PHOTOCATHODE ROUGHNESS IMPACT ON PHOTOGUN BEAM CHARACTERISTICS

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Abstract

Photocathode surface roughness has an impact on bunch duration, beam emittance at the exit of femtosecond photogun with an accelerating field that is considered in assumption of quasistationary one in the paper. The main problem in the investigation of the impact is determination of the field near the surface, statistical properties of which are defined in terms of the rms values of deviation and slope in profile line of the surface roughness. The results of the investigations, performed for the rms deviation and slope of roughness within respectively 1 – 500 nm and 2 – 20 degrees, are presented and discussed.

INTRODUCTION

Photoelectron guns for light sources, based on the FEL scheme, and for many other applications need to provide electron bunches with small emittance at high peak current. It is known that the magnitude of the transverse emittance of the photogun beam has the low limit, defined as the thermal emittance, on the levelof 0.3 π mm·mrad, for example, for a round beam of the 0.5 mm - radius with uniform particle density in space and effective temperature of 0.2 eV [1]. It is established also that this normalized thermal emittance is defined by only initial angle and energy spread of photoelectrons. But it will hold true in consideration of the photocathode surface without any roughness. All papers, published during last years and devoted to the emittance research, its growth and compression, do not consider the surface roughness effect on the beam characteristics.

The paper is the first where the consideration of the photocathode microrelief effect is attempted. The influence of the microrelief on the beam characteristics, namely: the effective transverse emittance of the beam and its bunch duration at the exit of the gun, - are determined in terms of their rms values as a functions of the rms deviation and slope in profile curve of the surface roughness. It is shown, in particularly, that the thermal transverse emittance can exceed the mentioned above magnitude by a factor of several tens in the case of using the accelerating field of the order of 1 GV/m and even at rather smooth photocathode roughness. As an example, the surface effect in streak camera with new principle of its operation [2] has been also considered. These characteristics have been obtained by means of the 3D microrelief regeneration, the 3D field computation with a proper precision and, finally, the beam dynamics simulation taking into account an initial distribution of photoelectrons in angle and energy. All these methods of calculation are shortly described in the paper also.

ROUGHNESS DESCRIPTION

The photocathode surface $z = f(x, y)$ is considered as a plane surface with microrelief and in the following assumption: the surface function represents a stationary random field of the z-values with ergodic property on the infinite plane of variables (x, y) and with mathematical expectation $E\{z\} = 0$ coinciding with a normal, non-perturbed plane of the photocathode.

Information of the surface properties according with standard specification of surface roughness is obtained from its 2D profile, measured, for example, with a scanning tunneling microscopy, that represents a random function with ergodic property also and can be described by series with periodic components [3]:

$$z = \sum_{n=1}^{\infty} A_n \cos(n\omega_0 x + \varphi_n)\,, \qquad (1)$$

where the phase φ_n is a random variable with uniform distribution within interval $[0, 2\pi]$.

In practice the infinite series (1) is cut off. In the case the coefficient A_n in the series (1) can be defined as

$$A_n = \frac{\sqrt{2}\sigma_z}{\sqrt{\sum_{n=1}^{N}\exp\left\{-\left(n\omega_0/2\kappa\right)^2\right\}}}\exp\left\{-\frac{1}{2}\left(\frac{n\omega_0}{2\kappa}\right)^2\right\}, \qquad (2)$$

where $\kappa \cong \sigma_{tg\alpha}/2^{1/2}\sigma_z$; $\sigma_{tg\alpha}$ - the standard deviation of the derivative of the function z in expression (1) with respect to x that is defined by using Parseval's theorem; σ_z - the standard deviation of the z- values in the profile. We shall call $\sigma_{tg\alpha}$ as rms slope and σ_z - rms height of roughness.

The correlation function $R_z(\tau)$ of the random process $z(x)$ in (1) can be represented as $R_z(\tau) = \sigma_z^2\exp(-\kappa^2\tau^2)$. Correlation length l_{cor} of the process is estimated as $l_{cor} = [ln(1/\eta)^2]^{1/2}(\sigma_z/\sigma_{tg\alpha})$ where η is a predetermined relative level of the correlation function.

