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DYNAMICS OF SHORT ELECTRON BUNCHES AT THE INJECTION STAGE

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ABSTRACT

The physical restrictions on the powers of the sources of short intense electron bunches on the basis of photocathodes are studied. These restrictions are due to an influence of the space charge of the bunch and radiation losses when passing the bunch through the anode hole. The critical beam current is estimated, beginnig from which the beam dynamics is strongly influenced by the space-charge field, and the estimations are made of the energy losses on account of transient radiation. For a detailed study of the dynamics of short bunches at the injestion stage, a computer program has been prepared using the $2^1/2$ *D* «cloud-in-cell» model. The internal field of the beam is determined in the program from the Maxwell equation. The computational results concerning the dependence of the bunch charge, its length and the energy losses because of radiation on the photocurrent are presented.

1. The papers [1—4] treats the problems concerning the creation of devices utilizing the sources of electron beams on the basis of a photocathode. In these sources the train are formed of short (up to 50 ps) intense electron bunches generated by a laser burst of the same duration. The bunches are employed either for further acceleration (Ref. [2]), or for the creation of RF generators (lasertrons) (Refs [3, 4]).

Fig. 1 illustrates the operational principle of a lasertron: a laser burst illuminates a photocathode imitating short electron bunches. These bunches are accelerated in a gap to which a constant accelerating voltage is delivered and then arrive at a r. f. cavity where their kinetic energy is converted to that of a r. f. field.

The variants of using guns with a photocathode and the parameters of electron beams are given in the Table where the following notations are introduced: U—cathode voltage, I—pulse current, f—bunch repetition frequency (it is equal to or multiple to the operating frequency of a generator or an accelerator, if the gun is employed); t—duration of a bunch, P—pulse power of the laser, τ—duration of a bunch train, λ—laser radiation wavelength, and W—peak energy.

In Ref. [2] the results dealing with a study of GaAs photocathodes are presented and it is shown that the photocurrent density can achieve about 180 A/cm and the maximum electric field on the photocathode is about 80 kV/cm.

The present paper is aimed at a study of physical restrictions on the number of particles in a bunch, which are determined by a space charge and radiation when they leave the accelerating gap.

Centre	Device	Beam parameters	Lazer	Status
SLAG	Injector	$U=200$ kV $I=12$ A $t=100\div1000$ ps	$\lambda=1.06/2$ nm	1981 Experiment
SLAG	Lasertron	$U=400$ kV $I=735$ A $f=2856$ MHz $t=60$ ps $\tau=1$ mks	$\lambda=1.06/2$ nm $W=100$ mJ $P=600$ kW	1986 Project
Tokyo Univ	Lasertron MARK-I	$U=30$ kV $I=100$ A $f=2884$ MHz $t=60$ ps $\tau=100$ ns	$\lambda=1.06/2$ nm $W=50$ mkJ $P=5$ kW	1984 Experiment

2. Let us consider the photoemission process of electrons at a high intensity of laser radiation. Let there be an accelerating gap to which the voltage U is applied and let photocurrent (photoemission current), determined by the amount of γ-quanta incident per unit time dn/dt and the quantum efficiency of the photocathode k_γ, be

$$I_e=edn/dt\,k_\gamma \tag{2.1}$$

Here e is the electron charge. The total charge Q_0 of photoelectrons is likely to be equal to $I_e t$ where t is the duration of a laser burst. Being restricted by its internal field, the bunch charge Q may prove, however, be less than Q_0, since a fraction of photoelectrons can return on the cathode. There is the critical current I_{cr} at which the electric field on the cathode vanishes when the laser burst stops. When I_e tends to I_{cr}, besides a decrease of the ratio Q/Q_0, the uniformity violates in the density distribution of the charge along the bunch, and the bunch length increases. In view of this, it is not desirable that the current I_e be higher than the critical value of I_{cr} whose magnitude depends on a geometry of the accelerating gap, voltage U and burst duration t. If the emission does not stop when the «head» of the bunch leaves the gap, I_{cr} is determined by the perveance $P_0(U)$ of the gun:

$$I_{cr}=P_0(U)\,U^{3/2}. \tag{2.2}$$

The value of P_0 is dependent on U at relativistic energies of electrons at the exit from the accelerating gap.

Let us estimate I_{cr} for the practically interesting case when all the bunch particles still are in the gap when the emission stops. The transient radiation fields are assumed, for a while, to have little influence on beam dynamics and the «head» of the bunch be at a distance of $d<L$ from the cathode (L is the lenth of the accelerating gap) at the moment when the injection stops, and its electrons are weakly-relativistic. In addition, let, when accelerated, the beam do not change its transverse size (for example, the Coulomb repulsive forces are compensated by the action of an external focusing magnetic field), the electrodes and the bunch are axisymmetric and the condition $d\lesssim r$, where r is the beam radius, be satisfied. Then the potential on the axis is

$$\varphi(z)=\begin{cases}\alpha z^{4/3} & 0\leqslant z<d\\ \beta z+\delta & d\leqslant z\leqslant L\ .\end{cases} \tag{2.3}$$

Since $\varphi(L)=U$, it follows from the continuity condition of the potential and electric field at the point d that

$$U_d=\varphi(d)=\frac{3}{4}\,\frac{d}{(L-d/4)}\,U\approx\frac{3}{4}\,\frac{d}{L}\,U. \tag{2.4}$$

Then

$$I_{cr}\approx P_0(U_d)\,U_d^{3/2}\left(\frac{L}{d}\right)^2=\left(\frac{3}{4}\right)^{3/2}P_0(U_d)\,U^{3/2}\left(\frac{L}{d}\right)^{1/2} \tag{2.5}$$

On the other hand, $d\simeq tv_d/2$ where v_d is the electron velocity at a distance d from the cathode, which is determined by the potential U_d. Expressing d via U, we obtain

$$d=\frac{3}{8}\,\frac{c^2t^2}{L}\,\frac{U}{U_0}, \tag{2.6}$$

where $U_0\equiv mc^2/e$, m is the electron mass and c is the light velocity.

