PULSED LASER HEATING OF THERMIONIC CATHODES IN RF GUNS*

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Abstract

The proposed injector design for the X-ray Free Electron Laser Oscillator [1] features a 100 MHz, ultra-low emittance thermionic rf gun [2]. The required beam rate is 1 to 10 MHz, so 90 to 99% of the beam must nominally be dumped. In addition, back-bombardment of the cathode is a significant concern. To address these issues, we investigated pulsed laser heating of the cathode to gate the emission. This may be preferable to a photocathode in some cases owing to the robustness of thermionic cathodes and the ability to use a relatively simple laser system. We present calculations of this process using analysis and simulation. We also discuss potential pitfalls such as cathode damage.

MOTIVATION

The proposed X-ray Free Electron Laser Oscillator uses a 100 MHz thermionic rf gun [2] . However, owing to the required undulator length and the corresponding round-trip time in the oscillator cavity, the required beam rate is about 1 MHz. If several oscillators are served by one injector, the desired beam rate might be as high as 10 MHz. This implies that 90 to 99% of the beam exiting the gun must be dumped. Because the gun produces a 1 MeV beam with an average current of 100 mA, the average beam power to be dumped is on the order of 100 kW.

Because the gun cathode emits continuously, beam is accelerated for 50% of each rf cycle. Electrons that leave late in the cycle do not exit the gun before the field reverses sign, and are back-accelerated into the cathode. This "back-bombardment" has been simulated [3] and found is unacceptable in terms of power and power density. One solution may be to use a laser to thermally pulse the cathode. In this concept [4], the cathode is held at an elevated temperature that is insufficient to allow significant thermionic emission. The cathode surface is pulsed above the emission temperature at, e.g., 1 MHz, by an IR laser.

THEORY

We used the one-dimensional diffusion equation to model pulse heating by nanosecond laser pulses. One might question whether the application of the diffusion equation is valid on such short time scales. A qualitative argument indicates that it should be. The mean time between collisions with impurities and lattice defects for conduction electrons in a metal is [5] $\tau = m/(ne^2\rho)$, where m is the electron mass, n the number density, e the charge, and ρ is resistivity. Using values for Tungsten gives $\tau \sim 1$ fs. This indicates that free electrons that pick up energy from the laser quickly share this energy with the lattice. The resistivity of CeB_6, another material of interest, is nearly the same as that for Tungsten, while the electron number density is about four times higher, giving a slightly longer collision time. Hence, the diffusion equation should be valid for nanosecond time scales for both materials.

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In our one-dimensional model, the temperature deviation $\tau(z,t)$ is a function of depth z into the cathode and time t. All heat transfer occurs from the surface into the semi-infinite cathode rod. We assume that material properties of the cathode, i.e., the cathode emissivity ϵ, specific heat capacity C_p, mass density ρ, and thermal conductivity K, are temperature-independent over the temperature excursion induced by the laser.

In terms of the thermal diffusivity $\kappa = \frac{K}{\rho C_p}$, the temperature profile is governed by the diffusion equation, the laser spatial and temporal profiles, and the boundary conditions, respectively given by

$$\frac{\partial}{\partial t}\tau(z,t) = \kappa\frac{\partial^2}{\partial z^2}\tau(z,t) + S(z,t), \quad (1)$$

$$S(z,t) = \frac{\epsilon}{\rho C_p}\frac{P_0}{\pi R^2}a(t)\delta(z), \quad (2)$$

and

$$\text{BC}: \ \tau(z,0) = 0 \qquad \left(\frac{\partial}{\partial z}\tau(z,t)\right)_{z=0} = 0, \quad (3)$$

where $S(z,t)$ is the laser profile, $a(t) = e^{-\frac{(t-t_0)}{2\sigma^2}}$ is the normalized envelope of the laser pulse of offset t_0 and width σ, P_0 is the peak laser power and R is the laser spot (assumed circular) radius on the cathode. The first boundary condition is the initial condition that the temperature rise be zero, while the second is the condition that there is no temperature gradient at the cathode surface. The cathode is placed at $z = 0$ and we seek to solve Eqns. 1 and 3 over the range $0 \le t < \infty$ and $0 \le z < \infty$ (ie. we assume the cathode is infinite in z). In Eq. 2 the delta function imposes the condition that the laser energy is deposited over a negligible distance inside the cathode material, i.e., on the surface.

Since the electrons from thermionic emission are generated at the cathode surface, we are only interested in the solution of the diffusion equation for $\tau(0,t) \equiv \tau(t)$. The solution is readily obtained using a Green's function.

$$\tau(t) = \frac{\epsilon P_0}{\rho C_p R^2 \sqrt{\pi^3 \kappa}} G(t) \quad (4)$$

$$G(t) = \int_0^t \frac{a(t')}{\sqrt{(t-t')}} dt' \quad (5)$$

where the Green's function integral $G(t)$ can be numerically determined by convolution of the laser pulse profile $a(t)$ with the function $t^{-1/2}$. The cathode surface temperature rise given by Eq. 4 represents a fast rise due to a few ns FWHM pulse from an infared laser.