By determining the power spectra of the process $z(x)$ by means of Fourier transform of $R_z(\tau)$ one can determine the highest frequency ω_m in our z-profile as a boundary frequency, below which a definite part of the energy k_P is contained: $k_P = \mathrm{erf}\{\sigma_z\omega_m/(2^{1/2}\sigma_{tg\alpha})\}$.

By taking $\sigma_z = 10$ nm, $\sigma_{tg\alpha} = 0.3$, $\eta = 0.01$, $k_P = 0.99$, as an example, it obtains: $l_{cor} = 0.14$ μm, $\omega_m = 0.08$ nm^{-1}, i.e. for description of the process in this case it will be enough to take in (1) $N \le 10$ and $\omega_0 \approx 0.01$ nm^{-1}.

It should be noted that for the surface regeneration, based on 2D series similarly to the series (1), the surface period ($a = 2\pi/\omega_0$) along each axes in the plane (x, y) has been taken five times as many as l_{cor}.

The description of the surface profile, outlined here, are in good agreement with experimental data, obtained for

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surfaces after electro-chemical polishing [4]. The regeneration of 3D surface and its all statistics properties are completely defined by only two parameters: the rms height and rms slope of roughness.

FIELD DETERMINATION

Distribution of potential $U(x, y, z)$ in space (in rectangular Cartesian coordinate system), restricted by two planar electrodes: anode at z = L and cathode with microrelief z = f(x, y) at its average z = 0, is determined by solving the following boundary problem for Laplace's equation: $\Delta U = 0$ and $U(x, y, f(x, y)) = U_0$, $U(x, y, L) = 0$ at the next terms of the solution periodicity $U(x, y, z) = U(x + a, y, z)$, $U(x, y, z) = U(x, y + a, z)$.

The solution of this problem admits its expression in the general form via the solution for the same problem with a smooth cathode surface:

$$U \cong U_{00} + \sum_{\substack{n,m=-N \\ n,m\neq 0}}^{N} C_{nm} e^{-\frac{2\pi z}{a}\sqrt{n^2+m^2}} \cos\left(\frac{2\pi}{a}(nx+my)+\varphi_{nm}\right), \qquad (3)$$

where $U_{00} = C_{00}(1 - z/L)$ is non-perturbed potential distribution, and coefficients C_{nm} should be determined to satisfy the boundary term on the cathode in the case of the surface microrelief consideration.

In the general case in (3) the term with second a transcendental number should be written, but its contribution is very small and it was omitted.

After defining coefficients C_{nm} the term in the form of sum in (3) will describe the part field, perturbed by the surface roughness.

For simplicity we rewrite the expression (3) in more general form:

$$U(x, y, z) = \sum_{n=1}^{N_1} C_n U_n(x, y, z), \qquad (4)$$

where $N_1 = 4(N + 1)^2$.

The coefficients of the series (4) are defined from the term of minimizing the following functional

$$F(C_1, ..., C_{N1}) = \sqrt{\frac{1}{a^2} \iint\limits_{\substack{0<x<a \\ 0<y<a}} \left(U_0 - \sum_{n=1}^{N_1} C_n U_n(x, y, f(x, y))\right)^2 dxdy} \qquad (5)$$

This is equivalent to solving the next system of linear equations relative to $C_1, \ldots, C_{N1}$:

$$a_{nm} C_n = b_m, \qquad n, m = 1, ..., N_1, \qquad (6)$$

where the coefficients a_{nm} and b_n are defined by expressions

$$\begin{aligned} a_{nm} &= \iint\limits_{\substack{0<x<a \\ 0<y<a}} U_n(x, y, f(x, y)) U_m(x, y, f(x, y)) dxdy \\ b_m &= U_0 \iint\limits_{\substack{0<x<a \\ 0<y<a}} U_m(x, y, f(x, y)) dxdy \end{aligned} \qquad (7)$$

For determination of the field near the surface roughness with the rms slope from 0.03 to 0.3 and the rms height of roughness from 0 to 500 nm there was taken $N = 30$ in the expression (3). We note, as an example, that at the rms slope of 0.3 and the rms height of 10 nm the relative error of the field calculation - of the order of 10^{-8}. This value is defined as the magnitude of the expression (5) divided into U_0.

