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CHARACTERIZATION OF ELECTRON BEAMS GENERATED FROM CU PHOTOCATHODES

V. Nassisi* and E. Giannico
Department of Physics, University of Lecce, I.N.F.N., C.P. 193, 73100 Lecce-I

ABSTRACT

In this work a slit-slit emittance meter is illustrated and the characteristics of electron beams obtained from photocathodes irradiated with excimer lasers are reported. In particular, we report the values of emittance and brightness of the electron beams from Cu cathodes irradiated with laser beams working at 308 nm, XeCl, and 222 nm, KrCl. With the slit-slit method the electron beam phase-space areas are determined selecting the beam in small beamlets and measuring the beamlet direction distributions by small cups placed after the slits. The higher current was obtained utilizing the KrCl laser. The laser beam was focused in a 4 mm^2 spot and the laser energy was established at 0.5 mJ. Under these experimental conditions the maximum current at the maximum accelerating voltage was 370 mA and the corresponding emittance and normalized emittance values were 18 and 9 [π mm mrad], respectively. From these values the beam brightness and normalized beam brightness resulted $1.14\text{x}10^9$ and $4.6\text{x}10^9$ A[π m rad]$^{-2}$, respectively. By increasing the energy and the spot KrCl laser beam the maximum extracted current was 16.4 A.

* Tel. 832 320495 Fax. 832 320505 E-Mail Nassisi@le.infn.it

I. INTRODUCTION

Metal photocatodes are new electron sources which can provide beam emittance much lower than those provided by thermionic ones[1]. By experimental data these photocatodes generated also high intensity electron beams more larger than those calculeted theoretically by Child-Langmuir law[2-4]. Utilizing the new UV photon sources, excimer laser, electron emission from almost metal cathodes applying the photoeletric process is possible.

The laminar beams represent ideal situations because their emittance values are approximately zero. In actual beams thermal velocities at the source and other imperfections always give rise to no laminar behavior. Then, an important parameter to quantify the beam quality is the beam-emittance [BE].

If the beam has two planes of symmetry (xz and yz with z the direction of propagation) we define the x-plane emittance ε_x as $1/\pi$ times the area A_x in xx' trace-plane [TP] occupied by the points represented by the beam particles at a given value of z

$$\varepsilon_x = \frac{A_x}{\pi}, \tag{1}$$

where x' denotes the gradient of the trajectories in the xz plane:

$$x'(z) = \frac{dx}{dz}, \tag{2}$$

analogously for the y-plane emittance ε_y.

Let us denote $f_6^0 = f_6^0(x, y, z, p_x, p_y, p_z)$ the density distribution function in the phase-space [PS] Γ_6, the density function $f_2^0 = f_2^0(x, p_x)$ in the phase-plane [PP], Γ_{2x}, is equal to:

$$f_2^0(x, p_x) = \int\int\int\int f_6^0(x, p_x, y, p_y z, p_z)dydzdp_y dp_z , \tag{3}$$

then the area occupied in the PP Γ_{2x} appears as the projection of the hypervolme occupied by the electron beam in the PS Γ_6 onto Γ_{2x}. The area occupied by the electron beam in this particular PP satisfying the condition $f_2^0 \neq 0$ is[5] :

$$A_x^0 = \iint_{f_2^0 \neq 0} dxdp_x = p_z A_x , \tag{4}$$

where p_z is particle invariant.
Substituting p_z in the Eq. (4) we have

$$A_x^0 = m_0 c\beta\gamma A_x , \tag{5}$$

where m_0 is the electron mass, $\beta = v/c$ with v the longitudinal electron speed, c the light speed and

$$\gamma = 1/\sqrt{1-\beta^2} . \tag{6}$$

The emittance values have an important property which can be deduced from Liouville's theorem in the PPs xp_x and yp_y, with p_x and p_y the canonical momentum corresponding to x and y position coordinates, respectively. The areas occupied by the electron beam in PPs are invariant quantities and the emittances vary in inverse proportion to p_z, therefore if the beam is not accelerated (p_z = constant) the emittances are also invariant quantities. Commonly the beam is accelerated, p_z is not constant, and it is possible to define two invariant quantities ε_{nx} and ε_{ny}, naminated "normalized emittance" in the respective TPs, defined as:

$$\varepsilon_{nx} = \beta\gamma\varepsilon_x \quad \text{and} \quad \varepsilon_{ny} = \beta\gamma\varepsilon_y . \tag{7}$$

The beam brightness [BB] is calculated by the following formula

$$B = \frac{I}{\varepsilon_x \varepsilon_y}, \tag{8}$$

where I is the total electron current.

