

# MODELING AND SIMULATION OF PHOTOEMISSION BASED ELECTRON SOURCES\*

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## Abstract

Photoemission based electron source allow producing electron beams with precisely controlled temporal and spatial profiles, high current and high brightness. Their development is critical to future short-wavelength light sources. To accurately characterize electron beams generated by the source, a full electromagnetic emission modeling is carried out in a self-consistent manner. It takes into account the Schottky-like modulation of the cathode quantum efficiency (QE). In pulsed operation, this effect causes the QE of the cathode to be time dependent. Thus, the electron bunch temporal profile is not the same as the laser pulse profile and it should be corrected according to this model. As an application, the PITZ injector installed at the DESY site in Zeuthen is considered. The emission process is modeled in the QE- and SC-limited (space-charge) regimes, respectively. Simulation results are in good agreements with the measurement data.

## INTRODUCTION

Photoemission based electron sources are widely used to generate high brilliance electron beams for coherent light sources [1–3]. Photoemission is a highly nonlinear process depending on the properties of the photocathode as well as on the dynamics of the charged particle beam in immediate vicinity of the cathode. These effects are, furthermore, mutually dependent. Specifically, the nonlinear space-charge (SC) field during photoemission can modulate the quantum efficiency (QE) of the semiconductor layer due to Schottky effect [4], while the cathode QE modifies the electron bunch distribution thereby influencing the beam dynamics in the gun. Thus, the approach used in beam dynamics simulations assuming a fixed particle distribution at the cathode may be inaccurate.

The main goal of this paper is to resolve this modeling issue, by developing a nonlinear SC field dependent dynamic emission model. The model takes into account the work function modification of the emitting layer due to the total field applied at the cathode. This includes the dc- (or rf-) cavity field of the gun as well as the SC field of the beam. In particular, in pulsed source operation this model results

in a time-dependent QE of the photocathode. Thus, the longitudinal profile of the emitted electron beam is no longer the same as the temporal profile of the cathode-illuminating laser pulse. Yet another effect is that, the near-cathode SC effects also affect the QE map of the cathode thus modifying the transverse distribution of the extracted electron beam. All these effects should be considered in the emission modeling and beam dynamics simulations.

As an application, the PITZ photoinjector [1–3] offers a good opportunity to validate our theoretical model and numerical simulation with measurement data. In the PITZ injector a Cs<sub>2</sub>Te photocathode is illuminated by a UV laser at the wavelength of 257 nm. In the following, we will describe the simulation procedure and then show the results obtained for the PITZ gun in the QE- and SC-limited emission regimes, respectively.

## PHOTOEMISSION MODELING

### Schottky-like Effect

This effect results from the reduction of the work function of the cathode material due to the presence of high electric fields applied. The QE of the cathode including the Schottky-like effect is given by [4]:

$$QE(x, y, t) = \eta \{ h\nu - [\Phi_w \mp \beta \Delta\Phi(x, y, t)] \}^2. \quad (1)$$

$$\Delta\Phi(x, y, t) = \sqrt{\frac{e^3}{4\pi\epsilon_0} E_{cath}(x, y, z=0, t)}. \quad (2)$$

where  $h\nu$ ,  $\Phi_w$  and  $\Delta\Phi$  are the laser photon energy, the cathode work function with no applied fields, and its reduction due to Schottky effect, respectively.  $E_{cath}$  represents the total normal electric field at the cathode.  $\beta$  is known as the field enhancement factor which is used to characterize surface conditions of the emission area.  $\eta$  is a form factor depending on material properties such as absorption coefficient, density of states and transition probability.

The total electric field at the cathode  $E_{cath}$  is a superposition of all dc and rf fields within the gun including the SC field of the beam. These fields are time and space dependent. Thus, the resulting QE of the cathode will generally vary with time as well as along the cathode surface.

Given expressions (1) and (2) for the cathode QE, the total emitted charge is given by [4]:

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$$Q_{tot}(\eta; x, y, t) = \eta \int_{t_0}^t \int_x \int_y e \frac{P_{las}(\tau)}{hv} \times \left\{ hv - \left[ \Phi_w - \beta \sqrt{\frac{e^3}{4\pi\epsilon_0} E_{cath}(x, y, z=0, t)} \right]^2 dx dy d\tau \right. \quad (3)$$

where  $P_{las}$  is the power of the laser pulse.

