IMPACT OF THE CATHODE ROUGHNESS ON THE EMITTANCE OF AN ELECTRON BEAM

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Abstract

An RF photo injector for the European XFEL should produce electron beams with normalized transverse emittance under 1 mm mrad. In order to achieve this high performance of the electron source the electric field at the photo cathode has to be increased up to 60 MV/m. The emittance budget of the optimized XFEL photo injector contains a significant part of thermal (intrinsic) emittance. A roughness of the cathode could lead to an additional uncorrelated divergence of the emitted electrons and therefore to an increased thermal emittance. The cathode roughness has been modelled using an analytical approximation and numerical simulations. The influence of the roughness parameters and the increase of the electric field have been studied.

INTRODUCTION

The main goal of the Photo Injector Test facility in Zeuthen (PITZ, [1]) is to optimize electron sources for FEL injectors, including already existing (FLASH) and future (XFEL) facilities. Increasing the maximum gradient at the photo cathode in the rf gun from 40 MV/m to 60 MV/m is one of the main improvements towards XFEL requirements. This implies (with taking into account an optimum launch rf phase) an increasing of the electric field at the photo cathode at the moment of the emission from 24 MV/m to 42 MV/m. The improved normalized beam emittance in the injector is expected to be under 1 mm mrad. Besides earlier suppressing of the space charge effect in the rf gun the gradient increase also leads to a significant increase of the contribution of initial (thermal) emittance in the total emittance budget.

The cathode roughness increases the intrinsic divergence of the emitted electron bunch. A model with a periodical roughness of the cathode is applied to study the geometrical emission effect in dependence on roughness parameters. A single bump model is used to study the impact of the applied electric field on the initial emittance.

THE MODEL OF THE PERIODIC SURFACE ROUGHNESS

2D model, normal emission only

Consider a cathode surface given by the formula

$$z = h\cos(kx) \quad , \tag{1}$$

where $2h$ is the roughness depth and $\lambda = 2\pi/k$ is the roughness period along the cathode surface. Let's consider first the case of the emission normal to the cathode surface, so $\varphi = 0$ (Figure 1a), what implies zero thermal emittance from the non-perturbed (no roughness) cathode.

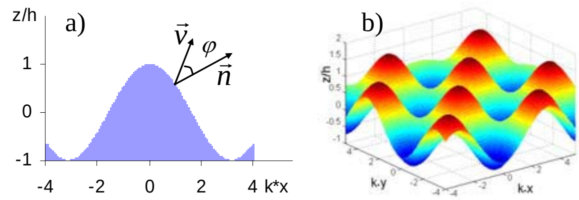

Figure 1: Periodic roughness, 2D (a) and 3D (b) models.

Transverse component of the electron velocity is

$$v_x = v_0 \frac{\xi \sin(kx)}{\sqrt{1+\xi^2 \sin^2(kx)}}, \tag{2}$$

where $\xi = kh$, v_0 is velocity of the emitted electron. After corresponding integration over the roughness period one can obtain an expression for the emittance induced by the rough cathode surface

$$\varepsilon_x^{2D} = \sigma_x \cdot \sqrt{\langle p_x^2 \rangle} \approx 2\sigma_x \sqrt{\frac{eE_0}{mc^2} h \cdot \left(1 - \frac{1}{\sqrt{1+\xi^2}}\right)}, \tag{3}$$

where σ_x is an rms electron beam size at the cathode, $p_x = \frac{v_x / c}{\sqrt{1 - v_0^2/c^2}}$ is the normalized transverse momentum and E_0 is the electric field at the cathode at the moment of the emission.

3D model, normal emission only

A cathode surface with periodic roughness is given

$$z = h\cos(kx)\cos(ky), \tag{4}$$

where $x - y$ isotropy is assumed (Figure 1b). Transverse component of the electron emission velocity:

$$v_x = v_0 \frac{\xi \sin(kx)\cos(ky)}{\sqrt{1+\xi^2\left(\sin^2(kx)\cos^2(ky) + \cos^2(kx)\sin^2(ky)\right)}}. \tag{5}$$

Transverse emittance induced by 3D rough cathode surface (4) is

$$\varepsilon_x^{3D} = \sigma_x \cdot \sqrt{\langle p_x^2 \rangle} \approx 2\sigma_x \sqrt{\frac{eE_0}{mc^2} h \cdot I(\xi)},$$

where

$$I(\xi) = \frac{\xi^2}{4\pi^2} \int_{-\pi}^{\pi} dX \int_{-\pi}^{\pi} \frac{\sin^2 X \cos^2 Y}{1+\xi^2\left(\sin^2 X \cos^2 Y + \cos^2 X \sin^2 Y\right)} dY. \tag{6}$$

One can show, that for the for same roughness parameters the emittance ε_x^{3D} is in a factor $\sim\sqrt{2}$ smaller than 2D one, because the effective roughness depth ($\sim hI(\xi)$) in

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the 3D case is smaller. A ratio $\varepsilon_x^{3D} / \varepsilon_x^{2D}$ is shown in Figure 2 as a function of the roughness parameter ξ.

