Analytical Thermal Analysis of Thin Diamond in High-Intensity and High-Repetition-Rate Application

SLAC NATIONAL ACCELERATOR LABORATORY
U.S. DEPARTMENT OF ENERGY
Office of Science

Ye Hong[1+], Bo Yang[1,2‡], Guanqun Zhou[3,4], Juhao Wu[3 §]

[1]University of Texas at Arlington, 500W 1st St., Arlington, Texas, USA

[2]Western Digital Company, Milpitas, California, USA

[3]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California, USA

[4]Institute of High Energy Physics, and UCAS, Chinese Academy of Science, China

[+]Contact: [+]ye.hong@mavs.uta.edu, [‡]bo.yang5@wdc.com, [§]jhwu@slac.stanford.edu

Introduction

In the present paper, an analytical steady-state solution for continuous-wave (CW) laser input is derived to address potential thermal issues in thin diamond. The temperature-dependent thermal properties of diamond, i.e., thermal conductivity and specific heat capacity, valid for temperature in the range from $100\,K$ to $3000\,K$, are used in the calculation. The objective of this study is to provide a quick estimation tool for determining operational guild line based on thin-diamond material properties and cooling condition under focused laser heating at high repetition rates. From the steady-state solution, by setting the central temperature $T_0^* \to \infty$, the thermal runaway condition can be defined. A relaxed thermal runaway condition can also be defined by setting T_0^* equal to a finite value, for instance, graphitization temperature, to address a particular effect of concern. The relationships between dimensionless terms of cooling edge distance to laser waist size ratio R/a, edge cooling temperature T_R, and critical (allowed) laser heating power fI are discussed. It shows that the critical heating power fI is higher with smaller R/a, and lower T_R. However, when it comes to design of an edge cooling system, there are limits such as the size of the working area and the size of the cooling device.

Problem Formulation

Consider a train of X-Ray pulses impinging perpendicularly at the center of a circular, thin diamond crystal at repetition rate f, as illustrated in Fig. 1. The circumferential sink temperature is held constant via a cooling system. The pulses are assumed to be Gaussian, and extremely short compared to all other time scales under consideration. The heat is deposited instantly while a laser pulse passes through the crystal. The problem is axisymmetric with radial axis r set from the center. The temperature field is assumed to be uniform in the through-thickness direction. The deposited energy is dissipated by conduction inside the plate only; any radiative heat transfer is assumed to be negligible.

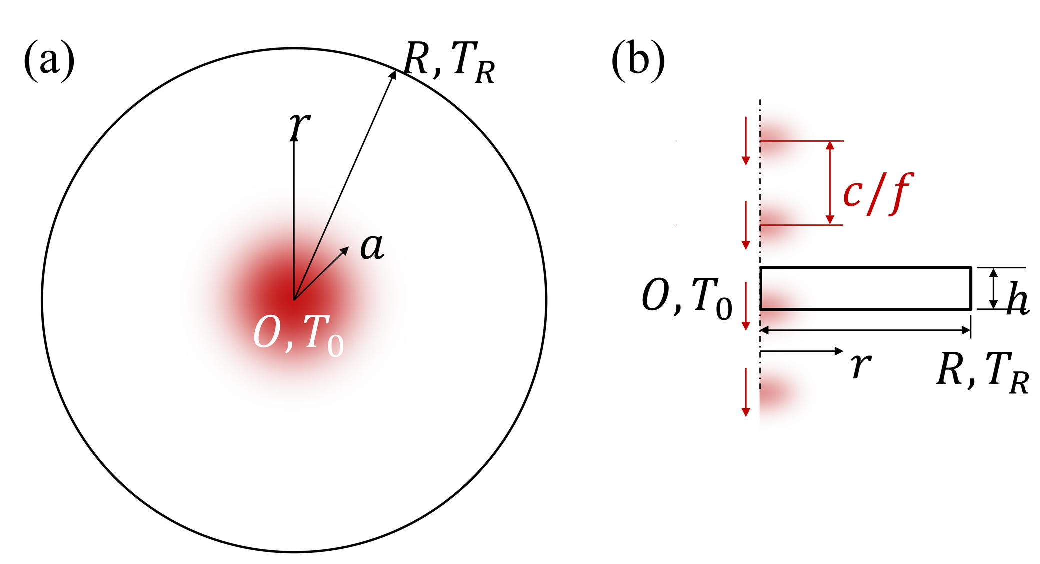

Fig 1.Schematic show of high repetition rate laser heating in a thin crystal: (a) top view and (b) side view.

