LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T020103-06-D *ADVANCED LIGO* 1/5/2004

Test Mass Material Down-select Plan

LIGO Science Collaboration, G. Billingsley ed.

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

Table of Contents

Appendices

1 Introduction

The baseline design for Advanced LIGO has been developed based on the use of sapphire as the test mass substrate material, because of its promising thermal and mechanical properties. At the same time, fused silica has not been forgotten as a viable alternative, mainly as a hedge against uncertainties in sapphire materials development. At some point a final decision must be made on the substrate material[1]; such a decision demands a thorough evaluation of interferometer performance impact and engineering issues, considering both materials on an equal footing.

This document is intended to inform the LIGO Laboratory and the Core Optics Working Group of the technical status of the test mass material development. It is also intended to be the primary resource for the review committee charged with recommending a test mass substrate material choice. For both sapphire and silica, this document contains:

1. A summary of the industrial development status.
2. A summary of thermal noise estimates.
3. A summary of optical and opto-mechanical properties, in relation to the current understanding of LIGO requirements.
4. A summary of thermal distortion modeling.
5. Plans for further tests and measurements during the evaluation period.

1.1 Definitions

Test Mass, either an Input Test Mass or End Test Mass.

Blank, a sapphire or glass right circular cylinder which is not ready for coating.

Substrate, a sapphire or glass right circular cylinder ready for coating.

1.2 Acronyms

List all acronyms and abbreviations used in the document.

1.3 Applicable Documents

Advanced LIGO Systems Design Document T010075-00

COC Conceptual Design Document
http://www.ligo.caltech.edu/docs/T/T000098-00.pdf

Core Optics Components Development Plan
http://www.ligo.caltech.edu/docs/T/T000128-00.pdf

[1] Or ‘materials’, leaving open the possibility of different choices for input and end test masses

2 Plans for near-term tests and measurements

2.1 Sapphire

LIGO received two ϕ31.4 cm × 13 cm a-axis sapphire blanks in February 2003, both grown by Crystal Systems International (CSI). These blanks have a commercial polish on all sides, performed by Insaco; they do not yet have mounting flats machined on the sides (required later for bonding the suspension 'ears'). According to CSI, one substrate is of 'good' optical quality, while the other is characterized only as 'mechanical quality'. For the substrate materials evaluation, we plan to measure and report findings on homogeneity, scatter, mechanical quality factor, and absorption of both pieces. The plans for these measurements are as follows:

- Homogeneity: to be measured at Caltech by G. Billingsley, using the phase-shifting interferometer; measurement aperture is 150 mm. Measurement time approximately 2 weeks per piece.
- Mechanical quality factors: have been measured at Caltech by Phil Willems, using a wire sling suspension. Both sapphire pieces had a mode with Q greater than or equal to 200 million, and thus meet the requirements for Advanced LIGO[1].
- Absorption: One piece has been measured at SMA Lyon[2], and shows significant high spatial frequency structure, with average absorption at roughly 60ppm/cm, ranging from 30 to 130ppm/cm. Two other pieces have been sent to Lyon for measurement, these results should be available by February, 2004.
- Scatter: Needs to be measured as it effects loss in the recycling cavity. The method is TBD.

After these measurements are complete the pieces are to have mounting flats cut, and are to be polished and coated in preparation for use in LASTI.

The Glasgow group has received a ϕ25 cm × 10 cm sapphire substrate. The material is from Crystal Systems, and it has been polished, including mounting flats on the barrel, by Wave Precision. It will be suspended by fused silica fibers, and mechanical *Q* measurements will be made.

2.2 Fused silica

The most significant open issue for fused silica is the value of the bulk mechanical loss. Steve Penn is investigating the effect of annealing on *Q* of various types of fused silica[3].

Phil Willems has measured the *Q* of an uncoated LIGO1 test mass spare, made from Heraeus 312. As reported in the April 25, 2003 Core Optics Downselect Committee Meeting[4], the fused silica had a highest *Q* at 120 million.

3 Optical and mechanical properties

3.1 Size

3.1.1 Sapphire

A sapphire crystal boule in general has defects in its outer regions, so that ending up with a given size sapphire blank requires starting with a significantly larger boule. Crystal System's production furnaces, of which they about 20 operational units, produce 13.5″ diameter boules; they conservatively estimate that the largest blank they could yield from these boules is ϕ28 cm × 10 cm (mass approximately 25 kg). Thus in January 2002, CSI embarked on a development program to consistently grow larger boules, with the goal of producing a 40 kg blank from a 15″ diameter boule. As of October 2002, they have performed five growth cycles in their 15″ diameter crucible, with the following results: 2 are of 'good' optical quality; 2 are 'mechanical quality'; 1 failed process (the piece cracked).

Given a 40 kg total mass, the aspect ratio which minimizes thermal (thermoelastic) noise (for an allowed optical per mirror diffraction loss of 15 ppm) was determined for the Advanced LIGO Systems Design, T010075-00 (see section 4.6): ϕ31.4 cm × 13 cm, from a boule which is nominally ϕ38 cm × YY cm.

3.1.2 Silica

Fused silica is available in very large sizes, in good optical quality. The situation with the various types of fused silica is as follows:

Vendor	Type	Special Properties	Size availability	Cost
Heraeus	311	More homogeneous than 312 Low abs. 2-5 ppm/cm	Heraeus glass is moulded to size & shape requested. Maximum mass is 75 kg (VIRGO has a quote for 75kg SV).	$8600/kg
	312	Was hard to polish for LIGO ITMs because of inhomogeneity Low abs. 2-5 ppm/cm		$5600/kg
	311SV	Low abs. 311, ≤ 1ppm/cm May be less homogeneous than regular 311		$10,500/kg
	312SV	Low abs. 312, ≤ 1ppm/cm		?
Corning	7980	12-15 ppm/cm absorption	Up to 18 cm thick, large enough diameter	$1900/kg
	Low-abs.	< 0.2 ppm/cm absorption	Not in production	?

