TEMPORAL QUANTUM EFFICIENCY OF A MICRO-STRUCTURED CATHODE*

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Abstract

In this work the experimental and simulation results of photoemission studies for photoelectrons are presented. The cathode used was a Zn disc having a work function of 4.33 eV. Two different excimer lasers were employed as energy source to apply the photoelectron process: XeCl (308 nm, 10 ns) and KrF (248nm, 23ns). Experimental parameters were the laser fluence (up to 70 mJ/cm^2) and the anode-cathode voltage (up to 20 kV). The output current was detected by a resistive shunt having the same value of the characteristic impedance of the system. The best values of global quantum efficiency were approximately 5x10^{-6} for XeCl and 1x10^{-4} for KrF laser, while the peaks of the temporal quantum efficiency were 8x10^{-6} and 1.4x10^{-4}, respectively. The higher efficiency for KrF is ascribed to higher photon energy and to Schottky effect. To enhance the Schottky effect, several electron-beam simulations using OPERA 3-D were carried out to analyze the influence of the geometrical characteristics of the diode.

INTRODUCTION

In the last years, the interest of many laboratories on electron sources, has grown. Electron beams are useful to get scientific devices such as free-electron lasers (FEL) [1], X-ray machines [2], electron beam therapy machines [3], ect. Among the various possibilities to get electron beams, the photoelectric effect is very promising for getting easily electron beams of high current of low emittance. In fact, experimental results have confirmed that pulsed electron beams by photocathodes are characterized by emittances much better than those achievable by thermionic guns [4, 5].

THEORY

The more general laser-generated electron emission from metal surfaces is governed by the generalized Richardson equation [6]:

$$J_n(t) = a_n A I^n(t)(1-R)^n T^2(t) F(\delta_n) \qquad (1)$$

where I is the incident laser power, R is the target optical reflection, A=120 A/(K^2·cm^2) is Richardson constant, T is the target temperature, $F(\delta_n)$ is the Fowler function of argument $\delta_n = (nh\nu - \varphi)/kT$, a_n are the quantum coefficients (with a_o=1) related to the quantum n-photon process, with $0 \le n \le N+1$, where N is the first integer number below to the ratio $\varphi/h\nu$. φ is the metal surface work function and $h\nu$ is the photon energy.

From the theory, for $h\nu < \varphi$, the emission is due to the contribute of multi-photon processes and the total current results expressed by:
the thermionic component,

$$J_0 = AT^2 \exp(-\varphi/kT) \qquad (2)$$

the n-photon process components, with $n < N+1$,

$$J_n(t) \cong a_n I^n(t)(1-R)^n J_0 \exp(nh\nu/kT) \qquad (3)$$

and the current component relative to the highest multi-photon process, with $n = N+1$,

$$J_{N+1} \cong a_{N+1} A I^{N+1}(t) T^2 (1-R)^{N+1} \times \left[\frac{1}{2}\left(\frac{(N+1)h\nu - \varphi}{kT} \right)^2 + \frac{\pi^2}{6} \right] \qquad (4)$$

In all the above equations, k is the Boltzmann constant.

For $h\nu > \varphi$, by the theory the emission has only two terms, because of the zero N value: J_0 and

$$J_1 \cong a_1 A I(t) T^2 (1-R) \times \left[\frac{1}{2}\left(\frac{h\nu - \varphi}{kT} \right)^2 + \frac{\pi^2}{6} \right] \qquad (5)$$

EXPERIMENTAL APPARATUS

Fig. 1 shows a sketch of the apparatus. A 100 cm focal length lens was utilized to lead the beam onto the target. A beam splitter (B) was used to send part of the laser beam to a photodiode (Ph) in order to control its waveform. The photoelectric charge measurements were performed in a vacuum stainless-steel chamber at 10^{-7} mbar by a turbo-molecular pump. The cathode was a pure Zn disk fixed on an electric stem connected to the chamber by an insulating flange. The cathode work function was 4.33 eV. The pulsed laser-induced photoelectric charge was measured vs. the voltage supply applied between anode and cathode. The anode was made by a stainless steel grid with 4 meshes per mm^2, presenting an optical transmittance of 64%. The anode-cathode distance was 3.7 mm and the maximum accelerating voltage was 20 kV.

To avoid signal reflections and to record the effective current pulses, the extremity of the cathode was connected to the ground by 15 resistors approximately of 1500 Ω. The experiments were performed by a KrF and a XeCl excimer laser of 5 and 4.02 eV, respectively. The KrF pulse time duration at FWHM and laser spot were 23 ns and 40 mm^2, against the corresponding values of the XeCl laser of 10 ns and 72 mm^2.

