AIP | Review of Scientific Instruments

Studies of electron beams propagation in space-charge regime

L. Martina, V. Nassisi, A. Pedone, P. P. Pompa, and G. Raganato

Citation: Rev. Sci. Instrum. **73**, 2552 (2002); doi: 10.1063/1.1482152
View online: http://dx.doi.org/10.1063/1.1482152
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v73/i7
Published by the American Institute of Physics.

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 7 JULY 2002

Studies of electron beams propagation in space-charge regime

L. Martina, V. Nassisi,[a] A. Pedone, P. P. Pompa, and G. Raganato
Laboratory of Applied Electronics, Department of Physics, Instituto Nazionale di Física Nucleare, C.P. 193, 73100 Lecce-I, Italy

(Received 8 November 2001; accepted for publication 5 April 2002)

We report the experimental characteristics of electron beam propagation under space-charge regime. The electron beams were generated by a Nb polycrystalline photocathode illuminated by two different excimer lasers, a XeCl (308 nm) and a KrCl (222 nm). The laser photon energies were very close to the Nd work function. The cathode surface was mechanically worked in order to study the photoemission from a smooth and a rough surface. At low accelerating voltage the electron beam was dominated by the space-charge effect and its resulting pulse never clipped as predicted by the Child–Langmuir law. Instead, it presented as fast a rise time as the laser one, an intermediate zone, and a tail longer than the laser pulse one. On the other hand, under saturation regime the output current wave form was similar to the laser one. The quantum efficiency was higher for the rough cathode. It corresponded to 3.2×10^{-5} and 6.7×10^{-7} for the KrCl and XeCl irradiation, respectively. The maximum current value was an electron bunch containing 980 mA (8.9 nC), by means of 1.7 mJ KrCl laser energy and 10 kV of accelerating voltage. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1482152]

I. INTRODUCTION

Recently, electron beam (EB) bunches with very short pulses and high peak brightness, at high repetition rates, are required for feeding free-electron lasers (FEL), syncrotron sources, and microwave devices.[1] Electron beams are generated by thermionic, field-emission, and photoemission effects depending on the application devices. Temporal characteristics of thermionic and field-emission sources are dictated by the time duration of the voltage applied to the extractor. It does not reach very low values, so these sources are not able to generate very short EBs to feed accelerators. On the other hand, pulsed EBs by photocathodes offer the advantage of getting pulses of rise time and time duration close to the laser ones. Besides, photoemission by metallic cathodes has demonstrated to be very efficient, particularly if stimulated by pulsed ultraviolet lasers.[2,3] These properties and the low emittance make these systems adapt to feed linear colliders.

In this work we study the photoemission from Nb cathodes because they are of interest in developing rf guns. Generally, superconductor half-cell cavities are coated by niobium metal, but electron sources having Nb photocathodes are not yet available. Such a device would contribute to decreasing the cavity contamination. The niobium photocathode quantum efficiencies were found to be 4.5×10^{-4} and 3.2×10^{-5}, if illuminated by a laser beam of 193 and 248 nm, respectively.[4] The geometric characteristics were also measured, namely the upper limit emittance values in the saturation condition. The minimum values resulted in 7 and 76 π mm mrad for the 308 nm (*s* polarization) and for the 222 nm (*s* polarization) wavelength, respectively.[5]

In this work we turn our attention to comparing the EB behavior under space-charge and saturation regime, for two unpolarized laser beams. The photoemission theory elaborated by Fowler[6] predicts the propagation in saturation regime, without any plasma generation. On the contrary, during the photoextraction the output current generates a plasma cloud, which modifies the maximum current and, as a consequence, also the beam propagation. Under space-charge regime the Child–Langmuir theory predicts a clipped current pulse,[7,8] particularly for high laser powers. Instead, the observed output current pulse presents a rise time, corresponding approximately to the laser one, without any cut on its intensity. It is very complex to explain these results. They depend on various experimental conditions and the reason for this behavior has not yet been studied deeply.

