Electron beam propagation in a space-charge regime

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Abstract

We report on the propagation of electron beams generated by a niobium photocathode illuminated by different wavelength excimer lasers. The cathode used was a polycrystalline disc. Its work function was 4.3 eV while the laser photon energy was 4.02 eV for the XeCl laser and 5.6 eV for the KrCl laser. The anode–cathode distance was variable as well as the saturation output current. At low accelerating voltage the beam was space charge dominated but its peak value was not limited by the Child–Langmuir calculated value. A fast shunt resistance allowed to record the electron beam generated with a fast rise time. The maximum output current was reached with the KrCl laser which provided an electron bunch containing 980 mA and 9 nC.

Keywords: Photocathode; Photoemission; Electron beams; Beams interactions with plasma

1. Introduction

Recent electron accelerator applications such as free-electron-lasers, synchrotron sources and microwave devices require e-beam bunches of very short pulses at high repetition rates and high peak brightness [1]. Electron beam can be generated by thermionic, field-emission and photoemission effect. Temporal characteristics of thermionic and field emitting cathode sources are dictated by the time duration of the voltage sources applied to the extractor. Photoemission by metal cathodes have demonstrated to be very efficient particularly if stimulated by pulsed ultraviolet lasers which generate electrons from many metals [2,3]. The electron beam time duration as well as its rise time is controllable by the laser pulse characteristics. These properties and the low e-beam emittance make these systems adapt to fed linear colliders.

We study the photoemission from Nb cathodes because they are interesting to develop RF-gun. The output current and the upper limit emittance at saturation condition had been measured [4]. In this work we point out our attention to investigate the behavior under space-charge dominated effect for two different wavelength lasers. During the photoextraction the output current generates a plasma cloud which modifies the maximum current and as a consequence also the beam propagation. By the Child–Langmuir theory, we expect a clipped current pulse [5,6]. Instead, the maximum output current increases as the laser fluence increases even if the theoretical space-charge conditions are reached. To explain this result is very complex. It depends on various experimental conditions and the reason of this behavior is not well understood.
Experiments performed on ferroelectric ceramic cathodes and field emission cathode, have demonstrated the plasma generation [6] even if laser beams are not applied. These data confirm that the plasma production is due to the output current. Besides, the laser fluence utilized does not increase too much the temperature. In fact to assess the maximum target temperature reached during our experiments we utilize the following formula [7]:

\[ T = T_0 + C I_0 \int_{-\infty}^{t} u(t) \frac{g(t - \tau)}{\sqrt{\tau}} \mathrm{d}\tau, \]  

where \( C \) is a constant, \( T_0 \) is the initial temperature, \( I_0 \) is the unreflected part of the incident irradiance, \( u(t) \) is the Heaviside function and \( g(t) \) is the laser temporal dependence. Putting the suitable values in Eq. (1), the maximum temperature reached by the cathode was of 342 K. This low value does not allow to get either thermionic emission or plasma generation.

2. Experimental apparatus

The experimental setup is described in Fig. 1. The UV laser sources were two home-made excimer lasers operating at 308 and 222 nm. A mirror (M) and a 100 cm focal length lens (L) were used to align the laser beam optics axis with the target surface. Two beam splitters (B) were used to send a part of the laser beam to a fast photodiode (Ph) Hamamatsu R1328U-02 and to a joulemeter Gentec ED-200 (JM). The photodiode was used as laser pulse shape detector and as trigger source.

A stainless steel grid was used as anode. The grid optical transmittance was 53% in order to allow the laser irradiation of the cathode. The anode–cathode distance was variable. The anode was connected to a dc power supplier. The accelerating voltage \( V_a \) could vary up to 12 kV. The cathode was connected to the ground by 22 resistors of 50 \( \Omega \) used as shunt. The shunt resistance did not perturb the electron beam propagation and allowed to record the electron beam generated with a fast rise time. Besides, the shunt was able to measure low current intensities. The theoretical attenuation factor was found to be 0.44 A/V and the experimental one 0.43 \pm 0.01 A/V.

The cathodes utilized in this experiment were carefully cleaned with methanol and before the photoextraction process about one hundred laser pulses were applied to remove impurities/adsorbed layers.

3. Experimental results

We give full details here of results obtained by the XeCl and the KrCl lasers. The laser spot was fixed at 63 mm\(^2\) and the distance anode–cathode, in the preliminary experiments, at 4 and 8 mm. Besides, two different cathodes were used having a smooth and a rough surface respectively. The roughness was 0.09 calculated by expression reported in [8].

3.1. XeCl laser

The laser energy was fixed at 4.2 mJ and the maximum accelerating voltage at 2500 V. Fig. 2 shows the peak current values as a function of the accelerating voltage for both anode–cathode distance utilized for smooth and rough cathode. It is evident that for accelerating voltage higher than 1 kV the output current is in the saturation regime. So, being the laser energy fixed for all the above
measurements, we expect only one current value. The observed discrepancy is more evident (in percent) at low accelerating voltage, namely under space-charge regime. At high accelerating voltage the electron beam waveform is very similar to the laser one, while at space-charge regime we observed a marked change on current waveform. In Fig. 3 we report the waveforms of the laser pulse and of the output current from rough cathode at 125 and 2500 V.

