LASER COOLING TO COUNTERACT BACK-BOMBARDMENT HEATING IN MICROWAVE THERMIONIC ELECTRON GUNS*

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Abstract

A theoretical study of the use of laser cooling to counteract electron back-bombardment heating (BB) in thermionic electron guns is presented. Electron beams with short bunches, minimum energy spread, and maximum length pulse trains are required for many applications, including the inverse-Compton X-ray source being developed at UH. Currently, these three electron beam parameters are limited by BB which causes the cathode temperature and emission current to increase leading to beam loading. Beam loading elongates the bunches by shifting the electrons' relative phases, introduces energy spread by reducing the energy of electrons emitted later in the macropulse, and forces the use of shorter macropulses to minimize energy spread. Irradiation of the electron gun cathode with a short laser pulse prior to beam acceleration allows the laser heat to diffuse into the cathode bulk effectively cooling the surface and counteracting the BB. Calculation of the the cooling produced by laser pulses of various duration and energy is presented.

INTRODUCTION

The principle limitation to the average current delivered by thermionic electron guns is due to back-bombardment heating (BB). Due to the oscillatory nature of the accelerating field in these guns, some electrons that are emitted from the cathode turn around before exiting the accelerating cavity and hit the cathode, increasing its temperature. The temperature increase can be decreased by use of a deflection magnet [1], but cannot be eliminated (our deflection magnet at UH provides a 28% decrease in BB rate [2]). This rise in temperature limits the macropulse length to 5 µs in our gun at UH, similar to other guns [3]. However, if the cathode is maintained at a lower temperature between macropulses (typically by a slow response time heater and feedback circuit) and the surface is heated with a laser just prior application of the RF accelerating voltage, the diffusion of the laser heat from the higher temperature cathode surface into the lower temperature bulk produces cooling of the surface as proposed by Madey [4]. In this work, the cooling effect of various length and energy laser pulses is simulated using a finite difference method (FDM). Results are shown indicating that macropulse lengths up to 23 µs can be achieved with heat from a 7 µs, 300 mJ laser pulse.

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SIMULATION

The temperature of the cathode is simulated with the one dimensional heat diffusion equation [5]:

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial z^2} - P_{\text{rad}}/(C_v V) + P_{\text{BB}}/(C_v V), \qquad (1)$$

with D the temperature dependent diffusivity from Tanaka [6]. The radiated power, P_{rad}, is non-zero only at the emitting surface (we neglected radiation at the other surfaces as it is small compared to BB due to the small temperature difference between the other surfaces and surrounding) and is defined by:

$$P_{\text{rad}} = \epsilon\sigma A(T^4 - (300K)^4), \qquad (2)$$

with ϵ the emissivity of LaB_6 [7], σ Stefan's constant, A the cathode area, C_v the temperature dependent volumetric heat capacity [6], and V the volume. Note that P_{rad} at the surface is also small compared to the BB in all cases except where the cathode surface temperature is brought to high values by short, high energy laser pulses. The BB power, P_{BB}, depends on many parameters include the energy distribution of BB electrons and the cathode material properties (in this case LaB_6) and has been calculated for our gun by McKee [8] at an emission current of 600 mA. Since the emission current changes with temperature according to the Schottky equation,

$$I_{gun} = AA_G T^2 e^{(\phi_{LaB_6} - d\phi)/(k_B T)}, \qquad (3)$$

and the number of BB electrons is roughly 30% of the emission current in the narrow temperature range of interest [8], P_{BB} is scaled linearly with emission current. In equation 3, A is the cathode area, ϕ_{LaB_6} is the work function, T is the temperature, and $d\phi = \sqrt{e^3 E/(4\pi\epsilon_o)}$ with E the applied electric field. The value of the work function, ϕ_{LaB_6}=2.43 eV, is determined empirically by fitting measured surface temperature and output current pairs to the Schottky equation with ϕ_{LaB_6} as a free parameter and is in rough agreement with values in the literature [3, 9, 10]. The Richardson constant for LaB_6 is $A_g = 29$ A/(cm^{2}K) [10].

Equation 1 is solved for 1.52 mm long, 1.5 mm radius cylinder with an FDM via:

$$\begin{aligned} &T(n+1,j) - T(n,j) \\ &= \frac{D\triangle t}{\triangle z^2}(T(n,j+1) - 2T(n,j) + T(n,j-1)) \end{aligned} \qquad (4)$$

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with the terms containing P_{rad} and P_{BB} added at each time step and n and j being the index of the time step and spatial bin, respectively. The spatial bin size is $\triangle z$ =1 µm and determines $\triangle t$ =27 ns through the stability condition of the FDM, $D\triangle t/\triangle z^2$ <0.5, with some extra slack to account for the change in the diffusivity D with temperature. The spatial bin size should be the typical deposition depth of a laser into a metal of 10-100 nm [11] to accurately model the deposition and diffusion of heat, but long simulation times and memory requirements force the use of the larger $\triangle z$ spatial bins. We show in the RESULTS section that the change in simulation results with the larger bins is minimal.

The simulations are run for laser pulse lengths from 1 to 30 µs and energies from 10 to 300 mJ. For each pulse length and energy the standby temperature of the cathode (temperature between macropulses) is adjusted so that dT/dt from only the diffusion of the laser heat (no BB) is equal and opposite to dT/dt from only BB (as we measured previously [2]) at the operational target temperature of T_{op} =1718 K. We denote the time after the laser pulse begins where the derivatives match as t_{match}. Back-bombardment heating is then turned on at t_{match}, simulating initiation of the RF macropulse.