With (2.6) substituted into (2.5), we obtain

$$I_{cr}=\left(\frac{9}{8}\right)^{1/2}P_0(U_0)\,UU_0^{1/2}\,\frac{L}{ct}. \tag{2.7}$$

From (2.7) it follows that the averaged over the period of bunch running, beam power P_e will satisfy the condition

$$P_e \lesssim \frac{ct}{\lambda} I_{cr} U \approx P_0(U_d)\, U^2 U_0^{1/2} \frac{L}{\lambda} = P_{cr}, \tag{2.8}$$

where $\lambda = c/f$.

Since, under the above assumptions $P_0 \propto r^2$ and the beam radius should not exceed the radius of a flight hole, proportional to λ, it follows from (2.8) that

$$P_{cr} \propto \lambda U^2, \tag{2.9}$$

i. e. the average power of the beam decreases with decreasing the wavelength. So, for example, at $\lambda = 4.2$ cm, $U = 400$ kV. $L \approx 4$ cm (the latter is determined by the electric photocathode strenght) and $ct/\lambda = 0.1$, $P_{cr} \approx 20$ MW.

Another physical restriction on the pulse current and P_e is associated with the radiation induced by a bunch during its passage through the anode hole. The radiated energy can be estimated using the «cutting» model. The bunch is assumed to be relativistic when it reaches the accelerating gap. The field of the point charge leaving the metallic surface with the light velocity is shaped as an infinitely thin hemisphere whose radius also increases with the light velocity (Fig. 2). In this case, it follows from the Gauss theorem that the module of an electric field strength vector at the point with cylindrical coordinates r, z, at the moment of time t_0, is equal to

$$|E| = \frac{q\delta(x)}{2\pi\varepsilon_0 r}, x = (r^2 + z^2)^{1/2} - ct_0, \tag{2.10}$$

where q is a charge and $\delta(x)$ is a delta-function. The energy radiated by a bunch of l long in a gap of the length L will be equal to that fraction of energy of the bunch field which is «cut» by the hole:

$$W_e \approx -\frac{Z_0 I^2 l}{2\pi c} \ln\left|\,\mathrm{tg}\left(\frac{1}{2}\,\mathrm{arc\,tg}\,\frac{a}{L}\right)\right|. \tag{2.11}$$

Here a is the radius of the flight hole, $I = q/lc$ is the pulse current of the beam and $Z_0 \equiv \sqrt{\mu_0/\varepsilon_0}$ is the wave impedance of the vacuum.

The ratio of the radiated energy to the kinetic energy of the beam is

$$\frac{W_e}{W_k} = -\frac{IZ_0}{2\pi U} \ln\left|\,\mathrm{tg}\left(\frac{1}{2}\,\mathrm{arc\,tg}\,\frac{a}{L}\right)\right|, \tag{2.12}$$

where U is the beam energy in eV. The right-hand side of (2.12) may be expressed via the average beam power P_e and the phase length of the bunch $\Delta\varphi (\Delta\varphi = 2\pi ct/\lambda)$:

$$\frac{W_e}{W_k} = -\frac{P_e Z_0}{\Delta\varphi U^2} \ln\left|\,\mathrm{tg}\left(\frac{1}{2}\,\mathrm{arc\,tg}\,\frac{a}{L}\right)\right| \tag{2.13}$$

The restriction on P_e follows from (2.13):

$$P_e < \frac{\Delta\varphi U^2}{Z_0 \ln(2L/a)}. \tag{2.14}$$

It is worth noting that the restriction on P_e, associated with the radiation, is usually weaker than that associated with the action of the space charge.

3. Beam dynamics in guns whose current is close to the critical one is possible to study in detail with the use of but numerical methods. The solution of such a problem involves a precise enough taking into account of the radiated fields and, hence, the solution of the Maxwell equations.

Some time ago we have prepared a computer program to calculate the dynamics of a high-current beam in a r. f. injector (Refs. [5, 6]). In this program the macroparticle models was used, the beam own field was defined by solving the Poisson equation and the unstationary problem of beam motion in a high-frequency electromagnetic field modulating the beam in density was solved. Since weakly relativistic beams were considered, the radiation fields were neglected.

In the known program BCI (Ref. [10]) the Maxwell equations are solved and the radiation fields are calculated, but the electron bunch is simulated by a one-demensional and constant-in-time current distribution whose maximum moves with the light velocity.

To solve the problem under study it is necessary a combination of the macroparticle model with the definition of the internal field of the beam from the Maxwell equations, which has required to prepare a specialized computer program.

In this program, while calculating the beam dynamics the «cloud-in-cell» model is employed (Refs [8, 9]). The beam and the surrounding electrodes are assumed to be axisymmetric. The electron beam is represented as a set of macroparticles having the finite longitudinal and transverse sizes, the latter varying depending on the nature of the beam motion. Thus, one can decrease substantially computational noises arising in the particle-in-cell model due to the charge fluctuations in the grid cell.