The normalized BB calculated by the following formula

$$B_n = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}} \tag{9}$$

is another invariant quantities of the beam motion, and for beams with axial symmetry along z axis, $\varepsilon_{nx} = \varepsilon_{ny} = \varepsilon_n$, is equal to:

$$B_n = \frac{I}{\varepsilon_n^2} . \tag{10}$$

The characteristics of the extracted electron beam were determined valuing the current direction distribution of the selected beamlets, see Fig. 1. To analyze the current intensity Faraday cups and/or Rogowski coils are used while the slit-slit method[6] can provided the beamlets direction spreads which are utilized to estimate the emittance value.

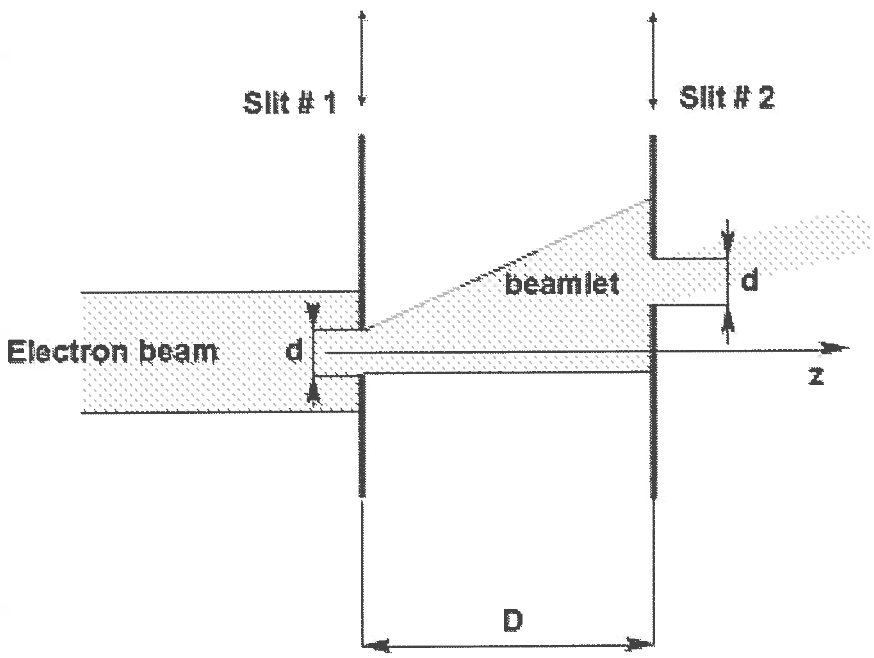

FIG. 1 – An example of the direction distribution beamlet measurement

To measure the beamlet divergence on x direction the two slits must be parallel to the y axis and to move along the x direction. The first slit, at the x position, allows to pass those electrons having the same x coordinate, while the second one allows to value the distribution function $f_2(x, x')$ on the x' dimension. For an ideal beam and slits of d width, the beam distribution function has the triangular shape with the base equal to $2d$, while it ought to be d at FWHM. Comparing these last parameters to the experimental ones, we can determine the beamlet angular spread. By plotting the distribution function on xx' plane the area occupied by the $f_2(x, x')$ determines the beam emittance.

II. EXPERIMENTAL SET-UP

The UV light was generated by two home made excimer lasers utilizing an Xe-Cl and a Kr-Cl mixture having photon energy 4,02 and 5.6 eV, respectively. These energy values are close to the work function of copper (4.5 eV). The excimer laser utilized was home-made and its characteristics were described in a previous paper[7].

