Appl. Phys. B 62, 527–532 (1996)

Applied Physics B Lasers and Optics

80 A/cm^2 electron beams from metal targets irradiated by KrCl and XeCl excimer lasers

A. Beloglazov[1,*], **M. Martino**[1], **V. Nassisi**[1]

[1]Department of Physics, University of Lecce, National Institute for Nuclear Physics of Lecce, C.P. 193, I-73100 Lecce, Italy
(Fax: + 39-832/325128)

Received: 23 May 1995/Accepted: 20 October 1995

Abstract. Due to the growing demand for high-current and long-duration electron-beam devices, laser electron sources were investigated in our laboratory. Experiments on electron-beam generation and propagation from aluminium and copper targets illuminated by XeCl (308 nm) and KrCl (222 nm) excimer lasers, were carried out under plasma ignition due to laser irradiation. This plasma supplied a spontaneous accelerating electric field of about 370 kV/m without an external accelerating voltage. By applying the modified one-dimensional Poisson equation, we computed the expected current and we also estimated the plasma concentration during the accelerating process. At 40 kV of accelerating voltage, an output current pulse of about 80 A/cm^2 was detected from an Al target irradiated by the shorter wavelength laser.

PACS: 29.25Bx; 42.55.Gp

New accelerator programs foresee the application of high-luminosity electron beams. In order to help this development, good quality beam injectors are necessary. These latter ones can be produced by using rf photocathode guns which have confirmed the possibility of getting emittances much lower than those provided by thermionic cathodes [1]. Recently, photocathodes could also be produced by irradiating metal targets with UV light [2]. They also seem to provide beam emittances much lower than those provided by thermionic sources [3]. Moreover photocathodes have a long lifetime, are made of low-cost material and can work in a moderate vacuum level.

The UV-light sources used in this experiment were excimer lasers whose photon energies can reach up to 6 eV. Due to this feature they allow the application of one-photon photoelectric process with almost all metals. This condition is interesting for generating electron beams of low emittance, in spite of space-charge effects and the target temperature increase which degrade the beam quality [3–5].

So it is of great importance to investigate the optimum conditions (laser wavelength, laser spot dimension, target material, etc.) in order to get a high-brightness electron beam.

An excess current has been observed in photocathodes in comparison to the theoretical values obtained for anode–cathode distances larger than the beam spot dimension. Such behaviour was explained by taking into account a plasma concentration near the cathode [6,7]. The plasma generates an electric field as large as hundreds of kV/m which hardly modifies the propagation conditions for space-charge dominated electron beams [8]. The plasma, which forms near the cathode, was measured in the absence of the accelerating voltage.

We used a simulation code to compute theoretical values of the current and emittance which are affected by the potential distribution and space-charge effects, while the experimental values are also affected by the source quality such as the target material and laser wavelength.

In this work, the output current and beam emittance vs accelerating voltage were studied for two different very common metals, Al and Cu, whose work functions are 4.2 and 4.5 eV, respectively. They are irradiated with two different UV excimer lasers: XeCl ($\lambda = 308$ nm) and KrCl ($\lambda = 222$ nm).

By solving the one-dimensional Poisson equation with a plasma charge concentration, we studied the beam propagation and the plasma evolution in the presence of the electron-beam transport.

1 Experimental setup

Figure 1 shows the acceleration chamber having two symmetric quartz windows and a horizontal array of small Faraday cups in front of the cathode. Each cup is 9 mm in diameter and 11.5 mm distant from the centre of the neighbouring cup. All cups are inserted into the

* On leave from Institute of General Physics, Moscow, Russia

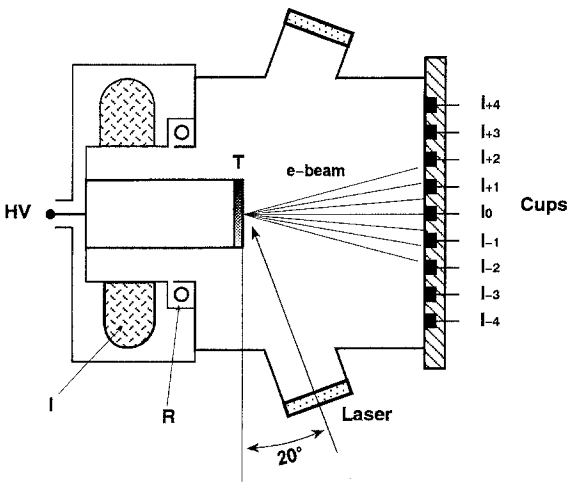

Fig. 1. Experimental setup of the vacuum chamber: HV high-voltage supplier, I insulator, R Rogowski coil, T metal target

grounded flange, insulated and connected to a 50 Ω BNC. So, the cups are able to detect only the electron-beam current and are not subject to the electromagnetic noise. The anode–cathode distance was 105 mm.