- Heat flux in radial direction: $j = \kappa \frac{\partial T}{\partial r}$
- Temperature dependent thermal conductivity: $\kappa = \alpha T^{-\beta}$
- Circumferential heat flux: $j = \frac{a^2 f i_0}{4hr}\left[1 - e^{-2(r/a)^2}\right]$
- Central-edge temperature ratio: $\frac{T_0}{T_R} = \left[1 - \frac{(\beta - 1) fI}{4\pi h \kappa_R T_R}\mathrm{Ein}\left(\sqrt{2}R/a\right)\right]^{1/1-\beta}$

$$\mathrm{Ein}\left(\sqrt{2}R/a\right) \equiv 2\int_0^R \frac{1-e^{-2(r/a)^2}}{r}\,dr$$

Results & Discussion

By using above κ_R values of α and β, setting $h = 110\,\mu m$ of a thin diamond crystal, steady-state runaway conditions are evaluated for various values of T_R, T_0^*, and R/a. Fig. 2 shows the variation of steady-state central temperature T_0 as a function of laser input power fI for various edge cooling temperatures from $100\,K$ to $300\,K$ and fixed crystal size to laser spot size ratio $R/a = 50$. Fig. 3 shows the critical power fI as a function of R/a for the definite runaway condition. it gives the perspective of

