LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Test Mass Material Down-select Plan

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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, 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: Three large pieces have been measured at SMA Lyon[2], the first shows significant high spatial frequency structure, with average absorption at roughly 60ppm/cm, ranging from 30 to 130ppm/cm. Two other pieces were later sent to Lyon for measurement, these results - the 250 mm sapphire mass from the University of Glasgow absorption varies from 29 to 110 ppm/cm with a mean value between 49 and 55 ppm/cm. The mechanical quality sapphire mass absorption varies from 10 to 53 ppm/cm with a mean value between 30 and 31 ppm/cm.

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.

Comment [GLB1]: What is the source? Does this still stand? Do we get/negotiate this requirement from AOS now?

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 20 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, 40-60 ppm/cm, and often quite variable in spatial frequency, 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 October 2003 LSC viewgraphs of R Route.[8] Early on, a small pocket (~cm-scale) of 10 ppm/cm absorption was seen in one sample (which also showed a region at 600 ppm/cm), demonstrating that the intrinsic optical absorption of sapphire is not higher than 10 ppm/cm. The first successful avenue for post-growth reduction of optical absorption was cooling at greater than 200 °C /hr in an H_2/N_2 atmosphere from an annealing temperature in the 1100-1300 °C range. A typical result of the intermediate temperature, rapid-cool process is from 50-70 ppm/cm (pre-annealed) to 25-50 ppm/cm (post-annealed), with an average improvement around a factor of 2. Post-annealed samples have displayed reasonably uniform (10-20% variation) along scan lengths of 5-10 mm. Most annealing tests and absorption measurements have been done on small samples, typically 25 mm dia × 10-12.5 mm thick which may or may not accurately represent the average properties found in full-size, high-quality LIGO test masses..

There has been one 75mm dia × 25mm high quality LIGO optical sample that was annealed at 1200 C° and rapidly cooled at 800 C°/hr, with a reduction in optical loss from 70-80 ppm/cm to 20-22 ppm/cm. This is a reduction in loss by a factor greater than 3, and the large improvement suggests additional testing of larger size, high quality LIGO sapphire optics to more accurately determine the percentage improvements that can be expected from the rapid-cooling process. This test did demonstrate that it is possible to rapidly cool intermediate-size samples without damage[8]. (If the need arises to prove this method on full-size pieces suitable for LIGO optics, it is recommended that further testing be carried out at Crystal Systems who have controlled-atmosphere furnaces of adequate size.)

The improvements achieved with rapid cooling from 1200 °C are metastable. Repeating the annealing process with slow cooling on the order of 25 °C/hr restores the sample to its pre-annealed loss value, suggesting the effect is due to a change in the point defect equilibrium in the sample and not out-diffusion of an extrinsic impurity. We do not have data on the long-term stability of the metastable equilibrium established by the rapid cooling process. It has been demonstrated that it is necessary to exceed ~1000 °C to establish the metastable equilibrium, but it is not yet known if this represents the thermal activation energy needed to reverse the process. Additional testing will be needed to establish this.

In contrast, 100-200 hr, high vacuum annealing in the range of 1800 °C followed by slow cooling on the order of 25 °C/hr has yielded equally significant reductions in optical absorption in 25 mm dia x 12.5 mm thick samples. A typical result of the high-temperature high-vacuum process from a pre-annealed absorption of 40-55 ppm/cm is 12-18 ppm/cm, with an average improvement around a factor of 3. One important difference is that this is achieved without the need for rapid cooling. A second is that the improvement appears to be permanent. Re-annealing at intermediate temperatures in H_2/N_2 followed by slow cooling does not restore the optical loss to its pre-annealed values, suggesting that the effect is more likely due to out-diffusion of one or more extrinsic defects rather than a change in the point defect equilibrium. Thus, it may be feasible to reduce the optical absorption in full-size LIGO test masses without rapid cooling. Since thermal diffusion times tend to scale as the square of the path length, the diffusion kinetics of the process will determine if full-size masses can be successfully heat-treated on an acceptable timescale. Testing of intermediate size CSI sapphire optics on the order of 50 mm dia by 50 mm long have been ordered for additional annealing studies to address this question. If the diffusion model is correct, one would expect smoothing of spatial variations on an order up to the sample thickness. Such homogenization effects can be studied using these same intermediate size test samples.

