DEVELOPMENT OF DISPENSER PHOTOCATHODES FOR RF PHOTOINJECTORS

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Abstract

Nonlinear photoelectric emission from Scandate dispenser cathodes using 1.06μm radiation in nanosecond scale pulses has been observed. Unlike single photon emission, the photocurrent is a strong function of both the initial lattice temperature and the applied electric field as well as laser intensity. Quantitative agreement is found between experimental data and the proposed model, especially with regards to temperature, field, laser intensity, and laser wavelength (λ) dependence. In particular, for long wavelength incident lasers, the majority of the absorbed photon energy heats the electron gas and background lattice, and photoemission from that electron distribution constitutes the emitted current.

INTRODUCTION

Photoemission sources for Free Electron Lasers[1] under development for a variety of scientific and industrial applications face unprecedented operational demands. FELs need photocathodes to be long-lived, reliable, produce nanoCoulomb (nC) bunches in picosecond (ps) time scales, and operate using the longest wavelength permissible. Such requirements often conflict. Low work function coatings on semiconductors have excellent quantum efficiency (QE), but degrade prematurely and have response times that are too great[2]. Metal photocathodes are rugged, long-lived, and prompt but have low QE and require ultraviolet (UV) drive lasers[3]. The wavelength of drive laser is obtained by non-linear conversion crystals. For the UV case, therefore, a great deal of waste heat (90%) will be dumped into the crystals, altering their operation. Moreover, the non-linear conversion process introduces fluctuations that scale as (Laser intensity)^n, where n is the harmonic number (4 for UV), and such fluctuations appear in the resulting electron pulses, resulting in degraded FEL operation. Nevertheless, photocathodes remain the only viable option for high power, short wavelength FELs.

We report on our investigations of the photoemissive properties of thermal dispenser cathodes, the traditional electron source of rf vacuum electronics devices where ruggedness and reliability are paramount. The low work function coating is maintained by the diffusion of, *e.g.*, barium, to the surface, replacing that which is lost due to desorption, evaporation, and sputtering. Such cathodes can be rehabilitated even when operating in non-ideal conditions. The work function is on the order of 2 eV, and scandate cathodes have shown an even lower work function of 1.8 eV.[6] Here, theoretical models are developed and applied to analyze experimental results. The modeling effort is directed to predict the performance of such cathodes in an FEL rf gun environment, where the laser intensities are orders of magnitude higher, the pulse lengths orders of magnitude shorter, and the applied fields larger, than are found in the present experimental arrangement.

THEORETICAL MODEL

Relationships exist relating the lattice temperature to the electron temperature under laser illumination[4]. Some approximations and observations simplify the calculation of the electron temperature used to estimate the emitted charge. First, the time scale of the laser pulse is 1 ns, but electron-electron and electron-phonon relaxation times are much smaller so that the electron and lattice temperatures are equal. Second, the temperature exponentially decays into the bulk with a decay length parameter L, *e.g,* $(T(x) - T_o)/(T(0) - T_o) = \exp(-x/L)$, where the length scale is L is a multiple of the Fermi velocity and the total scattering relaxation time: the multiplicative factor should be on the order of the square root of the ratio of the laser pulse time scale with the scattering time scale, or $n = \sqrt{(1 \text{ ns} / 0.1 \text{ ps})} \approx 100$. Third, given that the cathode is predominantly tungsten grains, the heating of the electron gas by the laser can be approximated using bulk tungsten parameters. We have found that, invoking these approximations, the electron temperature is the solution of

$$T_e^2\left(T_e - T_o\right) = \frac{3n^2}{\gamma}\left[\frac{G_o(t)}{B_{ep} + A_{ee}T_o}\right] \qquad (1)$$

where T_e and T_o are the surface and bulk temperature $G(t)$ is the energy per unit volume deposited by the laser as a function of time (presumed to be a Gaussian with a time parameter of 2.7 ns), γ is the ratio of the electron specific heat and the temperature (presumed constant), and B_{ep} and A_{ee} are the coefficients of the relaxation times

$$\tau_{ee}\left(T\right) = \frac{\hbar\mu}{A_o}\left(\frac{1}{k_B T}\right)^2 = \frac{A_{ee}}{T^2}; \tau_{ph}\left(T\right) = \frac{\hbar}{2\pi\lambda_o}\left(\frac{1}{k_B T}\right) = \frac{B_{ep}}{T} \qquad (2)$$

where μ is the chemical potential, A_o and λ_o are material-dependent (dimensionless) parameters for tungsten [see Ref. 4], and other symbols have their usual meaning. With the electron temperature and photon wavelength λ in hand, the emitted current can be evaluated. The detailed formulae to do so shall be presented separately; here, in the limit $\beta(\phi - \hbar\omega) \gg 1$ and $\beta\mu \gg 1$, it is approximated by