Let us introduce the function $\mu(z)$ representing attenuation of the perturbed filed against the z-distance that is defined by ratio: $\mu_z(z) = \sigma_{Ez}/\langle E_z \rangle$ (and the same manner for the x- component) where the sample average $\langle E_z \rangle$ and sample variance σ_{Ez} [3] are determined in the points being apart more than the correlation length.

The dependence of the field attenuation on the z-distance, expressed in units of the rms height of the roughness, for the case of the surface with the rms slope of 0.3 is shown in Fig.1.

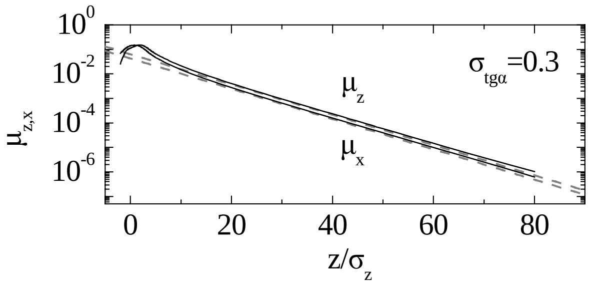

Figure 1: Dependences of attenuation for two components of the perturbed filed on the z-distance, expressed in units of the rms height of the roughness, for the surface with the rms slope of 0.3.

The attenuation for two components of the perturbed field, presented in Fig. 1, can be approximated by linear functions, as it is shown in the Fig. 1, namely:

$$\log\left(\frac{\sigma_{Ex}}{\langle E_z \rangle}\right) = -1.8 + \left(7 - \frac{z}{\sigma_z}\right)\left(0.006 + 0.186\sigma_{tg\alpha}\right). \qquad (8)$$

On the base of the expression (8) for the E_z - component the attenuation of E_x - component can be obtained with the relation $\sigma_{Ez}/\sigma_{Ex} \approx 1.5$.

Due to high speed of the attenuation the perturbed field is mainly localized on the length of about $100\sigma_z$. At the rms height of roughness σ_z of 10 nm this length will be 1μm. In comparison with the photogun accelerating gap length, that can be from 1 mm and up to several sm, the length of the perturbed field is rather short, but, as it can be shown in the next section, the influence of the field on the beam characteristics, first of all on the transverse emittance, can be significant.

BEAM PERTURBATION

Figures 2, 3 and 4 demonstrate the surface roughness effect in photoguns of planar configuration with accelerating field up to 1 GV/m [5] (Figs. 2, 3) and the effect in new type streak camera for registering both x-ray pulses and pulses in the range of visible light (Fig. 4).

All dependences have been defined for initial angular distribution of cosine-cube type. In the case of photogun the dependences in Fig. 2, 3 have been defined for initial parabolic energy distribution from 0 to 1 eV, and in the case of the camera (Fig. 4) the curves a, c - for gold photocathode, illuminated by x-ray [6], and the b - curve for photocathode S1 with the parabolic distribution from 0 to 0.5 eV and from 0 to 1 eV.

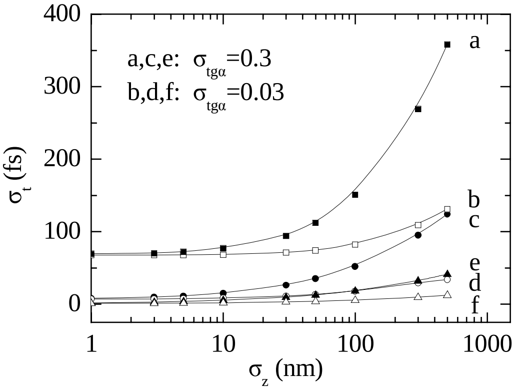

Figure 2: Dependence of rms time of flight of one- mm-length gap on the rms height of surface roughness for the following accelerating gap voltages: 10 kV – a, b; 100 kV – c, d; 1MV – e, f.

