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Numerical simulations of early-stage dynamics of electron bunches emitted from plasmonic photocathodes

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ABSTRACT

High-brightness electron sources are a key ingredient to the development of compact accelerator-based light sources. The electron sources are commonly based on (linear) photoemission process where a laser pulse with proper wavelength impinges on the surface of a metallic or semiconductor photocathode. Very recently, the use of plasmonic cathodes – cathodes with a nano-patterned surface – have demonstrated great enhancement in quantum efficiencies (Li et al., 2013 [1]). Alternatively, this type of photocathodes could support the formation of structured beams composed of transversely-separated beamlets. In this paper we discuss numerical simulations of the early-stage beam dynamics of the emission process from plasmonic cathodes carried out using the Warp (Friedman et al., 2014 [2]) framework. The model is used to investigate the properties of beams emitted from these photocathode and subsequently combined with particle-in-cell simulations to explore the imaging of cathode pattern after acceleration in a radiofrequency gun.

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1. Introduction

High-brightness electron sources play a crucial role in the development of compact accelerator-based light sources. A photoinjector typically combines a photocathode with a resonant radiofrequency (RF) cavity. The photocathodes often employed are metallic and require an ultraviolet laser pulse impinging on their surfaces. The development of photocathodes capable of attaining higher brightness or larger quantum efficiency is an active topic of research [3]. Most recently, the use of three-photon photoemission process was realized in photoinjector [4] and the associated electron-yield was shown to drastically improved by nano-engineering the cathode surface [1]. A sub-wavelength nano-patterned surface can increase the laser-pulse absorption thereby enhancing the overall quantum efficiency [5].

Following Ref. [1], we consider throughout this paper a photocathode engineered to have a periodic array of nanoholes with Gaussian profile. The early-stage beam dynamics of the electron photoemitted from the nano-holes surface is investigated for different geometries. Our investigations are conducted in the weak-field regime (where quantum tunneling is insignificant) and implements a multi-photon emission process in Warp [2,6]. Our approach consists in first modeling a single nanohole with proper electromagnetic boundary conditions and then replicating the generated macroparticle distribution to generate the beam distribution produced from the entire cathode surface (consisting of an array of nanoholes).

2. Electron-emission model

All the simulations were carried out with an augmented version of Warp program which includes a modified emission model. The model is based on a "piecewise" approach, which depending on the normalized vector potential of the incoming laser $a_0 \equiv \frac{eE_0\lambda}{2\pi mc^2}$ (where E_0 and λ are respectively the laser peak E-field and wavelength, and e and mc^2 the electronic charge and rest mass), applies a multi-photon or a field-emission model. In this paper we limit our studies to the weak field regime where the Keldish parameter $\gamma \equiv \sqrt{\Phi/(2U_p)} \gg 1$ (here U_p and Φ are respectively the laser ponderomotive potential and material workfunction). In such a regime, our model follows the generalized Fowler-Dubridge's (FD) law and the photoemitted current density is

$$\boldsymbol{j}_{FD}(\boldsymbol{x}, t, \nu) = \sum_n \boldsymbol{j}_n(\boldsymbol{x}, t, \nu), \tag{1}$$

where the partial current densities are given by $\boldsymbol{j}_n(\boldsymbol{x}, t) = C_n|\boldsymbol{S}(\boldsymbol{x}, t)|^n$, with $\boldsymbol{S}(\boldsymbol{x}, t)$ being the Poynting vector associated to the exciting laser evaluated at the emitting surface and the constant C_n compiles the material properties including

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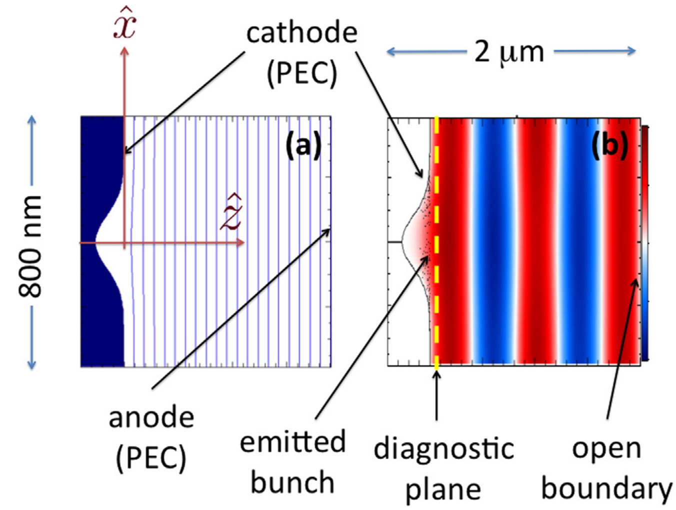

Fig. 1. Geometries used to solve the electrostatic problem with associated potential lines (a) and configuration used with the electromagnetic solver showing the laser transverse field (colored contours) and emitted macroparticle (black dots) close to the cathode surface (b). The "PEC" stands for perfect-conductor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

