ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

N.A. Solyak

COLLISION EFFECTS IN COMPENSATED BUNCHES OF LINEAR COLLIDERS

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НОВОСИБИРСК

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in Compensated Bunches
of Linear Colliders

N.A. Solyak

Institute of Nuclear Physics
630090, Novosibirsk, 90, USSR

ABSTRACT

The basic effects arising during a single pass of flat compensated bunches through each other at the collision point are considered. Under definite conditions the particle motion in bunches is shown to become unstable, thereby leading to a spatial seperation of a positive charge and a negative one inside the bunches and eventually to their discription. Either the incomplete charge compensation of one of the bunches or a local discription of the neutrality in it is considered as the initial perturbation. The magnitude of the initial perturbation has little infiluence on the luminosity and synchrotron losses. A comparison has been made of the luminosities which can be obtained for charged and compensated bunches having equal vertical sizes and a fixed nonmonochromaticity. It is shown that a considerable gain in luminosity can be achieved only at small values of the discription parameter D when the luminosity itself is no high.

I. INTRODUCTION

Further advance in high energy physics is held to be related to the development of the new direction — colliding linear electron-positron beams. The scientifically substantiated project of a linear collider at superhigh energies (VLEPP) was first reported at the International Seminar on the Problems of High Energy Physics and Controlled Thermonuclear Fusion devoted to the memory of G.I. Budker in (1978) [1].

At present, nearly all big accelerator centers are involved in the theoretical and experimental investigations on the projects of linear electron-positron colliders [2—6]. In Table 1 the basic parameters of linear accelerators designed at Novosibirsk (VLEPP), CERN (CLIC), SLAC (SC), KEK are listed (the data are taken from [3, 4, 6]).

One of the major problems of the creation of linear colliders at an energy of about 1 TeV is the problem of achieving high luminosity necessary to work in this energy range. The luminosity of the facility is roughly equal to

$$L=\frac{fN^2}{S}, \qquad (1)$$

where f is the colission frequency, N is the number of particles in bunches, and $S=4\pi\sigma_x\sigma_y$ is the effective cross section of the beams at the collision point.

Table 1

Design Parameters of Linear Colliders

Parameter	Unit	INP, Novosibirsk VLEPP		CERN CLIC		SLAC SC	KEK
Energy	TeV	0.5	1.	1.	1.	0.5	0.5
Repetition frequency	kHz	0.1	0.1	5.8	5.8	0.09	2.
Number of particles	10^{10}	20	20	0.535	0.535	1.8	4.8
Number of bunches	k	1	1	1	2	1	1
Working frequency	HHz	14	14	29	29	11.4	10
Acclelerating gradient	MeV/m	100	100	80	160	196	100
Accelerating length	km	2×5	2×10	2×12.5	2×6.25	2×3	2×5
Bunch length	σ_z, mm	0.75	0.75	0.3	0.3	0.04	0.6
Vertical size	σ_x, μm	3.0	3.0	0.065	0.065	0.4	0.43
Horizontal size	σ_y, μm	0.04	0.02	0.065	0.065	0.003	0.43
Ellipticity	$R=\sigma_x/\sigma_y$	75	150	1	1	133	1
Norm.vert. emittance	10^{-6} m·rad	2.1	1.1	2.8	2.8	0.05	18
$D=(2\pi n)^2$	—	7.0	7.0	0.91	0.91	10	0.45
Pinch parameter	H_y	2.2	2.2	3.5	3.5	~2	5.7
Nonmonochromaticity	Δ	0.05	0.1	0.19	0.19	0.27	0.1
Luminosity	10^{33}cm^{-2}s^{-1}	0.5	1.1	1.1	1.1	1.2	1.0
Average RF power	MW	2×7.5	2×15	2×80	2×80	2×20	2×100
Beam power	MW	1.6	3.2	5	5	0.13	7.5

Unlike cyclic storage rings where the collision frequency usually is 10^5-10^6 Hz, in linear colliders this frequency is limited from energetical considerations and also by the time required to cool the bunches down to an ultimately low emittance in a storage ring (equal to a few ms). The number of particles in the bunches, different in different projects, is $10^{10}-10^{11}$, i. e. it is comparable with that for cyclic colliders. Consequently, several-orders-of-magnitude gain in collision frequency can be conpensated only by a decrease in the transverse beam sizes at the collision point. Thus, the required luminosity $10^{32}-10^{33}$ cm^{-2}s^{-1} can be achieved in linear colliders with the use of intense bunches focused to a spot of very small area $S\leqslant 1$ μm^2 at the collision point. The main effects arising during a single pass of charged bunches through each other are considered in detail in Refs (7—11]. According to the proposal put forward by

A.N. Skrinsky, we consider here the collision effects for compensated bunches.

In Section 2 the main results on the collision of charged bunches are breafly reported. The collision effects for compensated bunches are considered in Section 3. A comparison of the luminosities achievable for the charged and compensated bunches is made in Section 4.

2. COLLISION EFFECTS IN CHARGED BUNCHES

In the electromagnetic field of the colliding beam the particles give off a portion of their energy for synchrotron radiation, thus giving rise to the nonmonochromaticity of the colliding beams [7]:

$$\Delta_0=\frac{16}{27\sqrt{3}}\frac{r_e^3N^2y}{\sigma_z(\sigma_x+\sigma_y)^2}, \quad r_e=e^2/mc^2, \tag{2}$$

where σ_z is the longitudinal size of a bunch, and σ_x, σ_y are the horizontal and vertical sizes.

The required level of nonmonochromaticity can be obtained if the bunches are made flat ($R=\sigma_x/\sigma_y>1$), keeping the same the transverse cross section at the collision point. From (1) and (2) one can find the horizontal and vertical sizes at the collision point:

$$\sigma_x=\left(\frac{16}{27\sqrt{3}}\frac{r_e^3N^2\gamma}{\Delta_0\sigma_z}\right)^{1/2} \tag{3}$$

$$\sigma_y=\frac{fN^2}{4\pi\sigma_xL}. \tag{4}$$

Such sizes are obtainable if the approriate emittances after beam acceleration do not exceed the limiting values equal to

$$(\varepsilon_x)_{lim}=\frac{\sigma_x^2}{\sigma_z}\gamma, \quad (\varepsilon_y)_{lim}=\frac{\sigma_y^2}{\sigma_z}\gamma, \tag{5}$$

where γ—relativistic factor. As is seen, for linear colliders the requirements for the vertical emittance of the beam are rather stringent. To satisfy it, it is necessary not only to have as small emittance as possible in a cooler but also to carefully adjust all the accelerating and focusing elements of the accelerator to reduce the stochastic heating during beam acceleration [13]. Another difficulty is the obtaining of flat beams with large relation between the sizes, for example, for the VLEPP parameters (Table 1)

$$S=3\frac{E(\mathrm{TeV})}{\Delta H_y}\,\frac{L(\mathrm{cm^{-2}s^{-1}})}{10^{32}}, \qquad (6)$$

where $H_y \simeq 1 \div 2$ is the luminosity enhancement parameter due to the pinch-effect.

