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69

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A Note on Reasons to Place LIGO Optical Components in Vacuum

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1 Summary

In this note, I give a short list of reasons why it is advantageous to put even "non-critical" LIGO optical components in vacuum.

2 Reasons

1. Turbulent fluctuations of the index of refraction of air can introduce "wiggle noise". This noise appears in many forms, including beam position noise, beam angle noise (known to astronomers as "seeing"), and fluctuations in beam size and intensity ("scintillation").

   The theory of turbulence is quite involved, but I was fortunately able to find some relevant experimental data on beam angle noise. The source was a very useful book by V.I. Tatarskii, *The Effects of the Turbulent Atmosphere on Wave Propagation.* Experiments (performed by others) showed a rather simple form for the beam angle noise. The noise is expected to have its peak at a frequency $f_0 = 0.22v_\perp/b$, where $v_\perp$ is the wind speed transverse to the axis of propagation and b is the width of the beam. (A specified wind speed is important to make use of the simplifying assumption, apparently a good one, that the spatial structure of the turbulence is to first order "frozen", so that temporal fluctuations are dominated by fixed structure being blown across the beam.) If b is about 1 mm, and if we assume that the air in the lab is not still, but wafts about at around 0.3 m/sec, then $f_0 = 70Hz$. The experiments showed roughly constant spectral density from a few tenths of f_0 to about ten times f_0. The rms amplitude of the fluctuations is proportional to the square root of the optical path length, as is to be expected from a random walk. Scaling the measurements to a path 20 meters long, we expect a wiggle of about $0.3 arcsec = 1.5 \times 10^{-6} radians$ rms. This corresponds to a spectral density from 20 Hz to 700 Hz of about $6 \times 10^{-8} rad/\sqrt{Hz}$. At higher frequencies, the spectral density falls as $f^{-4/3}$.

We can compare this amount of wiggle noise to that allowed in LIGO receivers if we have a model for the interferometer optics. I use the memo by Alex Abramovici, *LIGO Optics Vibration Levels Equivalent to Shot Noise in the Advanced Detectors*, along with some additional information on mode cleaners supplied by Alex over the phone. From his Table 1, Line 15, we learn that the allowed angular wiggle at 215 Hz is $2 \times 10^{-12} rad/\sqrt{Hz}$ at the input side of the recycling mirror. A likely final mode cleaner has a dewiggling factor of 150. There will also be some mode matching telescopes which reduce angular jitter by a factor of about 15. This means that the angular motion of the beam at the input to the final mode cleaner should be less than $4.5 \times 10^{-9} rad/\sqrt{Hz}$. The estimated noise level due to turbulence is more than an order of magnitude greater.

For completeness, we probably ought to investigate the other degrees of freedom of wiggle noise. Still, this example indicates the importance of turbulence-induced wiggle on interferometer performance.

2. Dust which settles on optical surfaces exposed to high laser power levels can cause degradation of those surfaces.

   Cleanliness will be a constant concern with the high power lasers planned for the LIGO. Ensuring clean surfaces at the time of installation will require careful handling. Maintaining the required level of cleanliness will be easiest by far if the optics live in an evacuated chamber.

3. Acoustic noise can drive motions of optical components at levels exceeding ground noise, short circuiting vibration isolation systems.

This mechanism is important in principle, but the rough numerical estimates show it to be of marginal importance at worst. The wiggle noise filtering provided by the mode cleaner and succeeding optics would allow motions of preceding components several orders of magnitude greater than ground motion. This is unlikely if we keep the experimental area reasonably quiet, in line with the spec in the Environmental Specifications memo.

4. Some of the optical components (e.g. Pockels cells) are hygroscopic.

   This could also be dealt with by keeping these components in sealed containers, at some cost in performance due to losses at the windows.

3 How much of the optics should be in vacuum?

The calculations of wiggle caused by turbulence were carried out for components preceding the final mode cleaner. In a design which has a preliminary mode cleaner (as Alex is proposing), there will be additional filtering for noise which precedes that cavity as well. These rough numbers indicate we might well get away with an exposed optical path for the space between the laser and the first mode cleaner.

The problems of dust will remain in any case. For this reason it may be simplest to evacuate all of the optics up to a window in front of the laser. I see no reason this part of the vacuum system couldn't be a simple pipe, with the components slid inside on an optical rail. Alex's vibration calculations indicate that components that early in the optical train will most likely require no isolation at all.

4 Caveats

There may in fact be other reasons which also argue for evacuation of the optics.

The strongest reasons I know of are the worries about turbulence and about dust. For early low power operation at performance levels substantially poorer than the "advanced detector" levels, exposed fore-optics could likely be tolerated. This might have advantages in ease of set-up and adjustment of these components. Eventually, though, it seems clear that evacuation of the space around the fore-optics will be required.