Table 1. Types of fused silica that could be used for Advanced LIGO test masses.

3.2 Absorption

3.2.1 Requirement

In principle, the effects of substrate absorption can be actively compensated. The absorption limit is set more by the allowed power loss than by optical distortion. Requiring that no more than 5 W, or 4%, of the total input power is lost to substrate absorption leads to a maximum allowed sapphire bulk absorption of 100 ppm/cm.

With fused silica, it is worthwhile taking advantage of available low-loss material, so that thermal distortions from the bulk absorption are very small compared to those from the coating absorption. Allowing the bulk absorbed power to be no more than 10% of the coating absorbed power gives an upper limit on fused silica absorption of 3 ppm/cm (assumes a test mass thickness of 25 cm, coating absorption of 0.5 ppm, and a cavity power gain of 800).

In either case, it is clear that thermal compensation will be required in order to provide optimal performance across a wide range of input power. The most recent summary of the thermal compensation system was October of 2002[5].

3.2.2 Sapphire

Sapphire boules grown by CSI display fairly high, and often quite variable levels of absorption [2]. The ability to compensate for high spatial frequency variations in sapphire may diminish at a frequency of 1.6/cm[6]. The Stanford materials group and CSI have been investigating the causes of absorption and means to reduce it through post-growth annealing. For a recent history and status of these efforts see technical note T030088-00[7] and the August 2002 LSC viewgraphs of R Route.[8] Early on, a small pocket (~mm-scale ?) of 10 ppm/cm absorption was seen in one sample (which also showed a region at 600 ppm/cm). Recently, the most promising avenue for reducing absorption appears to be a rapid cooling anneal of roughly 900 C°/hour. A typical result with this process is a pre-anneal absorption of 50-70 ppm/cm, and a post-anneal absorption level of 25-50 ppm/cm, reasonably uniform (10-20% variation) along the scan lengths of 5-10 mm. Most annealing tests and absorption measurements to date have been done on small samples, typically ϕ25 mm $\times$ 10 mm, there has been one ϕ75mm $\times$ 25mm piece similarly annealed.

These methods will need to be proven on full size pieces, plans for testing the annealing full size optics at Crystal Systems are in process.

3.2.3 Fused silica

Refer to Table 1 for absorption levels of candidate types of fused silica. Heraeus 311SV certainly has sufficiently low absorption, as does 312 SV, but 312SV is probably ruled out because of its poorer homogeneity. Absorption homogeneity in Heraeus fused silica has been shown to be quite good[9]. Corning has made an ultra low absorption glass which measures at or below the instrument floor for the photothermal deflection technique, roughly 0.2-0.5 ppm/cm. Unfortunately this material is not currently in production, and Corning has indicated that it requires a much larger volume order than LIGO could support to reinstate production. We continue to monitor this position.

3.3 Homogeneity

3.3.1 Requirements

Inhomgeneities in the input test mass substrates degrade the performance by reducing the buildup of the main carrier light, and the RF modulation sidebands (the latter being a significant problem if these sidebands are used for the GW readout). Considering first the carrier light, B Kells[10] has derived the following formula for the reduction in carrier power, and corresponding reduction in shot-noise limited strain sensitivity:

$$dP / P = (2\pi \cdot \mathrm{OPD} / \lambda)^2$$

where OPD is the rms optical path distortion in transmission through the ITM, over a central region of diameter 2.5× the beam radius, or 150 mm diameter in this case. Applying a limit of 1% for this reduction gives an inhomogeneity upper limit of: OPD < 17 nm-rms.

The effect on the RF sidebands can be more dramatic, since the distorted light will resonate in the near-degenerate recycling cavities. The effects of recycling cavity distortion on the RF sidebands is being investigated first for thermal distortions (see section XX); stay tuned for analysis on the impact of bulk inhomogeneity.

The levels we have been working with to date – what we have communicated to vendors, is a required homogeneity, over the central 200mm diameter, of better than 20 nm-rms double pass, with a goal of better than 10 nm-rms (measured in the frequency band below 4.3 cm^{-1}).

3.3.2 Sapphire

Choice of growth axis. Sapphire is difficult to grow along the *c*-axis, and technology is not at a state where boules are grown large enough to allow for side coring *c*-axis material. Initially, *m*-axis material was selected for Advanced LIGO because it was thought to be easier to polish than *a*-axis material. Contact with other users of sapphire led us to believe that *a*-axis material might be more homogeneous than *m*-axis material. This has been demonstrated to be true[11]. The only remaining reason to use *m*-axis material would be if there is some difference in the *Q*. This is currently under investigation, but is thought to be at a low enough level that coating mechanical loss will dominate.

Nature of the inhomogeneity. Inhomogeneities in *a*- and *m*-axis sapphire appear as linear striae, which are always parallel to the polarization of the probe laser. The inhomogeneity is of uniformly lower amplitude and lower spatial frequency when probed with a laser polarization that is parallel to the *c*-axis of the material. This effect has been verified at Caltech, CSIRO and Goodrich, using three different instruments. The effect was first noted at CSIRO, where an exhaustive set of measurements was performed to confirm the unusual effect[12].

Compensating for material inhomogeneity. Goodrich Corporation has undertaken an effort to compensate for inhomogeneity in sapphire by selectively polishing what would be the AR coated side of a LIGO test mass[13]. The idea is to remove material in places of high index in order to make the optical path length uniform through the material. Goodrich has demonstrated this technique on a 250 mm diameter by 100 mm thick piece, using computer controlled polishing. The resulting rms path difference measured by Goodrich is less than 10 nm single pass. Caltech has verified their

previous attempt, which resulted in 14 nm rms path difference. The piece will be returning to Caltech for verification of the 10 nm result.

