large error and after beam passage of the accelerator the beam size increases from zero to ≃17 units. In ten seconds after activation of the "adaptive alignment" system, the beam size decreases approximately by a factor 1000 and in 5 min of operation (T=4381), the beam size decreases by 5 orders of magnitude.

3 General layout of linear collider

With an account for all said above the general layout of the linear electron-positron collider can be given in following way (Fig.18):

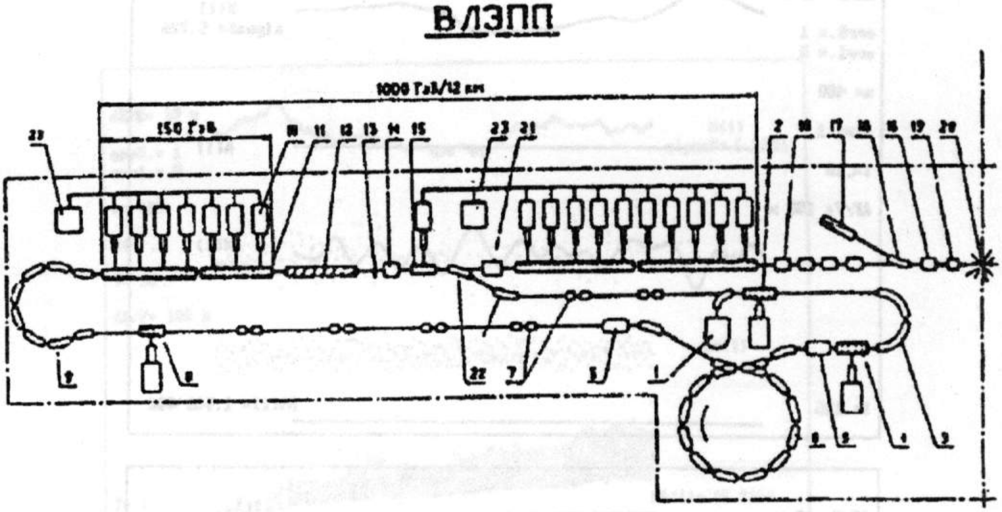


Figure 18: General layout of VLEPP (explanatory notes are given below in the text).

In the cooler-storage ring (6), an electron-positron bunch is cooled down to an ultimate low emittance because of synchrotron radiation and then, after its extraction and energy modulation in a buncher (9)(after its passage, the bunch length decreased down to $\sim 1mm$) the beam is injected into the main linac (11) where it is accelerated in an accelerating structure with a gradient of 100 MeV/m.

Upon reaching an energy of 100-150 GeV the beam passe through helical undulator (12), where it generates the beam of circularly polarized gamma-quanta and then continues its acceleration up to the final energy, and passes into the final focusing system (19) and after collision, the beam is deflected by a pulse field into the energy spectrometry system (18) and then, is is absorbed in an absorber (17).

Thus, we obtain the initial state which is then repeated many times.

A system of magnetic elements (5) provides the required spin manipulations. The suggested operation scheme does not require especially powerful electron beams for producing positrons and enable the operation with polarized beams of an arbitrary orientation at the collision point.[20]

Table 1 lists probable parameters of linear collider and Figs.19, 20 show the probable scheme of equipment location in a tunnel.

Basic parameters of probable linear collider

Energy (GeV)	2 x 250
Luminosity ($cm^{-2}c^{-1}$)	$1.2 \cdot 10^{34}$
Repetition rate (Hz)	300
Number of particles in a bunch	$(1 \div 2) \cdot 10^{11}$
Beam dimensions at collision point:	
$\sigma_x(\mu km)$	0.004
$\sigma_y(\mu km)$	2
$\sigma_z(\mu km)$	750
Number of klystrons	1300
Length (km)	7.5

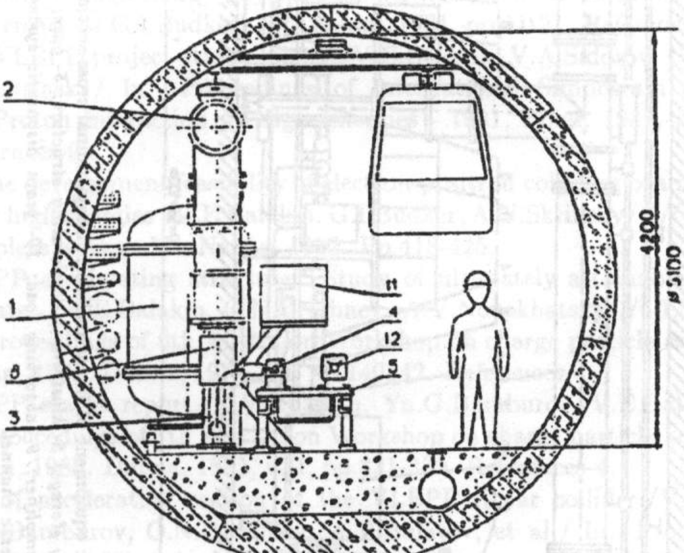


Figure 19: Basic equipment of linear collider. Tunnel cross-section. *1- high voltage source; 2- energy storage; 3- klystron; 4- accelerating structure; 5- base; 8- power amplifier; 11- control and power supply cabinets; 12- inverse channel.*

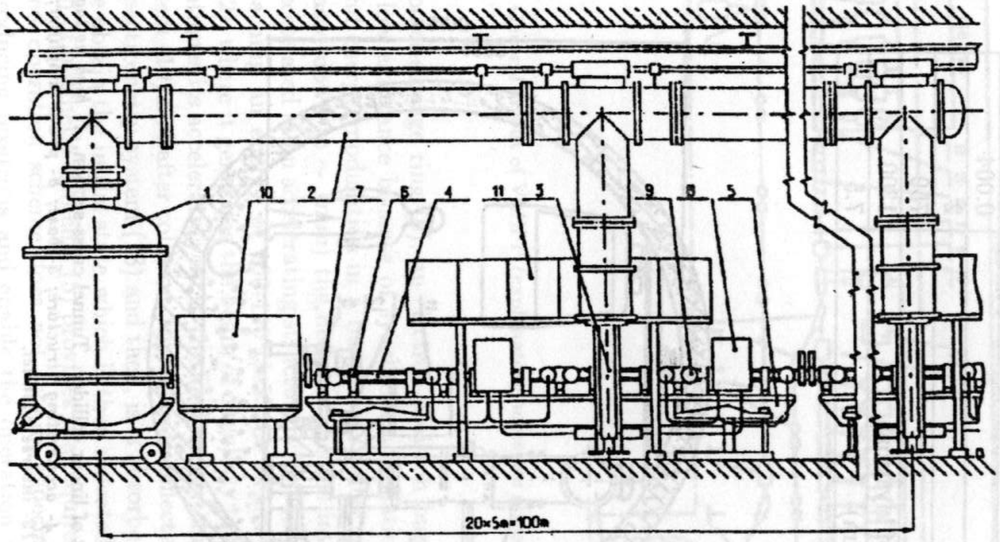


Figure 20: Basic equipment of linear collider. Longitudinal cross-section of accelerator. *1- high voltage source; 2- energy storage; 3- klystron; 4-accelerating structure; 5- base; 6- alignment device; 7- magnetic lens; 8- power amplifier; 9- absorbing load; 10- beam disgnostic system; 11- control and power supply cabinets; 12- inverse channel.*

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