We found also that the plasma generation depends mainly by the output current. In fact, experiments performed on ferroelectric ceramic and field-emission cathodes have demonstrated the plasma formation on their surface,[9] even if these cathodes work without laser irradiation.

II. EXPERIMENTAL SETUP

The lasers used in this work were two homemade excimer lasers operating at 308 nm with a XeCl mixture and at 222 nm with a KrCl mixture. The corresponding photon energies were 4.2 and 5.6 eV, respectively, while the cathode work function was 4.3 eV. The laser beams were led into the generating chamber by a mirror (M) and a convergent lens (L). Figure 1 shows a sketch of the apparatus. The lens focal length was 100 cm. Two beam splitters (B) were used to send part of the laser beam to a fast Hamamatsu R1328U-02 photodiode (Ph) and to a Gentec ED-200 joulemeter (JM). The pulse recorded by the photodiode was used as laser pulse monitoring and as the trigger source.

The generating chamber was made of stainless steel as well as the grid anode. The latter had an optical transmit-

[a]Electronic mail: nassisi@le.infn.it

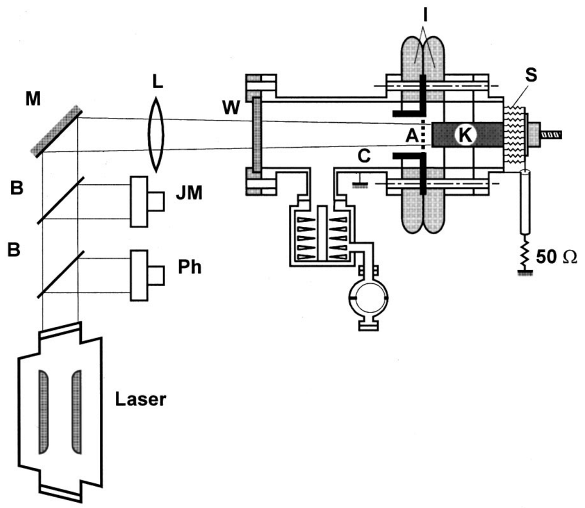

FIG. 1. Experimental apparatus. B: beam splitter; M: mirror; L: convergent lens: C: generation chamber; A: anode, K: cathode; I: insulators; S: shunt resistance; and W: quartz window.

tance of 53%, in order to allow the irradiation of the cathode. The anode–cathode distance could get different values by changing the position of the cathode. The anode was connected to a dc power supplier which provided the accelerating voltage. The maximum accelerating voltage was 12 kV, but during the electron extraction the values applied were lower, depending on the laser wavelength and power, in order to avoid the arc formation. The cathode was connected to the ground by 22 resistors of 50 Ω used as a shunt. The shunt resistance did not perturb the electron-beam propagation and allowed us to record the electron beam generated with a fast rise time. Moreover, the shunt was able to measure current intensities lower than Rogowski coils. The shunt calibration was accomplished by simulating the electron beam, by considering the current in a conducting rod, Fig. 2. This last was connected to the ground by a 50 Ω resistance and was supplied by a pulse forming line (PFL). The input voltage pulse was 16.8 V (0.42×40), which generated a current pulse of 0.34 A. As it can be seen in Fig. 3, the output signal is about 0.76 V and both the rise times were very close and limited by the oscilloscope characteristics. The attenuation factor was found to be 0.44 A/V as per the theoretical prediction.