Inhomogeneity measurements. Table 2 below summarizes all homogeneity measurements made of uncompensated LIGO sapphire. The trend for inhomogeneity in both *a*- and *m*-axis material is that it increases with the thickness of the material, i.e., it appears to be a bulk effect.

Some of the measurements cited in this table (S75M001-004) were part of a quick survey, where the surfaces were not subtracted. In these cases the surfaces were good enough to get an idea of the material quality. The material quality is most evident from the images, where circular features can be attributed to surface two and linear features are attributed to inhomogeneity. It is interesting to note that there is little evidence of linear striae in these thin pieces when the probe laser polarization is parallel to the *c*-axis of the material.

Sample ID	Orient. of polarization w.r.t. *c*-axis	Inhomog. (nm)		Substrate thickness (mm)	Image name	Comments
		P-V	RMS			
S75M001	Parallel	61	6	25	S75M001-ll	Circular ripples from S2 polish; not subtracted for survey, the image is a better indicator of variation
S75M001	Perp.	74	7	25	S75M001-T	Optic rotates, polarization is vertical
S75M002	Parallel	101	14	25	S75M002-ll	"
S75M002	Perp,	84	10	25	S75M002-T	"
S75M003	Parallel	65	8	25	S75M003-ll	"
S75M003	Perp.	94	11	25	S75M003-T	"
S75M004	Parallel	79	11	25	S75M004-ll	"
S75M004	Perp.	93	12	25	S75M004-T	"
S100A01	Parallel	33	6	50	S100A01-ll	
S100A01	Perp.	63	10	50	S100A01-T	
S120A01	Parallel	106	11	80	S120A01-ll	
S120A01	Perp.	116	13	80	S120A01-T	
SaphA	Parallel	179	20	80	SaphA-ll	Measured at CSIRO
SaphA	Perp.	154	25	80	SaphA-T	Polarization rotates, optic is fixed
SaphB	Parallel	152	27	80	SaphB-ll	"
SaphB	Perp.	280	49	80	SaphB-T	"
S250M01	Perp.	453	59	100	S250M01-T	Measured at CIT

Table 2. Summary of (uncompensated) sapphire homogeneity measurements. JPEG images of the measurements can be found at http://www.ligo.caltech.edu/~gari/LIGOII/homogpics/

Inhomogeneity compensation. Three techniques for compensating sapphire's bulk inhomogeneity have been proposed and explored to some level; all attempt to compensate phase distortions in the bulk with an intentional conjugate distortion of the 'back side' of the test mass (i.e., the anti-reflection coated side) via one of the following:

- Selective mechanical polishing
- Ion beam etching
- Fluid jet polishing
- Spatially tailored dielectric coating

A test of mechanical polish compensation has been performed by Goodrich on a ϕ250mm x 100mm substrate, sample S250M01 in Table 2. Their initial round of polishing resulted in a compensated residual inhomogeneity about 13 nm-rms; this was measured at Goodrich, and subsequently confirmed by Caltech metrology[14]. Goodrich was then contracted to perform a second round of polishing, essentially to see how well they could do. Goodrich has reported achieving less than 10 nm rms residual inhomogeneity, but has not yet been verified at Caltech. Their polishing technique results in a surface microroughness (of the back side) of 55 angstroms-rms (though they claim they have done better, and could if required).

CSIRO has made some initial trials on small samples of the last three techniques, and they conclude that both ion beam etching and dielectric coating could be capable of the required compensation[15] (LIGO-C020136; LIGO-confidential report). Surface microroughness actually improves with ion bombardment to ~1 Å rms. It would require a significant investment (~$100K) to take this process to the next level of compensation on a 75mm part.

More recently, ASML and Kodak have expressed interest and capability in the ion beam etching technique. No further compensation tests (other than Caltech measurements of the Goodrich piece) are planned before the substrate selection date. If sapphire is chosen, it is clear that there is more than one viable path to pursue.

3.3.3 Fused silica

Heraeus fused silica type 311 has a very low deviation in homogeneity, of order <2nm rms over 200 mm. Heraeus type 312 has higher deviations, of order 20 nm rms over 200mm.

3.3.4 Action needed

None

3.4 Internal Scatter

3.4.1 Requirements

For the interferometer power budget, loss from scattering in the ITM substrates should be held to a negligible level compared to power loss from the arm cavities. We set this scattering loss limit at 50 ppm for the ITM substrates (double passed), compared to an arm cavity loss of 6%. (Higher scattering could be allowed for the ETMs).

Scattered light can also produce noise if it reflects off some poorly vibrationally isolated surface and then recombines with the interferometer beam. It is difficult to even estimate the size of such coupling for ITM substrate scattering; no attempts have been made to determine scattering limits from this phenomenon. Scattering obviously does not heat the optic, and so will not cause photothermal effects.

For crystals (sapphire), internal scattering arises from crystal growth defects, inclusions, and Rayleigh scattering. For glasses (fused silica), internal scattering arises from bubbles and inclusions in the material, and from Rayleigh scattering. Rayleigh scattering is the scattering of light from inhomogeneities in the refractive index of a medium that are very small compared to the light wavelength. It is characterized by a $1/\lambda^4$ dependence of the scattered intensity on the light wavelength λ.

3.4.2 Sapphire

CSI categorizes their sapphire into 5 grades, based on a qualitative visual inspection of light scattering and lattice distortion. The top 3 grades, starting from the best quality, are labeled: Hemex; Hemlux; Hemlite. The best grade is only available in small volumes, as CSI must select rare regions within a boule. According to CSI, they expect our 40kg full size piece to be of Hemlite grade. We do not yet know what this means quantitatively.