To calculate the trajectory of a particular macroparticle, the equations of motion in an impulse representation were used, and the Bóris scheme was used to integrate them (Ref. [9]).

$$\mathbf{u}^{(-)}=\mathbf{u}^{n-1/2}+\mathbf{E}^n\Delta t\cdot e/2m\,,$$
$$\mathbf{u}'=\mathbf{u}^{(-)}+\mathbf{u}^{(-)}\times\mathbf{t}\,,$$
$$\mathbf{u}^{(+)}=\mathbf{u}^{(-)}+\mathbf{u}'\times\mathbf{S}\,,$$
$$\mathbf{u}^{n+1/2}=\mathbf{u}^{(+)}+\mathbf{E}^n\Delta t\cdot e/2m\,,$$
$$\mathbf{r}^{n+1}=\mathbf{r}^n+\mathbf{u}^{n+1/2}\Delta t/\gamma^{n+1/2}. \qquad (3.1)$$

Here $\mathbf{u}\equiv\mathbf{v}\cdot\gamma$, $\mathbf{v}$ is the velocity of a macroparticle, $\mathbf{r}$ its coordinate, and γ is the relativistic factor;

$$\mathbf{t}=\mathbf{H}^n\Delta te\mu_0/(2mc\gamma^n)\,,$$
$$\mathbf{S}=2\mathbf{t}/(1+t^2)\,.$$

This scheme is of the second order of accuracy. The macroparticle is assumed to have three velocity components: v_r, v_z and v_φ. The electric field is a superposition of the electrostatic accelerating field generated by an external source, and the eddy field induced by the beam; because of the axial symmetry, it has two components: E_r and E_z. The magnetic field is a superposition of the constant guiding field with two components (radial and axial) and the eddy field with the only azimuthal component.

The eddy electromagnetic field satisfies the Maxwell equations. To integrate them numerically, we have used the method with fractional steps (Refs [9, 10]), which yields the second order of accuracy. Fig. 3 shows the spatial arrangements of the points where the values of the field components are calculated.

Integrating the Maxwell equations over the areas of the appropriate contours, it is possible to obtain the following integration schemes:

$$E^n_{r,k}=E^{n-1}_{r,k}+\frac{\Delta t}{\varepsilon_0}\frac{2}{\Delta z_j+\Delta z_{j-1}}\left(H^{n-1/2}_{\varphi,k-1}-H^{n-1/2}_{\varphi,k}\right)-\frac{\Delta t}{\varepsilon_0}J^{n-1/2}_{r,k}\,,$$

$$E^n_{z,k}=E^{n-1}_{z,k}+\frac{\Delta t}{\varepsilon_0}\frac{4}{(2r_i+\Delta r_i)^2-(2r_i-\Delta r_{i-1})^2}\times$$

$$\times\left[(2r_i+\Delta r_i)\,H^{n-1/2}_{\varphi,k}-(2r_i\Delta r_{i-1})\,H^{n-1/2}_{\varphi,k-k_{\max}}\right]-\frac{\Delta t}{\varepsilon_0}J^{n-1/2}_{z,k}\,,$$

$$H^{n+1/2}_{\varphi,k}=H^{n-1/2}_{\varphi,k}-\frac{\Delta t}{\mu_0}\left\{\frac{E^n_{z,k}}{\Delta r_i}-\frac{E^n_{z,k+k_{\max}}}{\Delta r_i}+\frac{e^n_{r,k+1}}{\Delta z_j}-\frac{E^n_{r,k}}{\Delta z_j}\right\}, \qquad (3.2)$$

where $\Delta r_i=r_{i+1}-r_i$ and $\Delta z_j=z_{j+1}-z_j$. Thus, the quantities $\mathbf{E}$ and $\mathbf{r}$ are defined at the moments of time Δtn, while $\mathbf{H}$, $\mathbf{u}$ and $\mathbf{J}$ are defined at the moments of time $(n+1/2)\Delta t$.

For the equations of motion to be integrated, it is necessary to know $\mathbf{H}$ at the moment of time $n\Delta t$. It can be obtained by a simple averaging:

$$\mathbf{H}^n=\frac{\mathbf{H}^{n-1/2}+\mathbf{H}^{n+1/2}}{2}.$$

At the initial moment of time there is an electrostatic field in the gap. It may be defined solving the Laplace equation with the appropriate boundary conditions. Fig 3 demonstrates the points at which the values of the electrostatic field potential are defined. Integrating the Laplace equation over the torus whose cross section is formed by straight lines connecting the centres of the gris meshes, we obtain the difference scheme. The set of linear equations obtained were solved by means of the successive over relaxation method. For this purpose, the matrix of system B should be summetrized:

$$A\varphi=AB^{-1}B\varphi=AB^{-1}\psi=C\psi\,,$$

where $\psi=B\varphi$, φ is the vector of the values of the potential in the grid nodes, $C=AB^{-1}$, B is the diagonal matrix with the elements $B_{ii}=r_i(\Delta r_i+\Delta r_{i-1})$.

Although we integrate the Maxwell equations and the equations of motion with the second order of accuracy, calculational errors are, nevertheless, possible, which are associated with the fact that the density distribution of the current in the gap is calculated on the basis of the macroparticle model. As a result, the law of charge conservation and current continuity can violate. In view of this, it is desirable to check the accuracy of their fulfilment in the course of the process of computation in the computational process. Our computations have shown that, with the conservation laws fulfilled, the relative error constitutes about 10^{-3} if the grid includes about 10^3 elements and the number of macroparticles is about 10^3, in the solution of the model problems, and this error is no more than 10^{-2} in the calculation of the particular constructions.

Because the system we here consider is not resonant, the noise level in electromagnetic fields does not grow. In our calculations we have not, therefore, corrected the current density, which is required during the simulation of, for example, some plazma processes (Ref. 9).

The charge density is calculated at the moment of time $n \cdot \Delta t$, while the current density at the moment $(n+1/2)\Delta t$. In this case, the coordinates of the macroparticles at $(n+1/2)\Delta t$ are determined by averaging

$$\mathbf{r}^{n+1/2} = \frac{\mathbf{r}^n + \mathbf{r}^{n+1}}{2}.$$

Note that for the stability of the used scheme, the Courant condition should be satisfied:

$$\Delta t < \frac{1}{c[\Delta r^{-2} + \Delta z^{-2}]^{1/2}}.$$

This condition is somewhat modified if there are the boundaries with the radiation conditions.