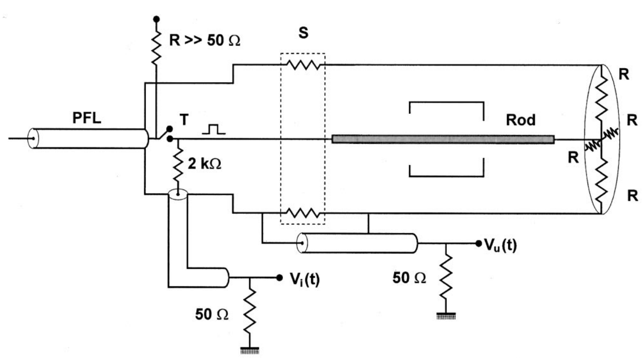

FIG. 2. Calibration system. PFL: pulse forming line; T: switch; S: shunt resistance; and R: matching resistance $R=200\ \Omega$.

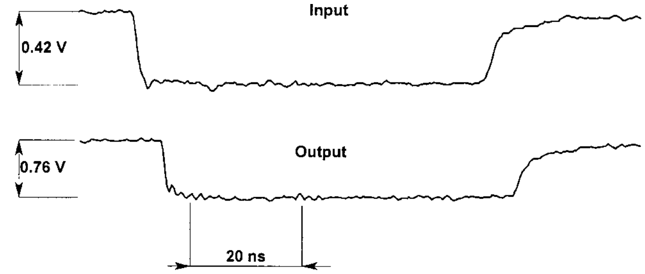

FIG. 3. Experimental results of the shunt calibration. Upper trace: input signal 0.34 A $(0.42\ \text{V}\times 40/50\ \Omega)$; Bottom trace: response 0.76 V.

III. EXPERIMENTAL RESULTS

Here we give full details of the results obtained from the smooth and rough cathodes illuminated by our two excimer lasers. The convergent lens reduced the laser spot $(1\times 2\ \text{cm}^2)$ on the cathode surface at about 63 mm^2. The cathodes were mechanically worked in order to obtain smooth and rough surfaces. The roughness was 0.09, calculated following Ref. 10. The anode–cathode distance, in the preliminary experiments, was fixed at 4 and 8 mm. Owing to the different laser photon energy and to the extracted current, the maximum accelerating voltage applicable and the beam energies were different for the XeCl and KrCl lasers. In the XeCl case the maximum energy was fixed at 4.2 mJ and the maximum accelerating voltage at 2500 V. With higher energies, or higher accelerating voltage, instabilities were induced on the accelerated electron beam.

The KrCl photon energy is higher than the XeCl one and, as predicted by Fowler, we expected a higher output current. In this case the maximum laser energy was fixed at 0.5 mJ and the maximum accelerating voltage at 10 kV in order to avoid short circuits. This accelerating voltage value was higher than the XeCl one.

We have theorized that the plasma generation is due mainly to photoextracted current, while the laser energy contribution is very low. As it can be seen in the next section, the KrCl induces a higher output current and consequently a higher plasma generation is supposed. However, we observed that a higher accelerating voltage for KrCl laser experiments can be applied without the generation of short circuits. This behavior can be ascribed to the short time duration of the KrCl laser, which reduces the probability of generating short circuits counterbalancing the plasma effect. The typical time durations of the laser pulses were 20 and 9 ns for the XeCl and KrCl lasers, respectively. In these considerations we exclude the material ablation, the target temperature being much too low for the above-mentioned laser energies.[11]

A. Experimental results from the smooth cathode

Figure 4 shows the peak current values induced by the XeCl and KrCl lasers as a function of the accelerating voltage for the two anode–cathode distances. The corresponding saturation regime is at a voltage higher than 1 and 3 kV, respectively. The different output current for the two anode–cathode distances, 4 and 8 mm, is very surprising, although the laser energy is the same. Changing the anode–cathode

