Space Charge Effect of Time-dependent Emission Current Excited from Ultrafast Laser

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Abstract: *Classical Child-Langmuir law(CL law) analytically demonstrates maximum steady current density transported. Á. Valfells et al. in 2002 presented its analytic modification under short pulse case. However, both above have not touched time-dependence problem. In this paper, an iterative calculation method to consider time-dependent short-pulse of electron flow is developed, confirmed by particle-in-cell(PIC) simulation. Our calculation shows that for ultrahigh laser field amplitude, space charge effect becomes notable and electric DC field can be an efficient parameter to tune the space-charge limit.*

Keywords: space-charge limit; Particle-In-Cell(PIC); time-dependence; ultrafast-laser-induced electron emission.

Introduction

Great efforts have been recently paid on research for femtosecond laser-metal interaction to proceed more easily the process to emit electrons [1–2] for miscellaneous purposes to provide ultrafast time-resolved information about the underlying dynamics of many processes in physics, chemistry and biology. However, when electrons emit out of any form of cathode, a question appearing more negligible can be whether space charge limit has been reached in such a process and a further step: whether this affect laser-tunneling mechanism.

Space charge limited (SCL) law gives maximum steady state current density to be transported across a gap D under a DC applied voltage ϕ between cathode and anode. For a vacuum gap, it is also known as the one-dimensional Child-Langmuir(CL) law, given by

$$J_{CL} = \frac{4\epsilon_0}{9D^2}\sqrt{\frac{2e}{m}}\phi^{3/2}, \qquad (1)$$

where ϵ_0 , e and m are vacuum permittivity, particle charge and mass, respectively [3]. This law is derived from a situation that the emitted electrons will experience a space charge field that is sufficient to suppress the electric field at the cathode to zero. The short pulse CL law derived by Á. Valfells *et al.* in 2002 [4] attributes corresponding limit to the pulse duration. It anticipates a much larger current density than Child-Langmuir law does.

However, when injection current density becomes time-dependent (for instance shown in inset of Fig. 1), repulsion between internal electron beam reshapes its own profile in spatial dimension as a result of non-uniform electron beam profile. Thus an attempt to obtain an easy corollary for time-dependent injection current density $J(t)$ goes invalid.

In this paper, we develop a numerical algorithm to calculate the time-dependent space-charge-limited current density of a short-pulse electron flow, based on our previous work on a non-equilibrium model to describe ultrafast laser-excited electron emission from a metallic surface under an applied electric field [2].

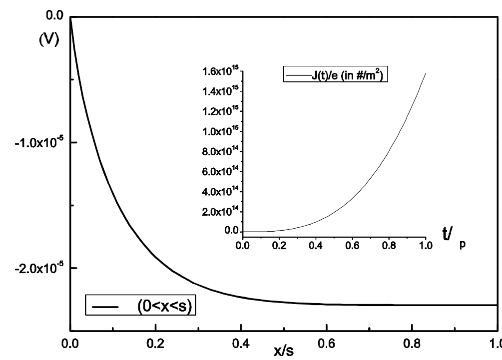

Figure 1 Additional electron potential distribution ($\Delta\phi(0 \le x \le s)$) within distance s as far as electrons reach. Physical parameters: occupation distance of emitted electrons s = 0.2196nm, electrodes spacing D = 1cm, ultrafast laser temporal length τ_p = 50fs, external electric field strength F_{dc} = 1 × 10^6 V/m, laser field amplitude F_L = 5GV/m, X_{CL} = 9.87814 × 10^{-5}. Inset: illustration of time-dependent function calculated from our model [2], taking the same parameters except τ_p = 10fs.

Model

Consider a metal-vacuum interface under an ultrafast laser pulse as well as an external constant electric field F_{dc}. Electrons first encounter a modified energy barrier potential due to electrostatic force and then possess a certain probability to penetrate it, i.e. a laser-excited tunneling process [1]. Whereas existent emitted electrons in spacing D reaching as far as distance $s(0 \le x \le s < D)$ resist electrons emitting out from metal. According to a modified Wentzel-Kramers-Brillouin (WKB) method, electron tunneling probability T(W) is calculated through energy barrier profile. Under modified energy barrier profile $V(0 \leq x \leq D)$ considering that emitted electrons apply a space charge field, time-dependent tunnelled current density function $J(t)$ is calculated [2]. Concrete steps are: first we try to determine trajectory of electron beam within space between cathode and anode. To constitute the spatial distribution for Poisson's equation we combine it with Newton's second law to account the induced additional space-charge potential.

Comparison with Particle-In-Cell(PIC) Simulation

We adopted a PIC finite-difference-time-domain (FDTD) numerical software (VORPAL) [5], run in 2 dimensions, where space charge limit effect is considered to be reached when reflection electron momentum is observed [6]. De facto, VORPAL 2D simulation data(magenta left triangle symbol with dashed line) do, behave slightly greater than our space charge(SC) limit electron count(wine square symbol), in inset of Fig. 2. Another observation is that both values are larger than what Valfells' formula (time-uniform injection current case in thick violet dashed line) predicts [7].

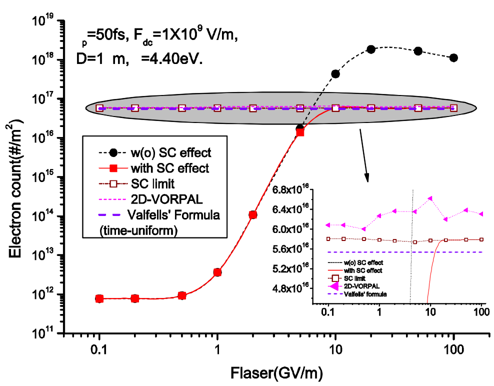

Figure 2 (Colour online) Laser-induced electron count density contrast with (red solid square) and without space charge effect (black dot) and space-charge limited electron count density (wine open square) (τ_p = 50fs, F_{dc} = 1GV/m), all three above from our mechanism. Space-charge limited electron counts from VORPAL simulation (2D) are displayed in magenta left triangle. To show difference of time-dependence of space-charge effect, space-charge limit electron counts from Valfells' formula are plotted in violet dashed line. Inset: enlargement of Electron count density contrast between data from VORPAL, our mechanism and Valfells' formula.

Results and Discussions

To summarize this paper, we develop a numerical algorithm to calculate a time-dependent short-pulse space-charge limited current density, based on our previous work on a nonequilibrium model to describe ultrafast laser-excited electron emission, confirmed by commercial PIC software. We conclude that space charge effect has to been considered during this emission process and calculate space charge limit current values. And laser field, pulse duration and metal work function are all un-sensitive parameters except that electric DC field is an efficient parameter to tune range of space-charge limit current.

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