Thus, the complete simulation scheme is as follows. We start to integrate with the definition of $\mathbf{E}^0$, $\mathbf{r}^0$, $\mathbf{u}^{1/2}$, $\mathbf{H}^{1/2}$ and $\mathbf{J}^{1/2}$. It is clear that $E^0 = \Delta\varphi$, $Z^0 = 0$, $\mathbf{J}^{1/2} = 0$ and $\mathbf{u}^{1/2} = 0$. We further perform the integration according to the scheme:

1) over the known values of $\mathbf{J}^{n+1/2}$, $\mathbf{u}^{n+1/2}$, we calculate $\mathbf{E}^{n+1}$ with respect to the known values of $\mathbf{J}^{n+1/2}$, $\mathbf{u}^{n+1/2}$ and $\mathbf{E}^n$;
2) we calculate $\mathbf{H}^{n+3/2}$ with respect to the known values of $\mathbf{H}^{n+1/2}$ and $\mathbf{E}^n$;
3) $\mathbf{H}^{n+1}$ is then calculated: $\mathbf{H}^{n+1} = (\mathbf{H}^{n+3/2} + \mathbf{H}^{n+1/2})/2$;
4) $\mathbf{u}^{n+3/2}$ is calculated with respect to the known values of $\mathbf{u}^{n+1/2}$, $\mathbf{E}^{n+1}$, $\mathbf{H}^{n+1}$;
5) we calculate $\mathbf{r}^{n+2}$ with respect to $\mathbf{u}^{n+3/2}$ and $\mathbf{r}^{n+1}$;
6) ϱ^{n+2} is calculated with respect to $\mathbf{r}^{n+2}$;
7) $\mathbf{r}^{n+3/2}$ is then calculated: $\mathbf{r}^{n+3/2} = (\mathbf{r}^{n+2} + \mathbf{r}^{n+1})/2$;
8) the current density $\mathbf{J}^{n+3/2}$ is calculated with respect to the known $\mathbf{r}^{n+3/2}$ and $\mathbf{u}^{n+3/2}$;
9) we test the satisfaction of the conditions $\operatorname{div}\mathbf{J} = -\frac{\partial\varrho}{\partial t}$ and $\operatorname{div}\mathbf{E} = \varrho/\varepsilon_0$.

The integration procedure is ended after the beam leaves the system; after that the energy emitted by the beam is calculated.

4. Using the above computer program, computations have been done for a gun schematically shown in the Fig. 1, at the following values of the parameters: $L=2$ cm, $a=1$ cm, $r=0.5$, $ct=1$ cm and $U=1$ MV. According to (2.7) and with the dependence of P_0 on the voltage taken into account, $I_{cr}=1$ kA; according to (2.12), $W_e/W_k \approx 8 \cdot 10^{-2}$, at $I=1$ kA. Following the bunch dynamics, one can distinguish convetionally three stages (Fig. 4):

a) the regime of small space charge when the bunch own field has little influence on its dynamics; in this case $I_e \ll I_{cr}$;

b) the transient regime when the bunch own field leads to a considerable elongation of it, but the space charge does not yet limit the emission; this regime corresponds to $I_e \sim I_{cr}$;

c) the saturation regime when $I_e > I_{cr}$. In this case, a large fraction of the photoelectrons return at the cathode, while the beam dynamics exerts great influence of its own field, including the radiation fields.

The occurrence of these regimes is well seen on the curves of Fig. 4 for which $I_{cr} \approx 1.5$ kA, which is in agreement with the estimation according to formula (2.7).

For $I_e < 1$ kA the bunch length remains, in practice, unchanged, and the radiation losses grow linearly with the energy (current) of the bunch. Here $d(W_e/W_k)/dI_e \approx 6 \cdot 10^{-2}$ kA^{-1}, which is in good agreement with the estimation according to formula (2.12); for these parameters this estimation yields the value $8 \cdot 10^{-2}$ kA^{-1}. At 1 kA$<I_e<$2 kA there occurs a drastic increase in the bunch length, whereas the charge is not yet limited. At $I_e > 2$ kA the space charge limits the current in the bunch. The bunch length, the ratio W_e/W_k and the energy spread change insignificantly with increasing the photocurrent (because the bunch charge does not grow). The quantity W_e/W_k is here small and is about 5%.

From the said above the conclusion may be drawn that it is not desirable to employ an electron gun with the photocurrent exceeding I_{cr} since in this case the photocurrent is utilized incompletely (and, hence, the laser power), and an elongation of the bunch sharply falls down the efficiency of a r. f. generator.

Thus, the most significant factor limiting the average power of the beam in the gun, without an additional beam compression after acceleration, is the action of the space charge rather than the radiation fields.

It is worth noting that the calculations, the results of which are presented in Fig. 4, have been made for the beam with constant transverse sizes since the longitudinal dynamics has been studied. This constancy can be provided by the introduction of a longitudinal magnetic field.

In our calculations the voltage U on the gap has been assumed to be constant. At the parameters indicated above this condition is satisfied rather well: on account of an appearance of a variable constituent of the current in the anode circuit, the voltage changes slightly.

The results obtained enables the conclusion to be drawn that the «classical» scheme of a lasertron (without the transverse bunch compression) is poor suitable for the creation of powerful (10^2-10^3 MW) r. f. generators at short wavelengths (5—10 cm). However, this scheme seems, in our opinion, to be interesting as an injector of periodic sequence of short and highly-efficient (up to 10^{12} particles) electron bunches.