One more effect occurring during a collision of charged bunches is the transverse dynamics of particles during the time of collision. If the bunches are oppositely charged, then the particles, as being in a strong field of the colliding beam oscillate in the transverse direction. The average number of oscillations in the horizontal and vertical directions for a collision equals

$$n_x=\frac{1}{2\pi}\left(\frac{r_e N\sigma_z}{\gamma\sigma_x^2}\,\frac{2R}{(R+1)}\right)^{1/2}, \qquad (7)$$

$$n_y=\frac{1}{2\pi}\left(\frac{r_e N\sigma_z}{\gamma\sigma_x\sigma_y}\,\frac{2R}{(R+1)}\right)^{1/2}, \qquad (8)$$

Instead of the dimensionless parameter n, one often introduces the disruption parameter D related to n as follows:

$$D_{x,y}=(2\pi n_{x,y})^2. \qquad (9)$$

For a long time, till the appearing of paper [11] in 1981, the most part of western physicists were wrong considering that the collision effects on the bunches were limited by the parameter $D \leqslant 1$. It led to the second wrong conclusion that the required luminosity in the linear colliders could be achieved only at high repetition frequencies. However, the value of parameter D can be considerably high $D \leqslant 36$, as it was shown in Novosibirsk at 1978 [1]). In practice, for flat bunches with $R \gg 1$ the motion in the horizontal plane may be neglected since $n_x/n_y = 1/\sqrt{R}$ and $n_y \lessdot 1$. The transverse dynamics of the beams at the collision point is only determined by the value of this parameter, and the bunches with different number of particles, energy, etc., but with equal n behave in a similar manner. In going from round bunches ($R=1$, $n_x=n_y=n_r$) to flat ones ($R \gg 1$) of the same cross section the parameter n becomes a factor of $\sqrt{2}$ smaller.

The transverse motion of particles leads to that the effective cross section of the beams at the collision point can be considerably

differ from the geometrical one determined by the beam emittance and the β-function. The luminosity of a collider is not described by a simple relation (1) but depends on the parameter n_x, n_y as follows [7, 12]:

$$L=\frac{fN^2}{4\pi\sigma_x\sigma_y}\,H_x H_y \eta, \qquad (10)$$

where $H_{x,y}=H(n_{x,y})$ is the enhancement parameter equal to the effective decrease of the appropriate size of the bunch; is the geometrical factor dependent on the collision angles θ_x, θ_y and on the β-function at the collision point:

$$\eta=\sqrt{\frac{2}{\pi}}\int_0^\infty \frac{\exp\left[-\frac{p^2}{\sigma_z^2}\cdot\left(1+\frac{\theta_x^2/\psi_x^2}{1+z^2/\beta_x^2}+\frac{\theta_y^2/\psi_y^2}{1+z^2/\beta_y^2}\right)\right]}{\sqrt{(1+z^2/\beta_x^2)(1+p^2/\beta_y^2)}}\,\frac{dz}{\sigma_z}, \qquad (11)$$

where $\psi_x=\sigma_x/\sigma_z$, $\psi_y=\sigma_y/\sigma_z$.

We assume the motions in the mutually independent x- and y-directions to be independent and, hence, their contribution to luminosity is additive (strictly speaking, this is not quite correct).

As the results of the computer simulation for round beams show, at small values of the parameter 0.25—0.5 the bunches are compressed (pinch effect) and a maximum enhancement in luminosity equals $H \doteq 6$ [11]. In flat bunches the pinch effect is observed only in the vertical direction and, hence, the luminosity enhancement is less here: $H \approx 2.2$ (see Figs 4, 5) [7—9].

When the number of oscillations further increases the enhancement reduces in all cases, and beginning approximately with $n \sim 1$, the dipole instability develops in the system of colliding beams, which causes the disruption of the bunches for the times shorter than the collision times. For round bunches ($D=32$) the border of instability development is in practice the same as that for the flat ones and depends rather slightly on the charge distribution inside a bunch. Theoretical models confirm the simulation results and indicate the excitation of the other higher-order modes at large n [14—15].

This instability border determines the highest luminosity attainable for charged bunches:

$$L \sim \frac{\pi P_0}{2e^2\sigma_z}\,n^2 \qquad (12)$$

where $P_0 = f \cdot N \cdot mc^2 \gamma$ is the power in each of the beam. For example, if $P_0 = 1$ MW, $2\sigma_t = 1.5$ мм, $n_{max} = 1$ then $L_{max} = 4 \cdot 10^{33}$ $cm^{-3}s^{-1}$. It is worth mentioning that this limit is due to only the collision effects and is achieved at $n=1$ if the beam emittance allows an obtaining of the required parameters of the beam at the collision point.

The bunch attraction weakens the requirements for the precision of beam matching and also increases the permissible angles at which the bunches can collide.

In a collision of the equally charged bunches their mutual repulsion leads to a considerable decrease in luminosity as compared to the charged [7, 8].

3. COLLISION EFFECTS IN COMPENSATED BUNCHES

To avoid the difficulties caused by a collision of the charged bunches, the offer has been advanced to use compensated bunches containing the equal number of electrons and positrons [16]. From a technical point of view, obtaining compensated bunches is a more complex problem. The simplest way is to accelerate the electron and positron bunches in the accelerator with their offset by a half wavelength and then to match them; note that at an energy of about 1 TeV this presents the known difficulties. In addition, the wake fields of the first bunch can disrupt the following beam. Another variant — independent acceleration of electrons and positrons in parallel accelerators and their convergence to a single compensated bunch — requires a double number of accelerators. The variant is realizable when one of the bunches has an energy much less than the basic one and is intended only for its compensation. Note that this variant is not so expansive as the second one.

