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Laser Beam Block Steady-State Temperatures

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1 Introduction

Recenty the MMT2 suspended optic in the 2 km interferometer fell. Evidence suggests (report pending) that the laser beam caused excessive heating and melting or failure under load. Beam blocks will be used to prevent the possibility of the beam from irradiating the wire. Currently this appears to be an issue only for the MMT2 and MC2 optics (further investigation pending). *The purpose of this note is to demonstrate via analysis that aluminum and stainless steel plates of at least 1 mm and 0.75 mm thickness, respectively, and surface area of at least 100 cm^2 are adequate beam blocks.*

2 Analysis

The power, P, delivered from the Mode Cleaner (MC) to the Mode Matching Telescope (MMT) is equal to the Pre-Stabilized Laser (PSL) out put power, 6 W, times the transmission efficiency of the Input Optics (IO) system up to the MMT[1], or P= 0.845 x 6 W = 5.07 W. The laser beam waist, w, at the MMT2 is 0.302 cm for the 2 km interferometer and 0.365 cm for the 4km interferometer[2]. The smaller, 2 km beam radius was used in the analysis. The laser beam irradiance is given by:

$$f(r) = \frac{2P}{\pi w^2} \exp\left(\frac{-2r^2}{w^2} \right)$$

where r is the radial distance from the center of the laser beam spot.

The property data required for a steady-state temperature analysis are shown in the table below.

Property	Aluminum	Stainless Steel
Emissivity @ 20C (~9 μm)	0.11 oxidized[3] 0.095 polished plate[4] 0.04 highly polished, foil	0.16 type 301, polished[5] 0.15 type 18-8, polished[6]
Absorptivity	0.22 polished@ 1.0 μm[7] (and 0.10 at 9 μm)	0.22 type 18-8 polished @ 3.6 μm[8]
Thermal conductivity (W/m/K)	119 type 2024 (low end of range)[9]	14.7 type 304 at 32F [10]

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[1] R. Adhikari, et. al., Input Optics Final Design, LIGO-T980009-01, pg. 66.

[2] T. Delker, et. al., Design Considerations for LIGO Made Matching Telescopes, LIGO-T970143-01, pg. 10.

[3] F. Kreith, Principles of Heat Transfer, 3rd ed., CR 1973, Intext Press, pg. 236.

[4] R. Siegel, J. Howell, Thermal Radiation Heat Transfer, 2nd ed., McGraw Hill, Appendix D, pg. 833.

[5] R. Siegel, J. Howell, Thermal Radiation Heat Transfer, 2nd ed., McGraw Hill, Appendix D, pg. 834.

[6] F. Kreith, Principles of Heat Transfer, 3rd ed., CR 1973, Intext Press, pg. 237.

[7] F. Kreith, Principles of Heat Transfer, 3rd ed., CR 1973, Intext Press, Fig. 5-10, pg. 238.

[8] F. Kreith, Principles of Heat Transfer, 3rd ed., CR 1973, Intext Press, pg. 237.

Since the most appropriate choices for emissivity appeared to be 0.1 for aluminum and 0.15 for stainless steel, these were used in the analysis.

Although a nonlinear analysis to properly account for the radiative boundary condition in vacuum is possible, defining the Gaussian beam profile is cumbersome with the nonlinear numerical tools on hand. Instead the linear heat transfer analysis of the SDRC IDEAS finite element code[11] was used so that it's surface functional heat flux loading capability could be used to represent the Gaussian laser beam heating. The radiation boundary condition was linearized with the following effective convection coefficient:

$$h_r = 4\sigma\varepsilon T_o^3 \delta T$$

where ε = emissivity (appropriate for temperatures slightly elevated above room temperature), σ = Stefan-Boltzmann constant = 5.67×10^{-8}, T_o = ambient temperature = 294K and $\delta T = T - T_o$. This is a conservative approximation (i.e. results in higher temperatures than actual). The error is approximately 23% on average and 35% at peak.

Although the actual beam blocks will be attached to other structure and thus has a conductive path, the conductances of these connections may be low and their details are not known (to me at least). A conservative assumption was made that there is no heat conduction and only radiative transfer of the absorbed heat.

The peak and minimum temperatures for 10 cm x 10 cm plates are shown in the following table and in the following contour plots. If the beam is off center, the peak temperature will increase some, but not significantly.

Material	**Thickness (mm)**	**Min. Temperature Rise (C)**	**Max. Temperature Rise (C)**
Aluminum	1.0	96	101
Stainless Steel	0.76	59	108

Given 200 cm^2 of surface area and the thermal conductivities of the two materials, the minimum temperature is responsible for most of the radiative loss to balance the absorbed beam power:

The peak temperature rises (above an assumed ambient of 21C, 294K) are about the same for the two beam blocks, well below safe limits and comparable to the aluminum bake temperature (120C).