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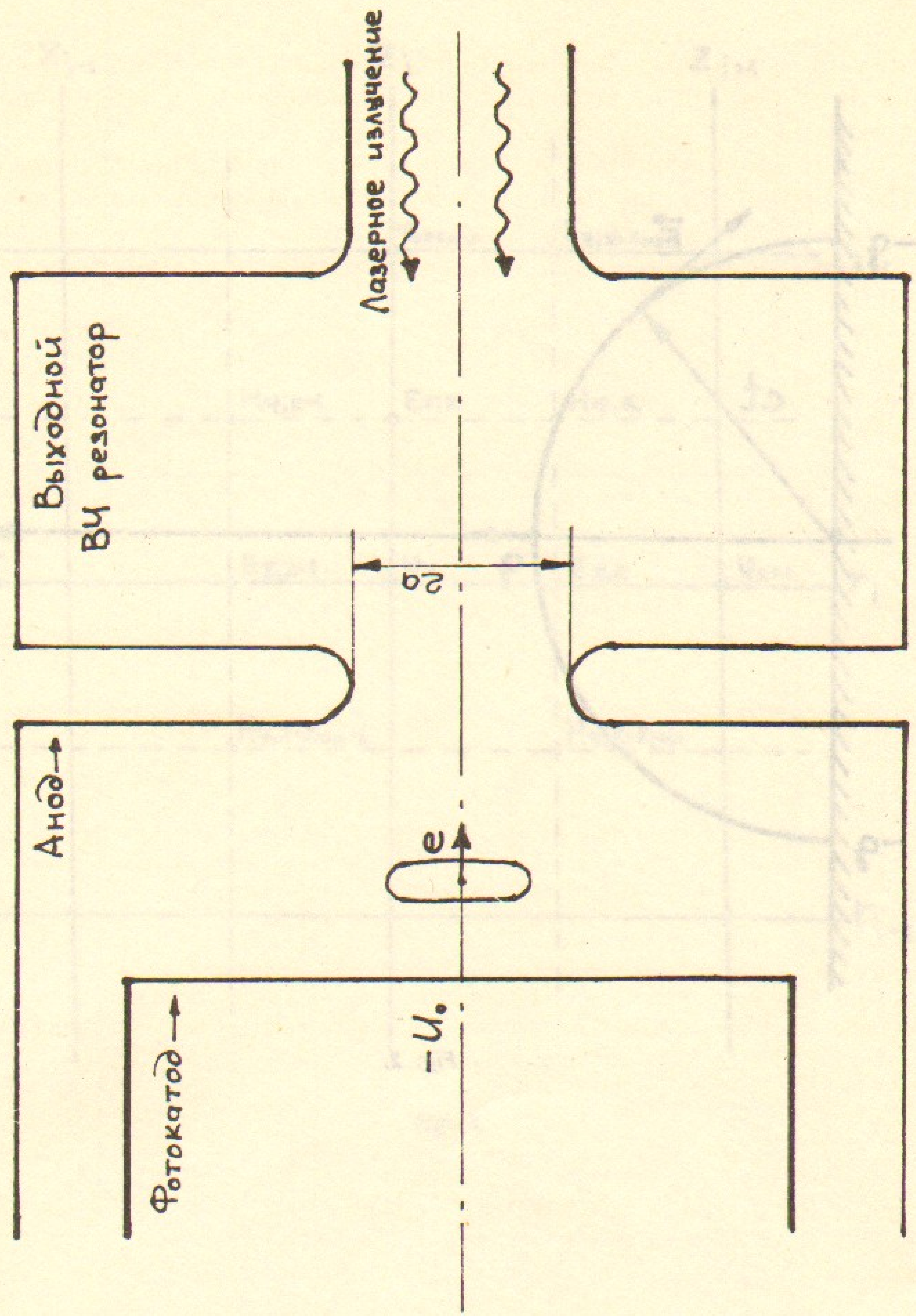

Fig. 1.