At first sight, the advantages of compensated bunches over the charged ones are evident: in practice, there are no internal electromagnetic fields in the bunches and, hence, the synchrotron radiation and the transverse motion of the particles are supressed at the collision point; this allows one to hope for an achievement of the higher luminosity.

However, as is shown in [9], the system of compensated bunches at the collision point proves to be unstable under certain conditions as well. The development of the instability results in a spatial separation of the charge inside the bunches for a time of collision,

while the interaction of the resulting charged fragments occurs similarly to the case of charged bunches. The charge separation can be initiated either by an incomplete compensation in any of the bunches, or by a local disruption of the neutrality in it due to, for instance, a shift, as a whole, of the electron bunch relative to the positron one in the vertical and horizontal directions.

Let us define the compensated bunches, by analogy with the charges, by dimensionless parameters (7) and (8) where is the total number of the particles.

Consider first the effect of the following factors on the collision effects:

1) incomplete compensation of one of the bunches:
   $\alpha = (N_+ - N_-)/(N_+ + N_-)$ — the compensation parameter;
2) the total charge in the bunches is compensated, but in one of them one charge is shifted in the vertical direction relative to the charge of opposite sign:
   $\varkappa = \Delta y/\sigma_y$ is the relative shift.

Below we present the results of the computer simulation of the collision effects for flat compensated bunches.

A. Development of the Instability

The process of instability development for cases 1, 2 is shown in Figs 1 and 2 for the initial parameters of the perturbations equal to $\alpha = 0.01$ (Fig. 1) and $\varkappa = 0.01$ (Fig. 2). The mechanism of instability development is rather simple; a local discription of the neutrality leads to the separation of electrons and positrons in a colliding beam thereby increasing, in turn, the charge polarization in the initial bunch. Thus, the system proves to be unstable.

For cases 1 and 2 the instability develops in a different way: the quadrupole mode of oscillations develops for case 1 (Fig. 1) and a dipole one — for case 2 (Fig. 2).

If the compensated bunch consists of an electron component and a positron one with very different energies, the instability develops already at small values of the parameter n, the low-energy particles are knocked out from the bunch (Fig. 3). For the remaining, high-energy charged components, valid are the previous for charged bunches results with the only difference that the remaining number of particle is two times smaller.

B. Luminosity

The dependence of the enhancement parameter $H=L/L_0$ for compensated flat bunches with uniform density on the parameter n is given in Fig. 4 where the initial perturbation is taken to be equal to $\alpha=0.01$. On this figure one can see also the behaviour of the enhancement function for charged bunches.

The results of the computer simulation for planar compensated and charged bunches with the Gaussian density distribution are constructed in the same coordinates in Fig. 5.

Unlike the charged bunches, there is no pinch effect in a collision of compensated beams, and the relative luminosity decreases with increasing the parameter n and, hence, the parameter $H=L/L_0$ should be more correctly reffered to as the luminosity suppression parameter in this case. The nature of the reduction in luminosity with increasing n depends slightly on the details of the density distribution in the bunches as is seen from the comparison of the curves in Figs 4 and 5.

C. Influence of the Initial Perturbation

In the previous calculations we have taken the values of the initial perturbation of the neutrality in bunches at a level of about 1% (cases 1, 2). Of interest is the question how a variation in the magnitude of the perturbation will have an effect on the final result.

In Fig. 6 one can see the influence of the compensation degree α on the relative luminosity for the bunches of uniform density at different values of n. For case 2, Fig. 7 illustrates the behaviour of the relative luminosity L/L_0 for two values of the parameter $\varkappa$, which are different by one order of magnitude.

One may conclude from these data that the variation of the initial perturbations within a broad range has practically no influence on the luminosity and the perturbations are here the initial one from which the instability develops.

D. Radiation Losses. Monochromaticity

An important property of compensated bunches is a suppression in them of synchrotron radiation, in contrast to charged bunches of the same sizes. Fig. 8 shows the results of the computer simulation of the nonmonochromaticity suppression function for flat compensated bunches: curve *1* is for monoenergetic bunches, curve *2* is for the bunches consisted of the charged components different in energy by a factor of 10. For comparison, the data obtained for charged bunches (curve *3*) can be found in this figure. The nonmonochromaticity suppression function is defined as $F_\Delta=\Delta/\Delta_0$, where Δ_0 is given by the expression 2.

At small values of the parameter n the monochromaticity of the compensated beams grows quadratically (the initial value $\alpha=0.01$). As n increases, the nonmonochromaticity of bunches having different energies is comparable with that of the charge ones, while for monoenergetic bunches it remains much less, up to the limiting values.

An analysis of the results obtained allows a conclusion to be drawn that in the most interesting range of the parameters (high values of n and a nonmonochromaticity of about 10%) the compensated bunches, consisted of electrons and positrons whose energy differs by one order of magnitude, yield no noticeable contribution neither to the luminosity nor to the losses for radiation in comparison with the charged bunches of the same sizes. In monoenergetic compensated bunches the relative energy losses are markedly less and this means that to obtain the given monochromaticity $\Delta=F_\Delta\cdot\Delta_0$ their horizontal size must be less than that of the charged ones, thus making it possible to hope for a gain in luminosity in this case.

4. COMPARISON OF THE LUMINOSITIES FOR CHARGED AND COMPENSATED BUNCHES

In comparison of the luminosities achievable in compensated and charged bunches we will assume that

1) the bunches are flat, the number of particles in them and their energy are equal;

2) in all cases the vertical size is the same (determined emittance and the β-function at the collision point);

3) the horizontal sizes are found from the condition for obtaining a necessary nonmonochromaticity.