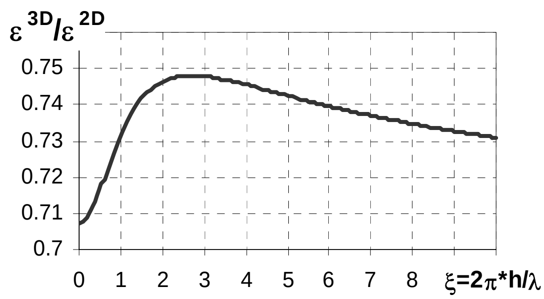

Figure 2: Emittance from 3D surface (4) compared to 2D case (1) vs. roughness parameter $\xi = 2\pi h / \lambda$.

2D model with emission distribution

In the case of nonzero non-perturbed thermal emittance there is an emission in a finite angle φ, as it happens i.e. by emission from the Cs2Te photo cathode. Using approach described in [2], one assumes that electrons are emitted isotropically in a cone with an angle $\varphi_m = \arccos\sqrt{E_A / E_k}$ with respect to the local surface normal, where E_A is the electron affinity of the emitting material and E_k is the electron kinetic energy. For the Cs2Te photo cathode $E_A \approx 0.2eV$, by a applying driving laser with 262 nm wavelength $E_k \approx 0.75eV$. This model yields a formula for the thermal emittance of the smooth cathode (no roughness assumed) [2]:

$$\varepsilon_x^{th,0} = \sigma_x \sqrt{\frac{2E_k}{mc^2}} \cdot \sqrt{\frac{2 + \cos^3\varphi_m - 3\cos\varphi_m}{6(1-\cos\varphi_m)}} . \tag{7}$$

Within an applied roughness model (1) a transverse momentum of the electron emitted at angle φ to the local normal is given

$$p_x = \sqrt{\frac{2E_k}{mc^2}} \cdot (\sin\varphi\cos\theta\cos\alpha + \cos\varphi\sin\alpha), \tag{8}$$

where θ is a local azimuth angle, $\alpha(x)$ is a rough surface slope obtained from (1):

$$\tan\alpha = -\xi \sin kx . \tag{9}$$

Applying triple integration to p_x^2 over $\varphi \in [0; \varphi_m]$, $\theta \in [0; \pi]$ and over the roughness period [3] yields a formula for the thermal emittance from the periodic rough surface:

$$\varepsilon_x^{th,rough} = \sigma_x \sqrt{\frac{2E_k}{mc^2}} \times \tag{10}$$

$$\times \sqrt{\frac{(2 + \cos^3\varphi_m - 3\cos\varphi_m)\cos\alpha_m + 2(1-\cos^3\varphi_m)(1-\cos\alpha_m)}{6(1-\cos\varphi_m)}},$$

where $\cos\alpha_m = 1 \Big/ \sqrt{1+\xi^2}$. Obviously, that in the absence of the roughness ($\alpha_m = 0$) the formula (10) is reduced to the expression (7).

Thermal emittance growth $\left(\varepsilon_x^{th,rough} / \varepsilon_x^{th,0} - 1\right)$ due to the cathode roughness is shown in Figure 3. From this plot thermal emittance growth <30% corresponds to the cathode roughness with $\lambda > 5h$, for 10% growth $\lambda > 12h$ is required. Preliminary cathode plug roughness measurements performed at INFN LASA (Milano) [4] showed that photo cathodes presently used at PITZ have roughness with $\sigma \sim 10nm$. In order to keep the thermal emittance growth under 10% it is necessary to provide a roughness period over 100 nm.

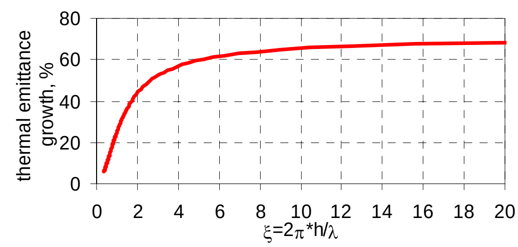

Figure 3: Thermal emittance growth vs. roughness parameter $\xi = 2\pi h / \lambda$. Ideal Cs2Te cathode parameters $E_A = 0.2eV$, $E_k = 0.75eV$ have been assumed [2].