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[9]. 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 notes T030088-00[10] and the recent LSC viewgraphs of R Route.[11] 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). The current annealing status:

- Reducing anneals at intermediate temperatures reversibly lower absorption
- Annealing at > 1100 º C in H2/ N2 yields reductions greater than 50%
  25- 30 pm/ cm achieved with passive cooling at rates of >200º C/ hr
  20 ppm/ cm achieved with forced cooling at rates of >400º C/ hr
  Cooling kinetics of the annealing process are controlling variables
- High temperature vacuum annealing reduces absorption by equal or

greater amounts without having to cool rapidly
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[12]. 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[13] 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[14]. 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. Therefore a-axis material is chosen for the baseline design.

Nature of the inhomogeneity. Inhomogeneities in *a*- and *m*-axis sapphire appear as linear striae, perpendicular or parallel to the c-axis, and 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[15].

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[16]. 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[17]. 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[18] (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 at least one method that will work. With investment, a better method may be developed.

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 low quality large sapphire pieces (inclusion scattering can be treated as a geometric cross sectional loss). We have looked 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

The group at UWA has measured Rayleigh scattering in Hemlite sapphire at 4ppm and 7ppm[19], compared with 13ppm reported by Benabid et al[21].

3.4.3 Fused silica

Fused silica can be reliably obtained with few or no inclusions, so that 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[20]. 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.*[21] 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 mm would allow an internal scattering of 10 ppm/cm.

3.4.4 Action needed

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 $(2\pi\delta/\lambda)^2$, where δ 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[22]. 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.[23]

3.6.2 Sapphire

At the level of the experimental sensitivity (~50ppm) no correlation of local polarization rotation with apparent inhomogeneity was found[24]. 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[25]. 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.[26] The coating performance required for interferometer performance is somewhat independent of substrate choice, with the exceptions of coating absorption, Young's modulus, thermal expansion, heat capacity, and thermal conductivity. 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. Minimizing thermal noise from the coating requires matching both the thermal and elastic impedances across the substrate/coating boundary. It seems possible to find a substrate/coating match that reduces coating thermoelastic noise[27], caused by the

mismatch in heat capacity, thermal conductivity, and thermal expansion, to the role of a technical noise source. Brownian thermal noise, due to internal friction in both coating materials as well as the substrate, will almost certainly be a limiting noise source in Advanced LIGO. A good match between the Young's moduli of the coating and substrate will help reduce the Brownian thermal noise. The rather large difference in Young's modulus between silica (72 GPa) and sapphire (~400 GPa) will require different coatings to achieve a good match.

4 Thermal Noise Estimates

4.1 Material properties

Ideally, the test mass thermal noise would be determined only by the properties of the 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 material properties. Past uncertainties in the thermoelastic properties of sapphire have been mostly resolved (although recent results from the TNI still have to be completely understood), so that we now have values for most properties (with the notable exception of internal friction) that we believe are accurate to within ~10%. For both materials, the property with the most uncertainty is the internal friction. 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 loss, for plausible ranges of each material. The table below lists the relevant parameter values for the comparison.

Parameter	***Sapphire***	***Fused Silica***
Equivalent 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.