As seen from Eq. (3), due to the Schottky effect, the emitted charge profile is generally not identical with the laser pulse shape. Likewise, the transverse distribution of the electron bunch,  $Q_{tot}(x, y)$  is no longer uniform over the emission area, because the QE map is modified by the nonuniform space-charge field at the cathode. In order to calculate the total extracted bunch charge, however, the characteristic cathode factor is needed. This parameter can be determined by contrasting simulation and measurement results for a selected set of operation parameters as described below.

### Cathode Characterization

The cathode characterization is conducted based on measurement data to take into account the contributions of the cathode material properties to the emission process. A self-consistent numerical approach has been designed to determine the cathode factor,  $\eta$ . The main procedure is shown in Fig. 1. Essentially, the emission process is computed iteratively starting with a guess value for the cathode factor. In every step of the iteration, the cathode factor is corrected such that the total predicted charge is the same as a measured value  $Q_{meas}$ . This procedure is repeated until numerical converge is reached. The cathode factor determined from this approach is used for simulations involving different sets of gun and beam parameters.

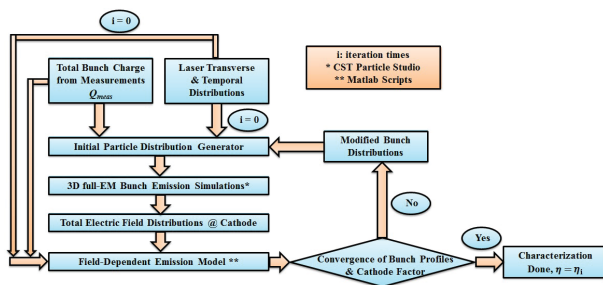


Figure 1: Iterative simulation scheme for photocathode characterization.

### Model Implementation

For model implementation, a 3D full electromagnetic tracking code is used, taking into account multiple effects of space-charge, image-charge and also relativistic field effects during photoemission [5, 6]. The code is based on a Lienard-Wiechert (LW) Particle-Particle (PP) interaction approach. It stores particle history and searches at every time step retarded times and positions for all beam particles [7].

In addition, the total rf and particle fields at the cathode are computed on-the-fly as a new particle is emitted. This allows to compute the individual (macro-) particle charges according to the modified emission model (3).

### APPLICATION

Using the above simulation approach, a series of electron bunch emission simulations are performed for the Cs<sub>2</sub>Te photocathode 1.6-cell copper rf photogun of PITZ and compared with measurements [2, 3, 8].

Figure 2 shows the dynamic Schottky-like modulation of the cathode QE on the right axis (blue curve) in comparison to the case without Schottky effect (dashed grey curve). Accordingly, time-dependent QE-induced modification of the transient bunch current distribution (red curve) is shown for a flattop-shaped cathode laser temporal profile of about 27 ps in total length (black curve). The maximum field gradient is about 46 MV/m. The QE slightly increases during moments of emission due to the fact that the applied rf field in the cavity reduces the work function of the cathode material. Then it gradually drops as the SC field of the beam is built up. Likewise, the QE tends to increase again at the end of emission as the SC density declines with more emitted particles escaping from the cathode region. This results in a corresponding modification of the emitted charge profile (red curve).

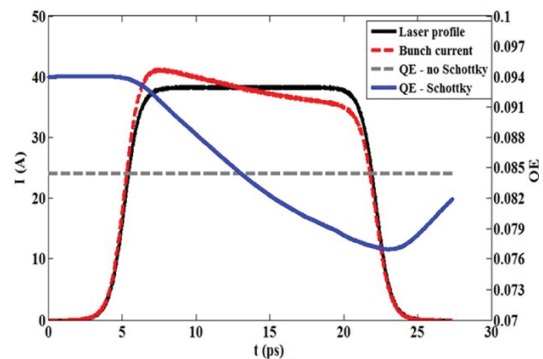


Figure 2: Dynamic QE-modulation due to Schottky effect and transient bunch current for a flattop laser profile.

Figure 3 shows the Schottky modification of the QE map on the transverse plane at different time instants. Note that this transverse QE modification is only due to the space charge field of the bunch at the position of the cathode. The QE map is homogeneous in the beginning of emission. As seen in the figure, a stronger SC field in the central area of the beam reduces the total field over this area of the cathode. This causes a relative decrease in the QE of the central area (left). This effect leads to QE variations between the center and the edge of the emission area by approximately 9% (right) by the end of emission for the extraction of 1 nC bunch charge using an rms cathode laser spot size of 0.4 mm.

