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AN IMPROVED MODEL FOR PHOTOEMISSION OF SPACE CHARGE DOMINATED PICOSECOND ELECTRON BUNCHES: THEORY AND EXPERIMENT*

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Abstract

The emission of a short highly charged electron bunch in a radiofrequency photogun is discussed. The traditional space charge limited emission numerical model is extended by an introduction of positively charged ions arising in the cathode region and dynamically changing during the emission. Estimates on the time characteristics of the charge migrating process in the semiconductor region are given. The numerical results are compared with the results of other numerical models and with experimental observations at the Photo Injector Test facility at DESY in Zeuthen (PITZ).

INTRODUCTION

High brightness electron sources are key components necessary for the successful operation of modern free electron lasers, new sources of synchrotron radiation and lepton colliders. For such facilities, it is required to have a rather high bunch charge (~ nC), a very small transverse normalized emittance (< 1 mm×mrad), rather short bunches (~ 1÷20 ps), and a small energy spread (<1 %). For example, for the European X-ray Free Electron Laser (European XFEL) photo gun, electron bunches with a charge of 1 nC/bunch and a normalized transverse emittance < 0.9 mm×mrad should be generated by an RF gun operating with a Cs_2Te photocathode at a high electric field on the cathode surface (~ 60 MV/m) and repetition rate up to 27,000 pulses per second. Detailed studies of the photoemission process are crucial for understanding the beam dynamics in space charge dominated photo injectors, without which it is difficult to achieve the high brightness.

TEST FACILITY AND SIMULATION MODEL

The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops and optimizes high brightness photo injectors for more than 20 years [1].

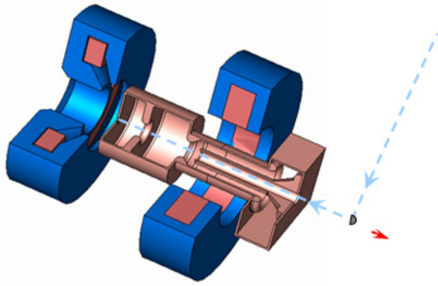

Figure 1: PITZ RF gun scheme.

The PITZ L-band 1.6-cell RF-gun (Fig. 1) consists of a 1.3 GHz copper cavity operated in π-mode fed by a coaxial RF power coupler and supplied with a pair of focusing solenoids. A molybdenum cathode plug with Cs_2Te film is inserted in the cavity back wall using a load-lock vacuum system.

For precise description of the space charge dominated dynamics in the RF-photogun beam measurements and computer simulations have been performed. Discrepancies between experimental data and simulation results have been observed for these measurements [2, 3]. The results of experimental studies on the bunch charge production and transverse emittance optimization revealed that the limiting current of the emitted beam obtained experimentally cannot be reproduced by ASTRA simulations [4] using the parameters of the experimental setup. The ASTRA code, used for these simulations, is one of the few in the world optimized to solve beam dynamics problems associated with photoemission and photoguns. In order to bring beam dynamics simulations closer to the experimental results the photoemission model for a space charge dominated regime has to be improved. A typical schematic of a semiconductor photocathode is illustrated by Fig. 2.

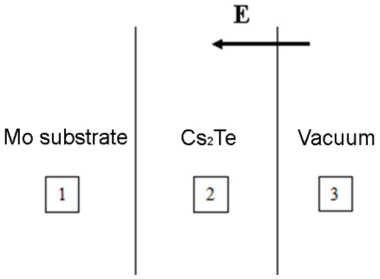

Figure 2: Photocathode model.

It consists of three regions: 1- molybdenum substrate, 2 - Cs_2Te film (< 0.1 μm), 3- vacuum. Since the photocathode is located in a strong electric field, the penetration of the field into the semiconductor film should be taken into account. With a field strength of $E \sim 10^7$ V/m on the cathode surface, it is necessary to create the following surface charge density σ to compensate this field inside the film:

$$E = \frac{\sigma}{2\varepsilon\varepsilon_0} = \frac{qN}{2\varepsilon\varepsilon_0},$$

where N is the surface charge density, ε and ε_0 is the dielectric permittivity of the photocathode film and vacuum respectively, q is a particle charge. Hence, assuming $\varepsilon \sim 10$, we obtain the surface charge density at the cathode $N \sim 10^{11}$ cm^{-2}. If the average concentration of carriers in a semiconductor is $n \sim 10^{15}$ cm^{-3} then the required number

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of charges is obtained at a thickness of $d = \frac{N}{n} \sim 1$ μm. That is, the field penetrates to a depth that is significantly greater than the thickness of the semiconductor film, i.e. the electric field easily reaches the substrate.