An HV power supplier fed the cathode (T). The accelerating voltage can vary up to 50 kV. A Rogowski coil (R) and an insulator ring (I) connected the cathode holder to the chamber. The laser beam was focused on the cathode by a 30 cm focal length lens at a grazing incident angle of 20°. The chamber was evacuated by a turbo-molecular pump down to 10^{-7} Torr.

The laser device used in this experimental work was described in a previous paper [9]. The standard mixture for 308 nm was Xe/HCl/He/Ne and the photon energy was 4.02 eV, comparable with the work function of the target metals, while for 222 nm the mixture was Kr/HCl/He/Ne and the photon energy was 5.6 eV, higher than the target metal work functions. The maximum output energy was higher than 300 mJ for XeCl and 100 mJ for KrCl, respectively.

In order to reduce thermionic emission and to avoid short-circuit due to plasma formation by the cathode microtips, mechanically polished mirror-like surfaces were used. The laser energies were chosen up to the short-circuit threshold. Neutral density filter along the laser axis were used to adjust the laser energy.

The minimum laser spot dimension used on the cathode was 2 mm in diameter. A Dove prism along the laser-beam path was used to turn the beam by 90° and to have a low horizontal divergence of the laser beam and as a consequence a circular focusing on the target. The spot size of the laser beam on the target was changed varying the target-lens distance.

In the experiments, two digitising oscilloscopes, a Tek. TDS 540 (1 Gs/s) and a Tek. TDS 620 (2 Gs/s), recorded the waveforms. The electron-current signals were detected by a fast Rogowski coil having an attenuation factor of 14.8 A/V[10], while the temporal shape of the laser pulse was detected by a fast UV-photodiode Hamamatsu R1328 U-02

2 Theory

The Richardson equations which determine the current densities of photoextracted electrons for XeCl and KrCl lasers are [9, 11]:

$$^{\mathrm{Al}}J_{308} = {^{\mathrm{Al}}a_{308}} T^2 I \exp[(4.02 - {^{\mathrm{Al}}\phi})/kT], \tag{1}$$

$$^{\mathrm{Al}}J_{222} = {^{\mathrm{Al}}a_{222}} I (5.6 - {^{\mathrm{Al}}\phi})^2/2k^2, \tag{2}$$

$$^{\mathrm{Cu}}J_{308} = {^{\mathrm{Cu}}a_{308}} T^2 I \exp[(4.02 - {^{\mathrm{Cu}}\phi})/kT], \tag{3}$$

$$^{\mathrm{Cu}}J_{222} = {^{\mathrm{Cu}}a_{222}} I (5.6 - {^{\mathrm{Cu}}\phi})^2/2k^2, \tag{4}$$

where a_{308} and a_{222} are the Richardson coefficients for the XeCl and the KrCl lasers, I is the laser intensity, T the target temperature, ϕ the target work function and k the Boltzmann constant. These equations are applicable for one-photon processes. The value of the temperature has to be calculated by solving the heat-diffusion equation taking into account the target physical–chemical properties and laser-energy density. The temperature evolution is computed by [12]

$$T = T_0 + C \int_0^{\infty} I(t) u(t - t') t'^{1/2} \, dt', \tag{5}$$

Where T_0 is the room temperature, C a constant which is dependent on the target material and $u(t - t')$ is the Heaviside function.

A theoretical formula for the current in space-charge dominated regime is given by the Child–Langmuir law:

$$I = pV^{3/2}, \tag{6}$$

where p is the permeance in units of $AV^{-3/2}$ and V the applied potential

For a paraxial electron beam, the emittance is defined as A/π, where A is the phase-space area occupied by beam particles. Then, the emittance upper limit in the plane of incidence of photoelectrons can be evaluated by the following formula [3, 13]:

$$\varepsilon_0 = r \Delta\phi/\pi, \tag{7}$$

where r is the spot radius and $\Delta\phi$ the total angular divergence.

