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Analysis of Potential Overheating of HAM1 PSL Viewport in Enhanced LIGO

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1 Introduction

Part of the LIGO document “Enhanced LIGO TCS Failure Modes and Event Analysis” is a finite element model study of the risk to the TCS zinc selenide viewport if it should absorb a large fraction of the incident power due to contamination. This document continues the analysis to the case of the HAM1 PSL viewport, which will pass up to 35 W of 1064 nm radiation into vacuum. The analysis herein suggests that at the very heaviest levels of contamination there is a significant risk of catastrophic viewport failure.

2 Parameters of the model

I modeled the thermal and elastic stresses on the viewport window using COMSOL 3.4 in two dimensions, assuming axial symmetry.

2.1 Mechanical and optical parameters

The viewport window is a 3” diameter by ½” thick fused silica disc with AR coatings on each side, and a 3 arc-minute wedge. In the model, neither the AR coatings nor the wedge were considered.

The viewport assembly diagram is shown in Figure 1, and is available in LIGO document D000073-A-D. The mechanical diagram for the special 10” to 6” zero length reducing flange can be found in LIGO document D000071-A-D.

Figure 1: assembly diagram for HAM PSL viewport.

QuickTime™ and a
decompressor
are needed to see this picture.

The viewport flange is designed such that the window is compressed between a 2.75” diameter O-ring on the vacuum side and a stainless steel flange with a centered 2.5” through hole on the air side. The window does not bottom out against the steel of the O-ring flange.

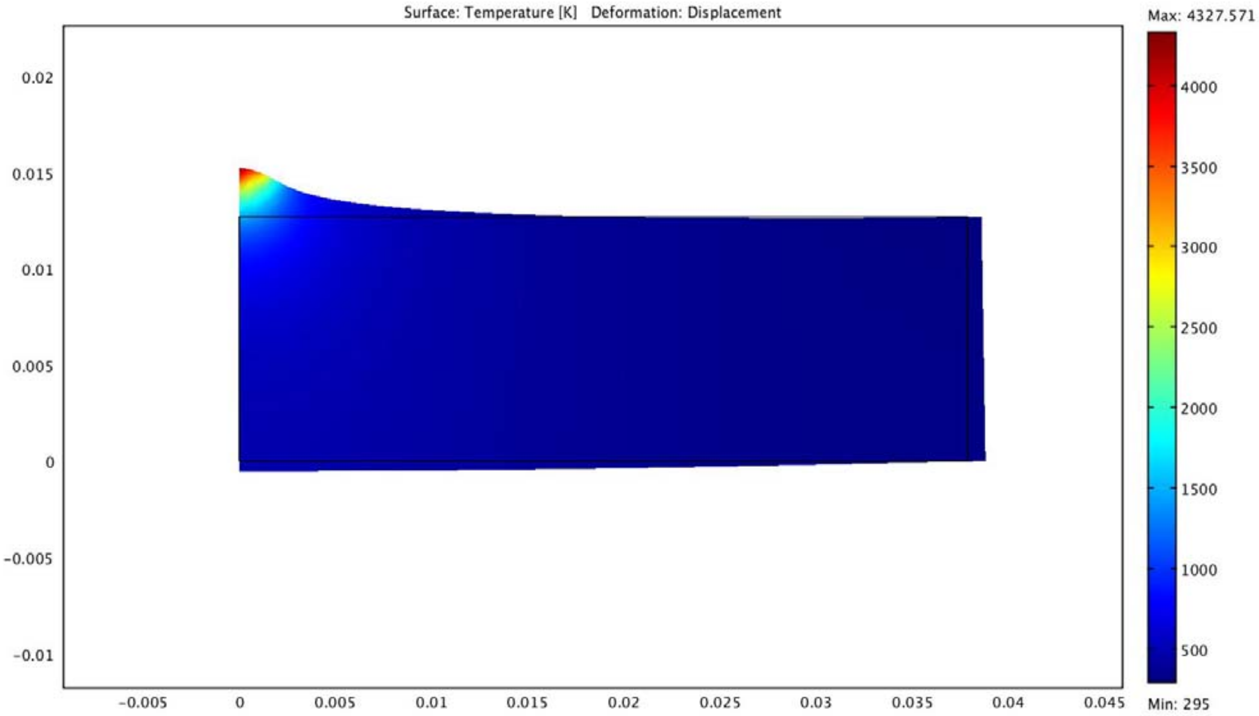
The mechanical forces assumed on the window were as follows. One atmosphere (1.01e5 Pa) of pressure was exerted uniformly on the air surface. A ring of opposing force with diameter 2.75” exerted on the vacuum surface approximated the action of the O-ring. This force had a Gaussian radial distribution with 6 mm width. To tune the magnitude of the O-ring force to precisely compensate the air pressure, I constrained the outer edge of the window on the air side not to move along the window axis in the model, and solved the model with varying levels of O-ring force until I found the level for which the reaction force required to constrain the edge was nulled. For this setting the constraint is fictitious and the model represents a disk supported near its bottom edge. Such an approach ignores the force exerted by the upper clamping flange. Nevertheless, for estimating the thermoelastic forces at the center of the mirror they should be sufficient.