In the standard steady-state photo emission model, electrons generated by a laser pulse leave the cathode, and the magnitude of the emission current is limited either by the space charge field of the emitted electrons including the image charge (when the total electric field on the semiconductor surface is equal to zero), or by the emissivity of the photocathode (the laser power and the cathode quantum efficiency).

Ongoing to picosecond laser pulse durations, which are necessary to obtain short electron bunches, the picture changes. In this case the regions of the substrate and the semiconductor should be considered separately. The electrons produced by the laser pulse are in a strong electric field E, which, as shown above, easily penetrates the film and quickly leaves it. It is easy to show that within the time t ~ 1 ps the electron velocities v reach

$$v = \frac{eEt}{\varepsilon \gamma m} \approx 10^6 \text{ m/s}$$

and the electrons move by the distance of the order of one micron, which is significantly greater than the thickness of the semiconductor. Since the number of free electrons in region 2 is limited, the rate of their influx will be determined by the difference in carrier concentrations, determined according to Fick's first law by the expression $\vec{j} = \rho\vec{v} = -eD\, grad\, n$,where ρ - is the charge density, D is the diffusion coefficient of the particle, n is the electron concentration. The diffusion coefficient D is related to the mobility of charge carriers by the Einstein’s relation. For electrons it reads as

$$D = \frac{kT}{e}\mu,$$

where k is the Boltzmann constant and T is the temperature. Since the diffusion velocity is less than the drift one, the positive charge will dominate in the region 2 (Fig. 2).

Thus, the region 2 turns out to be positively charged, and the amount of charge will dynamically change and be determined by the rate of outflow and inflow of electrons into the semiconductor region. The presence of such a charge inside the film can significantly increase a space charge limited emission current in the case of high charge density picosecond bunches.

SIMULATION RESULTS

The developed model is based on the 2.5 dimensional finite difference-time domain (FDTD) particle-in-cell (PIC) code SUMA [5]. This code has been tested and widely used to model various physical processes [6-9]. Part of the code responsible for the charged particles emission was modified according to our understanding of the physical process [10]. In the proposed model in the region 2 (semiconductor film), the number of electrons arising in the process of photoemission is equal to the number of positive charges. As the electrons (Q-) move to the region 3, positive charges (Q+) will dominate in the region 2, but their amount will be less than the number of electrons escaping from the region $Q^+ = Q^-(t)e^{-t/\tau}$. Partial compensation of the positive charge in the region 2 (defined by the positive charge relaxation time τ) is associated with the influx of electrons from neighbouring regions and is caused by the resulting difference in carrier concentrations.

The time dependence of the cathode emissivity corresponded to the temporal profile of the laser pulse, which has 21.5 ps FWHM and ~2 ps rise/fall times. A transverse charge density distribution during emission is uniform up to a given radius, and then falls off according to the Gauss's law.

The time dependence of the charge emitted by the cathode is shown in Fig. 3.

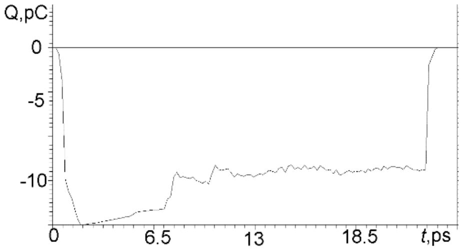

Figure 3: Emitted charge.

The time dependence of the positive charge remained in the region 2 is presented in Fig. 4.

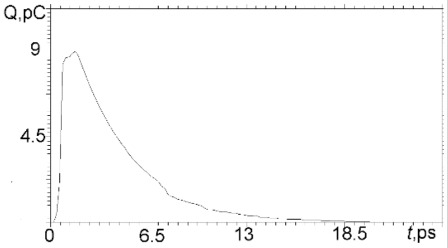

Figure 4: Positive charge, remained in semiconductor.

The presence of a positive charge in the region 2 significantly changes the emission process at a high charge density of the bunch at the photocathode. Figure 5 shows the change in the shape of the electron bunch current emitted from the photocathode with increasing of the initial charge (or laser pulse energy) on it without taking into account (top row of plots) and with taking into account (bottom row of plots) the presence of the positive charge in the region 2.