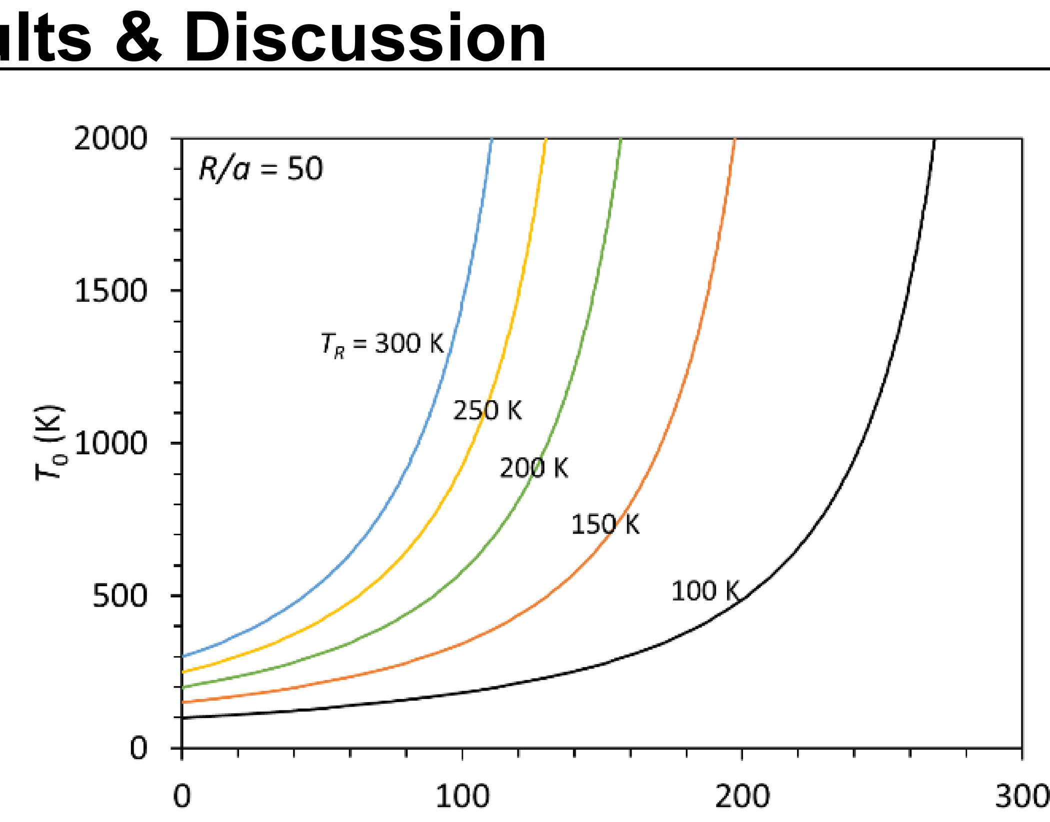

Fig 2: Variations of steady-state central temperature as a function of laser heating power for fixed $R/a = 50$ and various $T_R = 100, 150, 200, 250$ and $300\,K$

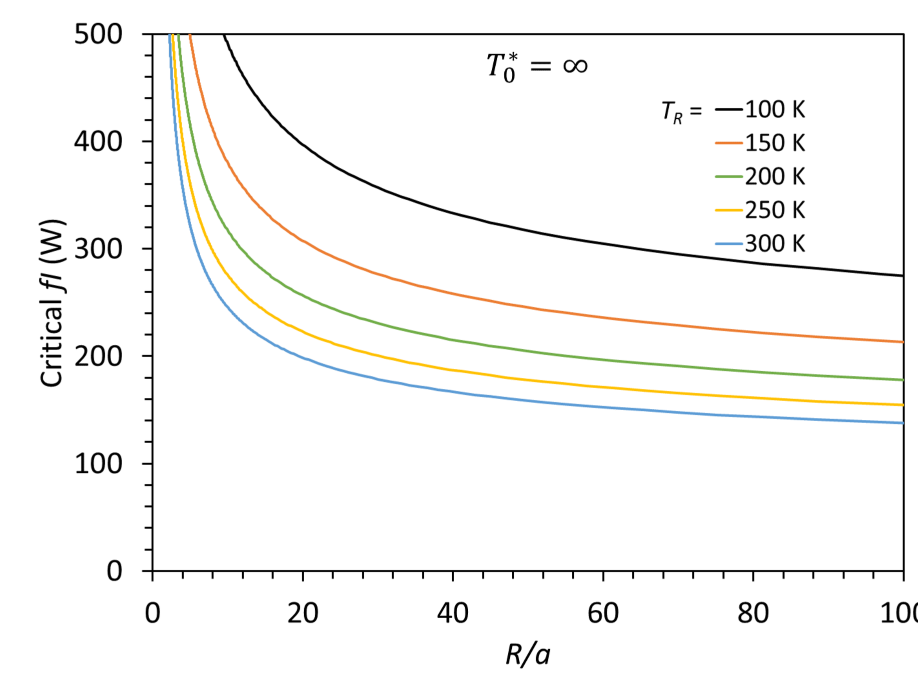

Fig 3: Variation of critical laser heating power at definite runaway condition ($T_0^* = \infty$) as a function of $R/a$for $T_R = 100,, 150, 200,\ 250\ and\ 300K$.

