Space-charge effect on the energy spectrum of photoelectrons produced by high-intensity short-duration laser pulses on a metal

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We consider the photoelectron spectra produced by a high-intensity short-duration laser pulse on a metal and present the results of a computer simulation of the electron-energy variations in a diode and beyond it, taking into account the space-charge effect. We show that the energy increase in the diode is indeed responsible for the unexpectedly high-electron-energy spectrum observed in a recent experiment by Farkas and Toth [Phys. Rev. A **41**, 4123 (1990)].

INTRODUCTION

The study of electron photoemission due to high-intensity short-duration laser pulses on surfaces is important for many reasons, one of them being its application to photoinjectors. The aim of many recent experiments is a better understanding of photoemission under such time and intensity conditions.

From recent experiments, Farkas and Toth [1] reported an observation of energy spectra of photoelectrons up to 600 eV, which is quite surprising compared with the few electron volts predicted by the classical laws of photoemission. No convincing explanations were offered, even in some recent proposals that discussed, for instance, multiphonon absorption by electrons [2].

In fact, a satisfactory interpretation of these experimental data can be given by considering Coulomb interactions inside the electron packet during its transit across the diode and beyond it. We present here the results of the computer simulation for such an effect.

Experimental results

In a first series of experiments by Farkas and Toth [1] called here experiment 1, Nd-glass laser pulses of 1 mJ energy and 8 ps duration with peak intensities varying from 13 to 25 GW/cm^2, are directed under grazing incidence on a gold surface. A $V_{\mathrm{ext}}=15$ kV potential applied by a grid located at 15 mm from the surface is used to extract photoelectrons. They are then slowed down over 15 mm by a potential $-V_{\mathrm{ext}}$ and their energies are measured by a retarding field analyzer coupled to an electron multiplier. The photoemitted charge is $\sim 2\times 10^{-12}$ C and the maximum current density is 60 A/cm^2, while the electron energy distribution reaches 100 eV for 13 GW/cm^2 and 600 eV for the maximum intensity 25 GW/cm^2 (Table I).

TABLE I. Values of maximum electrons energies measured for different peak laser intensities in Ref. [1].

Peak laser intensity (GW/cm^2)	Maximum energy of electrons (eV)
13	100
18	300
20	350
22	500
25	600

With a 20-GW/cm^2 laser intensity and with different extracting potentials, $V_{\mathrm{ext}}=5-25$ kV (reported here as experiment 2), the maxima of electron energy distributions are, respectively, 350 eV, when $V_{\mathrm{ext}}=15$ and 10 kV, and only 200 eV when $V_{\mathrm{ext}}=5$ kV. The ratio of these maximum energies is 1.75:1.

In a third experiment (experiment 3), a number of electrons comparable to that of experiment 1 is produced by a 20-ns duration ruby laser pulse of intensity ≤ 2 MW/cm^2, but then their energies correspond to the theoretical predictions, all below 10 eV. In another experiment [3] made with 100 MW/cm^2, electrons reaching 10 eV are observed (experiment 4).

Coulomb interactions

Farkas and co-workers [1,3] notice that space charge plays a role in some of the previous results; they think that they avoided this effect by choosing values such that the emitted charged is well below its limiting value. However, the analysis of experiment 1 measurements leads to the following remarks.

First, a peak current density of 60 A/cm^2 in 8 ps corresponds to a charge density fo 4.8×10^{-10} C/cm^2, that is to say $\sim 0.45 Q_L$, Q_L being the limit charge density related to the applied electric field $\mathcal{E}$. Here $Q_L=\varepsilon_0\mathcal{E}=8.85\times 10^{-10}$ C/cm^2 with $\mathcal{E}=1$ MV/cm, as in experiment 1. Second, from energetic characteristics of the laser pulse, it is easy to deduce the spot area but due to the laser energy loss during the beam transport it is probably overestimated, and the charge density may reach a higher value than the computed one. Taking into account the fact that emitted charge is proportional to I^4, the fourth power of laser intensity (the number of photons that have to be absorbed by an electron to overcome the surface barrier is here $N=4$), we report in Table II, the evaluations of laser spot radii, the respective charge

TABLE II. Calculation of percentage of the limiting space charge value Q_L for different peak laser intensities.

Maximum intensity (GW/cm^2)	Spot radius (mm)	Emitted charge densities Q (10^{-10} C/cm^2)	Q (% of Q_L)
13	0.55	0.09	1.7 – 2
18	0.47	0.77	8.8 – 11
20	0.45	1.3	15 – 18
22	0.42	2.1	24 – 32
25	0.40	4	45 – 54

densities Q and the intervals of percentages of Q_L, for each peak intensity in experiment 1.

For such a charge, which can reach $Q_L/2$, the spatial density of charges in the packet is very high because of the very short pulse duration. Even if the extraction of these charges is possible, the Coulomb interactions between the electrons, inside the burst, during their transit outside the cathode, cannot be neglected.

In experiment 3, a comparable total number of electrons is emitted in 20 ns (which corresponds to a packet 2500 times longer) and no anomalous energy distribution is observed. This confirms our hypothesis about the effect of electron interactions on the energy increase.