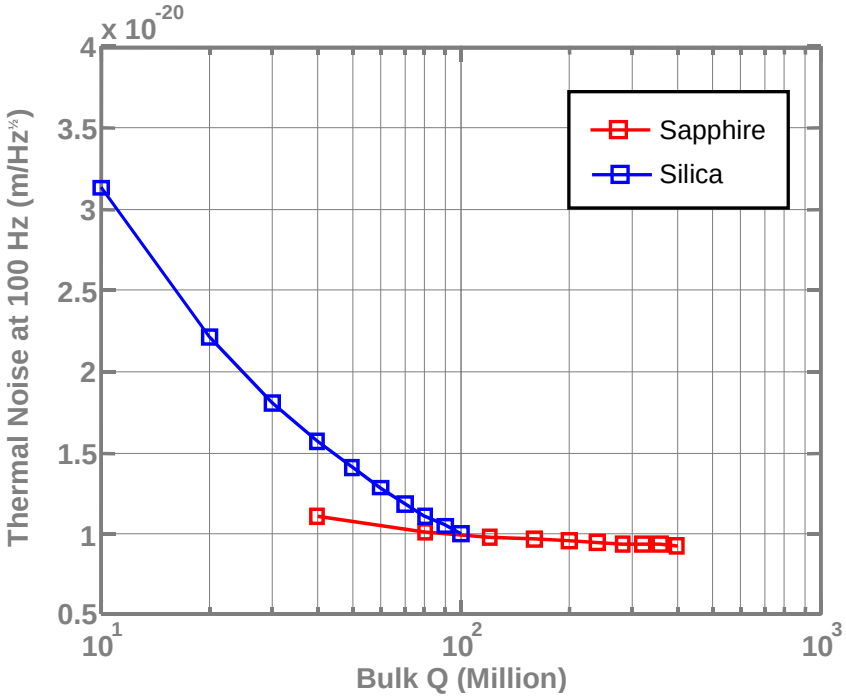

Figure 1. Thermal noise at 100 Hz as a function of test mass material mechanical loss parameterized by a modal Q, for plausible ranges for sapphire and fused silica. Plotted is the differential arm displacement noise (strain noise divided by arm length). Very low coating mechanical loss is assumed.

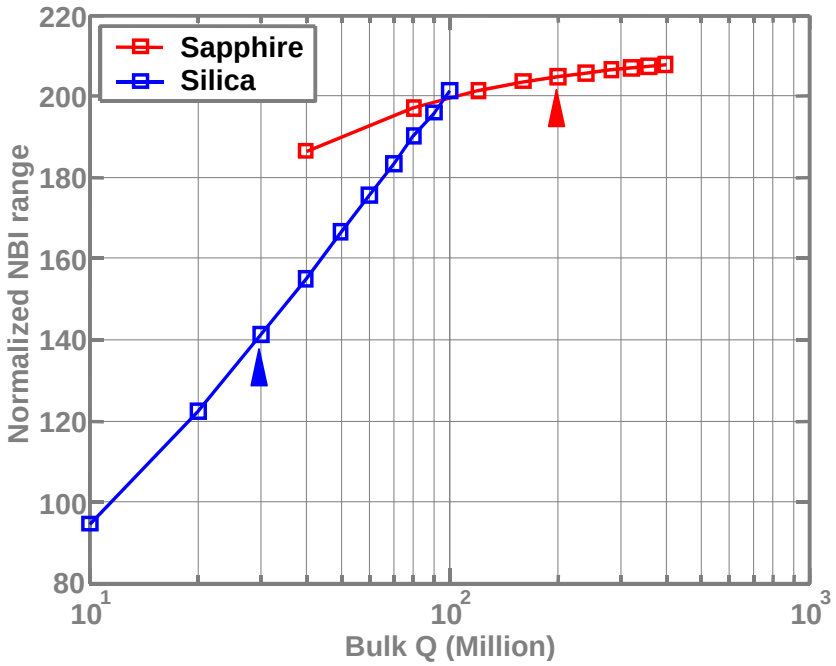

Figure 2. Comparison of neutron star binary inspiral (NBI) range for sapphire and fused silica test masses, as a function of the material mechanical loss parameterized by a modal Q. The nominal *Q* values are indicated by the markers. Very low coating mechanical loss is assumed.

Error! Reference source not found. Figure 1 and Figure 2**Error! Reference source not found.** show that the thermal noise prediction for sapphire is much more tolerant to uncertainty in the internal friction, which is not surprising since thermoelastic damping is dominant. The figures also show that if the mechanical loss of fused silica happens to be significantly lower 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. The highest modal *Q* of a fused silica sample observed to date is 200 million, observed at Syracuse.

There is accumulating evidence that loss in silica is due to a low-loss bulk and a lossy surface layer. The surface layer will contribute to thermal noise similar to a coating. There is also growing evidence that at least the bulk loss has a frequency dependant component, which gets lossier at higher frequencies. Since mechanical loss estimates for silica come from modal Q values measured between 400 Hz and 100 kHz, the loss in the advanced LIGO band around 100 Hz may be less than what is indicated by modal Q. Work is underway, centered at Hobart and William Smith College, to analyze a large amount of silica modal Q data, to try to develop a model that accounts for the surface loss and the frequency dependence.