Figure 4 shows comparisons for the total extracted bunch charge between measurements and simulations in terms of the cathode laser pulse energy. This is conducted for three

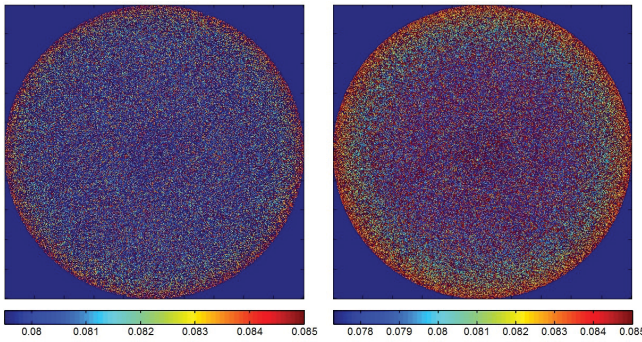


Figure 3: Transverse modulation of QE due to the dynamic Schottky effect at the cathode at different time instants. The total emission time is about 30 ps. Left:  $t=16$  ps; Right:  $t=30$  ps.

photocathodes in different conditions using two rf gun powers of 7.75 and 1.5 MW, and two temporal cathode laser profiles of 17 ps (FWHM) flattop and 1.5 ps (RMS) Gaussian, respectively. In all cases the total produced charge increases nearly linearly with the laser pulse energy. This is consistent with the charge extraction mechanism in the QE-limited emission regime [6]. Good agreements are reached between measurements and simulations. That is, the Schottky-based dynamic emission model is able to well predict the total extracted bunch charge from the cathode.

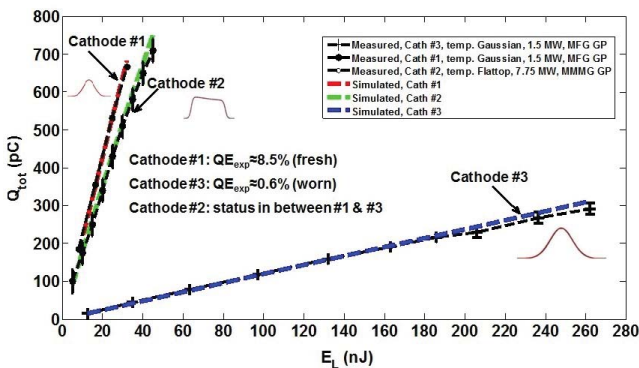


Figure 4: Total bunch charge versus laser pulse energy for three cathodes in different conditions using various machine parameters. MMMG: maximum mean momentum gain. MFG: maximum field gradient. GP: gun phase.

To further verify the emission model, a comparison of the bunch transverse emittance between simulation and measurement is performed. Using this model, a 0.1 nC electron bunch is extracted from the cathode and tracked to the first emittance measurement station at  $z = 5.74$  m, as shown in Fig. 5. A flattop temporal profile of the cathode laser pulse with 21.5 ps FWHM is applied. The rms laser spot size is 0.102 mm. The peak rf electric field at the cathode is about

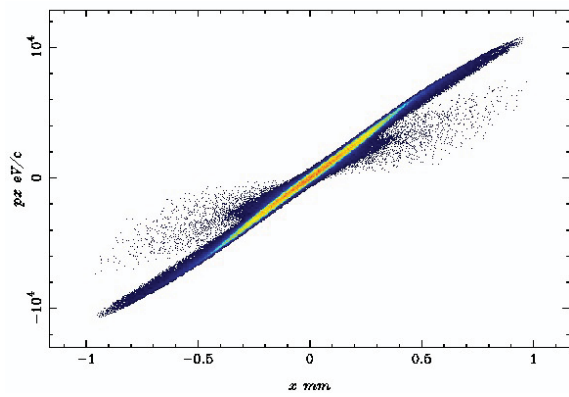


Figure 5: Transverse phase space for a 0.1 nC electron bunch at the first emittance measurement station.

60 MV/m. The simulation shows an optimized transverse bunch emittance of 0.19 mm mrad, which agrees with the measured minimum transverse emittance of about 0.21 mm mrad [2].

## CONCLUSIONS

A Schottky-based dynamic photoemission model is proposed and implemented with the 3D LW PP code. This model is able to modify the temporal and transverse distributions of the emitted electron bunch from cathode in transient emission process, by modulating the photocathode QE through Schottky effect. The SC effects in the gun cavity are included in the modeling which allows to take into account the transverse modification of the QE map. For validation, the model has been used in the photoemission studies of the PITZ injector. The total extracted bunch charges calculated from simulations coincide with measurements in the QE-limited emission regime for different photocathodes under distinct experimental conditions. A comparison of the bunch transverse emittance for a 0.1 nC bunch charge also shows a good agreement with measurement. Further modelings and simulations using this model for the SC-limited emission regime are still in progress.

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