Space-Charge Perturbation Effects in Photonic Tubes
Under High Irradiation*

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UCRL--86929

DEC2 018395

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ABSTRACT

Potential perturbation effects at the cathode region of a photonic tube can occur at high intensity due to space-charge. Using appropriate photoelectron energy distribution functions, the electric field at the cathode is calculated and its effect upon the spatial/temporal resolution is examined.

Introduction

Potential perturbation effects are investigated in the photocathode-grid region of a photonic tube under space-charge-limited condition. The results are based upon the solution of Poisson's equation with given photoelectron energy distributions. Although steady-state solutions are not strictly applicable to pulse operation, they do, however, give valuable guidelines for applications that involve pulse durations greater than the electron transit-time in the cathode-grid section of the tube. Since the electron transit-time in the extraction region of fast photonic tubes is typically less than 200 ps, these results should prove useful in the study of both spatial/temporal resolution degradation for the subnanosecond regime in photonic tubes.

*Work performed under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48.

The cathode-grid region of the photonic tube can be represented by a parallel-plane diode as shown in Fig. 1. When the diode current equals the space-charge-limited current, only a fraction of the emitted photoelectrons have sufficient initial energy to surmount the potential barrier (or the retarding electric field at the cathode). Electrons (which do not penetrate the potential barrier) scatter back from the potential minimum plane and get collected at the cathode. Previous results¹ using the Maxwellian energy distribution for electrons are not applicable to photonic tubes because photoelectrons are best described by either a quad-tail energy distribution² (QTED) or, in some cases, by a parabolic energy distribution³ (PED). Hence, by utilizing appropriate energy distribution functions, we will calculate the electric field at the photocathode under high irradiation and examine the effects upon the spatial/temporal resolution in a photonic tube.

Space-Charge Model

Following Rack¹, the space-charge in the diode is separated into two regions, shown as the α - and the β -region in Fig. 1. The reduced Poisson's equation for the α -region (between the cathode and the potential minimum) and the β -region (between the potential minimum and the grid) can be written once the electron energy distribution function is specified.

(a) QTED Case

The QTED is given² by

$$n(E_s) = A \frac{E_s}{(E_s + W)^4} \quad (1)$$

where E_g is the photoelectron initial energy, W is the barrier potential of the cathode-vacuum interface, and A is a normalizing factor. The reduced Poisson's equation that apply to each region of the space charge (designated with the subscript α and β) are the following:

$$\left[\frac{d\varphi}{d(k_q x)} \right]_{\beta}^2 = 8 \int_{\mu}^{\infty} \theta(1+\theta)^{-4} [\sqrt{\theta+\varphi} - \sqrt{\theta+\mu}] d\theta \quad (2)$$

$$\left[\frac{d\varphi}{d(k_q x)} \right]_{\alpha}^2 = \left[\frac{d\varphi}{d(k_q x)} \right]_{\beta}^2 + 16 \int_{-\varphi}^{\mu} \theta(1+\theta)^{-4} \sqrt{\theta+\varphi} d\theta \quad (3)$$

where φ , θ , and μ are normalized energy parameters given by

$$\varphi = \frac{eV}{W}, \quad \theta = \frac{E_s}{W}, \quad \mu = \frac{E_m}{W} \quad (4)$$

with eV the electron potential energy at any position x and E_m the initial energy of an electron which would come to rest just at the potential minimum V_m . The inverse dimensional factor, k_q is given by

$$k_q = \frac{2}{\sqrt{3}} \frac{1}{d} \left(\frac{J_e}{J_0} \right) \left(\frac{E_g}{W} \right)^{3/4}, \quad (5)$$

where E_g is the electron energy at the accelerating grid, and d is the cathode-grid spacing. The ratio of the emitted current density J_e to the space-charge-limited current density J_0 is given by an auxiliary equation

$$\frac{J_e}{J_0} = \frac{(1+\mu)^3}{(1+3\mu)} \quad (6)$$

(d) PED Case

The PED is given³ by

$$n(E_s) = \beta \left[1 - \left(\frac{E_s - E_0}{E_0} \right)^2 \right], \quad (7)$$