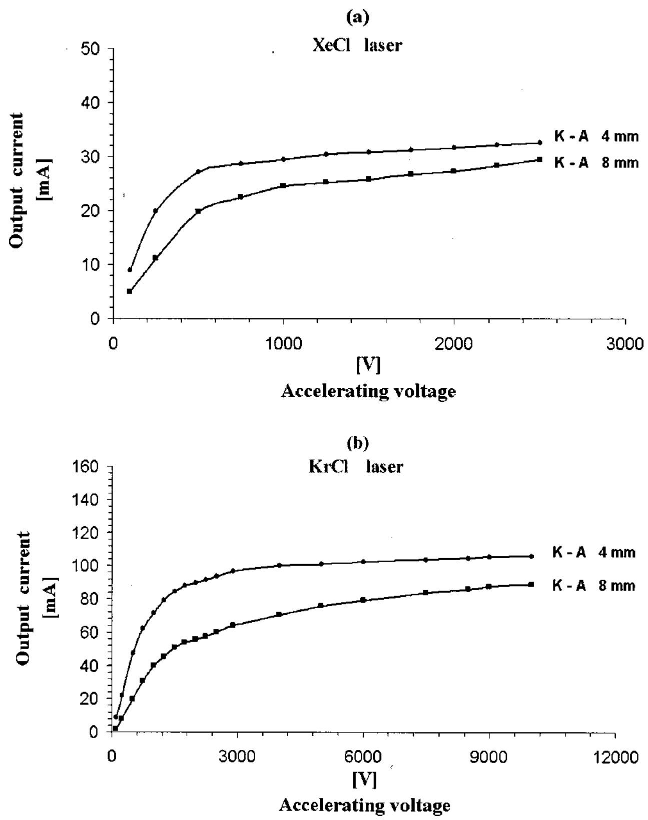

FIG. 4. Output current from the smooth cathode as a function of the accelerating voltage. (a) Data obtained by the XeCl laser and (b) data obtained by the KrCl laser.

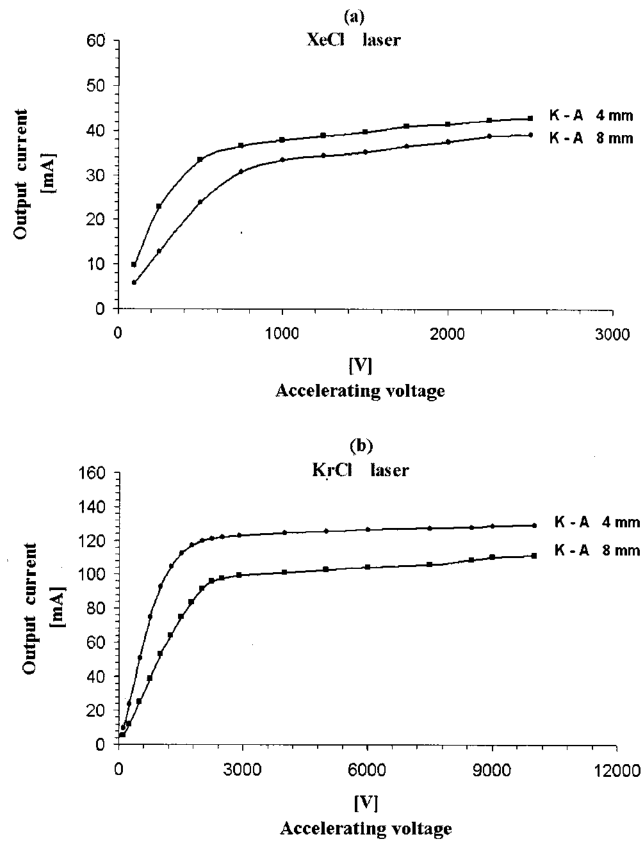

FIG. 5. Output current from the rough cathode as a function of the accelerating voltage. (a) Data obtained by the XeCl laser and (b) data obtained by the KrCl laser.

distance means applying a different electric field. Analyzing the traces of Fig. 4, we can observe that the experimental current increases as the applied electric field increases. This result can be justified guessing the presence of a new contribution even in the saturation regime: the plasma and its effect on the final electric field. The plasma evolves in the accelerating gap and shortens the anode–cathode distance, but under the saturation regime the output current should not increase. Really we do not know how the plasma increases the current. Next we will consider a plasma resistance and the plasma propagation into the diode. We also observe that increasing the electric field, the electron work function decreases and, as Fowler predicted, a quadratic increase of the extracted current is expected. Furthermore, the current discrepancy on anode–cathode distance is more evident (in percent) at low accelerating voltage than at high accelerating voltage. The current wave form is similar to the laser one in saturation conditions, while in space-charge regime its time duration is longer.