The normalised transverse beam emittance is defined as

$$\varepsilon_n = \varepsilon_0 \beta\gamma, \tag{8}$$

where β and γ are the usual relativistic parameters, $\beta = v/c$ with v the speed of the electrons and $\gamma = (1 - \beta^2)^{-1/2}$.

The normalised peak brightness of the beam is defined as [12, 14]

$$B_n = I/\varepsilon_n^2. \tag{9}$$

Under our experimental conditions the divergence accuracy is limited by the cup diameter and the anode–cathode distance. The minimum measurable emittance was about 30 (π mm mrad).

3 Experimental results

3.1 Aluminium targets

The results of Al targets irradiated with the XeCl laser are shown in Fig. 2. The laser energy was set at 1 mJ and the laser spot had a diameter of 2 mm. The beam values reach a saturation regime after an accelerating voltage of 25 kV. The saturated current value was 65 mA at an emittance as small as 33(π mm mrad). The extraction efficiency, defined as the ratio of the photoemitted current to the laser energy, was 65 A/J while the current density at 45 kV was 2 A/cm^2.

In Fig. 3, the emittance and output current of photoelectron beams generated by the KrCl excimer lasers on Al target are shown. The laser energy was set to 3.8 mJ and the laser spot to 2 mm. This time the electron current does not reach a saturation regime. The values of the current and emittance are much higher than the corresponding XeCl values. At 40 kV we detected a current of 2.4 A but with an emittance of 110 (π mm mrad). The efficiency was 631 A/J and the current density about 80 A/cm^2.

The currents waveforms of the cups #0, # + 1 and # − 1 recorded at 40 kV accelerating voltage along with the laser-pulse shape are shown in Fig.4.

With the same laser energy we irradiated the metal target by a larger spot (2 × 4 mm). Even at 40 kV, we measured higher current, of 5 A, but the density was lower, 62 A/cm^2. The efficiency was 1310 A/J.

3.2 Copper targets

The emittance and output current values of photoelectron beams generated by the XeCl excimer laser irradiating copper targets is shown in Fig. 5. The laser

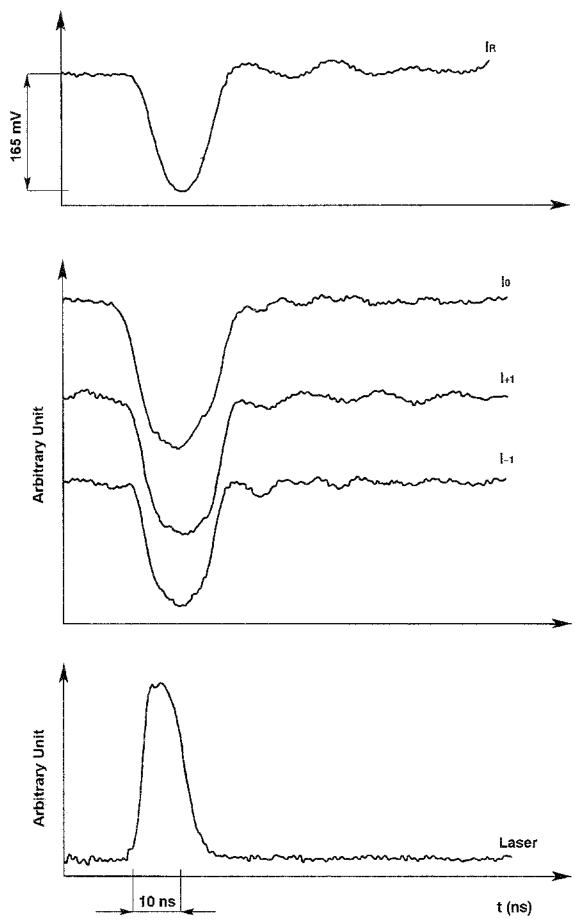

Fig. 4. Waveforms of output current detected by Rogowski coil I_R, by Faraday cups and laser-pulse temporal shape. The Al target was irradiated with 2 mm spot KrCl excimer laser at 40 kV of accelerating voltage