The total temperature of the cathode surface is given by $T(t) = \tau_0 + \tau(t)$, where τ_0 is the bulk temperature of the cathode. Eq. 4 was verified to agree with a numerical evaluation [4, 6] of the diffusion equation for both tungsten and cerium hexaboride (CeB_6) cathodes for a gaussian laser pulse of $\sigma = 2.5$ ns. For low repetition rate lasers, the bulk cathode temperature τ_0 is determined by the cathode heater filament. For the MHz class lasers required here, the average laser power is significant, so cathode cooling will determine the bulk temperature of the cathode. We present results for a low repetition rate laser gating experiment using a tungsten cathode elsewhere in these proceedings [7].

Given the temperature profile, the current density is given by the Richardson-Dushman equation,

$$J(t) = A_0 T^2(t) e^{-e\phi_{eff}/kT(t)} \quad (6)$$

where J is the cathode current density, A_0 is a constant characteristic of the material, ϕ_{eff} is the effective work function including the Shottky term, and k is Boltzmann's constant. The total current is $I(t) = A_{las}J(t)$ where A_{las} is the area of the laser spot. We assumed a CeB_6 cathode, for which [8] $\phi_{eff} = 2.21$ eV (taking a surface field of 23.5 MV/m) and $A_0 = 19.1$ mA/(mm K^2). Using $P_0 = 143$ kW, $\sigma_t = 2.5$ ns, $R = 0.5$ mm, $\tau_0 = 800$°K, and $\epsilon = 0.8$, we obtained the temperature rise and emitted current as a function of time, as shown in Figure 1.

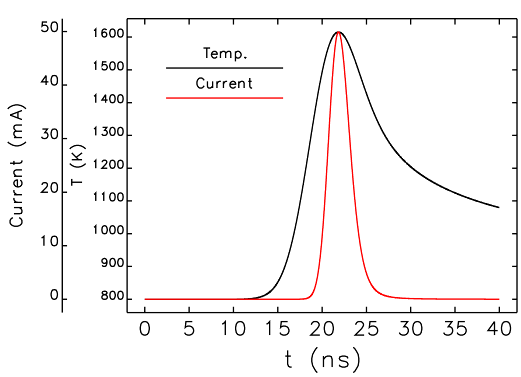

Figure 1: Temperature rise and current emitted by a CeB_6 cathode. See text for details.

In addition to solving Eq. 6, we wrote a program to numerically solve the diffusion equation, allowing us to visualize propagation of the heat pulse into the cathode. This code also includes radiative heat loss from the cathode surface, which is found to be a negligible effect. The result is shown in Fig. 2, where we see that the region of elevated temperature is sub-micron in thickness. The peak surface temperature agrees well with Fig. 1.

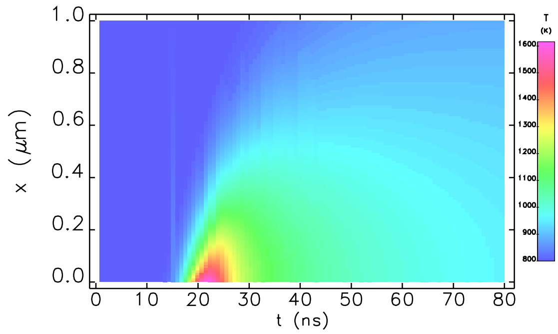

Figure 2: Spatio-temporal temperature profile for laser-pulsed CeB_6 cathode.

For high repetition rates the average laser power absorbed by the cathode may be quite high. In our example, the absorbed laser pulse energy is 0.7 mJ, giving an average absorbed power of 700 W and a power density of 900 W/mm^2. The average power is more than ten times what is expected from back-bombardment [3], while the peak power density is an order of magnitude lower. Unlike back-bombardment, the power distribution from the laser is expected to be fairly uniform across the surface of the cathode, which helps to prevent hot spots that may result in cathode damage. Clearly, if this scheme is used at the envisioned 1 MHz repetition rate, the cathode would require efficient cooling to remove the average power. Whether this is feasible is unknown. If not, it will limit the repetition rate below the desired 1 MHz. Further, there may be issues with transient stresses on the cathode material during each laser pulse. These are discussed in the next section.

As discussed in [3], there are other approaches to addressing the back-bombardment problem for the XFEL-O gun. Unfortunately, these do not simultaneously resolve the beam rate issue. However, there are other gating concepts that may address this [9].

THERMOMECHANICAL SIMULATION

We next simulate the thermal stresses encountered by a CeB_6 thermionic cathode being studied for use in the XFEL-O rf gun. The cathode must operate at or slightly above 1500 °C for several nanoseconds and then cool down several hundred °C in approximately the same amount of time, with a 1-MHz heating-cooling cycle. A transient thermal analysis was performed to optimize the laser pulse shape (≈ 5 ns FWHM) needed to provide the desired temperature response of the cathode for several possible cathode materials. In addition, thermal stresses developed in the cathode during heating-cooling cycles were analyzed. Both transient thermal analysis and thermal stress computations were performed using the ANSYS12 code.