B. Experimental results from the rough cathode

Figure 5 shows the peak current values induced by the XeCl and KrCl lasers, as a function of the accelerating voltage for the two diode gaps. With respect to the previous measurements, we obtain higher current values. The saturation regime thresholds are the same as the previous experiments, as well as the behavior on the accelerating voltage and on the anode–cathode distance.

Comparing the obtained results with the previous ones, the output current is about 30% higher. This result may be due to the higher electric field present on the cathode surface owing to its roughness. The electric field decreases the work function and the current increases as predicted by Fowler.

Under saturation regime the current pulses are similar to the laser ones, while under space-charge regime their time durations are larger. Figures 6 and 7 show the laser and current wave forms at 125 and 250 V for the XeCl and KrCl lasers, respectively. We can observe that the current pulse enlargement is again more evident for the XeCl laser.

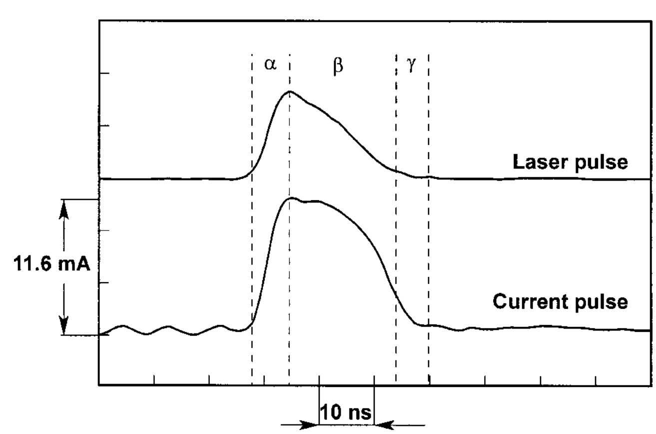

FIG. 6. XeCl laser and current wave forms from a rough cathode at 125 V of accelerating voltage and 4 mm anode–cathode distance.

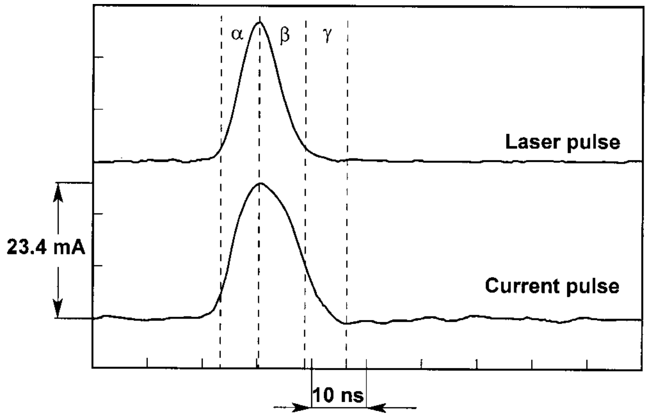

FIG. 7. KrCl laser and current wave forms from a rough cathode at 250 V of accelerating voltage and 4 mm anode–cathode distance.