Qualitatively, inclusions have been seen in large numbers in large sapphire pieces (inclusion scattering can be treated as a geometric cross sectional loss). We have tried to look at these inclusions with a long objective microscope; but were still seeing diffraction rings at 50× magnification. The best guess is that the upper limit on size for these inclusions is ~ 2 micrometers. We do know that one piece with a huge number of internal bubbles was polished to ~0.5 Angstroms rms roughness by Wave Precision. The presumption is that the bubbles must have broken through the surface because they were so numerous. Yet they appear to not affect the overall microroughness

Kells and Camp have examined Rayleigh scattering in small pieces: “It looks good.” It is not yet clear how and where the two new 40kg samples will be measured for scattering.

3.4.3 Fused silica

Fused silica can be reliably obtained with few or no inclusions, so that its scattering is dominated by Rayleigh scattering. In very pure fused silica, near 1064nm wavelength, Rayleigh scattering is a significant limit to the optical loss. The scatter measured in the best samples is consistent with density fluctuations that are frozen into the glass as it is cooled to below the glass transition temperature T_g. This is supported by measurements that show that the scattering tends to be lower in glasses with lower T_g due to impurities or annealing.

The lowest Rayleigh scattering measured in bulk fused silica at 1064nm is (0.64 ± 0.04) dB/km, by Rich and Pinnow[16]. This corresponds to 1.4 ppm/cm loss. Values less than 1dB/km (2 ppm/cm) are routinely achieved in optical waveguides. The only measurement on an interferometer test mass sample for which data are available comes from VIRGO. Benabid *et al.*[17] report the loss of two Suprasil samples to be 6.7 and 11.7 ppm/cm at 1064nm. Though 3-4% higher than the best results, the power scattered did have wavelength dependence consistent with Rayleigh scattering. A double-passed test mass thickness of 260 cm would allow an internal scattering of 10 ppm/cm.

3.4.4 Action needed

We need quantitative measurements of the loss in sapphire. The two large boules from Crystal systems are ideal candidates for this measurement since they span the range of material we are likely to receive. We do not yet have a plan for accomplishing this measurement.

3.5 Polish

3.5.1 Requirements

The Advanced LIGO system's design budgets 37.5 ppm as the average effective loss per test mass mirror. For the sapphire based design, the effective diffraction loss is 15 ppm, pushed to this level to reduce thermoelastic-damping noise. Subtract 0.5 ppm for coating absorption, and 22 ppm is allowed for loss due to polishing imperfections on sapphire. A possible breakdown between microroughness and larger scale distortions is

- Microroughness: 1 angstrom rms, 1.4 ppm loss
- Larger scale (< 4 cm^{-1}): ~20 ppm

Fused silica test masses can be relatively larger compared to the beam size, so that the diffraction loss can be made 1 ppm or so. So approximately 35 ppm loss can be allowed from large scale polishing distortions.

To relate this to a polishing distortion level, we refer to the FFT modeling results from B Bochner's thesis. The effective distortion loss is a function of the distortion level and the mirror diameter:

Distortion level over central 80 mm	**Mirror aperture radius/beam radius**			
	2.93	**3.66**	**4.39**	**5.12**
0.59 nm-rms	9.1 ppm			
0.89 nm-rms	20.5 ppm			
1.33 nm-rms	45.6 ppm	42 ppm	25 ppm	24 ppm
2.66 nm-rms	177 ppm			

Table 3. Effective per mirror loss due to mirror surface distortion, derived from B Bochner's FFT simulations (Table 3.1 and Figure 4.10 of his thesis). For the mirror:beam radius ratio, the average of the test mass beam sizes is used (ITM: 3.63 cm; ETM: 4.56 cm; avg: 4.1 cm). The mirror:beam radius ratio for the sapphire baseline design is 2.48.

These FFT simulations were characterized by an rms distortion level over the central 80 mm diameter of the mirror. If we scale the average mirror spot size in these simulations by the Advanced LIGO 6.0 cm mirror spot size, the equivalent aperture is 117 mm diameter.

The mirror:beam radius ratio for the baseline sapphire design is smaller than the smallest ratio used in Bochner's simulations (2.48 vs 2.93). We estimate an upper limit to the effective per mirror loss in the limit of a small mirror:beam radius ratio, where there is little effective recovery of scattered power, to be $(2\pi\sigma/\lambda)^2$, where σ is the rms surface distortion.

We can thus estimate polishing distortion requirements for an effective loss of 20 ppm; over the central 120 mm aperture:

- Sapphire: 0.75 – 0.9 nm rms
- Silica: 0.95 – 1.2 nm rms (depending on how large we make the diameter)

This assumes a microroughness of [1 angstrom in each case.

3.5.2 Sapphire

Polishing sapphire is more difficult than fused silica, due to its hardness and crystalline nature. The first experience with high-quality polishing of sapphire occurred at the end of 2000, CSIRO was contracted to polish a *m*-axis 15 cm diameter CSI sapphire piece, to the requirements of: *surface error*, < 1 nm-rms over central 120 mm diameter; *microroughness*, goal of less than 0.1 nm-rms.

The CSIRO polishing report can be found in C010237-00[18]. They achieved:

- Surface error: 1 nm-rms over central 120 mm diameter, 0.6 nm-rms over central 80 mm diameter (tilt, power, and astigmatism removed) These results are similar to CSIRO measurements of LIGO 1 optics, suggesting that the process may be metrology limited.
- Microroughness: 1.8 angstrom in the band 4.3-14000 cm^{-1}, though CSIRO felt that the higher frequency measurements were limited by measurement noise, and that the true microroughness is closer to 1.2 angstrom

CSIRO has published a report that ion beam etching lowers the microroughness to sub-angstrom levels. This could be an option if the polishing results are not sufficient.