where E_0 is the potential energy corresponding to the peak distribution, and β is a normalizing factor. The reduced Poisson's equation for the α - and the β -region are the following:

$$\left[\frac{d\psi}{d(k_p x)} \right]_{\beta}^2 = \int_{\sigma}^2 \rho(2-\rho) [\sqrt{\rho+\psi} - \sqrt{\rho-\sigma}] d\rho \quad (8)$$

$$\left[\frac{d\psi}{d(k_p x)} \right]_{\alpha}^2 = \left[\frac{d\psi}{d(k_p x)} \right]_{\beta}^2 + 2 \int_{-\psi}^{\sigma} \rho(2-\rho) \sqrt{\rho+\psi} d\rho \quad (9)$$

where ψ , ρ , and σ are normalized energy parameters given by

$$\psi = \frac{eV}{E_0}, \quad \rho = \frac{E_s}{E_0}, \quad \sigma = \frac{E_m}{E_0}. \quad (10)$$

The inverse dimensional factor is given by

$$k_p = \frac{2}{\sqrt{3}} \frac{1}{d} \left(\frac{J_e}{J_0} \right) \left(\frac{E_0}{E_g} \right)^{3/4}, \quad (11)$$

and the auxiliary equation is given by

$$\frac{J_e}{J_0} = \frac{4}{(4 - 3\sigma^2 + \sigma^3)} \quad (12)$$

Computations

The algorithm for computing the potential distribution involves first in determining E_m/E_0 and E_m/W from the auxiliary equations (6) and (12) for a given J_g/J_0 value. E_m/E_0 and E_m/W is then substituted into the differential equations for the α - and the β -region. The code computes solutions of eV/E_0 versus $k_p x$ and eV/W versus $k_q x$, for the PED and the QTED cases, respectively. The origin of the generated curves from the computation of the differential equations is at the potential minimum. The α - and the β -region curves are then combined onto one coordinate system with the origin shifted to the cathode plane. The combined curves are shown in Fig. 2 (QTED case) and Fig. 3 (PED case). A comparison of the figures reveals the potential minimum to be greater for the QTED case than in the PED case. This is due primarily to the relatively larger population of photoelectrons in the QTED that can surmount the potential minimum as compared to the photoelectrons from the PED.

The actual potential minimum position x_m with respect to the photocathode plane is shown in Fig. 4 for a diode having an interelectrode spacing of 2 mm and an applied voltage $E_g = 1$ KV. The curves have been computed for three different photocathodes S-1, cesium-iodide, and gold. The S-1 (Cs-Ag-O) photocathode is used primarily for application with the 1.06 μ m beam from the Nd:YAG mode-locked laser. The cesium-iodide and the gold photocathodes are used for soft x-ray diagnostics of high-temperature plasmas. The photoelectron energy spread Δ (full-width-half-maximum) is 0.30 eV for the S-1 cathode, 1.65 eV for the cesium-iodide cathode, and 4.05 eV for the gold cathode. For a specified Δ the required W for the QTED and the E_0 for the PED are shown in Table I.

In Fig. 4 for $J_e/J_0 = 10$ and for $\Delta = 4.05$ eV (QTED case), x_m is in the 80 μm range, whereas in the PED case x_m is in the 20 μm range. It is apparent that the specification of the Δ of the photoelectron energy distribution is not an appropriate index in evaluating space-charge parameters since the potential minimum V_m and its position x_m from the cathode is critically dependent upon the actual shape of the energy distribution curve.

Discussion

Space-charge potential perturbation effects can affect both the spatial and temporal resolution in a photonic tube. It is important to note that in real photocathodes the electric field becomes retarding for $J_e/J_0 > 1$. The application of a relatively large accelerating electric field is not necessarily sufficient in overcoming the retarding field due to space-charge. For example, for an applied electric field of -5000 V/cm (accelerating), the cathode field is 1150 V/cm (retarding) for the case of $W = .27$ eV and $J_e/J_0 = 2$, and 3700 V/cm for $J_e/J_0 = 10$. For $W = 3.7$, the cathode field is 7130 V/cm for $J_e/J_0 = 0$, which is about 50% greater in magnitude than the applied accelerating field.