RESULTS AND DISCUSSION

The simulations result in the temperature slightly dipping from T_{op}, flattening out, then rising slowly as depicted in Figure 1 for a 7 µs, 300 mJ pulse.

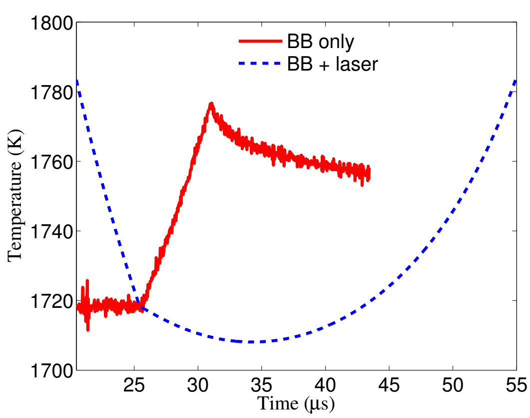

Figure 1: Comparison of temperature change with time due to BB only (red solid line, measured) and due to BB plus a 7 µs, 300 mJ laser cooling pulse (blue dashed line).

Our FEL at UH has been able to lase continuously during a 20 K ramp in cathode temperature, so for each pair of pulse length and energy a 'flat time', t_{flat}, was calculated by taking the difference between the time when the cathode temperature exceeds T_{op}+20 K and t_{match}. Each t_{flat} is plotted in Figure 2.

The results in Figure 2 indicate that the shortest, most energetic pulses produce the longest t_{flat}, however such high power pulses cannot be practically used to heat the cathode. Figure 3 shows that short, energetic pulses cause the

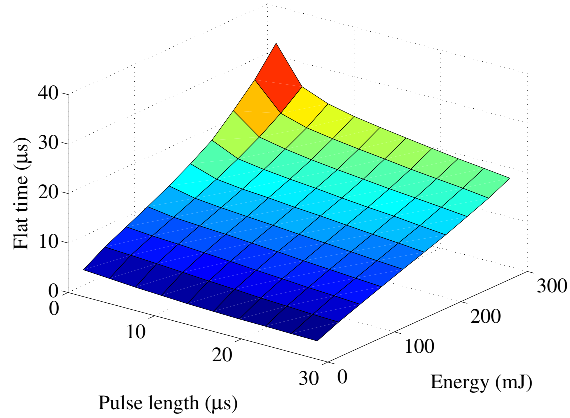

Figure 2: 'Flat times', t_{flat}, (described in the text) as a function of laser pulse length and energy. Note the slow drop in t_{flat} as the pulse length is increased at a particular pulse energy.

cathode surface temperature to exceed the melting point of LaB_6 of 2988 K [12]. Since t_{flat} decreases very slowly with pulse length and the maximum temperature decreases very rapidly with pulse length, long t_{flat} can still be achieved using long laser pulse lengths and high energy without exceeding the melting point of the cathode. For example, the 7 µs, 300 mJ pulse in Figure 1 has a t_{flat} of 23.1 µs and reaches a maximum temperature of 2759 K.

If the simulation spatial bin $\triangle z$ is decreased as described at the end of SIMULATION section, since all of the laser heat is deposited in a single spatial bin, the simulated maximum temperature of the cathode surface and the temperature gradient will increase for a given pulse length and energy. However, t_{flat} increases as the laser induced temperature gradient is increased (hence the trend of longer t_{flat} with higher energy), so lower maximum temperatures will be required for the same t_{flat} with smaller $\triangle z$. Simulation of a 7 µs, 300 mJ pulse with $\triangle z$ =500 nm showed a t_{flat} of 23.5 µs and a maximum temperature of 2815 K: a small change from the $\triangle z$ =1 µm case, indicating that the change in simulation results for the desired $\triangle z$ =100 ns should also be small.

CONCLUSION

Simulation of the one dimensional heat diffusion equation for a thermionic electron gun cathode incorporating radiation, back-bombardment heating, and diffusive laser cooling indicates that macropulse lengths up to 23 µs with less than 20 K temperature excursion can be achieved using a 7 µs, 300 mJ laser pulse. If this technique can be physically realized, a factor of 4 increase in macropulse length and a decrease in temperature rise is available. These improvements would result in an increase in the average current, a decreased change in emission current, less beam loading, shorter bunches, and less energy spread in the emitted electron beam removing the current limitations of thermionic electron guns and making them more suitable

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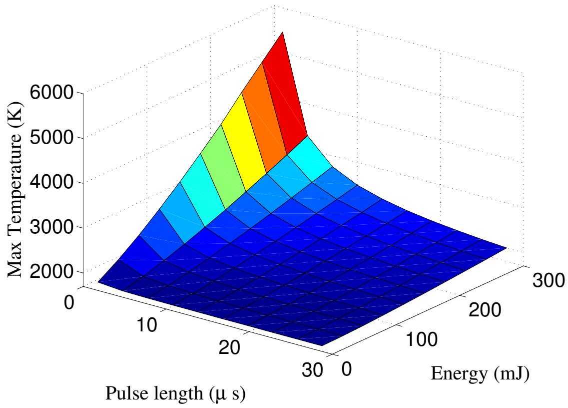

Figure 3: Maximum temperature of the cathode surface as a function of pulse length and energy. Note that fast drop in maximum temperature as the pulse length is increased at a particular energy.

for applications such as inverse-Compton X-ray sources.

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