To define the horizontal sizes of the bunches we write down the nonmonochromaticity equality condition for compensated and charged bunches:

$$F_{com}(n_{com})\Delta_{0com}=F_{ch}(n_{ch})\cdot\Delta_{0ch}\,, \qquad (13)$$

where F_{com}, F_{ch} is the radiation suppression functions (Fig. 8), the parameters $\Delta_{0com}, \Delta_{0ch}$ are determined, according to (3) by the expression (2) for the appropriate horizontal sizes $\sigma_{0com}, \sigma_{0ch}$. Expressing Δ_0, through n, we find from (2) and (8)

$$\frac{n_{com}^4}{n_{ch}^4} = \frac{F_{ch}(n_{ch})}{F_{com}(n_{com})}, \tag{14}$$

which determines implicitly the dependence $n_{com} = g(n_{ch})$, shown in Fig. 9. The relation of the horizontal sizes of the compensated and charged bunches with equal nonmonochromaticity is equal to

$$\frac{\sigma_{x\,ch}}{\sigma_{x\,com}} = g^2(n_{ch}). \tag{15}$$

Thus, the compensated bunches have the smallest horizontal size and correspondingly the smallest ellipticity as compared with the charged (6), but the values of the parameter n are higher for them. In both cases, the luminosity ratio is determined, according to (3) by the expression

$$\frac{L_{com}}{L_{ch}} = \frac{H_{com}(n_{com})}{H_{ch}(n_{ch})} \cdot \frac{\sigma_{x\,ch}}{\sigma_{x\,com}} = \frac{H_{com}(gn_{ch})}{H_{ch}(n_{ch})} g^2(n_{ch}). \tag{16}$$

Knowing the dependence of the anhancement factors for compensated and charged bunches (Fig. 4, 5) and also the function $g(n)$, one can define the luminosity relation represented as diagrams in Fig. 10. Curve *1* illustrates the uniform density in bunches, and curve *2* shows the case of the Gaussian distribution.

The data obtained enable a conclusion that a substantial gain in luminosity for compensated bunches can be achieved only for comparatively weak bunches ($n < 0.2$) when the luminosity itself is not high (see (12). If the beam density is high at the collision point the gain vanishes and beginning approximately with $n \simeq 0.9$ for the uniform distribution and $n \simeq 0.5$ for the Gaussian, the gain even in luminosity is observed which is due to that the small gain achieved as the bunch sizes decrease is cancelled by the gain in enhancement of H_y.

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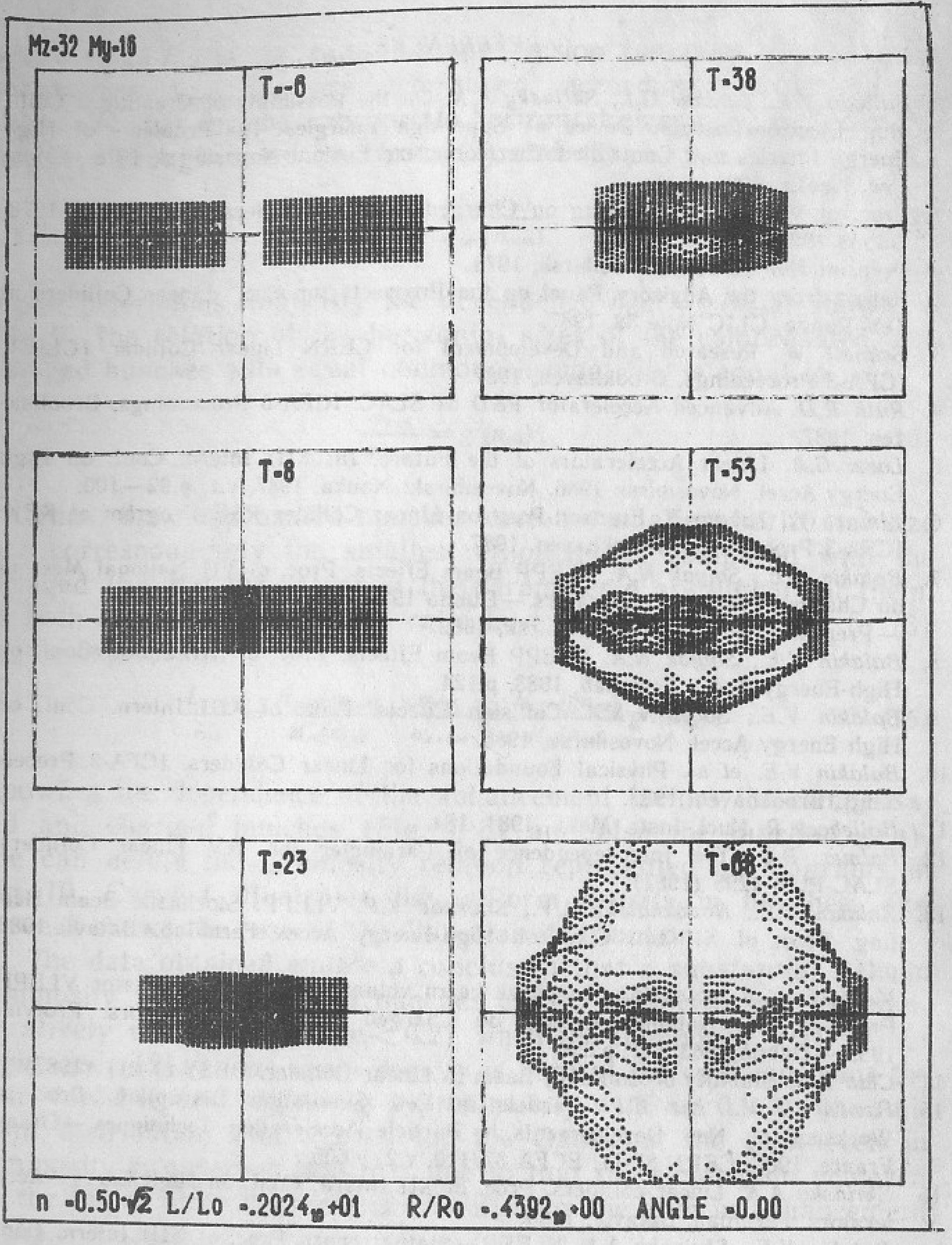

Fig. 1. The progress of instability for flat compensated bunches by weak disturbance of neutrality on one of them: $\alpha=0.01$, parameter $n_y=0.7$.