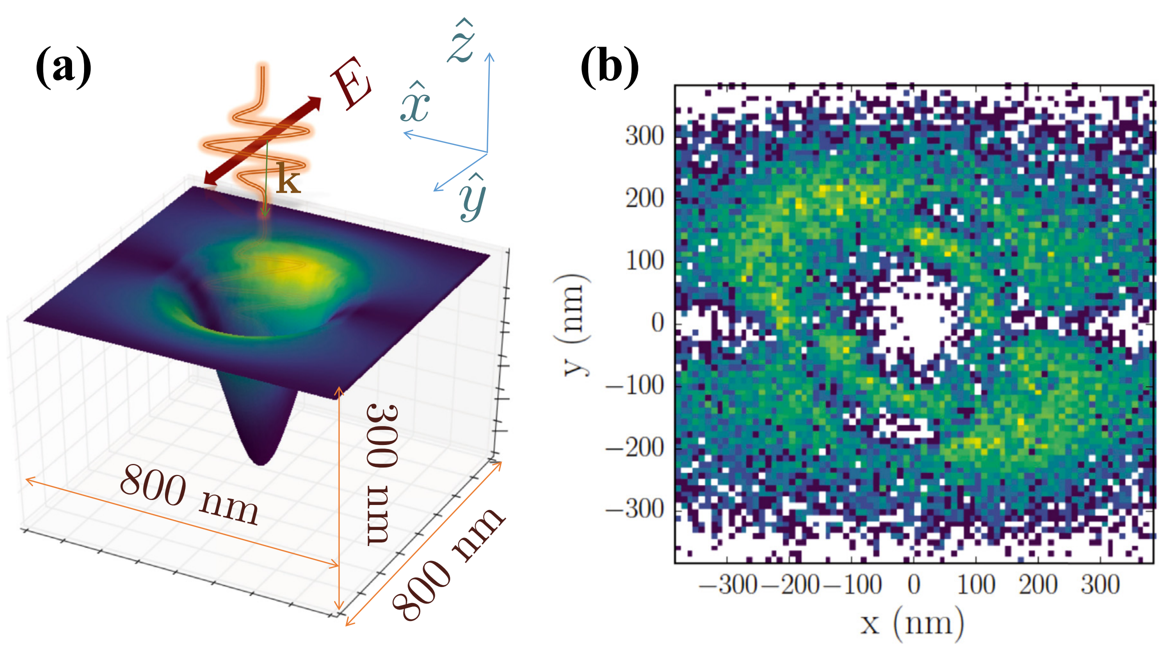

Fig. 2. Electromagnetic field (a) painted on the nanohole surface (the double arrow indicates the laser polarization, while $\boldsymbol{k}$ is the laser wavevector). Emitted electrons recorded 100-nm away from the nanocathode surface (b). The nanohole depth d and rms width w are $d = 264$ and $w = 155$ nm, respectively. a_0 is fixed to 6×10^{-5}.

reflection coefficient and multi-photon probability. The constants C_n can be directly measured experimentally; see [4,1,5]. Given Eq. (1), the number of electrons emitted within a elementary surface area $d^2\boldsymbol{A}$ at position $\boldsymbol{x}$ at integration time step t_i, is

$$\delta N(\boldsymbol{x}, t_i) = \frac{1}{|e|}\boldsymbol{j}_{FD}(\boldsymbol{x}, t_i).\, d^2\boldsymbol{A} \times \delta t, \tag{2}$$

where the elementary surface element is $d^2\boldsymbol{A} = d^2A\hat{\boldsymbol{n}}$, δt is the simulation time step, $\hat{\boldsymbol{n}}$ is the normal vector to the elementary surface area which depends on the computational-domain mesh size.

An example of implemented nanohole-cathode geometry appears in Fig. 1(a) and (b). The Gaussian nanohole is described by the profile $z(r) = -d\exp[-r^2/(2w^2)]$, where d and w are respectively the hole depth and rms width and $r \equiv \sqrt{x^2 + y^2}$ is the radial position with respect to the hole axis of symmetry.

In a first step an electrostatic solver (ES) provides the electrostatic field configuration in the cathode vicinity. The cathode-anode potential difference V is selected to mimic typical electric field sustained in radiofrequency (RF) guns ($E_0 \sim 100$ MV/m in S-band guns). An electromagnetic (EM) solver then simulates the propagation of a laser pulse launched at large z and traveling in the $-\hat{\boldsymbol{z}}$ direction; see Fig. 1(b). The ES and EM fields are both used as external fields during the particle emission and dynamics.

The EM solver also accounts for collective effects within the emitted particle bunch.[1] The particle distribution is saved at plane at $z = 100$ nm. Typical integration times are on the order of ~300 fs, i.e. 3 orders of magnitude smaller than the period of an S-band gun ($T \simeq 350$ ps for $f = 2856$ MHz) thereby supporting our

[1] In this work a particle-in-cell (i.e. mean-field) approach is implemented. Future improvements will include Coulomb collisions

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