*Work supported by V Com. INFN
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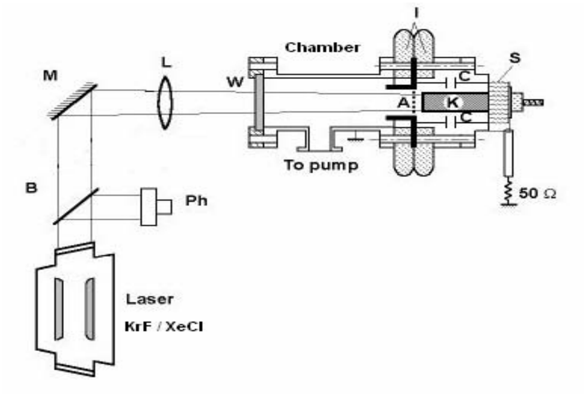

Figure 1: Experimental set-up.

RESULTS AND DISCUSSION

Using the XeCl laser the photoemission from metallic target would be studied mainly by the processes involving the one and two-photons, being $N = 1$. Then from Eq. (3):

$$J_{1,2}^{XeCl}(t) \cong a_1^{XeCl} A T^2 I(1-R)\exp\left(\frac{h\nu-\varphi}{kT}\right) + a_2^{XeCl} A I^2 (1-R)^2 \frac{1}{2}\left(\frac{2h\nu-\varphi}{k}\right)^2 \quad (6)$$

where the term $\pi^2/6$ has been neglected.

Fig. 2 shows the experimental results of peak current as a function of the accelerating voltage at different incident laser energies. The maximum output current was 2.3 A, reached at 12 kV. It is evident that the output current obtained at 11 mJ, reached the saturation regime at 2 kV.

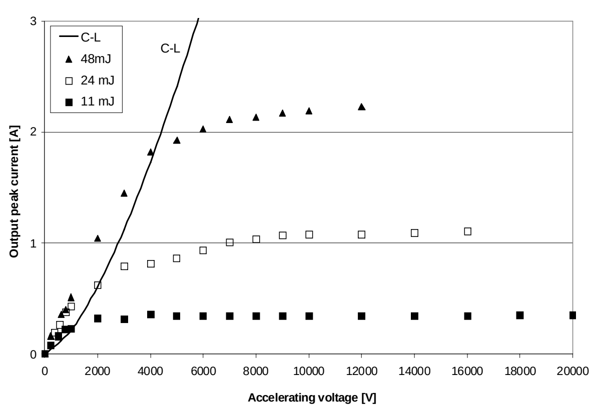

Figure 2: Experimental results for laser XeCl.

At higher laser energies the saturation regime is not very sharp and the photoemission efficiency increases as the accelerating voltage increases. This regime, that we call *linear regime*, can be considered like the overlapping of the saturation effect and the Schottky effect. It is important to observe that at linear regime the slope of the current versus the accelerating voltage increases as the laser energy increases and at low accelerating voltage the Child-Langmuir law is violated.

These results are due to the utilized real diode which presents a rough surface and a modulated anode due to the used grid. These conditions enhance the electric field on the cathode, which is responsible of the decreasing of the cathode work function. In fact, owing to the Schottky effect the work function decreases as:

$$\varphi = \varphi_0 - \sqrt{\frac{e}{4\pi\varepsilon_0}}\sqrt{\beta E} \quad (7)$$

where φ_0 is the zero field work function, E the electric field strength and β a constant. For a mirror-like surface $\beta = 1$. At low accelerating voltages and for different laser powers, different output currents are obtained, violating the Child-Langmuir (C-L) law. This behavior can be explained considering the plasma formation on the cathode which introduces an impedance into the cathode-anode region, shifting the C-L law [7, 8].

Besides, studies performed on the ions generation [9] demonstrated that the plasma expands and it could shorten the distance anode-cathode. The consequence is the increasing of the output current and in the space charge regime the modified C-L law takes the form:

$$I = 2.43x10^{-6} S \frac{(V - ZI)^{3/2}}{(d - vt)^2} \quad (8)$$

where S is the laser spot.

From Fig. 2 we observe that the current curve obtained at 11 mJ remains constant in the linear regime indicating a scarce influence of the plasma on the photoemission process, due to the low laser fluence.

The best value of global quantum efficiency (GQE) was approximately $5x10^{-6}$. We also calculated the temporal quantum efficiency (TQE) as the ratio of specific extracted electrons number on the specific incident photons number. The maximum TQE value was $8x10^{-6}$, reached at the laser pulse peak.

The KrF laser results were very similar to the ones obtained by the XeCl laser even if in this case the one-photon process was predominant. Then, using this laser, the photoemission process from metallic target would be studied mainly by the one-photon process, being $N = 0$. In fact, from Eq. (7) we have:

$$J_1^{KrF} \cong a_1^{KrF} A I(t)(1-R) \times \frac{1}{2}\left(\frac{h\nu-\varphi}{k}\right)^2 \quad (9)$$

where the term $\pi^2/6$ have been neglected.