Sapphire is a crystal of the trigonal symmetry system, and thus has six independent elastic constants, each of which can have an imaginary part that causes loss. The effect of these multiple

loss angles on the thermal noise, and especially any implications it has for the choice of axis of the mirrors has not been well studied. Work is underway at Caltech and MIT to better understand this aspect of sapphire loss. There are examples of sapphire modal Q measurements that are consistent with being limited by a surface loss at levels below 200 million (Numata 2001, Willems 2003). In each of these cases the polish was significantly rougher than will be needed for advanced LIGO and this likely contributed to the increased surface loss. What role, if any, surface loss could play in properly polished advanced LIGO sapphire optics is not known. The lowest frequency a sapphire modal Q has been measured is about 10 kHz, 2 orders of magnitude above the advanced LIGO frequency band. Measurements are being made at MIT on a sapphire rod with the lowest mode near 4 kHz, and geometry such that thermoelastic damping will limit the modal Q to about 200 million at this frequency. The influence of most of these effects on the sensitivity of advanced LIGO through Brownian thermal noise will likely be limited because of the dominant role of themoelastic noise in sapphire mirrors.

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. One example of the effects of coating mechanical loss on inspiral sensitivity is indicated in Figure 3. The effect of the coating on sensitivity depends on many parameters of both the substrate and the coating; internal friction, Young's modulus, index of refraction, heat capacity, thermal conductivity, and thermal expansion of both the low index and high index coating materials, as well as the substrate Young's modulus, heat capacity, thermal conductivity, and thermal expansion. Requiring coating thermoelastic noise to be less than 10% of the final limiting noise in all bands, which seems an obtainable goal, still leaves both coating materials' internal friction, Young's modulus, and index of refraction as well as the substrate internal friction and Young's modulus as active parameters.

Over the coating mechanical loss range 0-3 X 10^{-4} for perpendicular stresses, assuming no change in coating thickness from 8.3 μm on an ETM or Young's modulus of 214 GPa, the sapphire design range is reduced from 200 Mpc to 170 Mpc. If one assumes low internal friction silica ($\phi_{eff} < 5$ X 10^{-9}), the plot shows that such a material would suffer more quickly than sapphire from coating loss.

Figure 3 indicates the target maximum coating loss would be about 9 X 10^{-5} for sapphire, if a coating Young's modulus above 200 GPa and 8.3 mm ETM coating thickness can be maintained. If a softer coating is required, with a Young's modulus of 90 GPa but the same ETM coating thickness, a loss angle of 3 X 10^{-5} would be required. Conversely, if the stiff Young's modulus is held fixed but the material indices are such that the required ETM thickness is only 5.8 μm, then the loss angle need only be less than 1.5 X 10^{-4}. This loss angle is near what has been demonstrated with a silica/3% titania doped tantala coating from LMA/Virgo, although the Young's modulus is only 90 GPa with a required thickness 5.8 μm. Initial LIGO coatings

unfortunately show a loss of about 3 X 10^{-4} with a Young's modulus of 90 GPa and an ETM coating thickness requirement of 5.8 μm.

All 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. Finite element modeling by Kenji Numata shows that this analytical approximation slightly overstates the coating thermal noise. Ideally, a full analytical model that takes into account the finite size of the mirror relative to the beam would be used.