Wave Precision (formerly General Optics) has also polished small pieces of sapphire for LIGO. The surface figure on these pieces is similar to that found on fused silica polished at the same company, suggesting that the figure may be metrology limited.

Machining sapphire blanks for polishing is a very difficult process because of its hardness; this will require an added step in fabrication with a specialized vendor.

Compensation polish for the AR side of the ITMs may also be a separate step depending on the polisher(s) chosen for Advanced LIGO.

3.5.3 Fused silica

The best data on fused silica polishing capability comes from the initial LIGO test masses. These were polished by two different vendors. Metrology was performed on all optics at Caltech, and microroughness data was supplied by the vendors:

- Wave Precision (formerly General Optics) optics: typical surface error of 1.5 nm-rms, over the central 150 mm diameter; microroughness is less than 1 angstrom.
- CSIRO optics: typical surface error of 0.7-0.8 nm-rms, over the central 150 mm; microroughness is 1.5-1.8 angstroms.

3.5.4 Action Needed

Polish of the LASTI optics will be the first attempt at meeting polishing requirements on full size sapphire. In choosing either sapphire or fused silica the crucial element is metrology. There appears to be no fundamental physical limitation at this level.

3.6 Birefringence

3.6.1 Requirement

ITM birefringence has the only effect on interferometer performance. This is seen as a direct loss in the recycling cavity. The complete round trip loss budget in the power recycling cavity should be less than 0.3% according to the Advanced LIGO Systems Design Document.[19]

3.6.2 Sapphire

At the level of the experimental sensitivity (~50ppm) no correlation of local polarization rotation with apparent inhomogeneity was found[20]. This sensitivity is sufficient to exclude polarization scatter due to inhomogeneity from concern for advanced LIGO application. Correct orientation of the sapphire crystal with respect to the beam polarization is important and is addressed later in this document.

3.6.3 Fused Silica

Fused silica has nominal stress birefringence measured at the level of 0.005 radians P-V[21]. The power loss due to this effect is on the order of one part per million.

3.6.4 Action needed

None

3.7 Optical Coatings: optical quality

3.7.1 Requirements

The design requirements for coating optical quality are found in the Coating Development Plan.[22] The coating performance required for interferometer performance is independent of substrate choice, with the exception of coating absorption. Recent work by AOS indicates sensitivity to coating absorption uniformity at the level of 30 ppb when using fused silica test masses compared to sensitivity at the level of 1 ppm when using sapphire. Controlling absorption from contamination may prove to be a significant challenge.

The choice of coating also has an impact on thermal noise, this is discussed later in the document.

4 Thermal Noise Estimates

4.1 Bulk material properties

Ideally, the test mass thermal noise would be determined only by the properties of the bulk material, and other factors (attachments, coatings, charging) would have insignificant effects. Here

we make a sapphire-fused silica comparison of thermal noise predictions from the bulk material properties. Past uncertainties in the thermo-elastic properties of sapphire have been resolved, so that we now have property values that we believe are accurate to within ~10%. For both materials, the bulk property with the most uncertainty is the internal frictional loss, or material *Q*: for silica, large sample-to-sample variations in modal *Q*'s are seen, whereas for sapphire there simply isn't sufficient data to have high confidence in the nominal value. Thus we present here thermal noise predictions as a function of the bulk material *Q*, for plausible ranges of each material. The table below lists the relevant parameter values for the comparison.

Parameter	***Sapphire***	***Fused Silica***
Nominal Q	200 million	100 million
Thermal expansion coefficient	5.1×10^{-6}/K	3.9×10^{-7}/K
Thermal conductivity	33 W/m-K	1.38 W/m-K
Poisson ratio	0.23	0.167
Young's modulus	4.0×10^{11} N/m^2	7.3×10^{10} N/m^2
Density	3.98 gm/cm^3	2.2 gm/cm^3
Specific heat	770 J/kg-K	739 J/kg-K
Size (diameter x thickness)	31.4 x 13 cm	31.1 x 24 cm
Beam size (radius)	6.0 cm	6.0 cm

Table 4. Parameters used for the estimation of intrinsic test mass thermal noise.