Fig. 2 shows the experimental setup containing the acceleration chamber, the laser and the electric connections to oscilloscopes. In Fig. 3 a detailed of the emittance meter composed by an horizontal array of small Faraday cups and two arrays of slits made of stainless steel and 20 mm distant each other is shown. The first slit array is placed at 160 mm from the cathode while the second one is placed at about 1 mm from the cup flange.

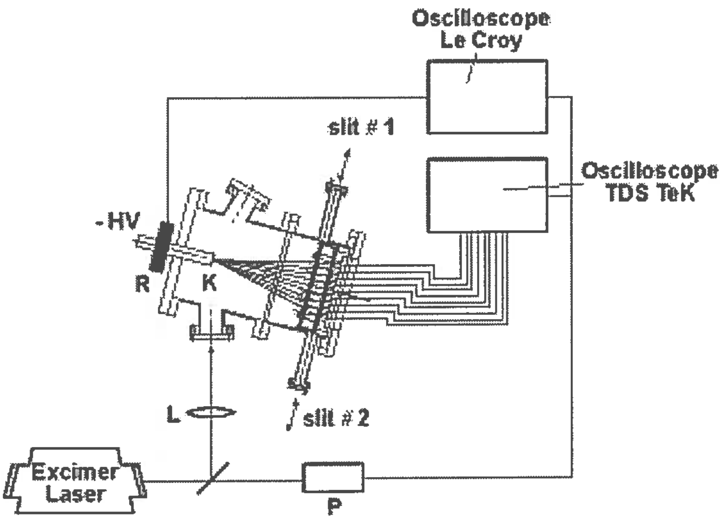

FIG. 2 – Experimental set-up of the accelerating chamber: -HV: Negative high voltage; R: Rogowski coil; K: Cathode; P: Photodiode; L: 30 cm focal length lens.

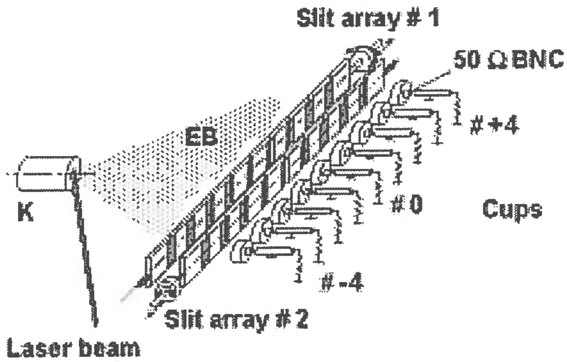

FIG. 3 – Emittance meter: K: cathode; EB: Electron Beam.

All cups are inserted into the grounded flange, insulated and connected coaxially to a 50 Ω BNC. So, the cups are able to detect only the electron current and they are not subject to the electromagnetic noise. The cups are 9 mm in diameter and 11.5 mm distant from each other, and each one corresponds to a slit of the first slit array and to a slit of the second slit array. This facility allows to record nine different current on laser shot. In order to overcome the limit on the lowest detectable current imposed by the noise oscilloscope level, the slit width have to be appropriately large 1mm. Another requirement on the slit width was also dictated by the mechanical step advance of the movable slit array, which fixed the tolerance of the slit width. Being 0.127 mm the lower mechanical step advance, the slit sides have to present a lower tolerance. So, the slit dimensions were analyzed by a HeNe laser illuminating two corresponding slits. Substantial diffraction phenomenon were obtained when two corresponding slits were positioned in such an way that the diffraction conditions were satisfied. By the diffraction patterns, see Fig. 4, the edge quality of the slits was estimated to be ± 0.01 mm and as a consequence the slit dimension resulted 1 ± 0.02 mm. In this case the uncertainty provided by the slits on the x' was 1 mrad.

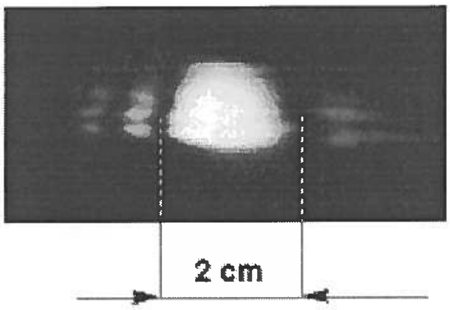

FIG. 4 – Diffraction pattern due to two corresponding slits when they are positioned in such way that the diffraction conditions were satisfied. The HeNe laser was placed at 250 cm from the slits and the diffraction pattern variation was estimated to be 0.5 cm.