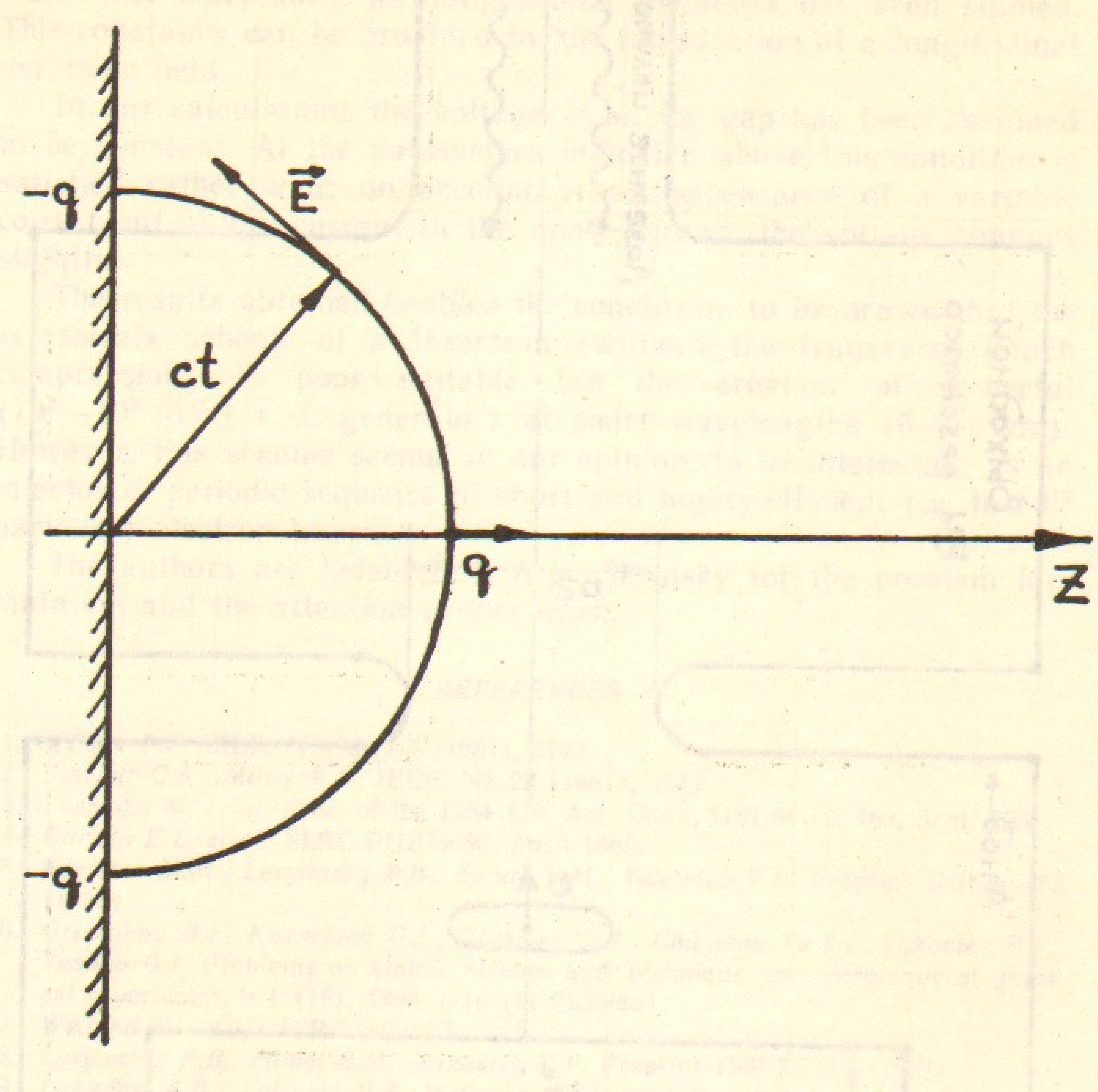
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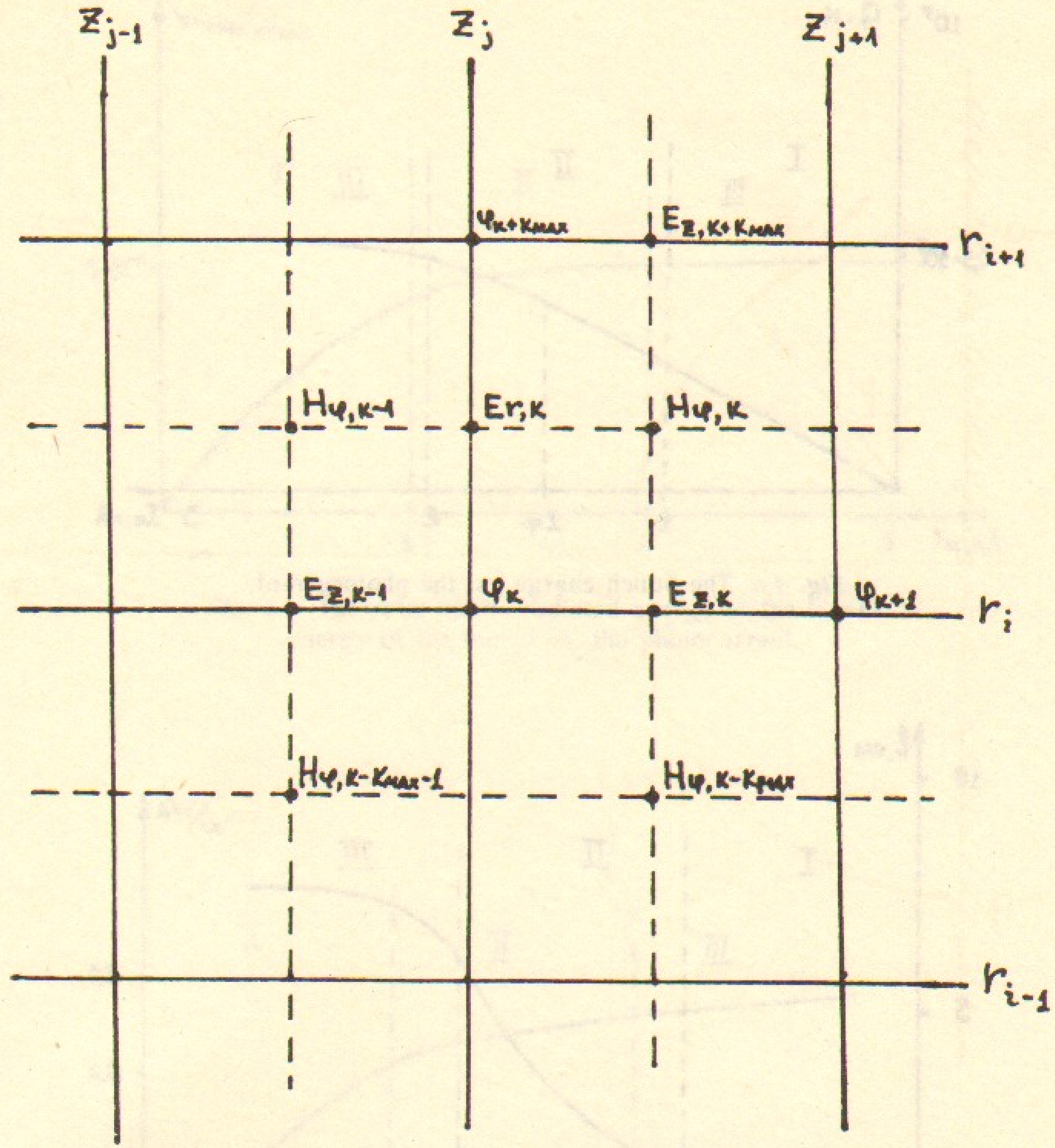
Fig. 2.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$H_{\varphi,k-1}$
$E_{r,k}$
$H_{\varphi,k}$
$E_{z,k-1}$
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$H_{\varphi,k-k_{max}}$

Fig. 3.