The input beam is assumed to be 35 W with 1.8 mm spot size, normally incident. All power is absorbed at the air surface.

2.2 Thermal parameters

The heat deposited into the window can be dissipated by re-radiation, conduction through the air or stainless steel flanges, and convection in the air. I assumed blackbody radiation with emissivity 0.9 on all surfaces of the window except directly under the clamping flange. Here I assumed the temperature fixed at 295K by the thermal reservoir of the vacuum tank. I assumed no conduction through the viton O-ring. The ambient environment was also assumed to be a blackbody at 295K. The resulting solution is shown in Figure 2. Note that the left side of the window corresponds to r=0 in this 2D axisymmetric model. Note also that no resistance to radial expansion by the O-ring or clamping flange is assumed in the model.

Figure 2: free thermoelastic solution of the PSL window heating with 35W incident. The deformation shown is not to scale.



Lastly, note that the temperature rise in the center of the window is over 4,000K. We will discuss this in more detail in Section 3.

Air convection in the beam tube and enclosure around the viewport is very difficult to estimate, and made even harder by the highly nonuniform temperature profile in the heated window. Only an experimental test could hope for real accuracy. Therefore, to set a rough bound on the importance of convection to the solution, I solved the model first assuming only radiative cooling, and then again assuming radiative cooling plus the COMSOL model library formula for convective cooling of a heated vertical surface in air[1]. Since COMSOL's formula does not account for the many obstructions to airflow in the real viewport enclosure, it overestimates the cooling. Therefore, the solutions for the window heating with and without this convective cooling should bracket the true solution. The maximum heat rise with and without the convective cooling was less than 1%, indicating that convection does not cool the window significantly.

Conduction through the air to the viewport enclosure, taken as a thermal reservoir at 295K, is simple to do in COMSOL. The default model library settings even account for the temperature dependence of the thermal properties of air. While COMSOL should be able to simultaneously solve for conduction and radiation through the air, I was not able to do this in a timely fashion. Therefore, I modeled the viewport enclosure as a cylinder 10" wide and 10" high with the window in the middle of one face with the temperature profile of the air surface of the window in Figure 2, and solved for the conductive heat flow only. The result was ~1W dissipated from the viewport into the air. Since this is a very small fraction of the power heating the window, it is reasonable to approximate the cooling of the window as purely radiative, except for conduction into the clamping flange, and the temperature profile shown in Figure 2 is reasonably accurate.

3 Interpretation of the model

The precision of the predicted 4,000K temperature rise should be greeted skeptically. The parameters in the model used to arrive at this result are not necessarily valid at such high temperature. The peak of the blackbody spectrum for 4,000K is well within the transparent wavelength band for fused silica at room temperature, and the emissivity and thermal conductivity of fused silica likely have a temperature dependence that this model ignores. Since the temperature of most of the window rises only a few hundred Kelvin, any possible increase of thermal conductivity will remain highly localized, and the central temperature will remain high. Any reduction in the emissivity from its near unity value will only make radiative cooling less efficient and raise the temperature further. The safest conclusion is that the fused silica will heat beyond its melting point of 2030K. For this reason, specification of the von Mises stress to estimate the risk of rupture is inappropriate.

Still, 35W of absorbed power in a comparably small spot on a glass substrate has been shown in the lab to make it white-hot[2]. The general experience of those in LIGO who weld fused silica suspensions is that heating a small spot of a fused silica body of much larger characteristic dimension (e.g. 1 mm in the middle of a flat surface more than 10x larger) is likely to induce a crack in the silica within a few minutes after the heat is removed. This occurs because the abrupt

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[1] By comparing a simple COMSOL model of a convectively cooled plate to a handbook approximation I was able to verify its accuracy at the 15% level.

[2] Volker Quetschke, mLIGO wiki entry, 9-11-2008.

removal of heat quenches the glass rapidly through its annealing temperature, freezing thermoelastic stress into the surface. Once it cools to room temperature, water vapor adsorbs onto the silica surface, attacking the stressed Si-O bonds. This is one reason why pins are bonded onto or machined into fused silica masses for fiber welding- if the dimension of the heated silica is comparable to the heated region the stress gradients are much smaller. This is also why welded glassware is routinely slowly annealed after fabrication.

Analysis of the temperature rise for nominal absorption (10’s of ppm) yields a maximum temperature rise of less than one Kelvin. In this case the maximum stress in the window is ~800 kPa and is due to the atmospheric pressure differential. If the absorption is as high as 10%, the maximum temperature rise is 854K, less than the annealing point of fused silica. The maximum von Mises stress in this case is 16 MPa at the center of the air face of the optic. This is uncomfortably close to the 37-80 MPa rupture strength measured by Mike Zucker at MIT, although he was studying borosilicate viewports, which may be weaker than fused silica.

4 Conclusion

This model indicates that, if the HAM1 PSL viewport becomes so heavily contaminated that it absorbs nearly the full 35W incident, the risk of catastrophic failure is significant. Therefore, efforts to prevent contamination are merited. Absorption at nominal levels presents no significant risk of failure.