An -HV power supplier fed the cathode. The accelerating voltage can vary up to 50 kV. A Rogowski coil[8], having an attenuation factor of 14.8 A/V, allowed to record the total output current.

The UV laser beam was focused on the cathode by a 30 cm focal length lens at a grazing incident angle of 20°. A Dove prism along the laser beam path and near to the output laser beam coupler was used to turn the beam by 90° in order to reach a low horizontal divergence of the laser beam and as a consequence to impress a circular focused beam on the target. In this way the minimum laser spot area used on the cathode was small less than 4 mm^2. The chamber was evacuated by a turbo-molecular pump down to 10^{-7} Torr

III. RESULT DISCUSSION

The cathode used in this experiment was a 1 mm thick Cu. Its surface was mechanically mirror-like polished to eliminate the impurities/adsorbed layers and the microtips in order to avoid short-circuits due the plasma expansion which can modify the beam propagation for space-charge effect[9] and to stabilize the photocurrent signals.

To determinate the beam emittance the beam spot was fixed at 4 mm^2 large and the laser energy was 0.5 and 2.5 mJ for the KrCl and XeCl laser, respectively. Under these conditions short-circuits due to the plasma formation were avoided. At the maximum accelerating voltage applied (50kV), the output current was 370 and 70 mA with the KrCl and XeCl laser, respectively. The higher value current was obtained with KrCl laser. This result can be ascribed to the high photon energy (5.6eV) of this laser which applied the one-photon photoelectric process, while, with the XeCl laser (4.02 eV) the two-photon photoelectric process was necessary to get electron emission from the cathode utilized in this experiment. The current and laser waveforms, when the cathode was investigated with the KrCl and XeCl laser at maximum accelerating voltage, are shown in Fig. 5. When the KrCl laser was used the output current pulse was as wide as the laser pulse duration, while when the XeCl laser was used the output current resulted about 85% narrower than the laser one. These behaviors point out that the photoextracted current with the KrCl laser was due mainly to the one-photon photoelectric process[10], while the photoextracted current with the XeCl laser can be expressed by an order higher than 1 on the laser intensity, implying that a multi-photon mechanism took place[10].

Analyzing the electron beam having the higher current (KrCl laser) we can observe, that the beam was in saturation regime for accelerating voltage higher that 40 kV, see Fig. 6.