Under pulse operation when $J_e/J_0 > 1$, the retarding electric field set up from the potential minima can introduce a loss in the spatial resolution. Electron trajectories that represent the dynamic focusing condition is shown in Fig. 5 for an electron having $E_s > E_m$. At high intensity, the photoelectron trajectory at the potential minimum undergoes a change from a diverging path to a converging path. At low intensity (in the absence of the potential minimum) the electron describes only the converging

path. The tangent of the trajectory at the grid when projected back to the axis gives the position of the virtual object. At low intensity the virtual object O is closer to the cathode plane as compared to that of the higher intensity case. Nominally, in image tube applications the focus voltage is adjusted at low intensity, well below the intensity that corresponds to the space-charge limited condition. Under pulse conditions (requiring higher intensity) it is well known that dynamic defocusing occurs. From the potential minima model, it is reasonable to assume that dynamic defocusing at high intensity is due to the shift in the virtual object point from O to O' as shown in the Fig. 5. Dynamically, according to this model, a weaker lens is required to focus the object onto the phosphor screen. Experimental confirmation has been obtained with a dissector/restorer framing camera tube⁴. For example, in 2-dimensional imaging spatial resolution loss occurs at high intensity for a fixed focus voltage; however, the resolution can be recovered by adjusting the focus to a lower voltage setting (a weaker lens).

Concurrent to the dynamic defocusing effects, there are also electron transit-time dispersion effects or temporal broadening effects^{5,6}. At high intensity the electron transit-time increases in the retarding field region, as well as in the accelerating region. In the accelerating region the transit-time can increase by 50% under space-charge limited condition⁵. If a parabolic potential distribution is assumed in the retarding field region, the transit-time to the potential minimum (distance x_m from the photocathode for $E_s > E_m$) can be expressed by

$$t = t_m \sinh^{-1} \left[\sqrt{\frac{1}{\frac{E_s}{E_m} - 1}} \right] \quad (13)$$

where

$$t_m = \frac{x_m}{\sqrt{\frac{2 E_m}{m}}} , \quad (14)$$

and m is the mass of the electron. Depending upon the photoelectron energy distribution and the potential minimum V_m , appreciable transit-time dispersion effects can be introduced from the retarding field region. Photoelectrons of energy, $E_m < E_s < 1.7 E_m$, have a transit-time $t > t_m$. If the peak of the energy distribution or Δ is within the range of E_m to $1.7 E_m$, temporal broadening effects could be enhanced because a larger population of slow electrons arriving at the grid will disperse, otherwise, an initially narrow pulse of electrons emanating from the cathode. For example from Fig. 4 a gold photocathode at $J_e/J_0 = 1.1$, the potential minimum ($V_m = 0.85$ V) is located at a distance of $20 \mu\text{m}$ from the cathode for the QTEO. Substitution of $E_m = eV_m$ and x_m into (14) gives $t_m = 36.6$ ps; hence, from (13) for $E_s/E_m = 1.01$, the transit-time is $t = 110$ ps, and for $E_s/E_m = 1.5$, $t = 42$ ps. If the population distribution of the electrons is significant in the energy range $1 < (E_s/E_m) < 1.5$ (for large transit-time), important contributions to the transit-time dispersion will be made from the initially retarding region of the cathode-potential minimum. This contribution will enhance the dispersion effects already discussed in Reference 5, because the perturbation is a significant fraction of the total dispersion time.

References

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Figure Captions

1. The potential profile in the cathode-grid region of a photonic tube for the space-charge model.
2. Normalized potential in the cathode-grid region for the photoelectron quad-tail energy distribution (QTED).
3. Normalized potential in the cathode-grid region for the photoelectron parabolic energy distribution (PED).
4. Potential minimum position for an interelectrode spacing of 2 mm and a grid-to-cathode voltage of 1 KV.
5. Electron trajectories for the dynamic defocusing model (not to scale). α is the retarding field region and β is the accelerating field region.

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Table I

Photocathode Parameters

Photocathode	Excitation	Δ (eV)	W (eV)	E_0 (eV)
S-1	1.06 μm	0.30	.27	.21
CsI	~ 1 keV x-rays	1.65	1.50	1.17
Au	~ 1 keV x-rays	4.05	3.70	2.83

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5