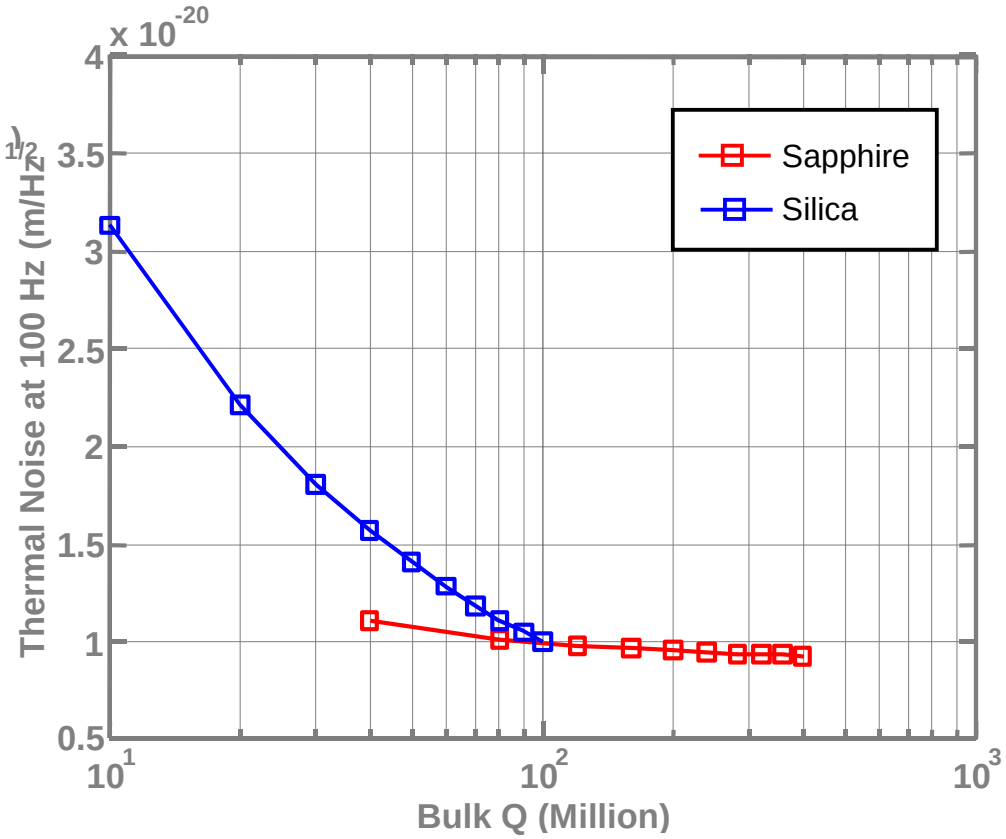

Figure 1. Thermal noise at 100 Hz as a function of test mass material bulk Q, for plausible ranges for sapphire and fused silica. Plotted is the differential arm displacement noise (strain noise divided by arm length). Very low coating mechanical loss is assumed.

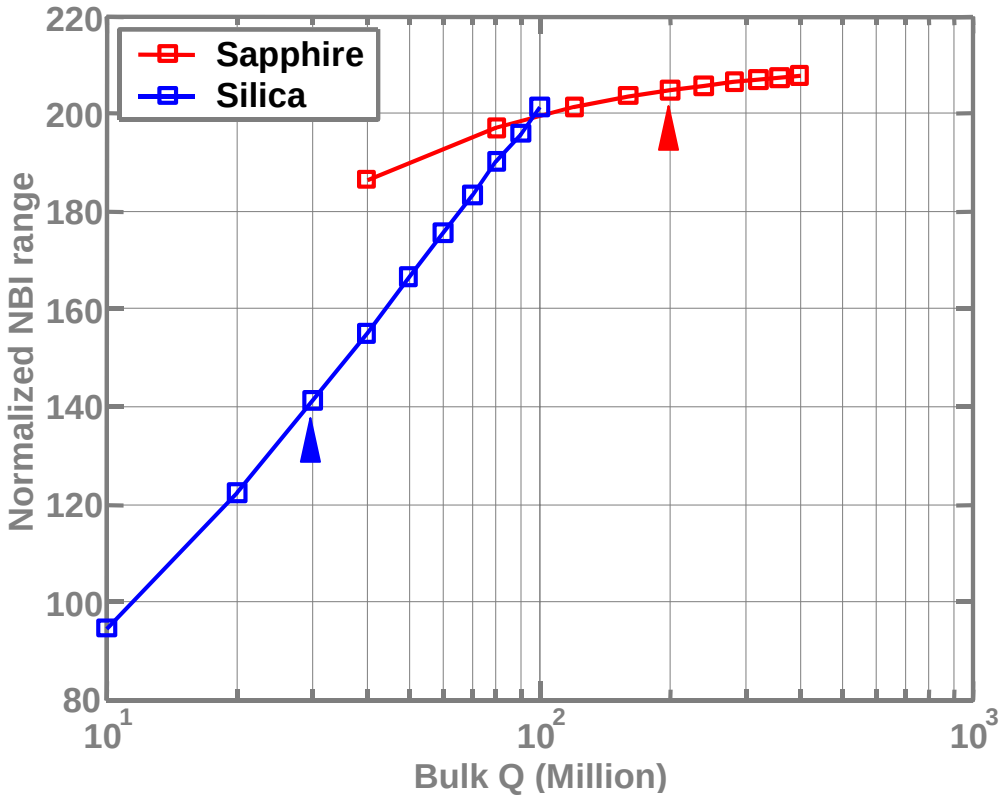

Figure 2. Comparison of neutron star binary inspiral (NBI) range for sapphire and fused silica test masses, as a function of the material bulk *Q*. The nominal *Q* values are indicated by the markers. Very low coating mechanical loss is assumed.

Figure 1 and Figure 2 show that the thermal noise prediction for sapphire is much more tolerant to uncertainty in the bulk material *Q*, not surprising since thermo-elastic damping is dominant. The figures also show that if the bulk *Q* of fused silica happens to be significantly higher than our nominal value, and if non-intrinsic effects were not significant, thermal noise with fused silica masses could be essentially as low as that with sapphire. We note that the highest modal *Q* of a fused silica sample observed to date is 200 million, observed at Syracuse.

4.2 Optical coatings: mechanical quality

4.2.1 Model results

Ideally we would require that any changes to the test mass material, such as addition of an optical coating, have a minimal impact on the astrophysical performance. 'Minimal impact', could mean, for example, a reduction in the binary neutron star inspiral distance benchmark of less than 5%. Unfortunately, investigations into current optical coatings indicate they would severely fail this requirement. Present understanding of the effects of coating mechanical loss on inspiral sensitivity is indicated in Figure 3. Over the loss range 0-2 X 10^{-4}, the sapphire design range is reduced from 200 Mpc to 170 Mpc. If one aims for high-*Q* silica (200M), the plot shows that such a material would suffer more quickly than sapphire from coating loss. Figure 3 indicates the target maximum

coating loss should be about 5 X 10^{-5} initial LIGO coatings unfortunately show a loss of about ~ 2 X 10^{-4}.

These calculations are made using finite size corrections for the bulk material thermal noise, but approximating the test masses as infinite half-planes for the coating thermal noise effects. .