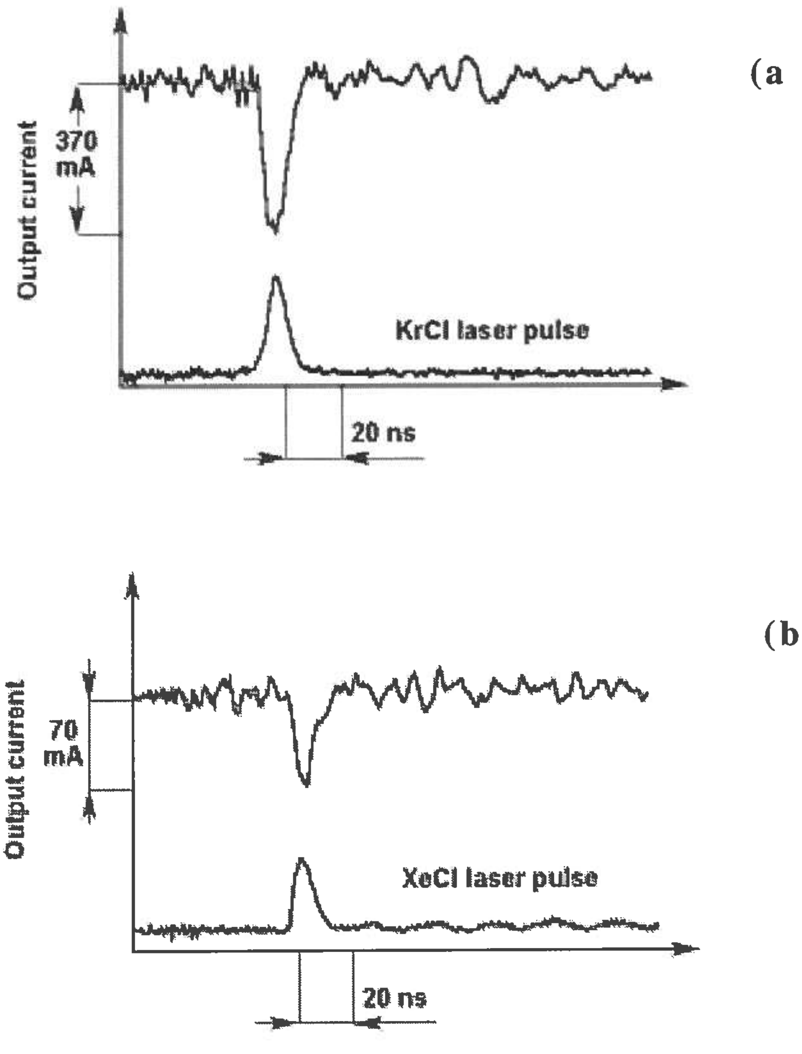

FIG. 5 – Current and laser pulse waveform cathode at 50 kV accelerating voltage. a) Output current and KrCl laser pulse; b) Output current and XeCl laser pulse.

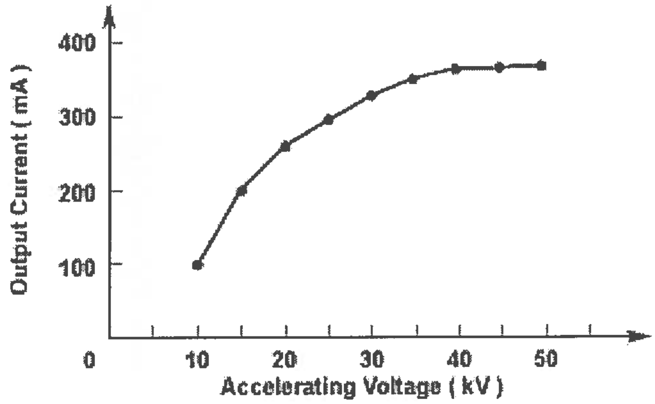

FIG. 6 – Total current obtained with the KrCl laser versus the accelerating voltage.

Figure 7 shows the cup currents obtained fixing the first slit and moving the second one at 50kV accelerating voltage. For investigating the BE at 50% of the peak density, we consider the beamlet width at 50% of maximum current recorded. The emittance plot in the *xx'* TP for the electron beam generated with KrCl laser is shown in Fig. 8 at 50kV accelerating voltage. With this laser, the BE value at 50 kV accelerating voltage was 18 [π mm mrad] and the corresponding BB was $1{,}14\times10^{9}$ A[π m rad]$^{-2}$. Applying the Eqs. (7) and (10) the normalized BE and the normalized BB values resulted 9 [π mm mrad] and 4.6×10^{9} A[π m rad]$^{-2}$, respectively. In order to estimate the bending due to the space charge of the only beamlet, we considered the influence due to maximum current density on electron directions. In this way the maximum bending was estimate to be 50 μrad. This value is two order lower than that obtained by the uncertainty of the slits and we can say that the beamlet transversal propagation was not influenced by space charge effects.

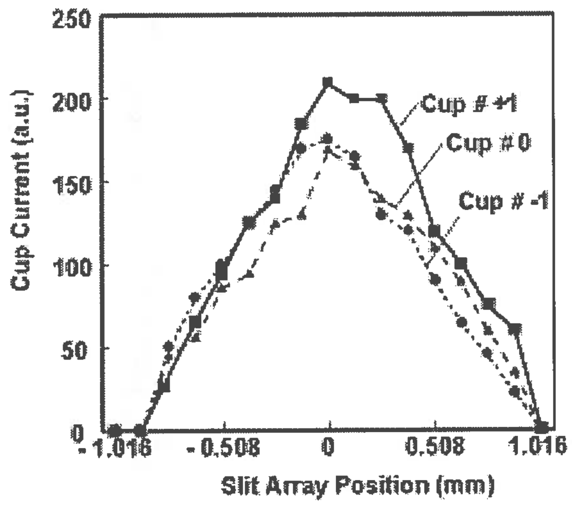

FIG. 7 – Typical beamlet profiles of the slit-slit measurement at 50 kV accelerating voltage.