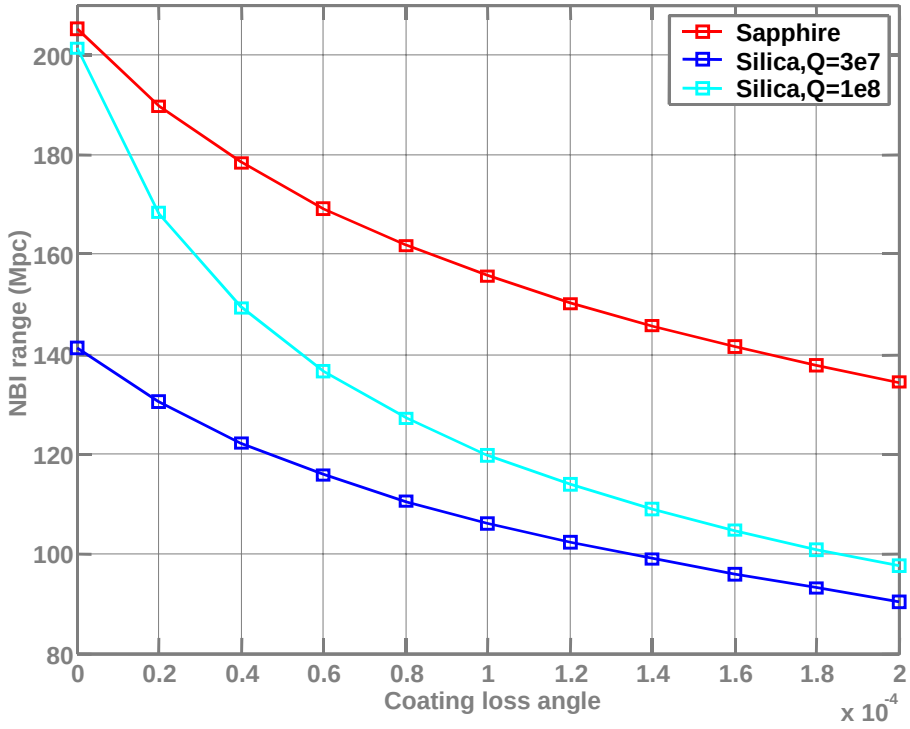

Figure 3. Neutron star binary inspiral range for a single interferometer of the indicated test mass material, as a function of the optical coating mechanical loss. Calculations are made with Bench 1.13, with coating thermal noise approximated by equation 23 of Harry et al[28].

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[29]. 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[30].

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

Thermal distortions impair the interferometer performance in several ways. Depending on the location and source of the distortion, the performance limit and the thermal compensation required to achieve it will vary.

5.1 Arm cavity distortions:

The HR surfaces of the test masses will deform under thermal loading to a degree that will substantially change the arm cavity mode size. This distortion cannot be compensated except by applying heat directly to the test mass itself, and most efficiently to the HR surface. The following table shows what the spot sizes at the test masses will be for an interferometer designed to have the correct test mass radii of curvature at full power, for cold operation, and for two types of compensation during cold operation: both test masses compensated, and only the ITM compensated.

		ITM spot size	ETM spot size
Silica	Hot, or both compensated	6.0cm	6.0cm
	Cold	8.5cm	8.5cm
	Cold, ITM compensated	6.8cm	6.6cm
Sapphire	Hot, or both compensated	6.0cm	6.0cm

	Cold	7.0cm	7.1cm
	Cold, ITM compensated	6.3cm	6.2cm

5.2 Recycling cavity distortions

The round-trip RF sideband optical loss expected from a sapphire ITM at full interferometer power is about 6%, assuming a bulk absorption of 30ppm/cm, which is typical of the large samples to date. This also assumes that the HR surface is not compensated at high power and of the correct ROC at low power. If instead the design has the ROC correct at high power operation, the optical loss no longer includes the thermal expansion of the HR surface and therefore drops to 1.8%. While this is large, it can be adequately reduced with a separate suspended thermal compensator plate. The interaction between simultaneous HR surface compensation and plate compensation has not yet been modeled.

In the case of a fused silica ITM, at high power operation the RF sideband optical loss at high power is 93%- the cavity will require a large amount of thermal compensation to build up significant RF sideband power. This degree of compensation should be attainable with a shielded ring heater acting on a compensator plate

The efficiency of extracting the GW sidebands from the arm cavity with the signal recycling cavity will depend on these distortion losses being reduced to a level well below the transmissivity of the signal recycling mirror, or 5%. This should be possible with either fused silica or sapphire, though it will be much easier with sapphire.

5.3 Bulk inhomogeneities

The absorption of fused silica seems to be very uniform, and since it contributes so little to the total absorbed power compared to the coating absorption we ignore it here. Note that later we will show the inhomogeneity of coating absorption to be a serious matter.

For sapphire, the bulk inhomogeneities have more influence, since the bulk absorption is the larger part of the total absorption. When the uniform 30ppm/cm absorption assumed above for sapphire is replaced by the absorption profile measured for a Pathfinder sapphire, the loss increases from 6% to 11%.