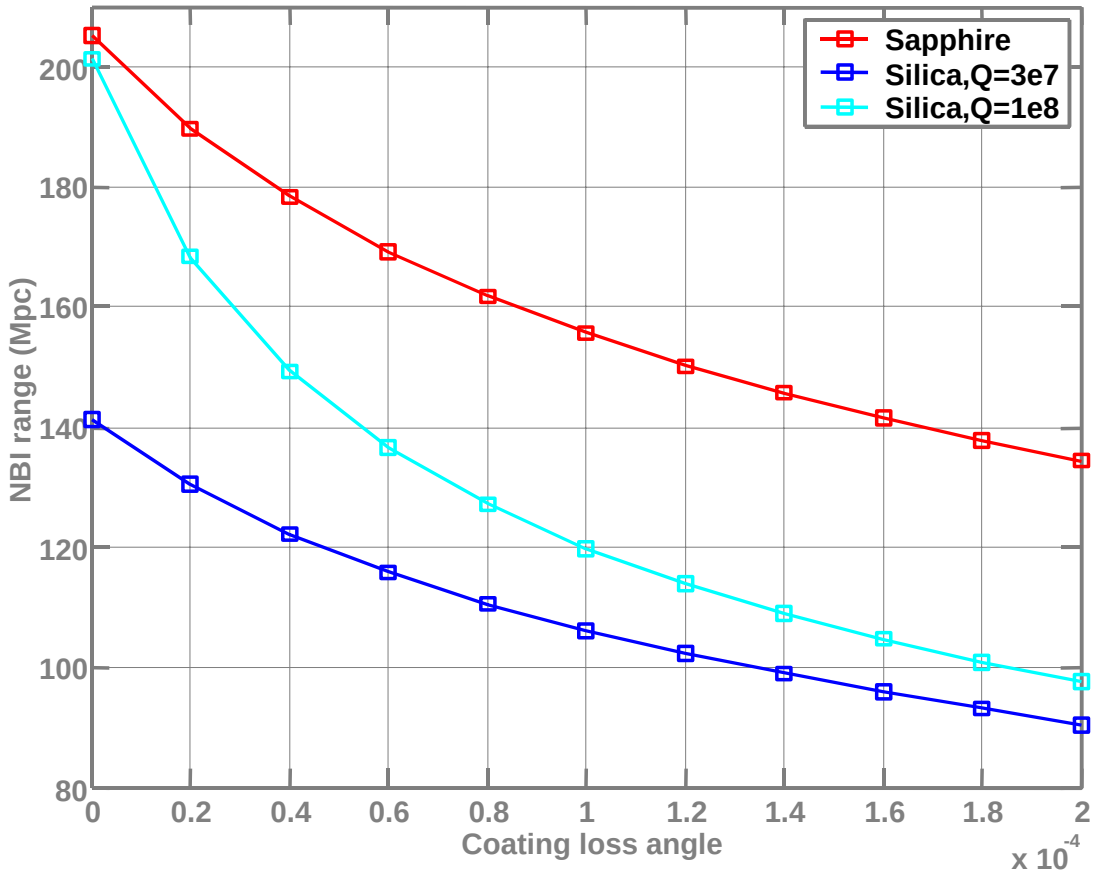

Figure 3. Neutron star binary inspiral range for a single interferometer of the indicated test mass material, as a function of the optical coating mechanical loss. Calculations are made with Bench 1.13, with coating thermal noise approximated by equation 23 of Harry et al[23].

4.2.2 Sapphire measurements

The Qs of two separate coated sapphire samples have been measured. One was reported at LSC Meeting 11, LIGO-G020324-00-R. The coating phi was 1.1 +/- 0.1 X 10^{-3} for a tantala/silica coating. The other was reported by K. Yamamoto et al. at the 2002 Aspen Meeting in Elba, http://131.215.114.135:8083/related/talks/23/yamamoto.pdf, gives a coating phi of about 5 X 10^{-4} at 77 K for a tantala/silica coating. Yamamoto also found the coating loss not to depend on temperature between 4 and 77 K.

4.2.3 Silica measurements

More work has been done on coating loss on fused silica than sapphire. The best coating phi measured on silica is 6.4 +/- 0.6 X 10^{-5} for an alumina/tantala coating[24]. It is not known whether identical coatings give different mechanical loss when laid down on silica and sapphire, although recent work on silica substrates indicates that the loss depends on the coating materials rather than any interaction with the substrate[25].

4.2.4 Action needed

Further research on coating losses is important and ongoing. Both silica and sapphire need substantial improvements in coating phi's as well as improved modeling of the thermal noise. The known differences between these two substrate materials with regards to coatings are not great.

4.3 Mechanical loss

4.3.1 Requirement

4.3.2 Status

Phil Willems notes that "Braginsky has identified a parametric instability between optical modes and test mass modes due to radiation pressure that gets worse for higher test mass *Q*'s but better the fewer test mass resonances below 1 MHz"

4.3.3 Comparison with fused silica

5 Thermal distortions

6 Miscellaneous issues

6.1 Attachments

6.1.1 Requirement

6.1.2 Status

Stress in sapphire/silica bonds has been observed. Heated sapphire/silica bonds (35C) and heating to 125C and back carries substantial risk of breakage. [26]

6.1.3 Comparison with fused silica

Creep seems to be less of an issue for silica/silica but there are no concrete results to date.

6.1.4 Action needed

More testing is needed to clearly define performance limits.

6.2 Alignment of Crystal Axis, Clocking

6.2.1 Requirement

Allowable loss due to alignment of sapphire must be considered a part of the recycling cavity loss budget of 0.3%. Kells notes[27] that a 1° misalignment between beam polarization and crystal axis result in ~600 ppm of loss.

6.2.2 Status

It has been demonstrated that homogeneity differences are smaller and of lower spatial frequency when the laser polarization is parallel to the c-axis for m- and a-axis material.