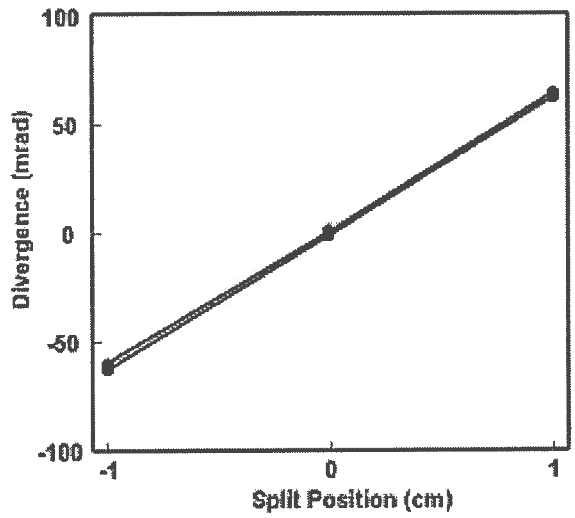

FIG. 8 – Emittance plot in the *xx'* TP of the e-beam at 50 kV accelerating voltage. The electron density along this contour line is 50% of the peak density in the *xx'* TP.

The output current obtained with the XeCl laser was very low and the electron beam was not affect by the space charge for accelerating voltage higher than about 10 kV and the BE value was 22 [π mm mrad] while the BB value was 0.14×10^{9} A[π m rad]$^{-2}$. Also in this case, applying the Eqs. (7) and (10) the normalized BE and the normalized BB resulted 11 [π mm mrad] and0.58×10^{9}

A[π m rad]$^{-2}$, respectively. The Table I report the experimental results of the electron beams generated with both lasers.

TABLE I – Experimental results of electron beams photoextracted from a Cu cathode at 50 kVaccelerating voltage.

Laser	Output Current [mA]	Emittance [π mm mrad]	Normalized emittance [π mm mrad]	Brightness A[πm rad]$^{-2}$	Normalized brightness A[πm rad]$^{-2}$	Quantum efficiency
KrCl	370	18	9	1.14 x 10^9	4.6 x 10^9	5 x 10^{-5}
XeCl	70	22	11	0.14 x 10^9	0.58 x 10^9	2 x 10^{-6}

Analyzing the electron beams obtained with KrCl laser on the accelerating voltage, see Fig. 9a, the BE decreased versus the accelerating voltage while the BB increased, how preview theoretically. The corresponding normalized BE and BB values versus the accelerating voltage are shown in Fig. 9b. These beam-parameters are not constants contrary to the theory. These behaviors can be ascribed to the space charge regime at low accelerating voltage, to no-paraxial approximation of the beam and to no-monoenergetic particles which contributed to increase the transversal electron temperature.

