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Amplification of intrinsic emittance due to rough metal cathodes: Formulation of a parameterization model

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ABSTRACT

Intrinsic emittance is often the limiting factor for brightness in fourth generation light sources and as such, a good understanding of the factors affecting intrinsic emittance is essential in order to be able to decrease it. Here we present a parameterization model describing the proportional increase in emittance induced by cathode surface roughness. One major benefit behind the parameterization approach presented here is that it takes the complexity of a Monte Carlo model and reduces the results to a straightforward empirical model. The resulting models describe the proportional increase in transverse momentum introduced by surface roughness, and are applicable to various metal types, photon wavelengths, applied electric fields, and cathode surface terrains. The analysis includes the increase in emittance due to changes in the electric field induced by roughness as well as the increase in transverse momentum resultant from the spatially varying surface normal. We also compare the results of the Parameterization Model to an Analytical Model which employs various approximations to produce a more compact expression with the cost of a reduction in accuracy.

1. Introduction

Development of ultra low intrinsic emittance electron sources for fourth generation synchrotron light sources is a need that has been clearly identified by the accelerator physics community [1]. Without the aid of synchrotron damping, the emittance of single pass fourth generation light sources is limited by the lowest achievable emittance at the cathode.

Much work is being invested into better understanding the photoemission process with discrepancies existing between theoretical and experimentally determined values of the intrinsic emittance [2–4].

Surface roughness is suspected to influence intrinsic emittance [4–8]. Other means of determining the influence of surface roughness on cathode emittance often rely upon numerical fitting for unknown parameters and often utilize data specific to a particular photocathode gun configuration [9,10].

Particular features of our model include: (i) a parameterization approach which permits the richness of a complete Monte Carlo (MC) model to be utilized with significantly faster computation time than would be needed to run the full MC computation; (ii) the ability to predict the influence on emittance of a variety of surface roughness conditions across a wide variety of metals and laser energies (cf. [5,11,13,19]); (iii) a limit case which reduces to the important analytical result given in the literature [14–16,18].

The final Parameterization Model has two main benefits. Firstly, the model contains the information carried by the complete MC simulation distilled down to one of two expressions, valid over different domains. Secondly, this parameterization approach yields final expressions that are general enough to be applicable to any combination of values of the photon wavelengths, material work functions, applied electric field, and surface roughness parameters.

2. Monte Carlo simulation

The Monte Carlo simulation presented here tracks the electron trajectories through Spicer's Three Step model [20–22] to stochastically determine the overall intrinsic emittance and quantum efficiency of metal cathodes. The effects of surface roughness are also included in the MC simulation.

Some distributions produced by the MC are given in Appendix A, showing the increase in the root mean squared (rms) transverse momentum with increased roughness.

2.1. Momentum distribution

The initial energy of the simulation's free electron, E_i, must be in the range $E_F + \phi_{eff} - h\nu \le E_i \le E_F$, where E_F is the Fermi energy,

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ϕ_{eff} is the metal's effective work function and $h\nu$ is the energy of the incident photon. Therefore the initial energy of the electron was determined by $E_i = E_F + R(\phi_{eff} - h\nu)$, where R is a random real number where $0 \le R \le 1$ and $h\nu \ge \phi_{eff}$. This evaluation of the initial electron energy relies on the assumption that the Fermi-Dirac distribution can be well approximated by a Heaviside step function [2], thus R follows a uniform distribution. This approximation holds for low thermal energies (where $k_B T \ll E_F$), which is likely for photocathodes [2].

Expressions for θ_{out}, p_z and p_x used in the MC simulation can be found as equations 16, 17 and 32 (respectively) in Ref. [2]. Here, p_x and p_z respectively denote the transverse and longitudinal momentum, and θ_{out} denotes the angle between the electron's motion after emission and the surface normal.

Spicer's model assumes only energy conservation and not momentum conservation. The lack of momentum conservation is explained through indirect optical transitions, where electron–phonon scattering randomizes the electron momentum. Detailed discussion on this can be found in Refs. [22,23].

2.2. Intrinsic emittance

The definition of intrinsic emittance used throughout this paper is the root mean squared (rms) emittance [24,25],

$$\epsilon_x = \frac{1}{\overline{p_z}} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2} \tag{1}$$

where $\overline{p_z}$ is the average longitudinal momentum and <> denotes ensemble average.

Making the standard assumption of an isotropic cathode surface, the cross term $\langle x p_x \rangle$ is zero. The normalized rms emittance is then expressed as [2],

$$\epsilon_{x,n} = \beta\gamma\epsilon_x = \frac{\sqrt{\langle p_x^2 \rangle \langle x^2 \rangle}}{m_e c} = \sigma_x \sigma_{px} \tag{2}$$

where $\sigma_x \equiv \sqrt{\langle x^2 \rangle}$ and $\sigma_{px} \equiv \sqrt{\langle p_x^2 \rangle}/(m_e c)$ is the dimensionless (i.e. scaled) rms transverse momentum.