In practical case the electron affinity is affected by many factors. It is well known that the quantum efficiency (QE) of the photo cathodes decreases with operation time; electron affinity increase due to the change of the cathode surface status is one of the possible mechanisms explaining QE degradation. On the other hand an applied rf field lowers the electron affinity due to the Schottky effect [5]. The electron affinity can be modelled as [6]:

$$E_A = \kappa E_{A,0} - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta_{ph}E_0} , \tag{11}$$

where κ is responsible for the increase with a time of the initial affinity $E_{A,0}$, β_{ph} is a field enhancement factor for photoemission, which partially can include also a surface roughness effect. A thermal emittance growth as a function of roughness period and electron affinity is shown in Figure 4 with a contour plot.

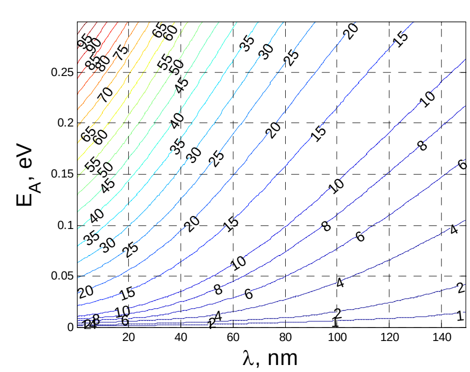

Figure 4: Thermal emittance growth $\left(\varepsilon_x^{th,rough} / \varepsilon_x^{th,0} - 1\right)$ given in % as a function of roughness period and electron affinity. For this plot $h = 10nm$, $E_k = 0.75eV$ is assumed.

DEPENDENCE ON ELECTRIC FIELD

In order to study the dependence of the initial emittance on the electric field during emission a model of single bump can be used. A two-dimensional model of the bump is described in [7]:

$$\frac{z}{b} = \sqrt{1+\frac{a^2}{b^2+x^2}} - 1, \tag{12}$$

where parameters a and b are constants depending on roughness depth and width. Typical bump shapes are shown in Figure 5.

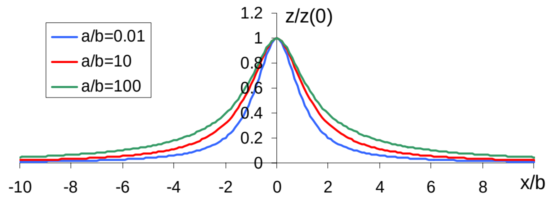

Figure 5: Rough cathode surface: single bump model (10). Upper curve corresponds to $a/b = 100$.

The choice of equation (12) for the rough cathode surface is motivated by the simple conformal transformation

$$\zeta = u + iw = \sqrt{(x + iz + ib)^2 + a^2} - ib, \tag{13}$$

which maps the electric field of a plane capacitor onto the field of the surface (12). An analytical expression for the electric field can be obtained from the corresponding conformal transformation

$$E_x + iE_z = \frac{-iE_o \cdot [x - i(y+b)]}{\sqrt{[x - i(y+b)]^2 + a^2}}. \tag{14}$$

The electric field lines are shown in Figure 6.

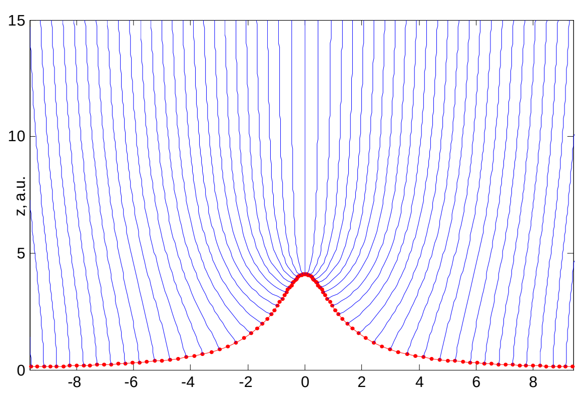

Figure 6: Electric field lines of the bump (10).

Once the electric field magnitude E_o and the bump parameters a and b are specified, the field profile is determined from (14) and particle position (x, z) and momentum (p_x, p_z) can be numerically integrated in time according to

$$\frac{d}{d(ct)}\begin{pmatrix} p_x/(mc) \\ p_z/(mc) \end{pmatrix} = \frac{e}{mc^2}\begin{pmatrix} E_x \\ E_z \end{pmatrix}$$
$$\frac{d}{d(ct)}\begin{pmatrix} x \\ z \end{pmatrix} = \frac{1}{\sqrt{1+p_x^2+p_z^2}}\begin{pmatrix} p_x \\ p_z \end{pmatrix}, \tag{15}$$

with initial conditions:

$$x_n(t=0) = x_{n0}; \quad z_n(t=0) = z_{n0};$$
$$p_{xn}(t=0) = 0; \quad p_{zn}(t=0) = 0. \tag{16}$$

Parameter u from (13) characterizes the location on the surface from which an electron is emitted ($w = 0$):

$$x_{n0} = \frac{u_n b}{z_n + b}; \quad u_n = n \cdot u_N / N; \quad n = 1...N$$
$$z_{n0} = -b + \sqrt{\frac{a^2 + b^2 - u_n^2 + \sqrt{(u_n^2 - a^2 - b^2) + 4u_n^2 a^2}}{2}}. \tag{17}$$

The last emission location u_N can be defined from the condition:

$$z_N = 0.01 \cdot z(0) = 0.01 \cdot \left(\sqrt{a^2+b^2} - b\right) \tag{18}$$

It should be noticed that within this approach the space charge effect is neglected.