3.2. KrCl laser

In this case the laser energy was fixed at 0.5 mJ and the maximum accelerating voltage at 10 kV. Fig. 4 shows the peak current values as a function of the accelerating voltage for the smooth and rough cathode. In this case for accelerating voltage higher than 3 kV the output current is in the saturation regime. As observed in the previous experiment, also in this case we expect only one current value. The observed discrepancy is more evident (in percent) at low accelerating voltage, namely under space-charge regime. The electron beam and laser pulse waveforms are very similar at high accelerating voltage, while at space-charge regime we observed a marked change on current waveform. Fig. 5 reports the laser pulse and the output current waveforms from the rough cathode at 250 and 10,000 V.
4. Discussion

As suggested in the previous sections, during the generation of the electrons, plasma is produced from cathode. The plasma modifies the accelerating voltage applied between cathode and anode owing to the crossing of electrons in it which provokes a decreasing of the voltage [9]. Besides, the plasma is created near to the cathode and the charges contained in it influence the propagation of the electrons [2]. Analyzing the laser and the current pulses at low accelerating voltage, one can asserts that electron emission is ascribed to photoelectric process and to the plasma contribute [1]. In fact, at low accelerating voltage the current pulse can result 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 coincident to laser pulse full-time duration measure at 10% and a tail (γ). The peak current never resulted clipped as we expect by the theoretical Child–Langmuir values. It seems that increasing the laser intensity the output current increases and the space-charge effect does not limit the current. We ascribe this behavior to the plasma expansion which modifies the anode–cathode geometry and the electron propagation.

In [9] the modified Child–Langmuir Law was reported, taking fixed the distance anode–cathode. Now, taking advantage of this suggestion, we assume that our diode follows the law

\[ I(t) = \text{const} A (V - Z I)^{3/2} F(t), \]

(2)

where const is a constant depending on the system of units, \( A \) is the laser spot area, \( V \) is the accelerating voltage, \( Z \) is a postulated plasma resistance and \( F(t) \) is a function of time which takes into account the laser intensity and other plasma effects. Notice that in this Ansatz we are taking \( Z \) to be independent on time, as a first rough approximation. Concerning \( F(t) \) we assume that it is basically driven by the laser intensity, but it takes account also of the current flowing from the plasma, which in turn depends on the time evolution of the plasma distribution. 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 distance anode–cathode. This time scale is in our experimental setup greater than the laser pulse length, however it could lead to a significant modification of the current output profile. Then, we parameterize this effect into \( F(t) \) by the expression

\[ F(t) = \frac{I_L(t) + I_P(t)}{I_0(d - vt)^2}, \]

(3)

where \( I_L(t) \) is the laser intensity, \( I_P(t) \) takes into account all plasma effects and \( I_0 \) is a suitable normalization constant which corresponds to the maximum value of the expression \( I_L(t) + I_P(t) \).

By rewriting our Child–Langmuir law as

\[ H^2 (I - V/Z)^3 = -I^2, \quad \text{with } H^2 = (\text{const} AF(t))^2 Z^3, \]
we can easily see that this third degree algebraic equation admits a real solution bounded in the interval

\[ 0 < I(t) < V/Z. \]

The minimum can be achieved for \( F(t) = 0 \), which in practice corresponds to the initial condition with zero laser intensity. On the other hand, the maximum is got in the limit \( F(t) \to \infty \), i.e. when the plasma fills completely the chamber and the short-circuit discharge occurs. Except this large time behavior, the output current never goes into a clipped regime as observed experimentally.

Actually this result is not explained and a deeper investigation is deserved. This is much more necessary when we consider a more close analysis of the solution of the above equation. Indeed, as we mentioned above, the current in the limit of \( H \) going to zero is zero, but this value is linearly approached, with a slope close to 1. So the observed enlargement of the width in the current output cannot be explained only in terms of the kinetic expansion of the plasma.

The exact expression of \( I_P(t) \) is not well known but from data of Figs. 3(a) and 5(a) the current takes value also after the laser pulse becomes zero. We ascribe this behavior to the plasma extinction.

We also verified the plasma generation at high accelerating voltage increasing the laser fluence. Under these conditions short circuit were
recorded. Generally, under high accelerating voltage the current pulse did not subject any enlargement, as can be seen in Figs. 3 and 5. By these figures we observe that plasma effect becomes marked with the lower photon energy. The maximum electric field applied was 0.64 and 3 MV/m for the XeCl and KrCl laser, respectively. These values decrease the cathode work function by the Schottky effect where the effective work function is given by the following law:

\[
\phi_e = \phi_0 - \sqrt{\beta E},
\]

where \(\phi_e\) is the effective work function, \(\phi_0\) is the zero field work function, \(E\) is the electric field and \(\beta\) is a constant. Increasing the electric field \(E\), \(\phi_e\) decreases and the laser effect becomes less evident.

The maximum current with \(d = 8\) mm from the smooth cathode was of 980 mA, 1.7 mJ KrCl laser. We measured also the beam geometric characteristics. The lowest upper limit normalized emittance value found was \(7\pi\) mm mrad, achieved by the s-polarised radiation of 308 nm [4].

References