5.4 Coating absorption inhomogeneities

Spots of high absorption in the coating of the test masses can also cause aberrations that impair interferometer performance, in both silica and sapphire. The following table shows the results of a calculation that studies the effect of a gaussian spot of 4mm waist that absorbs in excess of the coating average, on silica, at full interferometer power. The resulting bump on the surface of the test mass will scatter power from the arm cavity mode. The effect is largest if the spot is near the center of the interferometer beam.

Spot location	Absorption causing 1ppm loss
Centered spot	.25ppm
off 2cm in x	.37ppm
off 4cm in x	1.0ppm
off 6cm in x	4.9ppm
off –2cm in x	.35ppm
off –4cm in x	1.0ppm
off –6cm in x	4.9ppm
off 2cm in y	.35ppm

The next table repeats the analysis for sapphire.

Spot location	Absorption causing 1ppm loss
Centered spot	.57ppm
off 2cm in x	.81ppm
off 4cm in x	2.3ppm
off 6cm in x	11ppm

These numbers are indicative only; they are probably accurate to about 30%, but they do not consider changes to the arm cavity mode resulting from the change in ROC of the optic's surface, nor are the simultaneous effects of multiple spots considered. Modelling shows that the amount of loss scales as the net power absorbed for these small spots (i.e. a spot half the size with twice the absorption will absorb the same net power from the interferometer beam and scatter the same net power from the arm cavity mode.

Coating absorption inhomogeneity will be very difficult to compensate in Advanced LIGO. Both input and end test masses are equally vulnerable, and all might need to be compensated (it may be possible to compensate a bump on one test mass by actuating on the other test mass, but this seems unlikely). This compensation would require a CO_2 laser tailored to each test mass's inhomogeneity, and a sensor capable of measuring the HR surface deformation of each optic. Therefore, this analysis should set restrictions on the allowable coating absorption inhomogeneity. Note that sapphire is only slightly better by this measure.

Coating absorption inhomogeneities will also have an effect inside the recycling cavity. If a 4mm spot at the center of the coating absorbs at 1.2ppm rather than .5ppm, the excess power will be about 2.4mW. Modeling of the thermorefractive aberration in fused silica due to this heating yields an overlap integral of 99.88%, or .12% loss in the recycling cavity, assuming all homogeneous thermal lensing has been ideally corrected. CO_2 laser compensation of inhomogeneity causing this level of loss was modeled and demonstrated experimentally by Ryan Lawrence, where he was able

to reduce this loss by a factor of ten. By analogy to the surface distortion results, off-axis spots should be less critical by similar factors.

The final requirement on inhomogeneous thermal aberration is not yet well defined. One reasonable approach is to require that inhomogeneous thermal aberrations not exceed the residual static refractive index inhomogeneity after the compensating polish. This is specified in the COC DRD as less than 10nm rms for adequate coupling of carrier light into the arm cavity, along with the requirement that the RF sideband power buildup not be significantly reduced. Precisely what 'significantly' means in this context is not yet defined. Nevertheless, the overall amplitude of thermal aberration in the above case is peaked at about 10nm in a small region around the center of the optic, so the rms is presumably far less. It would appear that, so long as point absorbers in the ITM do not dissipate more than about a few mW and are rare, CO_2 laser compensation of coating inhomogeneity in fused silica seems a viable option.

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. [31]

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[32] 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

Optics should have same mass, whether sapphire or silica. Assuming same mass there are no actuation issues.

6.3.2 Status

A) Mechanical Issues

The main issue from a mechanical viewpoint is that silica is larger (34 cm diameter x 20cm thick), compared to sapphire (31.4 cm diameter x 13 cm thick).