Dowell and Schmerge [2] derived an analytical expression for σ_{px}, which will be used throughout this paper as a point of comparison, being the rms transverse momentum from a metal cathode with no roughness. The expression is,

$$\sigma_{px} = \sqrt{\frac{h\nu - \phi_{eff}}{3 m_e c^2}}. \tag{3}$$

2.3. Surface roughness

The cathode surface can be crudely modeled by a sine function of amplitude a and period of $2\pi/k$. More realistically, any cathode surface roughness can be more accurately described by the Fourier summation of many sine waves of varying amplitudes and spatial frequencies. However as the intrinsic emittance is (as defined earlier) the rms of an ensemble of electron trajectories, taking the average of the increase to the emittance introduced by each sine component, should adequately describe the effect of roughness in the system. See Appendix B for further investigation into the validity of this approach.

For small amplitude roughness ($a \ll 2\pi/k$), the electric field resulting from a potential applied between a flat plate and a sinusoidal surface can be modeled by summing over the various Fourier components constituent in the rough surface terrain [7,12]. The combined *field distortion effect* and *slope effect*, defined by Bradley in [7], produce the following transverse momentum for a single particle,

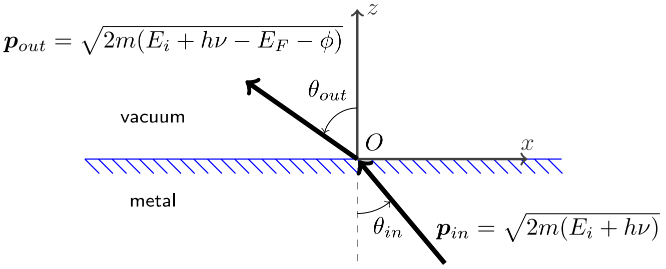

Fig. 1. Electron trajectories during the photoemission process. Transverse momentum ($p_x = |p_{out}| \sin(\theta_{out})$) is conserved during this final stage of Spicer's Three Step Model [20,21].

$$p_r = e \int_0^\infty \sum_{n=1}^\infty E_0 a_n k_n \exp(-k_n z(t)) \times \sin(k_n x(t)) dt + \textit{slope effect}. \tag{4}$$

The *slope effect* is minimal compared to the *field distortion effect* [9], increasing the emittance by on average less than 1%. It is however still included in the MC simulation, appearing as an alteration to the rms transverse momentum that results from the final stage of Spicer's model. The magnitude of the slope effect depends upon where on the surface the electron is emitted. The four regions highlighted in Fig. 2 were used to project the momentum onto the transverse plane to evaluate *slope effect*, as it appears in Eq. (4).

For $\cos\Phi < 0$,

$$\textit{slope effect} = \begin{cases} p_t \cos\left(\frac{\pi}{2} - \tau - \theta_{out}\right), & \text{if } 0 < \theta_{out} < \left(\frac{\pi}{2} - \tau\right) \\ p_t \cos\left(\tau - \theta_{out} + \frac{\pi}{2}\right), & \text{if } 0 < \theta_{out} > \left(\frac{\pi}{2} - \tau\right) \end{cases} \tag{5}$$

For $\cos\Phi > 0$,

$$\textit{slope effect} = \begin{cases} p_t \cos\left(\tau - \frac{\pi}{2} + \theta_{out}\right), & \text{if } \frac{\pi}{2} - \tau < \theta_{out} < \frac{\pi}{2} \\ p_t \cos\left(\frac{\pi}{2} - \theta_{out} + \tau\right), & \text{if } \tau < \theta_{out} < \frac{\pi}{2} \end{cases} \tag{6}$$

where p_t is the magnitude of the total momentum vector and $p_t = \sqrt{2m_e(E_i + h\nu - E_F - \phi)}\cos\Phi$ and τ is the angle subtended by the sinusoidal baseline and the tangent to the roughness terrain (see Fig. 2), given by $\tan\tau = ak\sin(kx)$.

Utilizing the simplifications outlined in [7], Eq. (4) can be rewritten as,

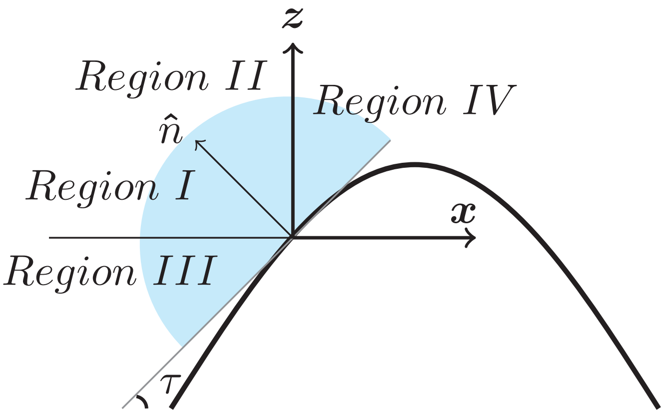

Fig. 2. Roughness regions used in Eqs. (5) and (6).