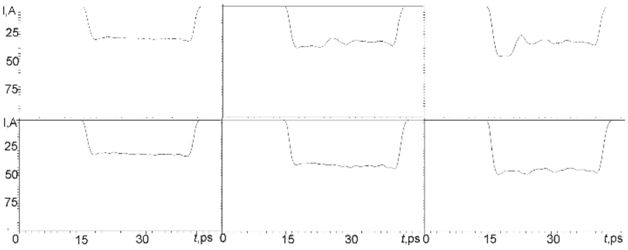

Figure 5: Current pulse from the photocathode with increasing charge (0.4 nC, 0.7 nC, 1.0 nC) without (top row of plots) and with taking into account positive charge on semiconductor (bottom row of plots).

It can be seen that in the old model, which does not consider the presence of a dynamically changing positive charge in the region 2, with a laser pulse energy increase the beam current amplitude stops growing and the shape is distorted, which can be explained by the formation of a virtual cathode. If the appearance of a positive charge in the region 2 (new model) is taken into account, the picture changes. With an increase of the laser pulse energy the amount of positive charge Q^+ increases as well, and as a results, the photocurrent amplitude continues to grow, and the bunch current profile distortion is significantly smaller. This behavior can be explained by the partial compensation of the space charge forces of the emitted electrons by the increased amount of positive charge in the region 2.

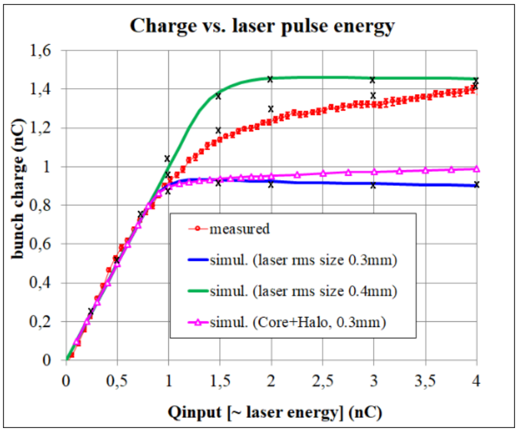

Figure 6: Emission curves measured at PITZ (red curve) compared to the simulation results from ASTRA (green, blue and magenta curves) and from SUMA (crosses).

Figure 6 shows dependence of the bunch charge on the laser pulse energy, measured and calculated by the ASTRA code for different transverse laser pulse distributions [3]. The blue and green curves correspond to the beam $\sigma_{xy} = \sqrt{\sigma_x \sigma_Y}$ size of 0.3 mm and 0.4 mm, the magenta curve depicts the results of the applied transverse core+halo laser distribution model [11], and the red curve shows the experimental curve. As it could be seen, due to the strong space charge effect, the ASTRA results cannot reproduce the experimentally obtained current values from the cathode. Increasing of the rms spot size used in ASTRA simulations from the experimental 0.3 mm by ~30% (to 0.4 mm) leads to the higher saturation level of the emission, but the simulated curve does not follow the measured one. Results of SUMA simulations are shown in Fig. 6 with crosses. Cross-check with the old emission model are in a good agreement with corresponding ASTRA simulations. The newly implemented photoemission model employing the positive charge within the Cs_2Te photocathode film yields significantly better agreement with the experimental data. Parameter $\tau = 4 \cdot 10^{-12}$ is fitted for one point of the experimental emission curve and fixed as a material constant in all further calculations. This gives us confidence in the validity of the model applied.

Figure 7 shows experimental studies on the RF field influence on the emitted bunch charge [12] supplied with corresponding SUMA results on it.

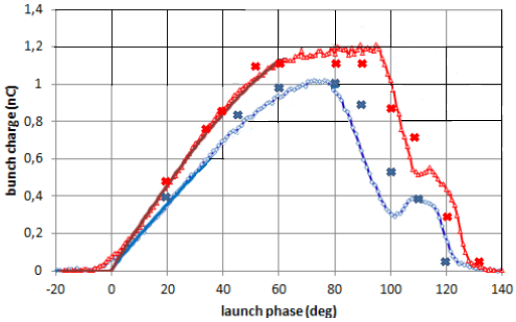

Figure 7: RF lunch phase influence. $E_{cathode,max}$=62 MV/m (red curve) and $E_{cathode,max}$=47.6 MV/m (blue curve). Crosses mark the SUMA calculation results.