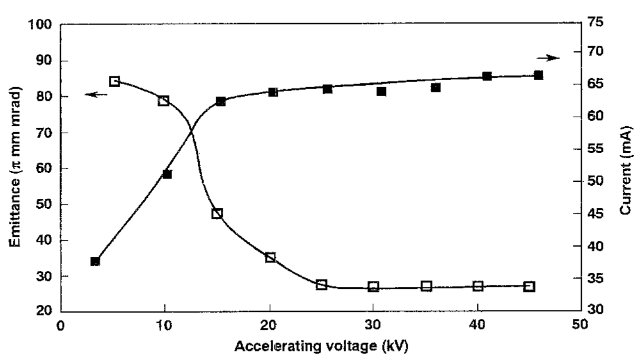

Fig. 2. Emittance (□) and output current (■) vs the accelerating voltage The Al target was irradiated with a XeCl excimer laser

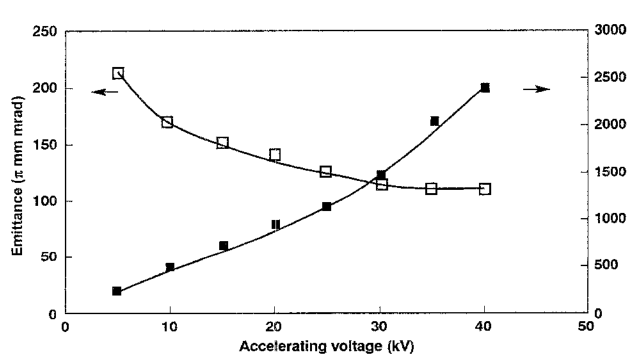

Fig. 3. Emittance (□) and output current (■) the accelerating voltage. The Al target was irradiated with a KrCl excimer laser

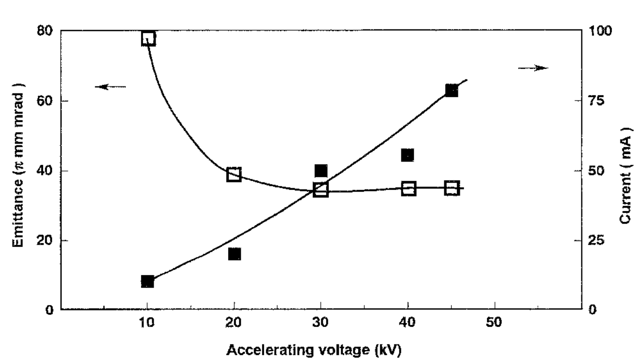

Fig. 5. Emittance (□) and output current (■) vs the accelerating voltage. The Cu target was irradiated with a Xecl excimer laser

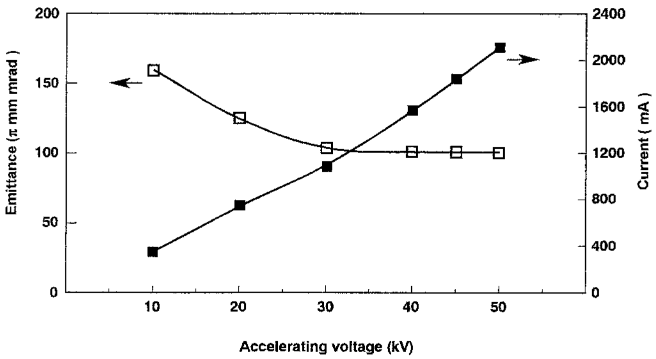

Fig. 6. Emittance (□) and output current (■) vs the accelerating voltage. The Cu target was irradiated with a KrCl excimer laser