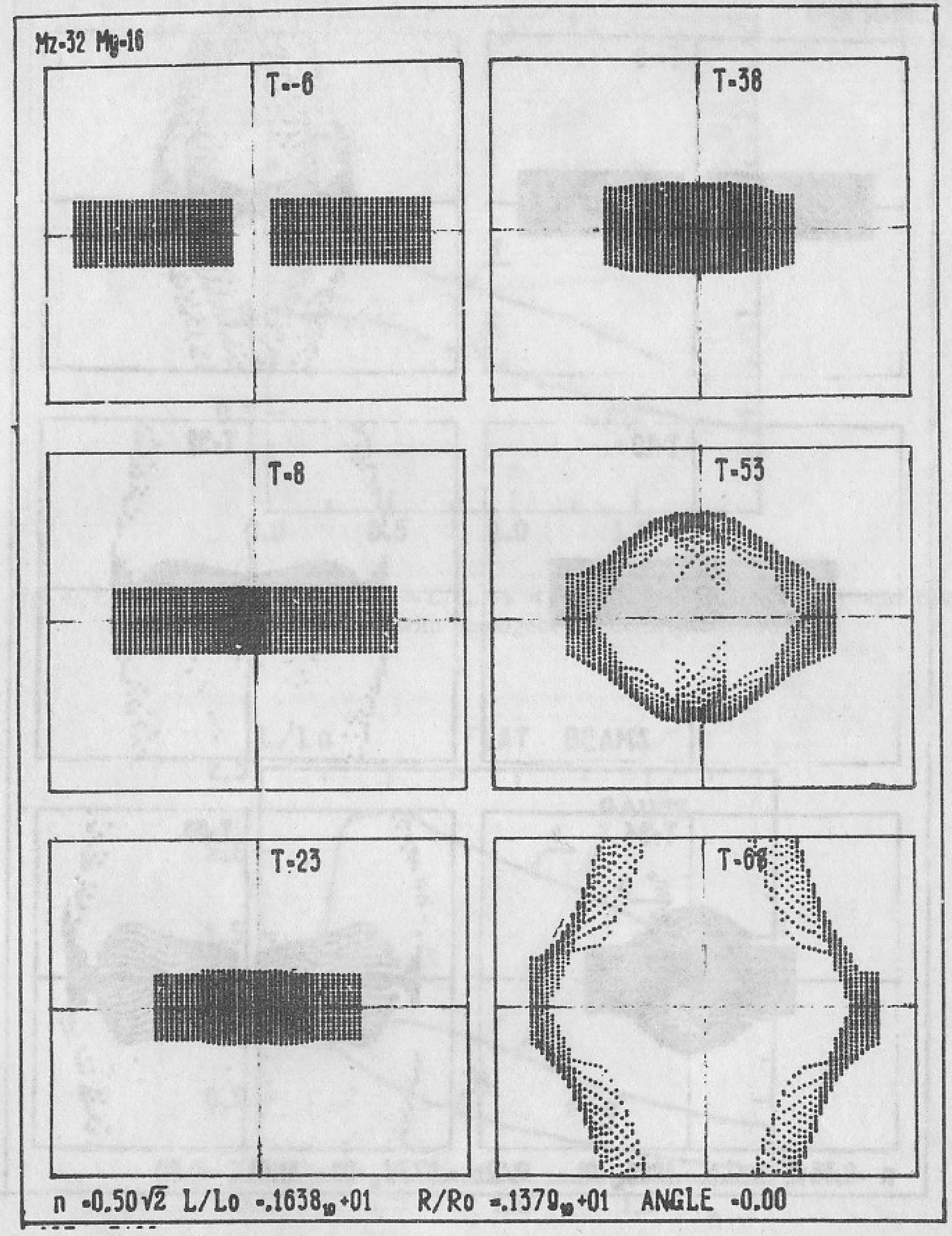

Fig. 2. The progress of instability for flat compensated bunches by relative offset of one sign charge in vertical direction: $\varkappa_y=0.01$, parameter $n_y=0.7$.

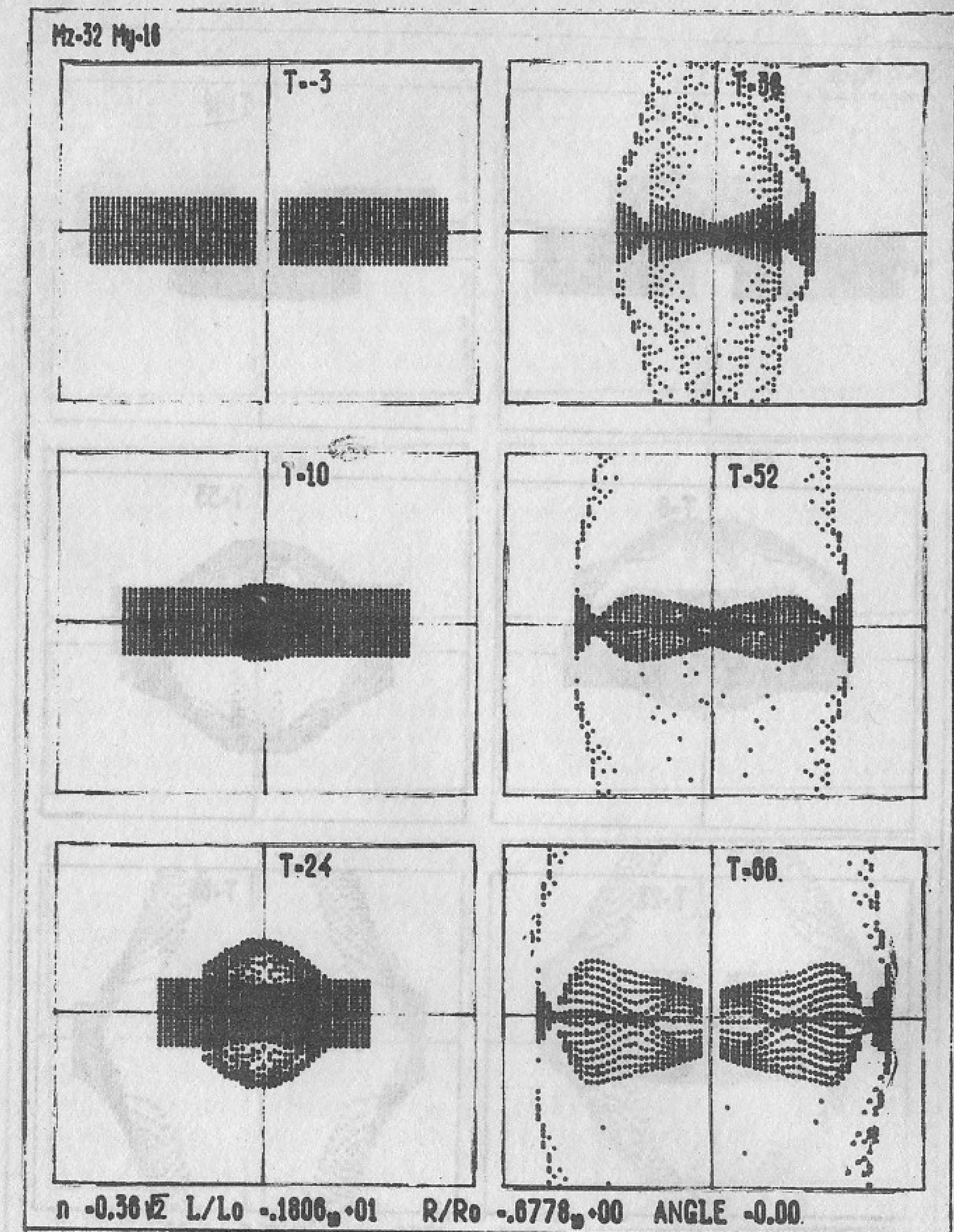

Fig. 3. The progress of instability for flat compensated bunches whose electron and positron components have very different energies $\gamma_1/\gamma_2=10$.