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[9] P. Yoder, Opto-Mechanical Systems Design, Marcel Dekker, cr 1986, pg. 78.

[10] F. Kreith, Principles of Heat Transfer, 3rd ed., CR 1973, Intext Press, pg. 634.

[11] Structural Dynamics Research Corp., IDEAS Finite element analysis, MS7

Figure 1 Temperature Contours (K) for a 10 cm x 10 cm x 1 mm Aluminum Plate (ambient temperature = 294K)

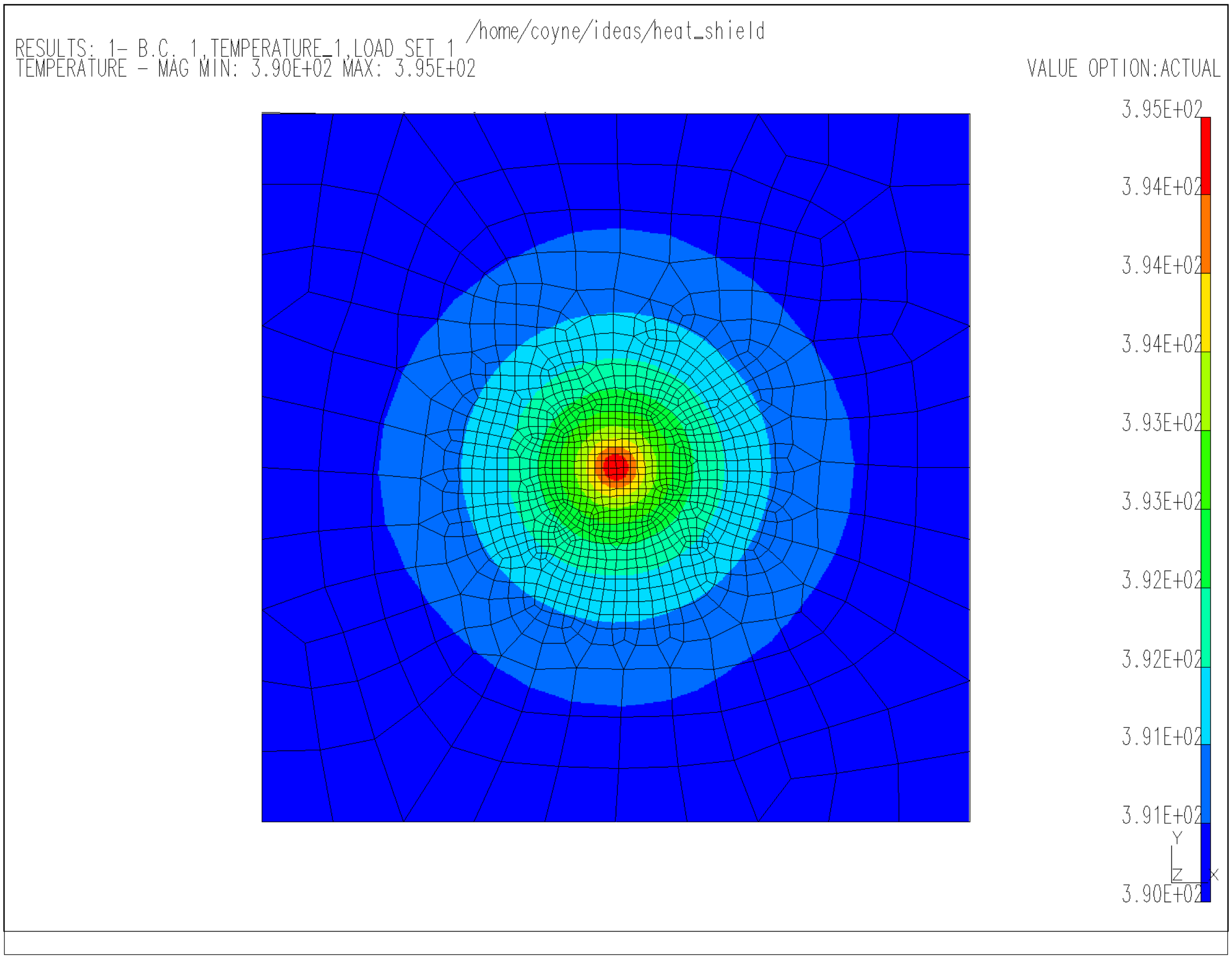

Figure 2 Temperature Contours (K) for a 10 cm x 10 cm x 0.76 mm Stainless Steel Plate (ambient temperature = 294K)