LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T020103-02-D   *ADVANCED LIGO*   08/05/02

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

-D

Appendices

Error! No table of figures entries found.

Table of Tables

Error! No table of figures entries found.

Table of Figures

Error! No table of figures entries found.

1 Introduction

The baseline design for Advanced LIGO test masses calls for the use of sapphire, because of its promising thermal and mechanical properties. There has been a concerted effort to bring the optical properties of sapphire up to a level that supports the detection goals of Advanced LIGO. The material down-select decision for Advanced LIGO is scheduled for December, 2002. As of this date we will either continue with or abandon the baseline design. Fused silica is the backup material in the event the sapphire baseline is shown to be not ready.

1.1 Purpose

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. The paper is also intended to outline the process for making the down-select decision. The document summarizes the current state of sapphire development in comparison to the Advanced LIGO requirements. Recommendations for further test are made to ensure that the LIGO Lab has all data necessary to make the down-select decision.

1.2 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

1.3 Acronyms

List all acronyms and abbreviations used in the document.

1.4 Applicable Documents

Advanced LIGO Systems Design Document T010075-00

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

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

CSIRO Sapphire Polishing Report C010237-00
http://docuserv.ligo.caltech.edu/docs/internal/C/C010237-00.pdf

CSIRO Sapphire Homogeneity Report C000672-00
http://www.ligo.caltech.edu/~gari/LIGOII/homogeneity.htm

Bill's analysis of sapphire inhomogeneity (e-mail)

CSIRO Ion Beam Etch Report C020136-00

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

Absorption status table Roger Route

1.5 Plan

1.5.1 Schedule

The down-select decision is scheduled for December 2002. The design of the Suspension and Active Thermal Compensation subsystems wait on final determination of a test mass material.

We will receive two 314 x 130 mm a-axis sapphire blanks in October 2002. These blanks will have a commercial polish on all sides, and will not yet have mounting flats machined on. Between October and December we plan to measure homogeneity, scatter and absorption and report findings. This is a very aggressive schedule, we had originally planned on having our first full size blanks in June, 2002. After the down-select measurements are complete the pieces are to have mounting flats added, and are to be polished and coated in preparation for use in LASTI.

1.5.2 The Down-select Process

A committee will be selected from amongst the LIGO Laboratory and LIGO Scientific Collaboration community. This committee will be chosen to represent the interests of

-D

scientific reach as well as any subsystem directly affected by the core optics, namely Input Optics, Auxiliary Optics and Suspensions. The committee will be responsible for deciding if sapphire in its current state, meets the technical requirements of Advanced LIGO, with acceptable levels of cost and risk.

2   Requirements

It is assumed that Sapphire can be manufactured to meet the requirements for Advanced LIGO. Each requirement is listed, followed by the basis for that requirement, where known. The current status is summarized and compared with fused silica; finally the actions needed to prove that sapphire can be made to meet the requirement are listed.

2.1   Size

2.1.1   Requirement

40Kg, for Sapphire 314 x 130mm

2.1.2   Basis

Advanced LIGO System Design Document Work by P. Fritschel

http://www.ligo.caltech.edu/docs/T/T010075-00.pdf

2.1.3   Status

380 mm a-axis sapphire boules have been grown. CSI has made 4 growth attempts since January 2002. One of these has resulted in a boule they term good. We are buying the good one and one of the others to get an idea of the quality spectrum we can expect in full size sapphire. These pieces must be analyzed before the down-select decision can be made.

The Fused Silica alternative need not be limited to 40 Kg, this should be modeled as part of the down-select decision: At what size FS mass does the astrophysical reach equal 40Kg sapphire (if ever?)

2.1.4   Comparison with fused silica

Low absorption (~1ppm/cm) fused silica from Heraeus can be made available in sizes larger than 40Kg, the exact limit has not been explored.

2.1.5   Action needed

Accept delivery of test masses (to be used for LASTI), and determine if the properties of these large masses are the same or similar to the smaller pieces that have been used for test and development.

Model; At what size FS masses does the astrophysical reach equal 40Kg sapphire (if ever)

-D

2.2 Absorption

2.2.1 Requirement

< 20 ppm/cm throughout the central 120 mm diameter of the substrate.

2.2.2 Basis

Advanced LIGO System Design http://www.ligo.caltech.edu/docs/T/T010075-00.pdf

Melody model, this needs to be modeled using the updated version.