IV. DISCUSSION

As we said in the previous sections, the plasma is produced from the cathode during the electron photoemission. The plasma modifies the accelerating voltage applied between the cathode and anode, provoking a decrease of the voltage.[12] Besides, the plasma itself can photo-emit electrons modifying the primary electron beam.[2] Analyzing the laser and the current pulses at low accelerating voltage, one can assert that the electron emission may be ascribed to the photoelectric process and to the plasma contribution.[1] In fact, for the rough cathode and KrCl laser, at low accelerating voltage, the current pulse can be 30% larger than the laser one. In this experiment the current pulse presented a fast rise-time equivalent to the laser one (α), an intermediate zone (β), and a tail (γ). In Figs. 6 and 7, α is the laser pulse time corresponding to 10% of the pulse maximum to the pulse peak, β is the laser pulse full time corresponding to the peak to 10%, and γ is the laser pulse full time corresponding from 10% to zero. Nevertheless, we can observe that in the γ zone the laser intensity is very low while the output current is large. Besides, the current pulse result is never clipped, as we expect from the Child–Langmuir law.[12] We ascribe this behavior to the plasma expansion, which modifies the anode–cathode geometry and, as a consequence, the electron propagation.

Under space charge regime the modified Child–Langmuir Law[12] takes into account the decrease of the accelerating voltage and the decrease of the anode–cathode distance. Now, taking advantage of this suggestion, we assume that our diode follows the law

$$I(t)=C\times\frac{A(V-ZI)^{3/2}}{(d-vt)^2}G(t), \tag{1}$$

where C is a constant depending on the system of units, A is the laser spot area, V is the accelerating voltage, Z is the plasma resistance, and $G(t)$ is a function of time which takes into account the laser intensity and other plasma effects. We assume that $G(t)$ is basically driven by the laser intensity, but it also accounts for the current flowing from the plasma, which in its turn depends on the time evolution of the plasma distribution.

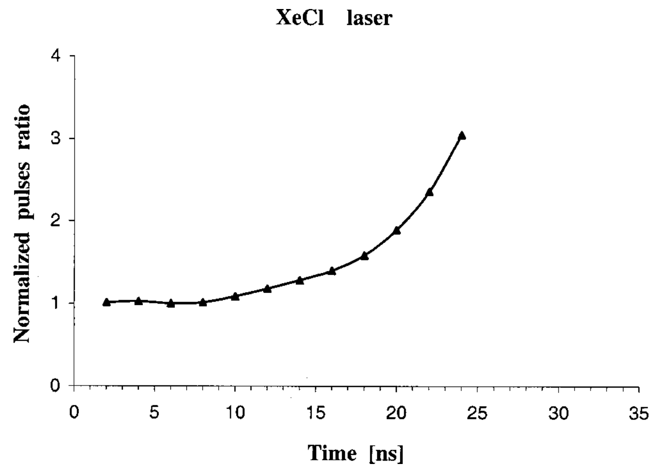

FIG. 8. Plot of the rate of the output current on the laser pulse vs the evolution time, for the XeCl experiment.

In particular, one of the main phenomena is the expansion of the plasma in the chamber, leading to a short circuit in a finite time $t_0=v/d$, where v is the plasma velocity and d the anode–cathode distance. Since in our experimental setup t_0 is greater than the laser pulse length, it only leads to a significant modification of the current output profile. Then, we parametrize this effect into $G(t)$ by the expression

$$G(t)=\frac{I_L(t)+I_P(t)}{I_0}, \tag{2}$$

where $I_L(t)$ is the laser intensity, $I_P(t)$ accounts for all plasma effects, and I_0 is a suitable normalization constant, which corresponds to the maximum value of the expression $I(t)+I_P(t)$. The plasma contribution, expressed by $I_P(t)$, depends on the output current and takes into account the electron relaxation time τ by the following expression:

$$I_p=I_{0L}tIe^{-t/\tau}. \tag{3}$$

In fact, plotting the ratio of the output current on the laser pulse versus the evolution time, Figs. 8 and 9, we observe an increase of the curve in correspondence to the laser pulse tail. The τ values for both experimental cases are approximated to 5 ns. Now, considering the pulses emitted by