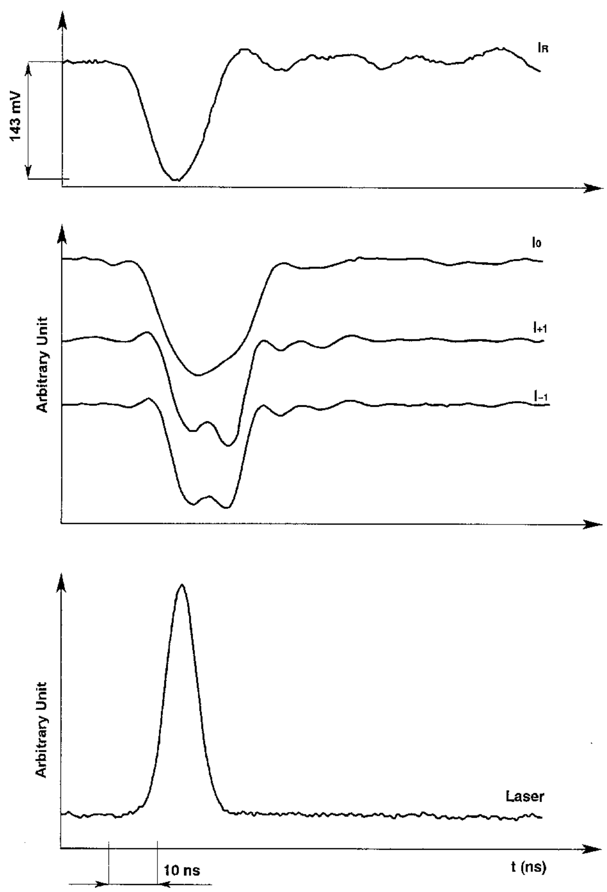

Fig. 7. Waveforms of output current detected by Rogowski coil I_R, by Faraday cups and laser-pulse temporal shape. The Cu target was irradiated with 2 mm spot KrCl excimer laser at 50 kV of accelerating voltage

energy was set to 8 mJ and the laser spot was 2 mm in diameter. It is evident in Fig. 5 that the output current does not reach the saturation regime. The values of current and emittance are quite low: at 50 kV the maximum current was 90 mA with an emittance of 35 (π mm mrad); the extraction efficiency was 11 A/J and the current density 2.9 A/cm^2.

Irradiating the Cu target with 5 mJ KrCl laser energy, we obtained very high values of current and emittance (Fig.6), like in the case of Al targets. At an accelerating voltage of 50 kV we detected 2.1 A with an emittance of 100 (π mm mrad). This time the density was 67 A/cm^2 and the extraction efficiency 420 A/J. From these data we can note that the current does not reach the saturation regime. In Fig. 7, it is possible to view the current waveforms obtained from the Rogowski coil and Faraday cups at 50 kV as well as the laser-pulse shape.

Even in this case we irradiated the metal target with a larger laser-beam spot (3×5 mm^2), but with the same energy. At 50 kV accelerating voltage the measured output current was about 6.4 A. The current density was 42 A/cm^2 and the extraction efficiency 1280 A/J.

4 Discussion

Comparing the experimental results it is evident that we obtained larger output currents on both the metal targets when we used the KrCl excimer laser. The KrCl photon energy is more than 1 eV higher than the work function of the two metals, while the XeCl photon energy is comparable or lower. This can explain the large difference between the extraction efficiencies obtained during the experiments. Indeed the current density is higher when Al targets, which have the lowest work function, were irradiated with small spot.

The current enlargement in relation to laser-pulse duration can be ascribed to thermal effects [2] which increases the photoemission at the end of the laser pulse. In fact for Al irradiated with the shorter wavelength and the smaller laser spot, the Rogowski coil waveforms were about 30% longer than the laser pulse, while the width of the central-cup signal was about twice larger. This last result can be mainly ascribed to space-charge effects more evident with high-current densities.

When the spot was larger the current peak was higher but the current density was lower than that measured with the smaller spot and consequently the space charge effect had less influence. In this case the width of the Rogowski coil pulse and the central-cup signal were about 27 and 40% larger than the laser duration. This last result can be explained by the lower laser fluence used, and consequently by a lower target temperature resulting therefrom.

For Cu targets we recorded a similar behaviour but with different percentage due to the features of the material.

We also note that in the experiments performed with the shortest wavelength, the FWHM time duration of the central cup #0 was higher than those of the other external cups. The different behaviour of the Faraday cups can be explained by some propagation effects due to the space charge of the electron beam. In fact, the outer cups recorded current pulses with less enlargement than that seen by the central cup, because this one is strongly affected by space-charge effects.

About the minimal emittance reachable, we performed laser irradiations with the 2 mm diameter spot size on Al targets but with different laser energies. With 0.15 mJ we obtained 150 mA at 40 kV while with 0.19 mJ we obtained 440 mA at 40 kV and the emittance value was always 35 (π mm mrad). This emittance value is close to the minimum measurable one with our diagnostic device. Indeed, the divergence measurement is the sum of the intrinsic part (due to the source quality) and of the geometric part (due to the non-parallel equipotential lines in the anode–cathode region). This last influence could be eliminated with a larger cathode in order to get parallel potential lines and to generate paraxial beam.