2.2.3 Status

Stanford has seen pockets of low absorption at 10ppm/cm level in small pieces. Typically annealing will only bring the absorption of small pieces to the 30-40 ppm level. Absorption has not been measured on a large piece. We don't know if we should expect a difference in absorption based on size. Negotiations are underway to have the two full size pieces measured at Lyon, where they have the hardware to scan large substrates. We are hoping to use the same calibration piece as has been used at Stanford.

Arguably, we could (with AOC) compensate for absorption... Ryan Lawrence draws some limits, see http://www.ligo.caltech.edu/~gari/LIGOII/Downselect/AbsScale.pdf

2.2.4 Comparison with fused silica

Heraeus low absorption fs absorbs ~1ppm/cm of the 1064nm input. Corning makes an ultra low absorption glass which measures at or below the instrument floor for the photothermal deflection technique, roughly .2 - .5 ppm/cm. The current feeling is that, at the ppm level, the coating is the limiting absorber.

2.2.5 Action needed

Stanford will attempt to anneal a 75mm x 25mm piece to see if there is a difference in absorption between the 1cm and larger pieces.

Measure and map the absorption of full size pieces.

2.3 Homogeneity

2.3.1 Requirement

< 10 nm rms for the ITM only.

2.3.2 Basis

Advanced LIGO System Design http://www.ligo.caltech.edu/docs/T/T010075-00.pdf and

LIGO 1 optical homogeneity levels, assume the loss in strain sensitivity goes as 1-rms^2.

-D
2.3.3 Status

 <14 nm demonstrated compensation on 250mm dia x 100mm thick substrate. < 10 nm rms has been reported by Goodrich, but has not yet been verified at CIT. Microroughness is 55 angstroms rms.

CSIRO has demonstrated good control of material removal with ion beam etching of sapphire (LIGO-C020136). Microroughness actually improves with ion bombardment to ~1 Å. It would require a significant investment (~100K) to take this process to the next level of compensation on a 75mm part. I suggest that we wait until the downselect to pursue this technology. I do believe it is a better approach than the machine compensation done by Goodrich.

There is some question as to whether a or m axis material has lower inhomogeneity. The only way to know conclusively is to buy a cube of material and measure along both axes. M-axis material is supposedly easier to polish than a-axis material. Small (3X1) substrates of both a- and m-axis have shown little or no inhomogeneity. We will know the homogeneity level of the full size a-axis pieces after they are delivered.

It has been conclusively demonstrated that the level of inhomogeneity in an a or m-axis piece measures lower when probed with a laser polarized parallel to the c-axis of the material. We should have a write up on this (Gari)

2.3.4 Comparison with 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. Heraeus 311 is available in all the sizes of interest, but costs roughly twice what the 312 material costs.

2.3.5 Action needed

Measure full size pieces as soon as possible. Measure both axes of a cube to determine if a given piece measures differently when viewed along the a or m-axis.

Determine if 55 Å is acceptable as a loss in the recycling cavity.

2.4 Internal Scatter

2.4.1 Requirement

3×10^{-3} is specified in the Advanced LIGO System Design document (http://www.ligo.caltech.edu/docs/T/T010075-00.pdf)as a good number to use for total power recycling cavity loss. Divide this amongst all surfaces and bulk material.

2.4.2 Basis

3×10^{-4} total loss in the power recycling cavity is used in Bench.

2.4.3   Status

Bill and Jordan have examined Rayleigh scattering in small pieces. "It looks good." It would be great if we could get some numbers.

Inclusion scattering can be treated as a geometric cross sectional loss. Inclusions have been seen in large numbers in large sapphire pieces, CSI feels that this should not be a problem. We have tried to look at these inclusions with a long objective microscope, we were still seeing diffraction rings at 50x. The best guess is that the upper limit on size for these inclusions is ~ 2 micrometers.

2.4.4   Comparison with fused silica

Fused silica has higher Rayleigh scattering (need a number) but can be reliably obtained with few or no inclusions.

2.4.5   Action needed

Examine the "good" and "not so good" full size pieces from crystal systems. Measure the scatter of these pieces quantitatively if possible; the system at Lyon may be able to do this. Perhaps the "not so good" pieces can still be used as ETMs. We do know that one piece with a huge number of internal bubbles was polished to ~0.5 Angstroms by Wave Precision. The presumption is that the bubbles must have broken through the surface because they were so numerous.

2.5   Polish

2.5.1   Requirement

<1nm rms.

2.5.2   Basis

Similar to LIGO1 requirements. Advanced LIGO modeling assumes < 75 ppm round trip cavity loss.

2.5.3   Status

This has been demonstrated over a 120mm diameter, with a microroughness of <1.5 angstroms rms. This is at the same level as the fused silica ITMs used in LIGO 1.