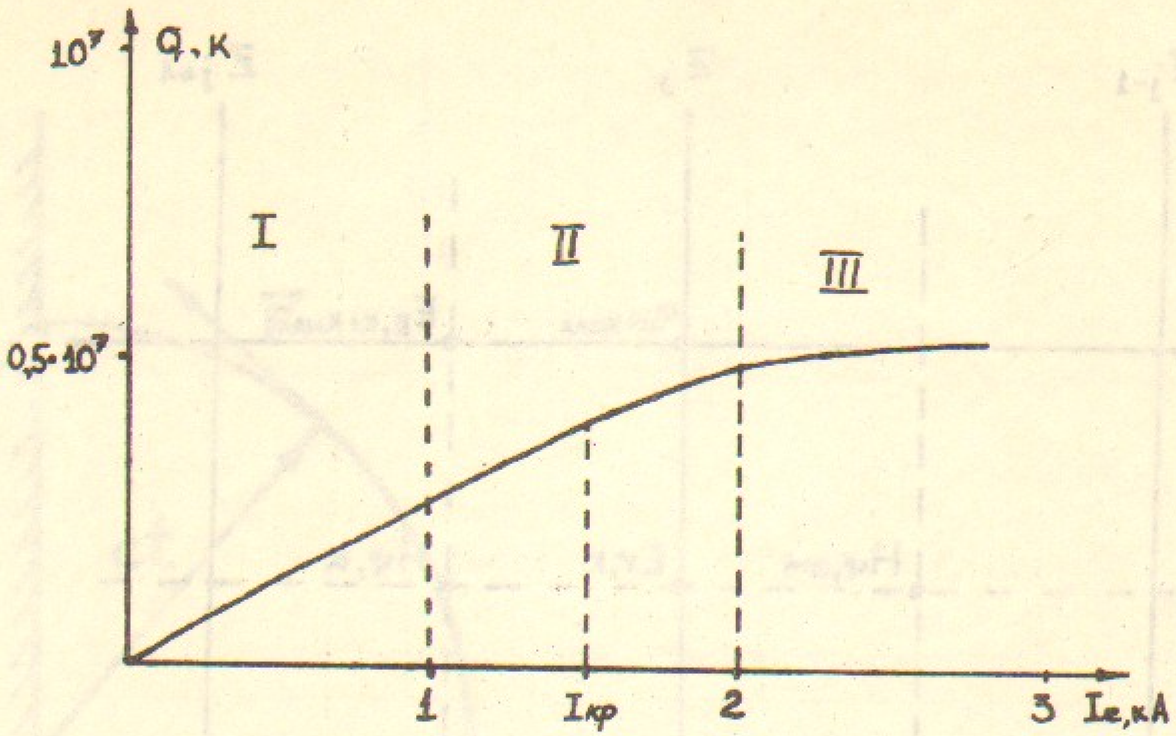

Fig. 4,a. The bunch charge vs. the photocurrent.

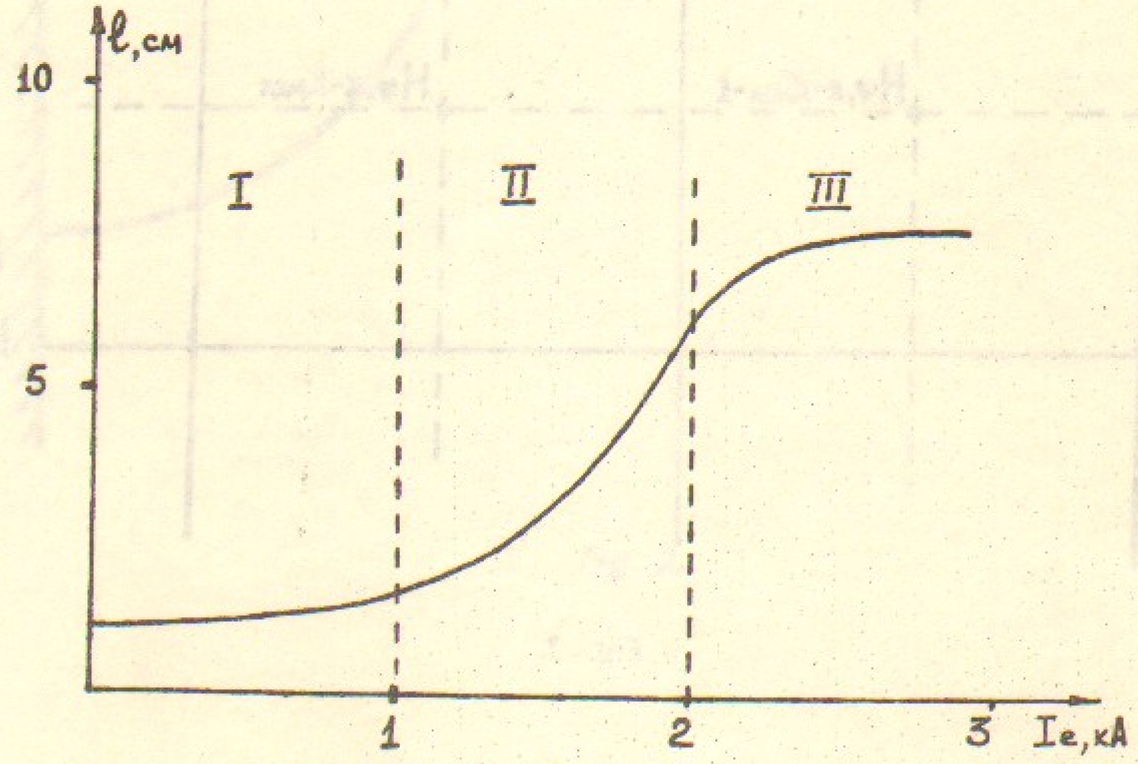

Fig. 4,b. The bunch length vs. the photocurrent.