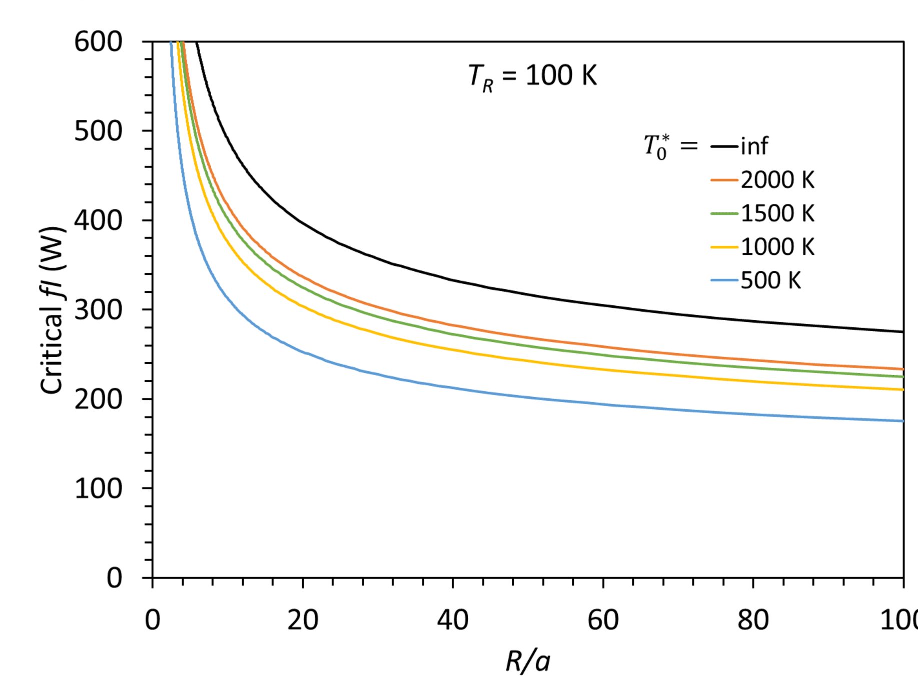

Fig 4: Variation of critical laser heating power at definite runaway condition ($T_0^* = \infty$) as a function of R/a for $T_R = 100\,K$.

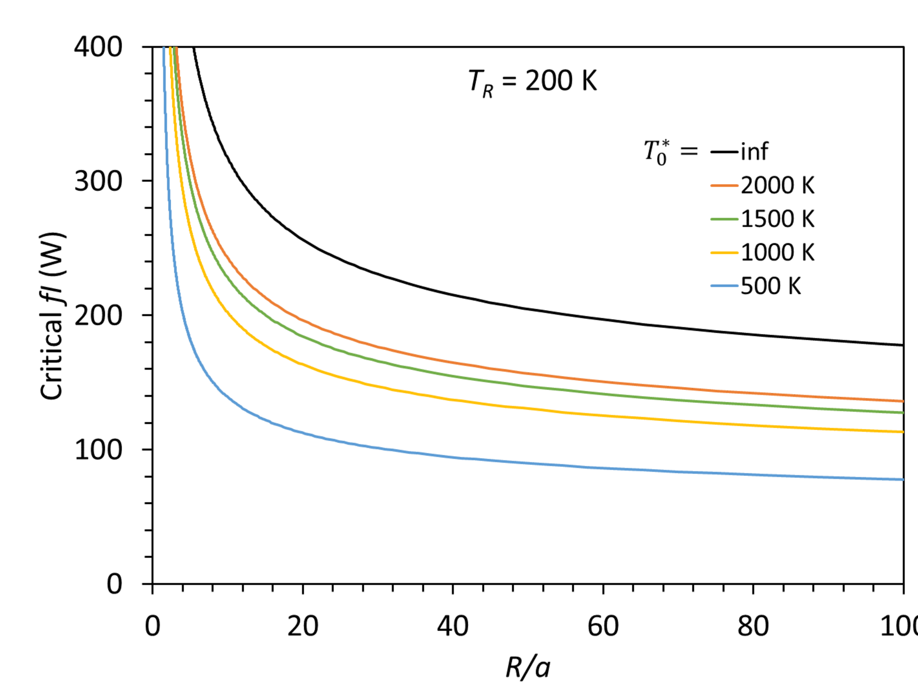

Fig 5: Variation of critical laser heating power at definite runaway condition ($T_0^* = \infty$) as a function of R/a for $T_R = 200\,K$.