By this theory, the main current component is directly dependent on the difference between the single-photon energy and work function value. Fig. 3 reports the peak current values as a function of the accelerating voltage, for different laser energy: it is possible to note that the maximum output current was 12 A at 14 mJ, with 16 kV accelerating voltage. In this case the TQE value was approximately 1.0 x 10^{-4} at the laser pulse onset time, whereas it increased of 40% at the pulse tail assuming the value of nearly 1.4 x 10^{-4}.

Even in this case at low accelerating voltage the Child-Langmuir law is apparently violated: the change of the upper limit of the current, in fact, is due to a change of the geometric conditions.

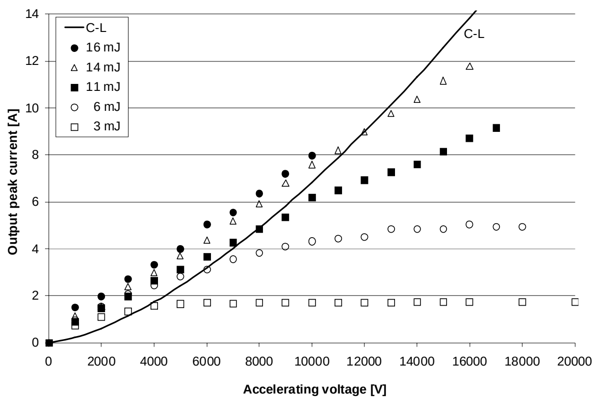

Figure 3: Experimental results for laser KrF.

We suppose the plasma formation like measured in a previous work [7], has an edge velocity of approximately 34 km/s [8]. Therefore during the laser irradiation the distance anode-cathode can shorten, increasing the maximum current value.

From Eq. (1) one can observe that the temporal behavior of J depends on the temporal dependence of I and T. Therefore, in order to control the photo-emitted current it is indispensable to know the temporal shape of I and T.

The intensity I is easily deducible by the laser source, while the temporal shape of T is much more complicated. Indeed, the behavior of the temperature is described by the following law [10]:

$$T(t) = T_o + CI_o \int_0^t g(t-t^{'})t^{'-1/2}dt^{'} \qquad (10)$$

where T_o is the initial temperature, C is a constant dependent on cathode material and $I_o g(t)$ is the temporal profile of the laser intensity. Considering the maximum laser energy employed in this work (16 mJ and 48 mJ for KrF and XeCl laser, respectively) and the laser pulse waveforms, the maximum temperature values obtained were nearly 440 K for KrF and 500 K for XeCl laser.

Cathode SEM microanalyses have shown the presence of rough surfaces for used cathodes. This result had stimulated the study of the photoemission under the influence of high electric fields that decrease φ, increasing the photoemission. Then, the presence of tips enhances the photo-emitted current and, consequently, the local temperature. In these points, therefore, the boiling point is almost certainly reached and low density plasma formation is a plausible fact.

This one was confirmed carrying out electron-beam simulations by OPERA 3-D software. Simulating the photoemission by cathodes with micro-structures we found that the output current was dependent on cathode roughness. The distance between tips was set 30 µm and their height was set 0.4 µm. Figure 4 shows the diode used for simulation. The simulation results pointed out an output current higher than the one obtained by a mirror like surface.

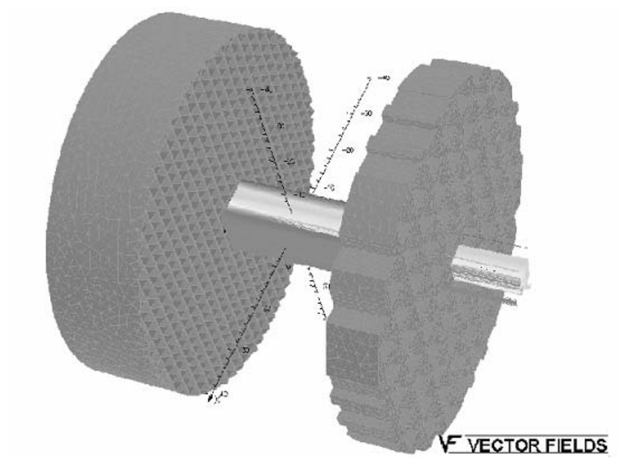

Figure 4: Diode used for the simulation by OPERA 3-D.

CONCLUSION

We have demonstrated that the quantum efficiency of a metal photocathode can be higher than the value present in literature if the plasma influence is not negligible. All depends by the difference between the laser photon energy and the target work function. The maximum found TQE value was $1.4\text{x}10^{-4}$, very close to the semiconductor photo-cathodes GQE. Indeed, when extraction tests with a lower laser photon energy (4.02 eV) were performed, the GQE was of the order 10^{-6} and the current pulse FWHM duration was narrower than the laser pulse one, owing to the 2-photon process, necessary to overall the cathode work function. Output values higher than these expected by the CL law were obtained and justified by the micro-structured cathode surfaces.

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