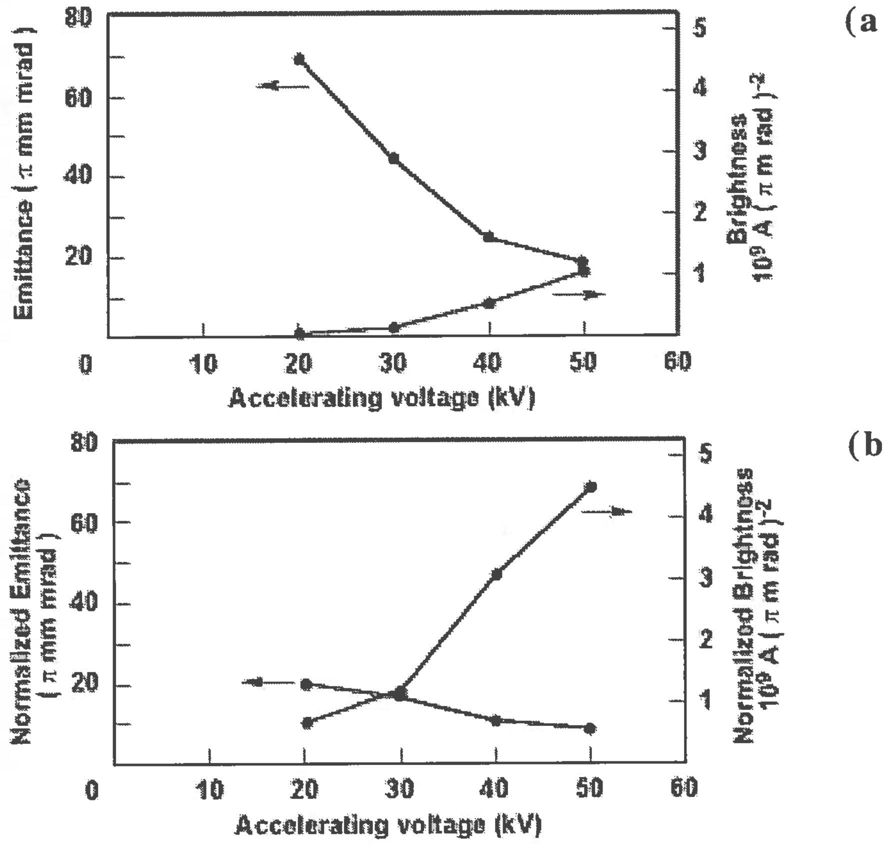

FIG. 9 – Emittance and brightness on accelerating voltage. a) emittance and brightness; b) normalized emittance and brightness of the electron beam generated by the KrCl laser.

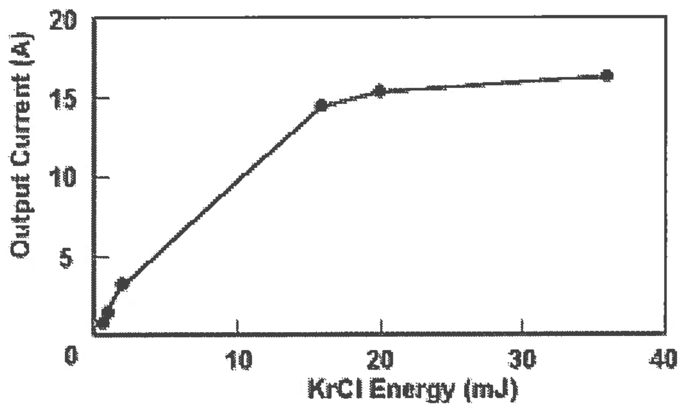

FIG. 10 – Output current on the KrCl laser energy from a 70 mm^2 large cathode at 50 kV accelerating voltage.

In figure 10 is shown photoextracted current versus the laser energy fixing the KrCl spot laser at 70 mm^2 and the accelerating voltage at 50 kV. At 36 mJ laser energy the maximum current extracted was 16.4 A. By this result we deduce that the quantum efficiency is not a constant but it decrease as laser density increases because, at high laser energy, the electron beams are space charge dominated which contributes to decrease the quantum efficiency. With the above laser energy the total extracted charge was about 200 nC.

IV. CONCLUSION REMARKS

In this work we have analyzed the electron beams generated from a Cu cathode illuminated by two excimer laser (KrCl and XeCl). The one-photon photoelectric process is applied by the higher photon energy (KrCl) which allow to produce the higher photoextracted currents .

In order to value the beam quality we have measured the beam emittance with the slit-slit method. This technique allow to value the angular distribution of the beams in exam on the arbitrary x transverse position. With KrCl laser beam with 4 mm^2 spot and 0.5 mJ energy the maximum current was 370 mA, the BE value was 18 [π mm mrad] and the normalized BB was 4.6×10^9 A[π m rad]$^{-2}$. With XeCl laser beam with 4 mm^2 spot and 2.5 mJ energy the maximum current was 70 mA, the BE value was 22 [π mm mrad] and the normalized BB was 0.58×10^9 A[π m rad]$^{-2}$.

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