6.2.3 Comparison with fused silica

No alignment necessary with fused silica

6.2.4 Action needed

6.3 Suspension issues, actuation/size

6.3.1 Requirement

6.3.2 Status

6.3.3 Comparison with fused silica

Assuming 40kg masses no matter what, sapphire and silica are not so different to suspend. Silica would be larger, of course. It is easier to get a heavier penultimate mass for silica than sapphire due to the difference in densities.

6.4 Servo Control, Resonances

6.4.1 Requirement

6.4.2 Sapphire

6.4.3 Fused silica

6.5 Cost comparison

Fused silica input masses are ~1.5% more expensive than sapphire. Fused silica end masses are about half the cost of sapphire end masses. Sapphire input masses require compensating polish, which about makes up for the difference in price between sapphire and fused silica ITMs. Cost is not a significant driver in this decision.

6.6 Delivery

6.6.1 Requirement

6.6.2 Sapphire

Crystal Systems currently has one furnace configured for growing the 380 mm boules. Their VP of research has stated that and additional furnace could be fitted for growing the large boules, and that they can meet our final delivery rate with this added capacity.

6.6.3 Fused Silica

Corning and Heraeus have huge capacity. It can take a year to get into the queue for a Heraeus delivery, but the product arrives in volume.

Effects of high silica Q and coating Young's modulus on advanced LIGO, Harry - Jan '03 http://www.ligo.caltech.edu/docs/T/T030007-00/T030007-00.pdf

Measurements of the quality factors of sapphire and fused silica masses - Willems April '03 http://www.ligo.caltech.edu/docs/T/T030087-00.pdf

---

[1] Loss due to anisotropic characteristics of sapphire - D. Lopez, G. Harry, P. Willems, D. Busby, D. Coyne Sept '03 http://www.ligo.caltech.edu/docs/T/T030228-00.pdf

[2] Large sapphire substrate absorption measurements, S.M.A.- VIRGO (PPT) Remillieux April '03 http://docuserv.ligo.caltech.edu/docs/internal/C/C030208-00.pdf

[3] Silica Research Plan for Advanced LIGO - Penn May '03 http://www.ligo.caltech.edu/docs/T/T030102-00.pdf

[4] Report to the April 25, 2003 Core Optics Downselect Committee Meeting, P. Willems, D. Busby http://www.ligo.caltech.edu/docs/T/T030087-00.pdf

[5] Thermal Compensation Update R. Lawrence, D. Ottaway LIGO- G020502- 00- R

[6] Allowable absorption scale in Sapphire - R. Lawrence http://www.ligo.caltech.edu/~gari/LIGOII/Downselect/AbsScale.pdf

[7] Stanford results on heat treatment of Sapphire - Route April '03 http://www.ligo.caltech.edu/docs/T/T030088-00.pdf

[8] Absorption Studies in Optical Coatings and Sapphire Crystals', R. Route, M. Fejer, A. Alexandrovski, and V. Kondilenko. http://www.ligo.caltech.edu/docs/G/G020374-00.pdf.

[9] Absorption profile of 311SV measured at Lyon (from T010087-00, pg 6) - June '01 from T010087, page 6. http://docuserv.ligo.caltech.edu/docs/internal/C/C010655-00.pdf

[10] Analysis of sapphire inhomogeneity (Kells, e-mail) http://www.ligo.caltech.edu/docs/T/T000150-00.pdf

[11] Homogeneity of Sapphire, a vs. m axis - Billingsley August '03 http://www.ligo.caltech.edu/docs/T/T030177-00.pdf

[12] Summary and CSIRO Sapphire Homogeneity Report, http://docuserv.ligo.caltech.edu/docs/internal/C/C000672-00.pdf

[13] Joel Askinazi et. al., Recent Advances in the Application of Computer Controlled Optical Finishing to Produce Very High Quality, Transmissive Optical Elements and Windows, Goodrich Corporation, Optical and Space Systems Division, http://www.ligo.caltech.edu/docs/P/P030028-00.pdf

[14] Map of Goodrich compensating polish http://docuserv.ligo.caltech.edu/docs/internal/C/C020137-02.pdf

[15] CSIRO Homogeneity compensation and Ion Beam Etch Report C020136-00 http://docuserv.ligo.caltech.edu/docs/internal/C/C020136-00.pdf

[16] Rich and Pinnow , Applied Physics Letters, 20, (1972) 264.

[17] Benabid *et al.,* Optics Communications, 167, (2000) 7.

[18] http://docuserv.ligo.caltech.edu/docs/internal/C/C010237-00.pdf; for a picture of CSIRO's metrology result, see also http://www.ligo.caltech.edu/~gari/LIGOII/sapphia1.gif

[19] P. Fritschel, Advanced LIGO Systems Design Document, http://www.ligo.caltech.edu/docs/T/T010075-00.pdf

[20] Polarization Scatter Through Sapphire Substrates - W. Kells L. Zhang L. Cardenas Sept. '03 http://www.ligo.caltech.edu/docs/T/T030189-00/T030189-00.pdf

[21] Birefringence profile of Virgo substrate, measured at Lyon, June 2001. From LIGO-T010087-00 page 1. http://www.ligo.caltech.edu/docs/T/T010087-00.pdf

[22] Coating development LIGO-C030187 http://docuserv.ligo.caltech.edu/docs/internal/C/C030187-00.pdf

[23] G.M. Harry et al., Class. Quantum Grav., 19, (2002) 897.

[24] D.R.M. Crooks et al., Class. Quantum Grav., 19 (2002) 883.

[25] Penn et al, Class Quantum Grav 20, 20 (2003) 2917

[26] Observations on sapphire-fused silica bonds - Armandula - March '03 http://www.ligo.caltech.edu/docs/T/T030046-00.pdf

[27] Polarization Scatter Through Sapphire Substrates - W. Kells L. Zhang L. Cardenas Sept. '03 http://www.ligo.caltech.edu/docs/T/T030189-00/T030189-00.pdf