Ratio of the thermal emittances, defined for the cathode surface with roughness and without it: $\eta_\varepsilon \equiv \equiv \tilde{\varepsilon}_{xn}(\sigma_z,\sigma_{tg\alpha},\theta_0,W_0)/\tilde{\varepsilon}_{xn}(0,0,\theta_0,W_0)=\tilde{v}_x(\sigma_z,\sigma_{tg\alpha},\theta_0,W_0)/\tilde{v}_x(0,0,\theta_0,W_0)$, as function of roughness parameters is shown in Fig. 3.

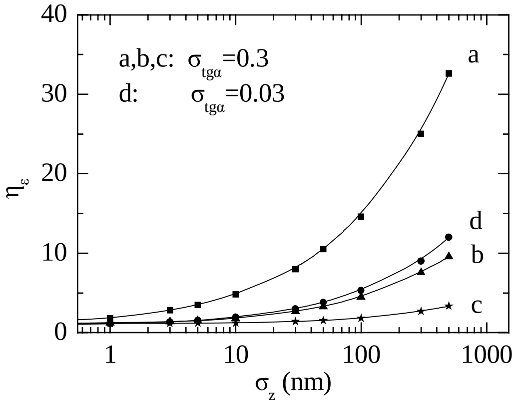

Figure 3: Dependence of ratio of the thermal emittances, defined for the cathode surface with roughness and without it, η_ε on the rms height of surface roughness for the next accelerating field: 1 GV/m – a, d; 100 MV/m – b; 10 MV/m – c.

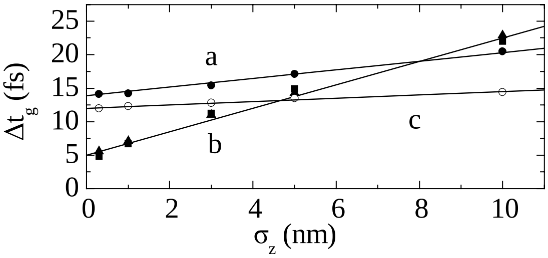

Figure 4: Dependences of temporal resolution of the modulating gap of new type streak camera [2] on the rms height roughness at its rms slope $\sigma_{tg\alpha}$ of 0.3 and 0.1 for a gold photocathode, illuminated by soft x-ray, – **a** ($\sigma_{tg\alpha}$ = 0.3) and **c** ($\sigma_{tg\alpha}$ = 0.1), and **b** ($\sigma_{tg\alpha}$ = 0.3) – photocathode S1, illuminated in frequency range of visible light, i.e. the case when initial energy spread from 0 to 0.5 eV and from 0 to 1 eV.

In Figure 4 the temporal resolution was obtained for the accelerating voltage of 10 kV and amplitude of RF-voltage of 10 kV of 3 GHz, applied to the gap of 10 mm. More in detail of the camera one can find in paper [2].

CONCLUSION

From the considerations, outlined in the paper, one can conclude the following:

characteristics, required for description and regeneration the surface roughness, are completely defined by only two parameters: the rms height and rms slope of the roughness;

the surface mircorelief can be described by 2D series of periodic components with phases as a random variables;

statistical characteristics of the field, perturbed by the photocathode roughness, are completely described via the rms height and rms slope of the roughness;

the perturbed field can be determined in fact with any predetermined precision in practice;

the thermal transverse emittance, at the rms height of roughness more of the order of 10 nm and at the surface field of the order of 100 MV/m and more, will be mainly defined by the surface roughness even at rather smooth roughness with its rms slope of 0.3 and less;

at the rms height of roughness of the order of 0.1 μm and the surface field of the order of 1 GV/m [5] the thermal transverse emittance will exceed the established magnitude for the smooth surface by a factor of several tens;

for getting temporal resolution not worse 20 fs in streak camera with new principles of operation [2], in the case of registering pulses both of visible light and x-ray radiation, the rms height of roughness must not exceed 10 nm.

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