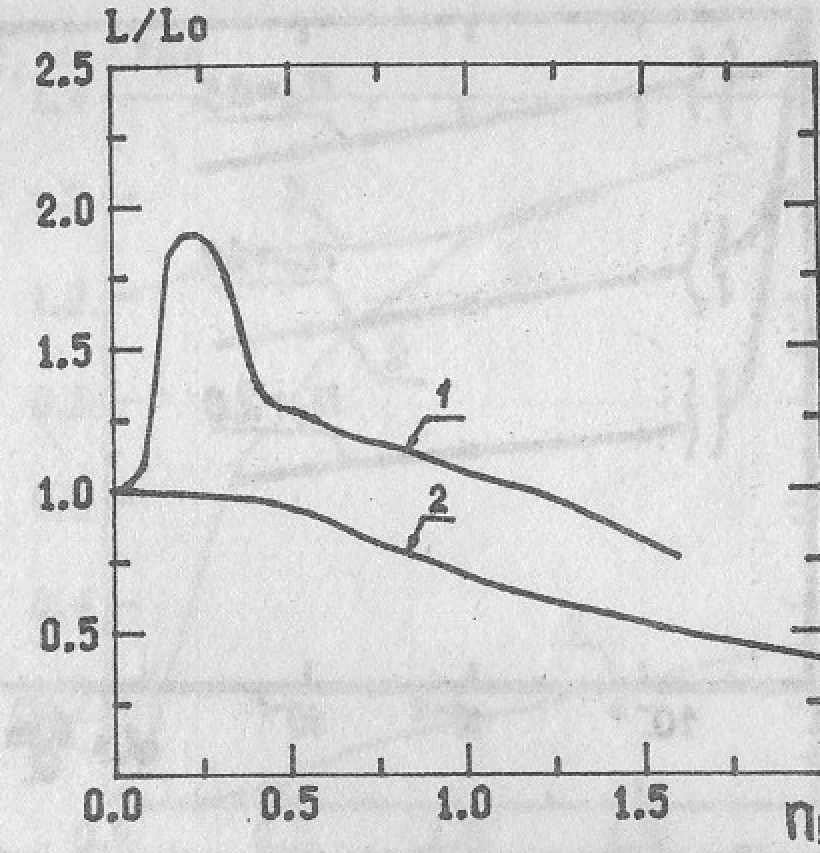

Fig. 4. Enhancement parameter $H=L/L_0$ vs n for oppositly charged (1) and compensated (2) bunches with homogeneous density distribution.

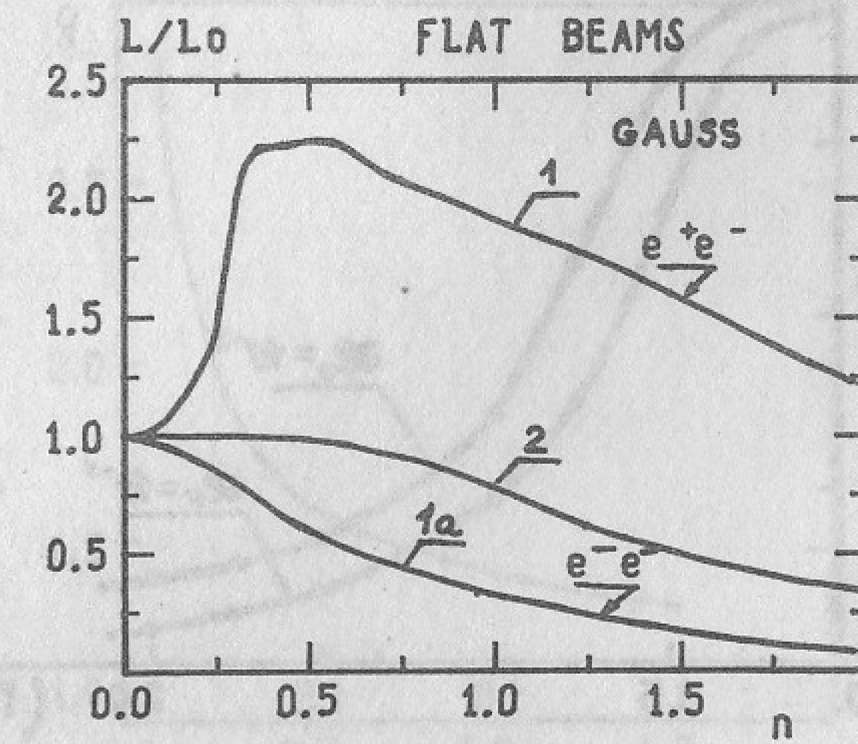

Fig. 5. Enhancement parameter for oppositly charged (1), equally charged (1*a*) and compensated bunches (2) with Gaussian density distribution.