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$$J_{\lambda}\left(T,\Phi\right) \Rightarrow \left(1-R\right)\frac{\left(2\pi\hbar\right)^{2}}{m\omega\mu^{2}} I_{\lambda}(t) J_{RLD}\left(T,\phi-\hbar\omega\right) \quad (3)$$

where J_λ is the photocurrent, β is the inverse temperature $1/k_BT$, $\hbar\omega$ is the photon energy, $I_\lambda(t)$ is the laser intensity, J_{RLD} is the Richardson-Laue-Dushman equation for thermionic emission, ϕ is the barrier height above the chemical potential (*i.e.,* work function minus Schottky factor), and R is the reflection coefficient (taken as 50% hereafter). The electron is assumed to be transmitted if its energy after photon absorption exceeds the surface barrier height: quantum mechanical tunneling via a modified transmission probability calculation[7] will be deferred to a future work. A detailed theoretical analysis, has shown that asymptotically the QE is

$$QE\left(\hbar\omega > \phi\right) = \theta\left(1-R\right)\left(\frac{\hbar\omega-\phi}{\mu}\right)^{2}$$

$$QE\left(\hbar\omega < \phi\right) = \frac{\theta\left(1-R\right)}{\left(w+1\right)^{3/2}}\left(\frac{\Delta t_e}{\Delta t_\lambda}\right)\left(\frac{\hbar\omega}{q}\right)\left(\frac{J_\lambda\left(T_{\max}\right)}{I_\lambda\left(0\right)}\right) \quad (4)$$

$$w = \left(1-\frac{T_o}{T_{\max}}\right)\left(2+\frac{\left(\phi-\hbar\omega\right)}{k_B T_{\max}}\right)$$

where θ is the fractional coverage of the surface by the low work function coating and Δt is the time constant of the electron or laser pulse. The proportion of the surface covered by low work function material on a dispenser cathode is a thermally regulated phenomenon: temperatures within this study are considerably lower than those generally used when the cathode is run as a thermionic emitter. Surface coverage factors are therefore presumed low. The field used in the Schottky factor is enhanced due to surface roughness (Figure 2): a simple model easily generates enhancement factor of 4x.

EXPERIMENTAL PROCEDURE

Scandate cathodes fabricated by Spectra-Mat Inc.[5] were illuminated by a Q-switched Nd:YAG laser with full width at half maximum (FWHM) pulses of Δt = 4.5 ns. The field between the cathode and anode was varied from 0 to 2.5 MV/m. The laser was focused to a circular spot on the cathode with a FWHM area of approximately ΔA = 0.3 cm^2; "current density" below is defined as the ratio of total emitted charge with Δt and ΔA. The photon wavelengths (in nm) of the 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} harmonics of the Nd:YAG laser are 1064, 532, 355, and 266, respectively. The electron emission from 2^{nd}, 3^{rd}, and 4^{th} harmonics exhibited "normal" photoemission characteristics, that is, the emission was proportional to the incident laser intensity and independent of electric field low (0.1 to 2.0 MV/m) field gradients: the QE at these wavelengths are shown in Figure 1

The FWHM illumination area of the incident laser was 0.3 cm^2 implying the e^{-2} simulation radius is 0.5249 cm. The cathode was a 1.27 cm diameter rod. The anode was a tube with a 1.27 cm inner diameter and a 2.54 cm outer diameter. The edges of the anode facing the cathode were rounded, and sat inside a dielectric tube with an inner diameter of 3.175 cm. The anode-cathode separation was 0.4 cm. Simulation showed that with a 1 kV anode potential, the tangential and perpendicular fields were, at the center, 0 MV/m and 0.17 MV/m, respectively, while at the edge (where the illumination was weak), they were 0.2 MV/m and 0.45 MV/m, respectively. The electron temperature is therefore greatest where the laser intensity is strongest, and occurs near the center of the beam spot. The cathode surface, shown in Figure 2, was corrugated due to machining, and therefore field enhancement occurs. Except for Figs. 1&2, λ =1064 nm in all figures.