We simulated our experiments by E-Gun code [15]. We inserted our experimental setup characteristics (cathode shape and size, anode shape and size, anode–cathode distance, 1 mm initial radius, etc.) and computed the behaviour of the maximum current. Figure 8 shows the maximum current against the accelerating voltage. The emittance value was always 74 (π mm mrad). At an accelerating voltage of 50 kV we obtained a current of 800 mA; Figure 9 shows the relative equipotential surfaces and electron beam computed by E-Gun. The experimental current values, more than 2 A, are larger than the simulated values.

The large difference between the theoretical and experimental values for the currents of more than 1 A is due to the presence of a positive plasma near the cathode. This positive charge was detected by inserting a probe near the Al cathode which was irradiated by the KrCl laser with no accelerating voltage [6–8]. From this data a spontaneous electric field on the cathode surface of about 375 kV/m was estimated and the corresponding charge density was fitted by the exponential law $\rho_p \exp(-x/x_0)$, where x_0 was 0.001 m

To understand the effect of this plasma charge we solved numerically the one-dimensional Poisson equation including the presence of the plasma [8]:

$$\frac{dV}{dx^2} = \frac{Ik}{V^{1/2}\pi(r + \frac{1}{2}\Delta\phi x + \beta x^{1/3})^2} - \frac{\rho_p}{\varepsilon_0} e^{-x/x_0}, \tag{10}$$

where I is the total current, $k = (\mathrm{m}/2\mathrm{e})^{1/2}/\varepsilon_0$ a constant equal to 190000 ($\mathrm{A}^{-1}\mathrm{V}^{3/2}$),$r = 0.001$ m the initial radius, $\Delta\phi/2$ the half beam divergence, $\beta = 0.09\,\mathrm{m}^{2/3}$ along with $x^{1/3}$ form a correction term [8], and ρ_p the plasma charge density. In this code we used, as parameters, the experimental current values, divergence and plasma charge density and we computed the accelerating voltage at 105 mm from the cathode. Without any external accelerating voltage the measured plasma charge density was 3.3 mC/m^3. For $I = 1$, 1.5, and 2.4 A the plasma charge density increased and the computed total accelerating voltage resulted similar to the experimental ones.

In Table 1, the results of the computations are shown. E is the spontaneous electric field on the cathode calculated by $E \approx \rho_0 x_0/\varepsilon_0$

Figure 10 shows the computed plasma charge density vs the accelerating voltage. As can be noted the plasma density increases as the voltage increases.

The best brightness value was $1.07 \times 10^9\,\mathrm{A}(\pi\,\mathrm{m\,rad})^{-2}$ obtained by irradiating the Al target with a KrCl excimer laser at 40 kV of accelerating voltage while the normalised transverse emittance was 49 (π mm mrad).

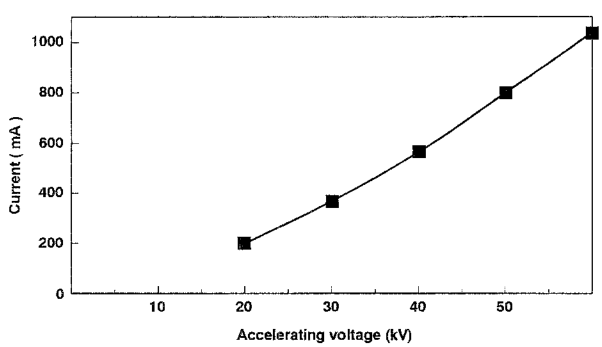

Fig. 8. Output current vs accelerating voltage. The data were computed by E-Gun code

Table 1. Results obtained by the one-dimensional Poisson equation simulation code

Current [A]	ρ_p [mC/m^3]	E [kV/m]	Voltage [kV]
2.4	5.88	660	40
1.5	4.24	480	30
1	3.46	390	20

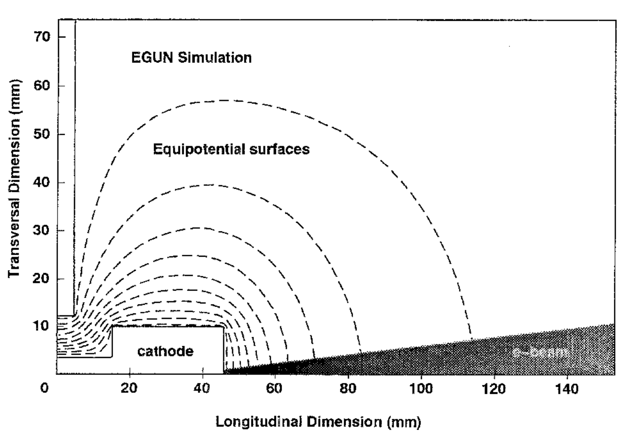

Fig. 9. Electron-beam simulation for a 50 kV acceleration voltage and an initial radius of 1 mm. The output current was of 800 mA