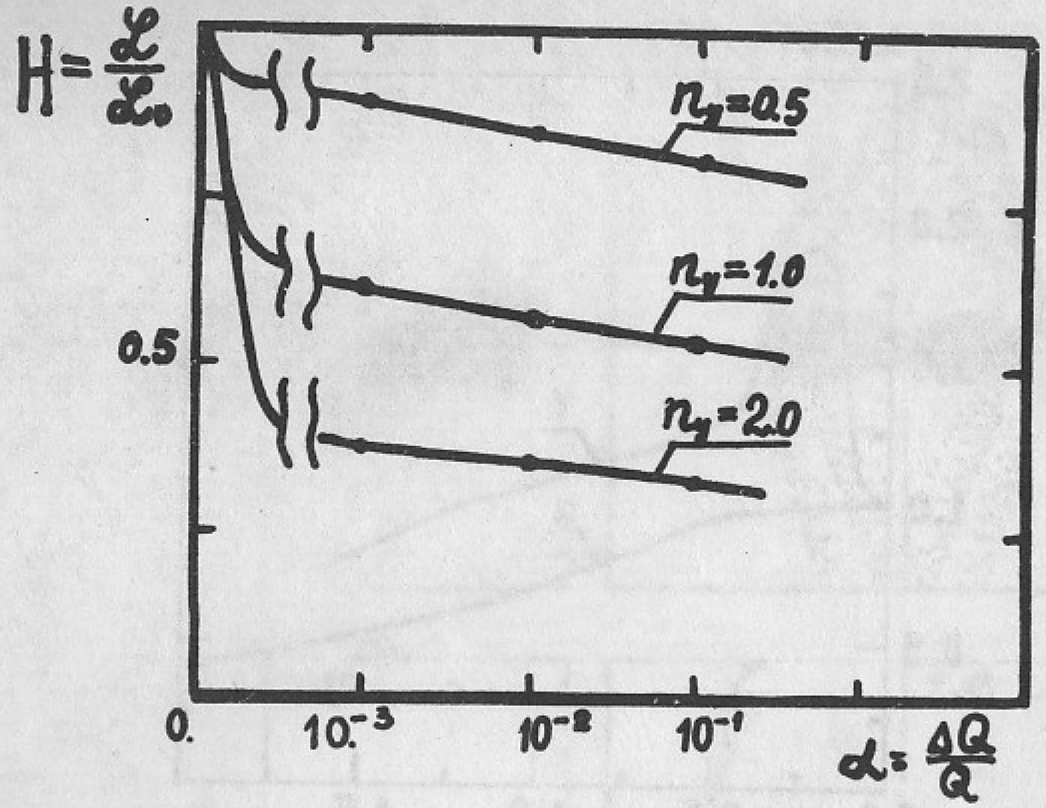

Fig. 6. The effect of unaccurate charge compensation on luminosity.

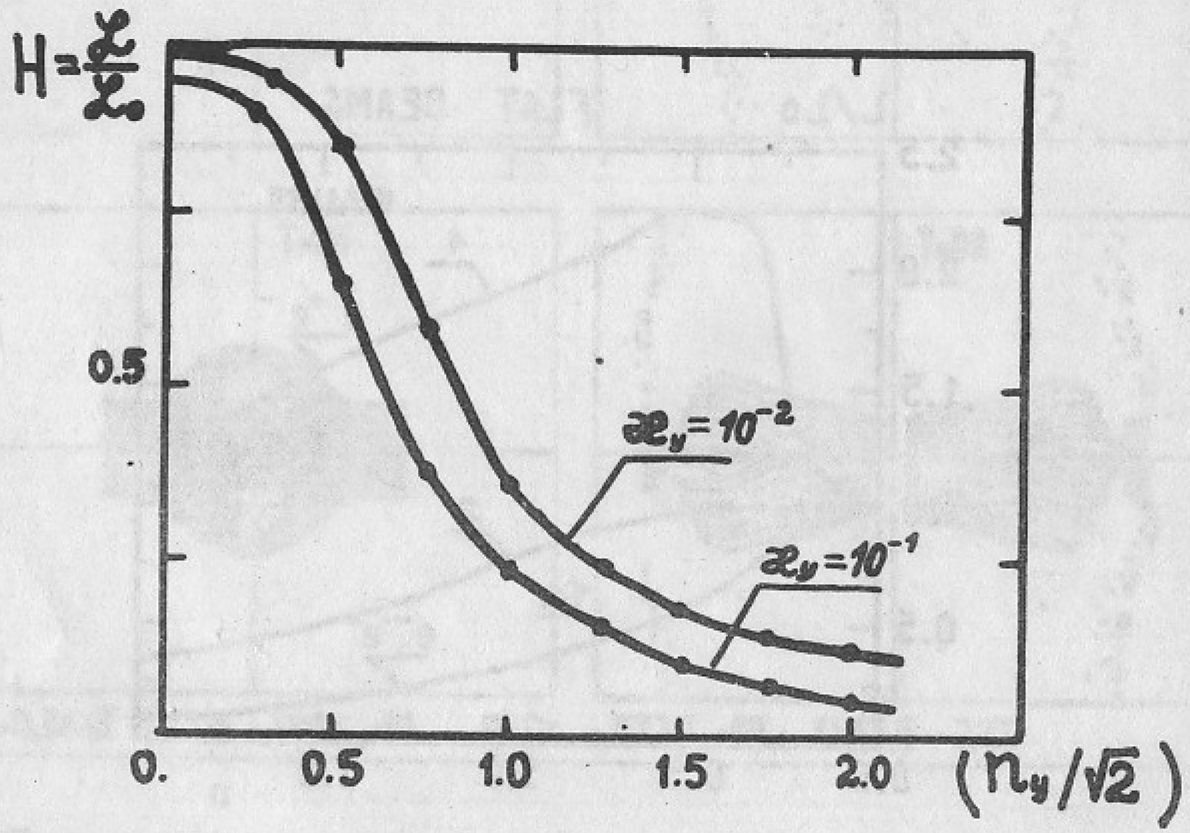

Fig. 7. The effect shifting of one of the bunches on the luminosity.