Shown in Figure 7 are typical numerical results of the local electron divergence $p_x/(mc)$ as a function of the emission parameter u/u_N at the moment in time when electrons reach the region of homogeneous field. At this z-position the electric field varies along x-axis not more than by 1%, it means that the field at this distance from the cathode does not "feel" the rough surface.

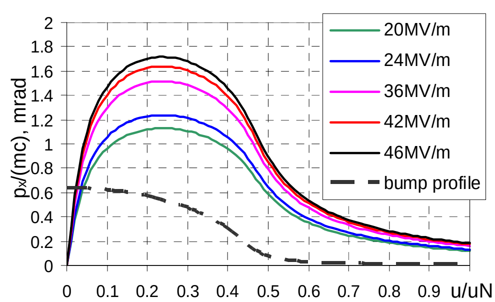

Figure 7: Local divergence as a function of u/u_N for various E_0. Roughness parameters: depth $h \approx 20nm$, width $\lambda = 10nm$ ($a = 21.52nm; b = 1.57nm$).

An estimation of the emittance growth due to the increase of the applied electric field could be done based on the analysis of the electron divergence for various roughness parameters. Emittance growth as a function of the applied electric field in comparison to the case of $E_0 = 24MV/m$ is shown in Figure 8. Relative emittance growth for various bump widths λ has a slope of about $2\%/(MV/m)$, so field increase up to $42MV/m$ results in a ~30% emittance growth.

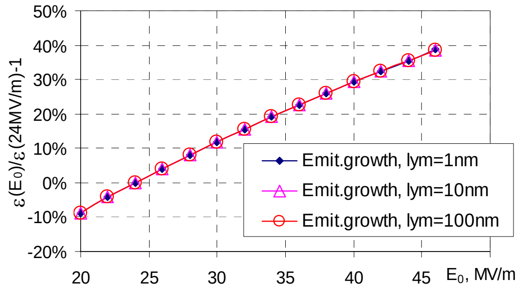

Figure 8: Emittance growth as a function of the electric field, compared to the emittance at $E_0 = 24MV/m$.

Simulations based on the assumption of the neglecting the space charge effect have been performed. Modelling the space charge limited emission from the bumpy cathode surface in the steady state regime [7] showed that the space charge may reduce the deterioration effect of the surface roughness. But from the other hand the cathode roughness may result also in additional density non-homogeneity of the emitted electron beam, which could lead to degradation of the beam quality.

CONCLUSIONS AND OUTLOOK

The photo cathode roughness contributes to the initial emittance of the electron beam. Several models of the cathode rough surface have been used to estimate the effect of the thermal emittance growth. Thermal emittance growth induced by the cathode roughness has been studied for different roughness parameters, including photo emission issues from a Cs2Te photo cathode.

Since one of the main improvement steps toward XFEL requirements is an increase of the maximum rf gun gradient from 40 to 60 MV/m, the impact of increasing the field at the cathode has been studied. The model of single bump has demonstrated that the increase of the electric field at the cathode could result in a ~30% growth of the roughness contribution to the initial thermal emittance.

Studies on the role of the space charge effect during emission from rough cathode as well as more detailed measurements of the cathode roughness have to be performed in order to improve the understanding of the thermal emittance features.

ACKNOWLEDGMENTS

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REFERENCES

[1] A. Oppelt et al., “Status and first results from the upgraded PITZ facility”, FEL 2005, Stanford, Aug.2005.
[2] K. Floettmann, “Note on the thermal emittance of electrons emitted by Cesium Telluride photo cathodes”, TESLA FEL Reports 1997-01, 1997.
[3] J. Schmerge, private communication.
[4] D. Sertore, private communication.
[5] R.Gomer, “Field emission and field ionization”, American Institute of Physics, New York, 1993.
[6] J.-H. Han, “Dynamics of electron beam and dark current in phototcathode rf guns”, PhD thesis, Hamburg University, 2005.
[7] Y. Lau, “Effects of cathode roughness on the quality of electron beams”, J. Appl. Phys 61(1), Jan. 1987.