The main challenge in modeling the cathode response to laser pulse heating is to properly recognize the nature of interaction between the laser beam and the material of the cathode. For pulse lengths in the nanosecond range, our assumption is that the temperature fields can be predicted correctly by solving the diffusion equation without the need to consider non-Fourier effects [10]. However, there are conflicting data in the literature [11, 12] as to whether the stress distribution can be predicted by quasi-static structural model or thermoelastic wave propagation, and whether the spallation has to be considered for our combination of pulse lengths and laser intensity.

In order to accurately capture temporal temperature peaks and yet limit the computation time, the model of the cathode was divided in three zones. In the cathode tip zone that extended 2.5 μm inwards, the mesh was finest and the mesh size in the direction of the heat transfer was 0.1 μm. The cathode response was modeled for several different temporal pulse profiles of a 250-μJ laser. The results, shown in Fig. 2, indicate that the 250-μJ laser is capable of producing the required temperature peaks and that the shape of the temperature response is defined with the temporal profile of the laser pulse. The shape of the response is similar to the experimentally observed change in laser-induced electron emission of the Injector Test Stand gun at the APS [7].

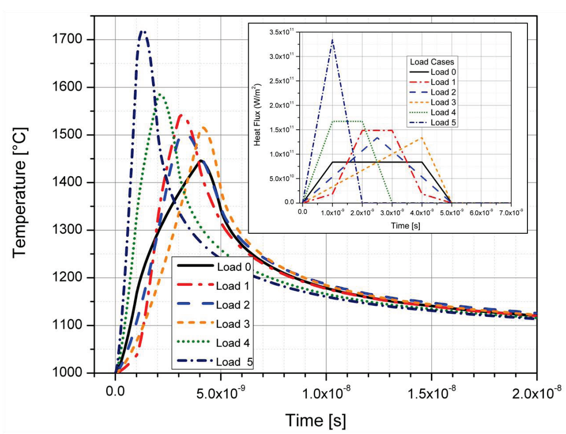

Figure 3: Cathode temperature response to various laser pulses power density profiles.

The results of quasi-static structural analysis, based on the temperature distribution at the time of the peak temperature for the load (heat flux) case 1 (see Fig. 2), are shown in Figure 3. Maximum values of equivalent stresses (1.4 GPa) occur in the center of the cathode tip. High stress areas are also observed at the border between the exposed and unexposed areas of the cathode tip (the diameter of the tip is 1.2 mm while the diameter of the exposed area is 1mm). These high stress results indicate further investigation based on the thermoelastic stress wave propagation is necessary.

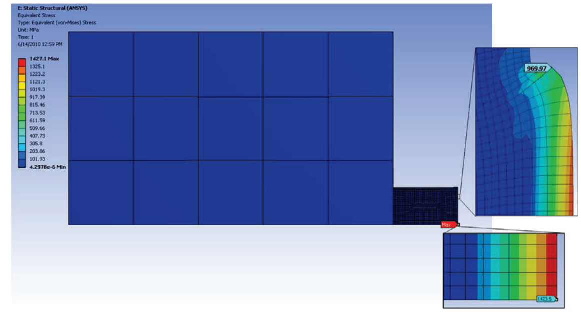

Figure 4: Stress distribution in the cathode for a given surface peak temperature due to the laser pulse.

CONCLUSION

We have developed a simple theory of laser gated thermionic cathode electron emission based on the 1-dimensional diffusion equation and the Richardson-Dushman equation. The diffusion equation was solved analytically using a Green's function and checked against two different numerical simulations. The model is simple enough to allow straightforward comparison to simulation and experimental analysis. The model was used to successfully analyze data taken using a standard APS thermionic rf gun in the APS ITS [7]. It was also used to benchmark the ANSYS code used in the thermomechanical stress analysis of a laser heated cathode under XFEL-O injector conditions.

We obtained good agreement between the FEA and analytical results for the thermal analysis of the cathode response to laser heating. Preliminary stress distribution computations indicate high maximum stress values. Further investigation based on the thermoelastic stress wave propagation is necessary.

REFERENCES

[1] K. J. Kim *et al.*, Phys. Rev. Lett. 100, 244802 (2008).

[2] P. N. Ostroumov *et al.*, Proc. LINAC08, 676-678 (2008).

[3] M. Borland *et al.*, these proceedings.

[4] M. Borland, private comminication, 1993.

[5] C. Kittel, *Introduction to Solid State Physics*, 5^{th} edition, J. Wiley and Sons, 1976.

[6] B. Brajuskovic *et al.*, Proc. MEDSI-6, to be published.

[7] N. S. Sereno, *et al.*, these proceedings.

[8] K. Togawa *et al.*, Phys. Rev. ST Accel. Beams 10, 020703 (2007).

[9] X. Dong *et al.*, these proceedings.

[10] X. Wang and X. Xu, Journal of Thermal Stress, 25 457-473 (2002).

[11] W. M. Steen, *Laser Material Processing*, 3^{rd} Edition, Cambridge University Press (1995).

[12] I. Gilath *et al.*, Journal of Material Science, 23 1825-1828 (1988).