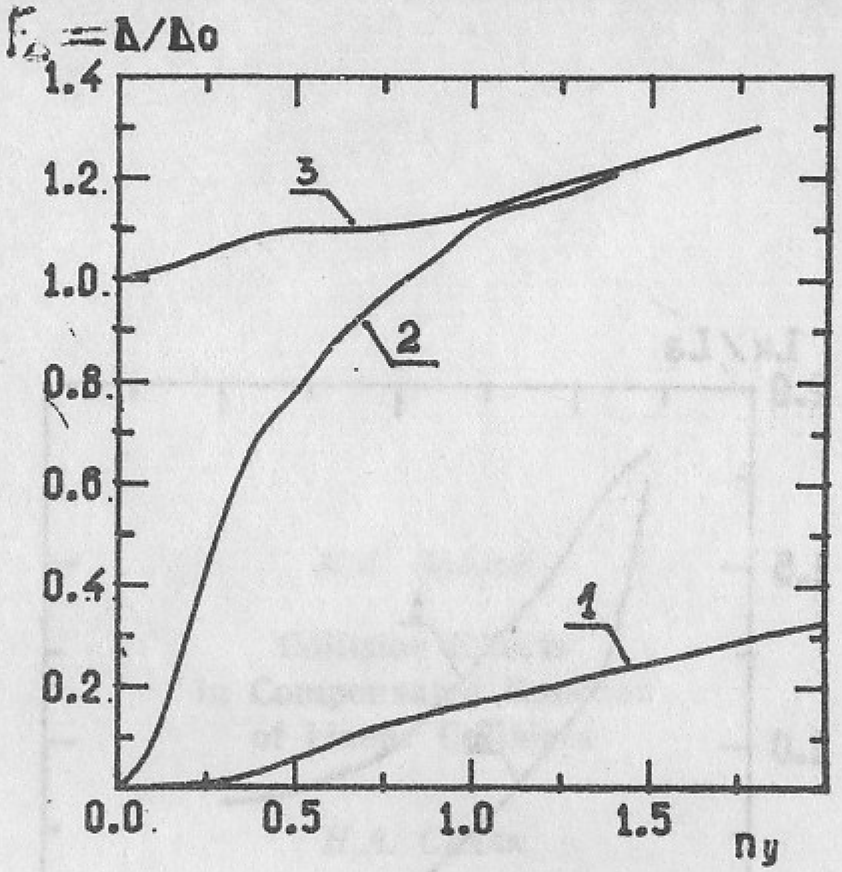

Fig. 8. Relative radiation losses for compensated monoenergetical (1) and non-monoenergetical (with $\gamma_1/\gamma_2=10$) (2) bunches and so for charged ones.

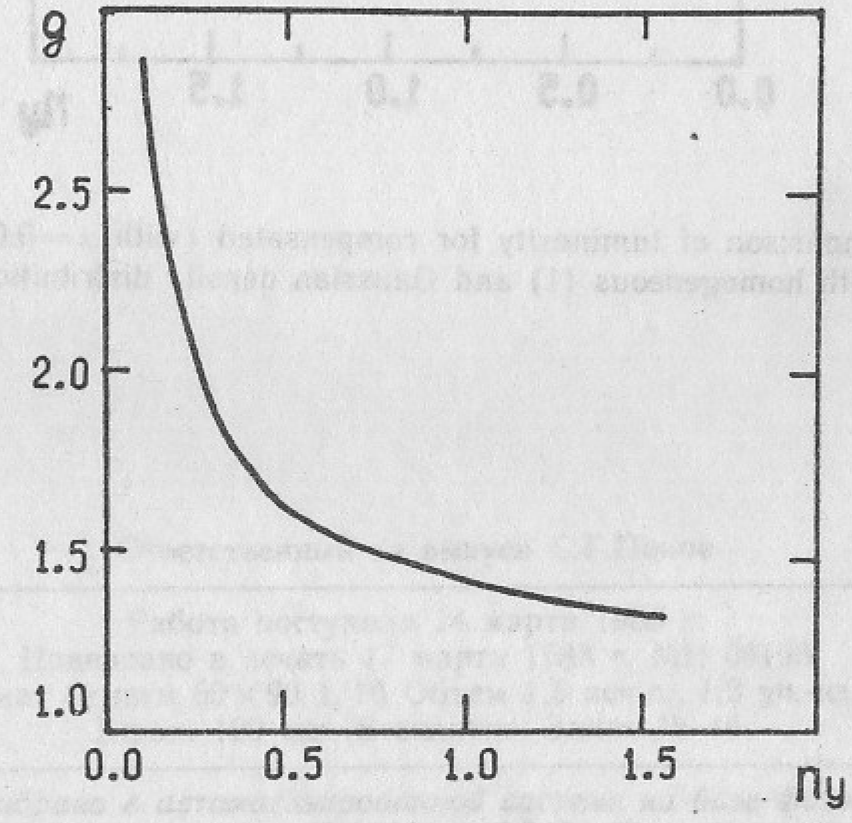

Fig. 9. Function $g(n)$ describes the relation of horizontal sizes of compensated and charged bunches.

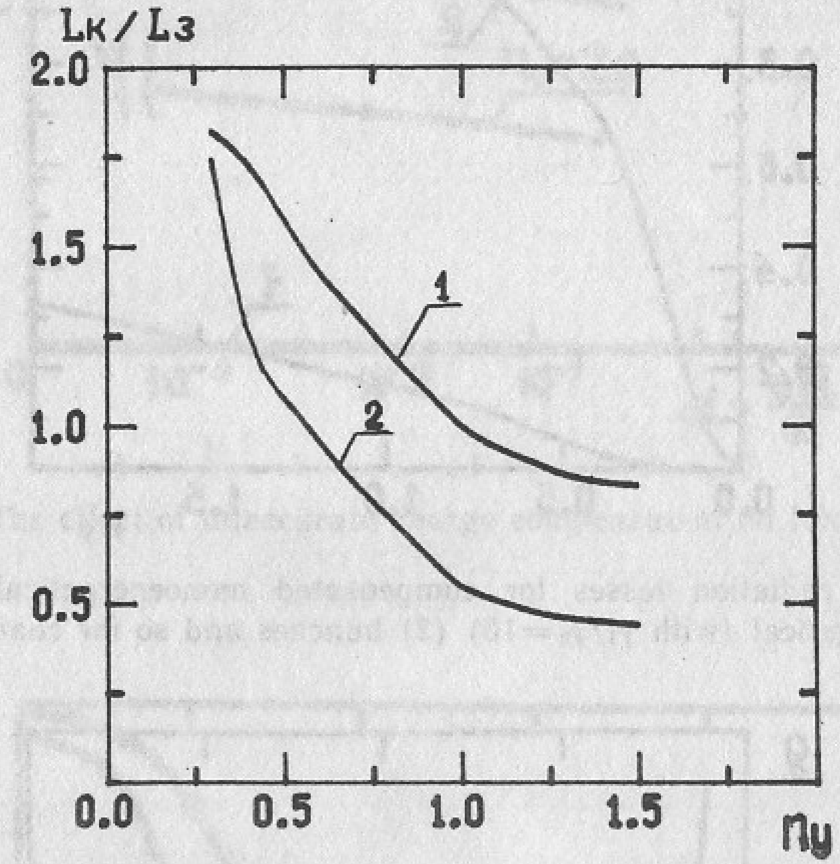

Fig. 10. The comparison of luminosity for compensated (with $\alpha = 0.01$) and charged bunches with homogeneous (1) and Gaussian density distribution in them.

N.A. Solyak

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