Results of the transverse normalized emittance comparison for various emission charges are shown in Fig. 8, where the experimental results on the transverse emittance optimization from [2] are used as a reference. At all cases, we have rather good results agreement.

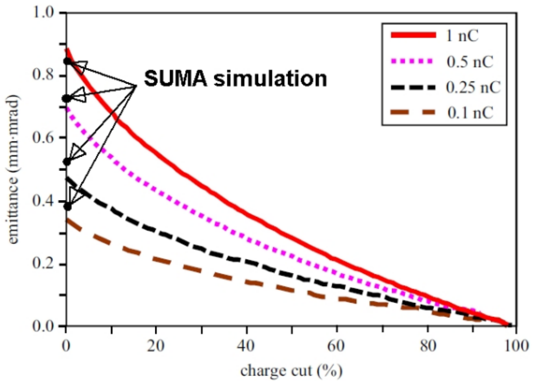

Figure 8: Minimum geometric mean emittance as function of a charge cut [2]. The 100% emittance corresponds to the no charge cut (0%) case.

CONCLUSION

A new model of the photoemission from a semiconductor photocathode in a space charge dominated regime was proposed and implemented in the SUMA code. It implies a finite rate of the positive charge flow inside the photocathode film which (partially) compensates the space charge field of the emitted electrons. The new model was applied to the experimental data from the PITZ RF photogun operated in a space charge dominated regime corresponding to the high brightness performance of the photoinjector. The results show better agreement of the newly proposed model with experimental data than the old model. Further investigations are ongoing.

REFERENCES

[1] M. Krasilnikov *et al.*, “Experimentally minimized beam emittance from an L-band photoinjector”, *Phys. Rev. Accel. Beams*, vol. 15, p. 100701, 2012. doi:10.1103/PhysRevSTAB.15.100701

[2] S. Rimjaem *et al.*, "Optimizations of transverse projected emittance at the photo-injector test facility at DESY, location Zeuthen", *Nucl. Instrum. Methods,* vol. 671, pp. 62-75, 2012. `doi:10.1016/j.nima.2011.12.101`

[3] M. Krasilnikov, Y. Chen, and F. Stephan, "Studies of space charge dominated electron photoemission at PITZ", *J. Phys.: Conf. Ser.*, vol. 1238, p. 012064, 2019. `doi:10.1088/1742-6596/1238/1/012064`

[4] K. Floettmann, "ASTRA particle tracking code", `http://www.desy.de/~mpyflo/`.

[5] V. I. Rashchikov, "Electromagnetic field calculation in complex geometry structures", *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations,* vol. 10, no. 18, pp. 50–53, 1990.

[6] S. M. Polozov and V.I. Rashchikov, "Longitudinal motion stability of electrons inside the plasma channel of LPWA", *Cybernetics and Physics*, vol. 7, pp. 228–232, 2018. `doi:10.35470/2226-4116-2018-7-4-228-232`

[7] V. I. Rashchikov and A. N. Didenko, "High power microwave generation in virtual cathode systems", *1991 IEEE Particle Accelerator Conference*, vol.5, pp. 3111–3113, 1991.

[8] A. N. Didenko, V. I. Rashchikov, and V. E. Fortov, "Mech anism of generation of high-intensity terahertz radiation under the action of high-power laser pulsed on a target", *Tech nical Physics*, vol. 56, pp. 1535–1538, 2011.

[9] V. I. Rahchikov and A. E. Shikanov, "Compact plasma re flex tride for neutron generation", *IEEE Transactions on Plasma Science*, vol. 47, no. 2, pp. 1279–1282, 2019. `doi:10.1109/TPS.2018.2889710`

[10] S. M. Polozov and V. I. Rashchikov. "Simulation studies on the radiofrequency gun saturated emission", *Cybernetics and Physics*, vol. 9, pp.103–10, 2020. `doi:10.35470/2226-4116-2020-9-2-103-106`

[11] M. Krasilnikov *et al.*, "Investigations on Electron Beam Im perfections at PITZ", in *Proc. of Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 165-167.`doi:10.18429/JACoW-LINAC2016-MOPLR013`

[12] M. Krasilnikov, "Measurements and modelling of space charge assisted photoemission at PITZ", *presented at Photocathode Physics for Photoinjectors 2012*, Cornell University, Ithaca, NY, USA, Oct. 2012.