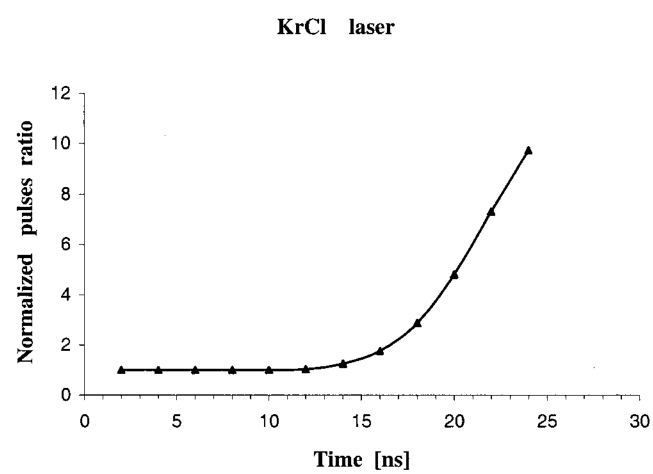

FIG. 9. Plot of the rate of the output current on the laser pulse vs the evolution time, for the KrCl experiment.

the rough cathode (Figs. 6 and 7), we observe that in both cases the rise times of both the current and laser pulses are very close, indicating a linear dependence, likely due to the low plasma production in the onset time. This behavior can be justified by the plasma generation dependence on time.

The maximum electric field applied was 0.64 and 3 MV/m for the XeCl and KrCl lasers, respectively. These values decrease the cathode work function by the Schottky effect, where the effective work function is given by the following law:

$$\phi_e = \phi_0 \sqrt{\beta E}, \tag{4}$$

where ϕ_e is the effective work function, ϕ_0 is the zero field work function, E is the electric field, and β is a constant. Increasing the electric field E, ϕ_e decreases and the output current increases as $(h\nu - \phi_e)^2$.[6] At the same time, the laser effect becomes less evident and the output current strictly follows the laser time evolution.

The maximum current with $d = 8$ mm, at 10 kV, from the smooth cathode was 980 mA (8.9 nC/bunch), for the 1.7 mJ KrCl laser.

After the above discussion, we conclude that it is possible to extract photoelectrons from niobium cathodes using excimer lasers, operating in the near UV (NUV) and far UV (FUV) range. The quantum efficiency, calculated utilizing the rough cathode data, results in 6.7×10^{-7} for the NUV radiation and 3.2×10^{-5} for FUV laser. These values are consistent with data reported in Ref. 4.

In this work we have tried to explain the experimental results of the photoextracted electrons at low accelerating voltage, even if it is very involved owing to the plasma influence.

[1] J. M. Watson, IEEE Trans. Nucl. Sci. **32**, 3363 (1985).
[2] A. Beloglazov, V. Nassisi, and M. Primavera, Rev. Sci. Instrum. **66**, 3883 (1995).
[3] D. Charalambidis, E. Hontzopoulos, C. F. Fotakis, G. Farkas, and C. Toth, J. Appl. Phys. **65**, 2843 (1989).
[4] L. N. Hand and U. Happek, Nucl. Instrum. Methods Phys. Res. A **372**, 335 (1996).
[5] A. Donateo, L. Martina, and V. Nassisi, Rev. Sci. Instrum. **72**, 3596 (2001).
[6] R. H. Fowler, Phys. Rev. **38**, 45 (1931).
[7] C. D. Child, Phys. Rev. **32**, 144 (1971).
[8] I. Langmuir, Phys. Z. **15**, 346 (1914).
[9] V. F. Puchkarev and G. A. Mesyats, J. Appl. Phys. **78**, 5633 (1995).
[10] V. Nassisi and M. R. Perrone, Rev. Sci. Instrum. **70**, 4221 (1999).
[11] D. J. T. Lin and T. F. George, J. Appl. Phys. **54**, 382 (1983).
[12] V. Nassisi and V. Stagno, J. Appl. Phys. **76**, 3769 (1994).