1) We are currently designing the controls prototype ETM assuming sapphire is the test mass material - thus the prototype test mass (made from metal with glass faceplates for actuation tests) has a sapphire-sized footprint, as has the penultimate mass. The detailed design for the controls prototype is now ongoing, and metal has already been cut. Thus even if the downselect decision is to change to silica as the baseline, we offer the proposal that the controls prototype continues to be developed as if sapphire were the material of choice. We have time to refine the design for a silica test mass in the noise prototype if a change is made to the baseline.
2) The overall design has been chosen so that if the test mass baseline were changed from sapphire to silica, there is as much commonality of design as possible (overall length of structure, upper masses, blades etc) , to minimise the work necessary to update the design for the new material: ref. NAR presentation at LSC in Hannover, Aug 2003 (LIGO-G030437-00-Z)
3) Considering the mechanical layout, and taking into account the commonality referred to in 2) above, the major changes moving from sapphire to silica would occur in detailed design of the support structure and associated pieces, such as the "tablecloth" supporting the OSEMS, the catcher used for assembly and support of the penultimate and test mass, the positioning of earthquake stops etc. We believe that we can fit a silica mass into the overall footprint without enlarging the footprint, i.e.the outer dimensions of the support structure would not be increased. This is helped by the proposal that the reaction chain would mimic the size of a sapphire test mass, whatever the test mass material (as illustrated in G030437-00-Z) so that if silica is used in the main chain, the overall increase in size of the two pendulum chains, in particular in the direction parallel to the laser

beam, is minimised.
One proviso on this - if the SEI/SUS dynamic coupling analysis (currently ongoing) concludes that a completely different concept for the structure needs to be explored and developed, then the footprint and support structure interfaces may change, and the larger silica size could become more significant.

4) There may be a difference in some aspects of the suspension design required if the thermal compensation schemes for the two materials are significantly different. We do not have enough input on this topic at present to make further comments on this.

B) Materials issues

1) We are assuming that if sapphire is used, the penultimate mass will be made of dense glass - preferably SF2, which has a density of 3860 kg/m^3 close to that of sapphire (density 3980 kg/m^3) , or SF4 (density 4790 kg/m^3). If silica is used the penultimate mass would also be silica. The procurement of suitable sizes of these materials, and the cost implications, are issues which need to be taken into account.

2) The bonding issue: since the ears are made of silica, using sapphire involves two types of bonding between different materials - i.e. silica/sapphire and silica/ SF2(4), whereas with silica test mass and penultimate mass, all bonds are silica/silica. In terms of risk, silica/silica is less risky - there is no difference in coefficient of thermal expansion, and there is already extensive experience of making and using silica/silica bonds in the GEO suspensions.
Estimate of risk associated with 2) (from JH): Using DHS scale (1 = perfectly confident, 0.5 = 50-50 chance will work)
i) Bonding: 0.95 (both)
ii) Possible excess noise: silica = 0.90-0.95, sapphire = 0.8 to 0.9

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 Charging issues

Both Gaussian and non-Gaussian noise from charge buildup on the optics are potential issues for advanced LIGO. Preliminary theoretical modeling of Gaussian noise due to charge was done by Weiss in T960137-00-E. This work shows the importance of the correlation time of the charge on the optic to noise. For both silica and sapphire, this time has not been measured, although some preliminary work on surface conductance of silica has been done at Glasgow. Non-Gaussian charging events on a silica sample have been observed for over many years in an experiment at Moscow State University, described in G040090-00.

To date, nothing done either theoretically or experimentally with charging can distinguish between silica and sapphire as a test mass material. A research plan for the LSC has been developed (T040070-00-R) to further investigate charging issues. Direct measurements of charge correlation times are planned using Goddard Space Flight Center's Kelvin probe. Experiments with ion implantation into both substrate materials are planned by collaboration between Glasgow and the University of Surrey in Britain to increase the surface conductance and thereby improve the correlation time of the charge. A modernization of the charging experiment at Moscow is also planned, including the addition of a sapphire sample. Preliminary results from these efforts are possible before the downselect decision is made.

6.6 Cost comparison

Comparison of cost is based on previous quotes from vendors. The Crystal systems quote is over two years old, the Heraeus quote (Fused silica) is recent. Edge polish and compensation polish are correct to within 50%.

	Cost each ITM		
Activity	Sapphire	Fused Silica (Heraeus 311)	Fused Silica (Heraeus 312)
Raw Blank	100000	125000	68000
Edge polish	8000		
comp. Polish	40000		40000
S1 polish	47000	57000	57000
Totals	195000	182000	165000

6.7 Delivery

6.7.1 Requirement

6.7.2 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.

6.7.3 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

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