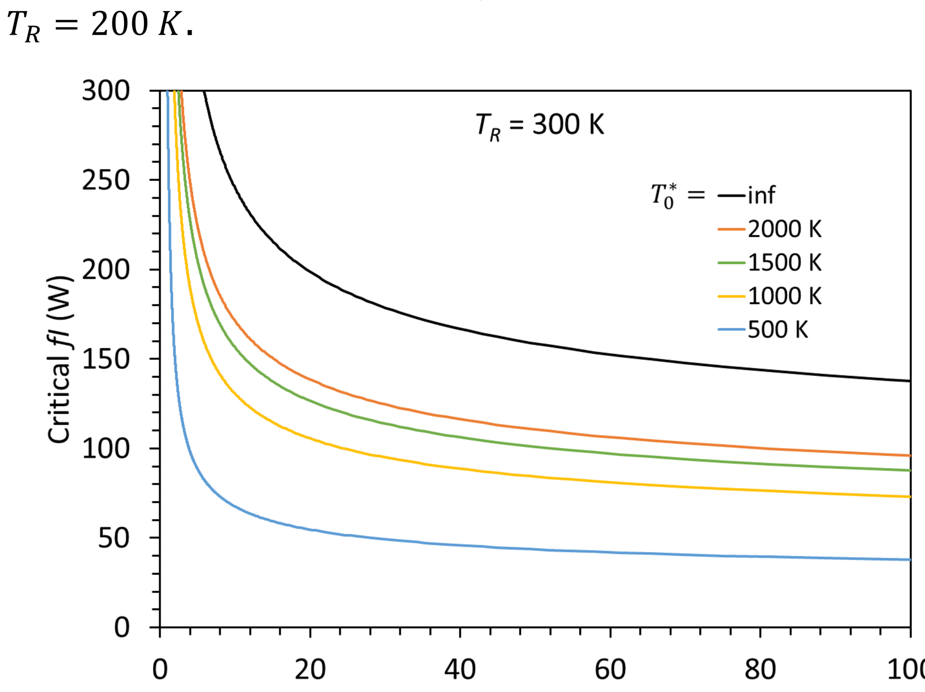

Fig 6: Variation of critical laser heating power at definite runaway condition ($T_0^* = \infty$) as a function of R/a for $T_R = 300\,K$.

viewing the variation of critical power with varying cooling edge distance but a fixed laser spot size. Similarly, Figs. 4-6 show critical power fI as a function of R/a for various target tolerable temperatures with edge cooling temperatures $T_R = 100, 200$ and $300\,K$, respectively.

As seen from Fig. 2, steady-state central temperature T_0 increases relatively slowly with increasing laser input power at small power magnitudes. It then increases rapidly at higher power magnitudes, and eventually approaches to infinity at a critical power, at each one of the cooling temperatures. At the critical power, the definite thermal runaway condition is reached.

Lowering edge cooling temperature improves the critical power fI. However, it cannot eliminate the thermal runaway, as shown in all Figs. 2-6. The critical runaway conditions are sensitive to the cooling temperature and cooling edge distance when R/a ratio is small, i.e., when the cooling edge is close to the laser spot, as shown in Figs. 3-6. For a given laser spot size a, moving cooling edge closer to the laser does not help very much critical power fI for large ratios of R/a. Depending on cooling edge temperature, when R/a is in the range of $10 - 20\,\mu m$, the improvement rises abruptly. Practically, this strategy of imposing heat sink this close may work for large spot sizes, for instance, $a > 100\,\mu m$. However, for small spot sizes, for instance, $10 - 20\,\mu m$, it can be challenging.

Setting lower target runaway temperature, the critical (allowed) power fI would be lower. The reduction in critical fI is more significant at higher cooling edge temperature. These results as shown in Figs. 3-6 can help estimate the effect semi-quantitatively for different lab settings.

Conclusions

Thermal analysis of thin diamond crystal under high-repetition-rate high-intensity laser heating is carried out to address the potential thermal issue, analytically. The steady-state solution for CW laser heating is derived. It can be utilized as an efficient estimation tool for future design and optimization calculations. The results in a few selected cases are plotted and discussed for definite thermal runaway condition by setting $T_0^* \to \infty$. The solution can also be used for estimation of relaxed thermal runaway conditions by setting T_0^* to a finite temperature, required by optical performance or at graphitization temperature. Although diamond is a thermally superior material, thermal fatigue may also be worth attending, while pushing the limit under such extreme laser heating. These results can provide a meaningful guild line in designing the optical devices and its edge cooling system for high-intensity high-repetition-rate XFEL applications. It can also be used as operational parameter setup guild line to the end users.

Acknowledgments

This work is supported by the US Department of Energy (DOE) under contract DE-AC02-76SF00515 and the US DOE Office of Science Early Career Research Program grant FWP-2013-SLAC-100164.

Date: 09/03/2019