Calculations

We published recently [4] a computer simulation of the temporal lengthening of a short electron pulse during its transit across a diode. This code also gives the values of energies and locations of the electrons. It takes into account the spatial and temporal distributions of the charge, the Coulomb interactions of electrons with each other and with the image charge created when they leave the cathode, and finally the effect of the applied potential, according to the diode geometry.

We first apply this code to the experiment 1 situation, thus considering electrons emitted without initial speed, during 8ps, accelerated by 15 kV on 15 mm and then slowed down by -15 keV on the next 15 mm. For simplicity, the electron beam is assumed uniform in time and space, and divided for computational convenience into eight micropulses emitted at 1-ps intervals. In each micropulse all electrons are supposed to have the same characteristics. The micropulse number 1 represents the electrons of the beam front, the number 4 is for electrons at the end of the first half of the beam, and the number 8 is for electrons of the tail.

We especially compute electron energies E_{15} at the anode (15 mm from the cathode) and E_{30} after their slowing down (30 mm from the cathode, where they are measured) and their transit times t_{15} and t_{30}. Two different charge densities are considered: $Q=0.1Q_L$ [Table III(a)] and $Q=0.5Q_L$ [Table III(b)], which corresponds in experiment 1 to the peak intensities 18 and 25 GW/cm^2, respectively.

A dispersion $\pm\Delta E_{15}$ appears around the central value of electron energy $E_{max}=15$ keV at the anode. When Q varies from $0.1Q_L$ to $0.5Q_L$, ΔE_{15} increases from 1.6% to 3% of E_{max}, i.e., some hundreds of electron volts. This result does not violate the energy conservation principle as the average electron energy in the whole pulse is always 15 keV.

At 30 mm of the cathode, electrons in the micropulses 1–4 keep a part of their extra energy and the front of the pulse is even accelerated by the Coulomb repulsion due to the following micropulses. The electrons of the second part of the pulse come back to zero energy.

Finally, we observe that predicted energies E_{30} of the front micropulse are very close to the maximum ones measured in experiment 1: 331 eV instead of 300 eV for 18 GW/cm^2, 554 eV instead of 600 eV for 25 GW/cm^2.

Then, we compute the effect of a potential $V_{ext}=5$ kV on a charge density $Q=0.1Q_L$, the same as in the calculation of Table III(a) to simulate experiment 2. Results are reported in Table IV. Transit times of electrons are considerably increased. Energetic dispersion at the anode is $\pm2.5\%$ of 5 keV and the energy of the first micropulse at 30 mm is 172 eV. The ratio of the energies 331 eV (for $V_{ext}=15$ kV) and 172 eV (for $V_{ext}=5$ kV) is 1.90:1, that is close to the ratio 1.75:1 of experment 2 for 20 GW/cm^2.

Experiment 3 corresponds to a quasicontinuous working regime of the diode [5], because of the laser pulse duration of 20 ps is much longer than the 415 ps transit

TABLE III. Energies and transit times at the anode (15 mm) and after slowing down (30 mm). $V_{ext}=15$ keV and charge densities: (a) $Q=0.1Q_L$ ($\Delta E_{15}/E_{max}\approx1.6\%$); (b) $Q=0.5Q_L$ ($\Delta E_{15}/E_{max}\approx3\%$).

Micropulse	E_{15} (keV)	t_{15} (ps)	E_{30} (eV)	t_{30} (ps)
		(a) $Q=0.1Q_L$		
1 (front)	15.24	412	331	772
4	15.04	420	30	820
8 (tail)	14.79	430	0	
		(b) $Q=0.5Q_L$		
1 (front)	15.44	407	554	754
4	15.04	426	52	825
8 (tail)	14.60	453	0	

TABLE IV. Energies and transit times at the anode (15 mm) and after slowing down (30 mm) for charge density $0.1Q_L$. $V_{ext}=5$ keV; $\Delta E_{15}/E_{max}\approx2.5\%$.

Micropulse	E_{15} (keV)	t_{15} (ps)	E_{30} (eV)	t_{30} (ps)
1 (front)	5.13	704	172	1304
4	5.02	727	18	1408
8 (tail)	4.88	758	0	

time of a single electron between cathode and anode in the diode. But when intensity is increased (experiment 4), the charge density grows. From electron energies computed for $V_{ext} = 15$ keV and a very low charge density $Q = 4\times10^{-5}Q_L$, simulating the long pulse duration, we observe at the anode an energy dispersion of about $\pm0.2\%$. In such conditions, the front micropulse energy at 30 mm from the cathode is 22 eV. The photoelectron energies at the cathode are then affected by this phenomenon when electrons reach the measuring apparatus.

CONCLUSION

From our simulations, it is clear that the experimental results reported in Ref. [1] do not correspond to an unknown process, but are the consequences of the very high electron density in the pulse. The Coulombian interactions between electrons in an external field of 1 MV/m are sufficient to explain an energetic dispersion of a few percent of the energy supplied to the photoelectrons for their acceleration outside the cathode, giving to the first photoelectrons, after slowing down, a residual energy up to 600 eV when $I = 25$ GW/cm^2. Such a dispersion is also in agreement with conclusions of two more recently published works [6,7].

This shows the limit of an accurate analysis of the characteristics of emitted electrons: the spatial density of charge has to be strongly reduced. If the purpose of the study is very high photoelectron densities or very short pulses, the energy spectrum cannot be obtained without a deconvolution taking into account the diode characteristics, but this is quite difficult to achieve.

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