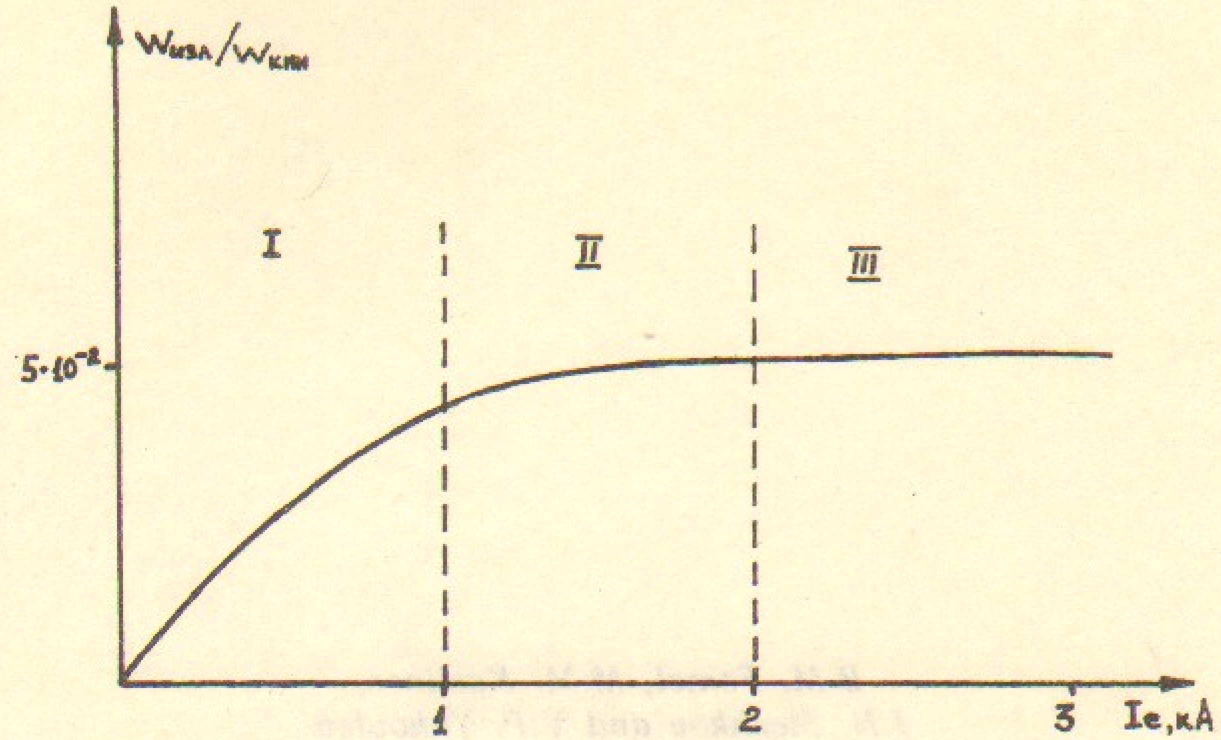

Fig. 4,c. The ratio of the radiated energy to the kinetic energy of the bunch vs. the photocurrent.

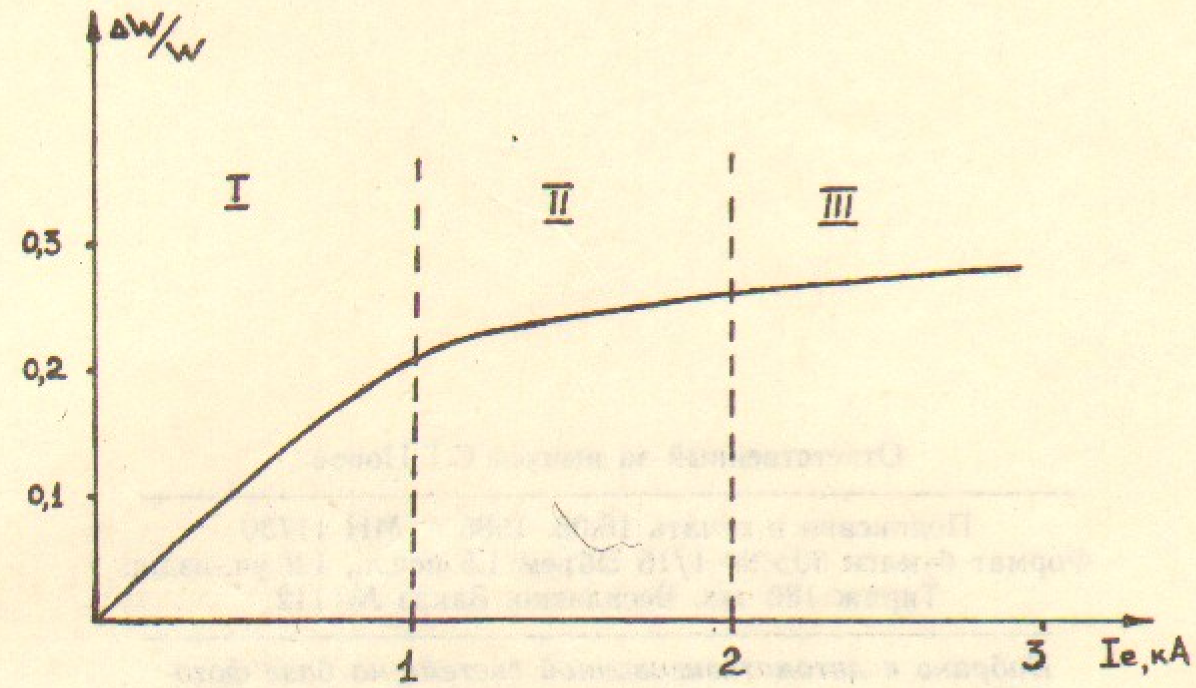

Fig. 4,d. The relative energy spread vs. the photocurrent.

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