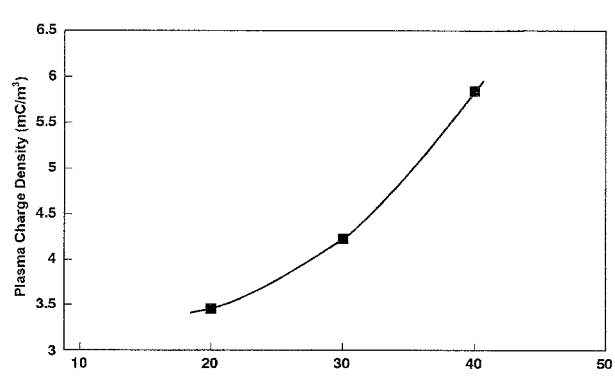

Fig. 10. Plasma charge density vs accelerating voltage. Results computed by one-dimensional Poisson simulation code

5 Conclusion

We obtained electron beams of high-current density, with a maximum value of $80\,A/cm^2$, and with a moderate emittance. The Al targets performance seems better than Cu targets. We did not reach a saturation regime with acceleration voltages up to 50 kV when the metal targets were irradiated with KrCl.

We used a standard code (E-Gun) to compute the current behaviour. The theoretical current was much lower than those experimentally detected. To explain this difference we made a measurement of the plasma and we observed the presence of a positive charge. We solved, successfully, the one-dimensional Poisson equation taking into account the plasma charge near the cathode. The high current having the lowest emittance was 440 mA at 40 kV from the Al target illuminated with the XeCl laser. The emittance value was 35 (π mm mrad). This value could become lower, modifying the experimental apparatus in order to get paraxial beams, allowing our diagnostic device to measure beam divergences due only to source quality.

Acknowledgement. The authors would like to thank Dr. V. Stagno for the EGUN simulation.

References

1. D.W. Feldmann, S.C. Bender, B.E. Carlsten, J. Early, R.B. Feldman, W. Joel, D. Johnson, A.H. Lumpkin, P.G. O'Shea, W.E. Stein, R.L. Sheffield, L.M. Young: IEEE J. QE-**27**, 2636 (1991)
2. V. Nassisi: Nucl. Instrum. Methods A **340**, 182 (1994)
3. D. Charalambidis, E. Hontzopoulos C.F. Fotakis, G. Farkas, C. Toth: J. Appl. Phys. **65**, 2843 (1989)
4. A. Beloglazov, M. Castellano, M.S. Causo, V. Nassisi, P. Patteri: In *Proc. CLEO94*, Amsterdam, IEEE Cat. no. 94TH0614-8 (1994) p. 147
5. V. Nassisi, A. Pecoraro:Nucl. Instrum. Methods A **341**, 137 (1994)
6. Y. Kawamura, K. Toyoda, M. Kawai: J. Appl. Phys. **71**, 2507 (1992)
7. M.S. Causo, M. Martino, V. Nassisi: Appl. Phys. B **58**, 19 (1994)
8. A. Beloglazov, V. Nassisi, M. Primavera: Rev. Sci. Instrum. (submitted)
9. V. Nassisi, V. Stagno: J. Appl. Phys. **76**, 3769 (1994)
10. V. Nassisi, A. Luches: Rev. Sci. Instrum. **50**, 900 (1979)
11. R.H. Fowler: Phys. Rev. **38**, 45 (1931)
12. J.T. Lin, T.F. George: J. Appl. Phys. **54**, 382 (1983)
13. W.Namkung, E.P. Chojnacki: Rev. Sci. Instrum. **57**, 341 (1986)
14. J.S. Fraser, R.L. Sheffield, E.R. Gray: Nucl. Instrum. Methods A **250**, 71 (1986)
15. W.B. Hermannsfeltds: Stanford Linear Accellerator 9 Rep. **226** (1979)