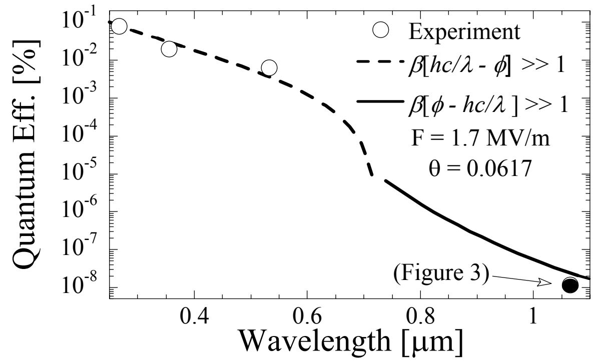

Fig. 1: Measured QE at various λ for Scandate dispenser cathode. Lines refer to Eq. 4. Black dot = same in Fig. 3.

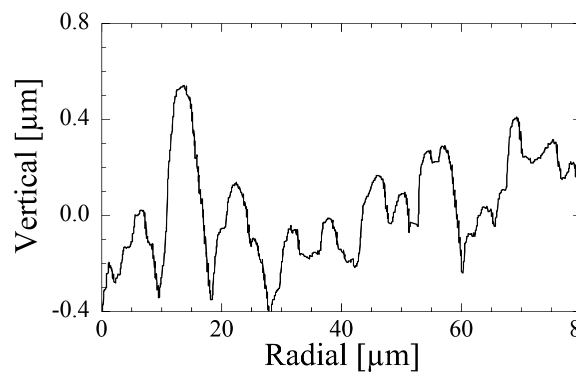

Fig 2: Cathode surface cross-section profilometry plot.

RESULTS

The experimental parameters varied are laser intensity, macroscopic field, and bulk temperature. The QE of various metals reported in the literature serve as an independent confirmation of the values used in the theoretical analysis. Parameters which are unknown, such as the exact value of the reflectivity, work function at the emission site, proportion of the emission sites participating, thermal factors of the dispenser cathode, *etc.*, use appropriate generic parameters (*e.g.,* R = 50% Φ = 1.8eV) or are treated as effective parameters.

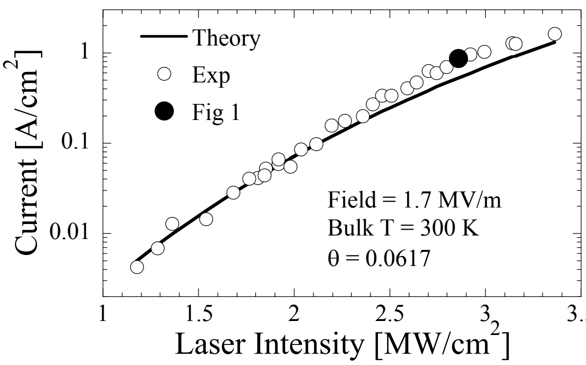

Fig. 3: Current Density *vs.* laser intensity.

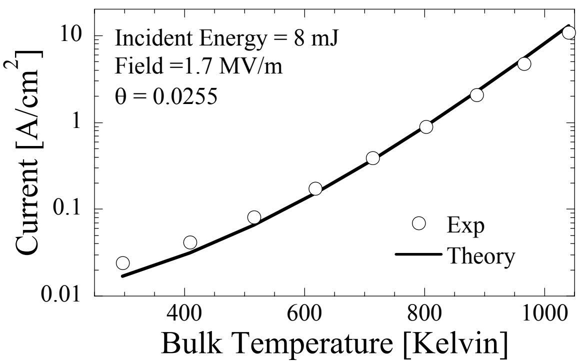

Fig. 4: Same as Figure 3, but for variation in temperature

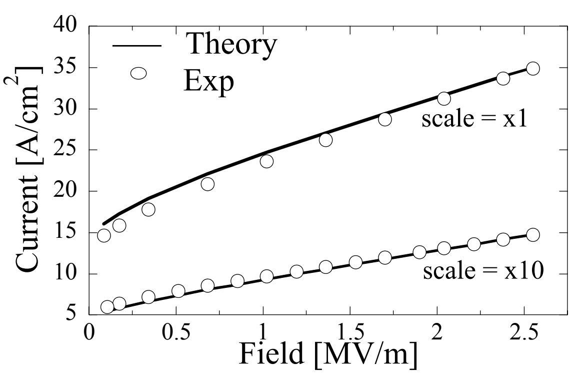

Fig. 5: Same as Figure 3, but for variation in field (top) 5.3 MW/cm^2, 713 K; (bottom) 2.9 MW/cm^2, 633K