CSIRO has published a report that ion beam etching lowers the microroughness to sub-angstrom levels. This may be interesting to investigate if loss proves to be a limiting factor in the IFO.

2.5.4   Comparison with fused silica

Fused silica is slightly easier to polish than sapphire, but the required levels of polish have been demonstrated on both materials. Machining sapphire blanks is a very difficult process due to it's hardness, this will require an added step in fabrication with a specialized vendor.

2.5.5 Action needed

Demonstrate this level of polish on full size a-axis sapphire.

2.6 Stress birefringence

2.6.1 Requirement

2.6.2 Basis

2.6.3 Status

It is not clear if the birefringence that has been seen in CIT metrology is because the crystal is not well aligned with the optical surfaces and/or, if there is induced stress. Most likely it is a combination. The effect is a ripple of ~2nm amplitude in the transmitted wave front. Clearly the homogeneity will dominate at this level. It is not clear how much light is lost to the other polarization in this instance.

2.6.4 Comparison with fused silica

2.6.5 Action needed

Clarify stress birefringence. Perhaps by adding weight to the top of an optic which is supported in a v-block. The system at Lyon may be able to measure this as well.

2.7 Coatings

2.7.1 Requirement

Ideally we would require that any changes to the test mass material such as an optical coating have a minimal impact on the astrophysical performance. Minimal impact would be a reduction in the distance a single advanced LIGO interferometer could see a binary neutron star inspiral by 5 percent or less. This requirement demands that the coating phi be less than 1.5×10^{-5} on a sapphire substrate, or the effective Q of the test mass be greater than 63 million.

2.7.2 Basis

BENCH 1.13 with the coating thermal noise approximated by Eqn. (23) of G. M. Harry et al, Class. Quantum Grav., 19, (2002) 897. The thermal noise due to the substrate Q incorporates the finite size of the mirrors, but the coating thermal noise assumes infinite mirrors. This could be a significant approximation.

-D

2.7.3 Status

The Q 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.

2.7.4 Comparison with fused silica

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, see D.R.M. Crooks et al, Class. Quantum Grav., 19 (2002) 883. It is not know 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.

(Gregg needs a DCC number for a paper we are writing on this so we could have a citation here, has to bug Linda Turner to have it issued.)

To achieve the requirement (less than 5 percent reduction in BNS range) silica requires a coating phi less than 2 X 10^-5, or an effective Q of 24 million. This is not a significant difference from sapphire.

2.7.5 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. Coating mechanical loss will probably not be an important parameter for the down-select.

2.8 Thermal Noise

2.8.1 Requirement

2.8.2 Basis

2.8.3 Status

2.8.4 Comparison with fused silica

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

-D

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	30 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	5.5 cm