CONCLUSION

We have found that the theoretical model of a laser-heated electron gas giving rise to photo-thermal-field emission is consistent with experimental findings of infra-red laser illumination of a Scandate dispenser cathode. The surprisingly good quantitative agreement between experiment and simulation, seen in the Figures, bodes well for theoretical extrapolation to parameters not achieved experimentally but nevertheless representative of future devices. Temporal characteristics of the laser and the limitations of the test cell constrain the power density and electric fields achieved to well below those characteristic of an rf photoinjector. Nevertheless, extrapolations based on the present study clearly indicates that dispenser cathodes function as a promising photocathode candidate, as indicated by the theoretical extrapolations performed in Fig. 7.

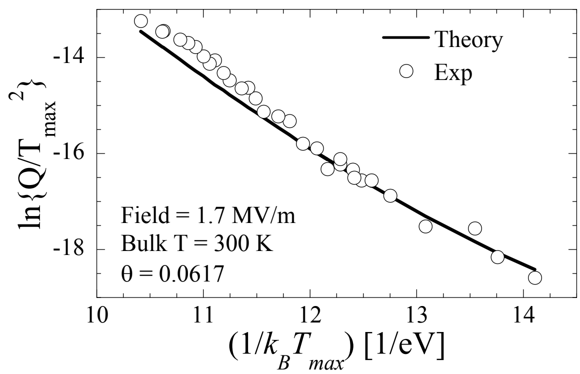

Fig. 6: Demonstration that current follows *field & photo-enhanced thermal emission model* (Eq. (3)). Max temperature evaluated via Eq. (1) for center of laser pulse.

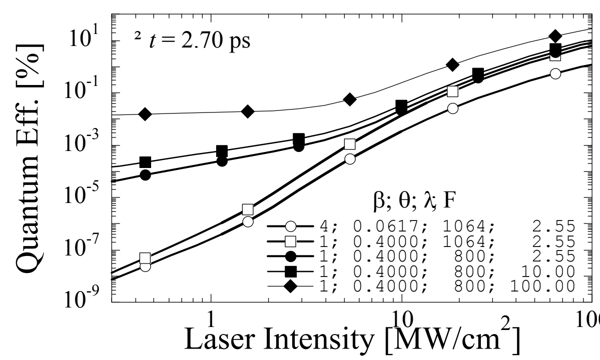

Fig. 7: Extrapolation for other θ, λ[nm] and F[MV/m]for Scandate cathode. β=1 means no field enhancement

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REFERENCES

[1] P. G. O'Shea, H. Freund, *Science* **292**, 1853 (2001).

[2] W. E. Spicer, A. Herrera-Gómez, SLAC-PUB-6306 & SLAC/SSRL-0042, Aug 1993; P. Michelato, *Nucl. Inst. Meth. Phys. Res.* **A393**, 455 (1997).

[3] J. A. Nation, L. Schächter, F. M. Mako, L. K. Len, W. Peter, C.-M. Tang, T. Srinivasan-Rao, *Proc. of the IEEE* **87**, 865 (1999)

[4] N. A. Papadogiannis, S. D. Moustaïzis, J. P. Girardeau-Montaut, *J. Phys. D: Appl. Phys.* **30**, 2389 (1997); N. A. Papadogiannis, S. D. Moustaizis, J. Phys. D: Appl. Phys. 34, 499 (2001).

[5] Spectra-Mat, Inc., 100 West Gate Drive, Watsonville, CA 95076. http://www.spectramat.com

[6] R. Thomas, *Naval Research Laboratory* (*unpublished data obtained from A. Shih and J. Yater*).

[7] K. L. Jensen, P. G. O'Shea, D. W. Feldman, *Appl. Phys. Lett.* **81**, 3867 (2002).