Table 1. Parameters used for the estimation of intrinsic test mass thermal noise.
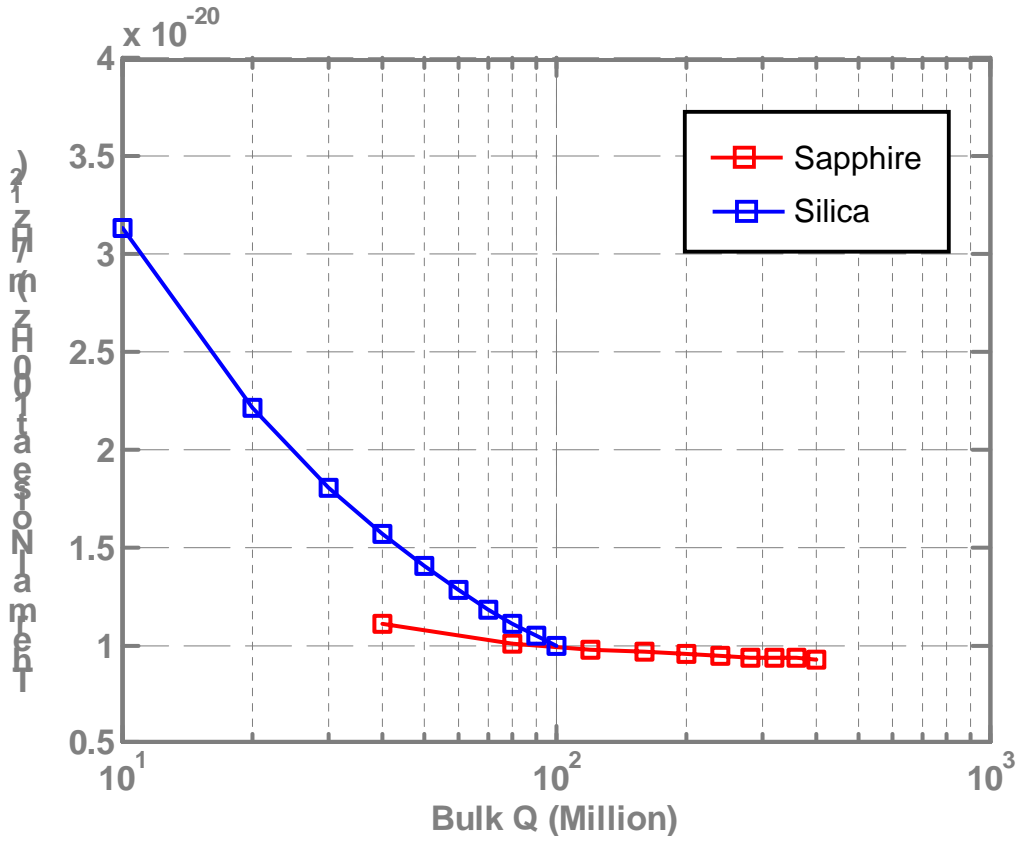
Figure 1. Thermal noise at 100 Hz as a function of test mass material bulk Q, for plausible ranges for sapphire and fused silica. Plotted is the differential arm displacement noise (strain noise divided by arm length).
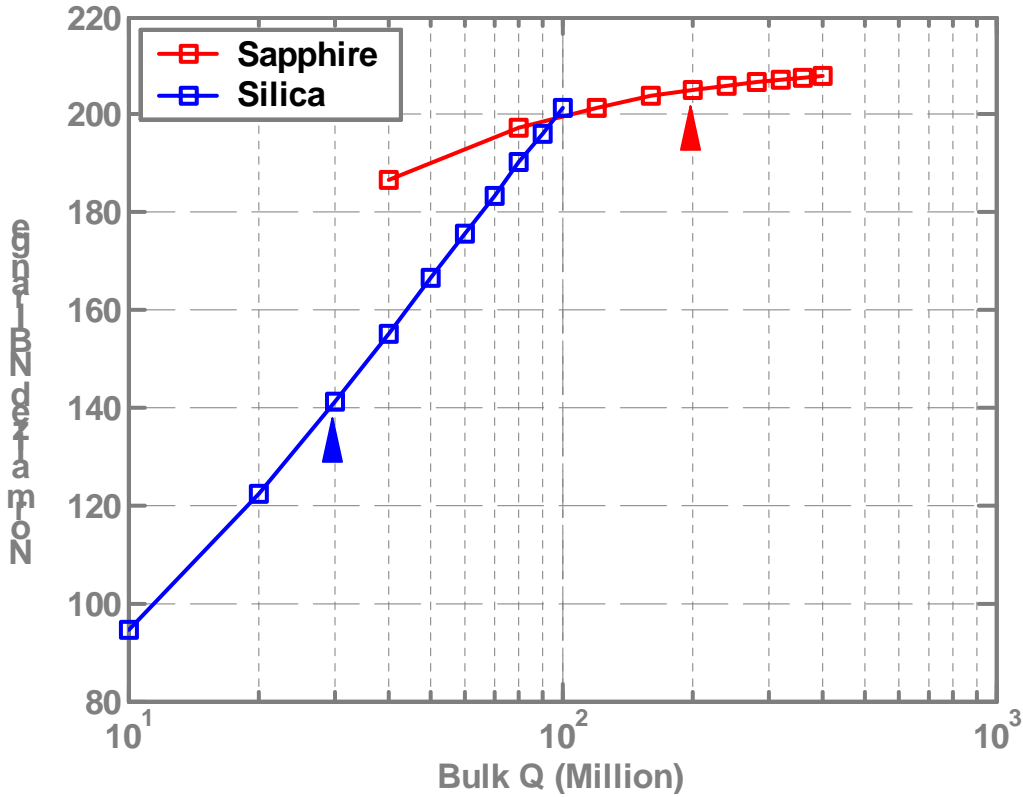
Figure 2. Comparison of neutron star binary inspiral (NBI) range for sapphire and fused silica test masses, as a function of the material bulk *Q*. The nominal *Q* values are indicated by the markers.

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 approximately 60 million.

2.8.5   Action needed

2.9   Mechanical loss

2.9.1   Requirement

2.9.2   Basis

-D

2.9.3 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"

2.9.4 Comparison with fused silica

2.9.5 Action needed

2.10 Attachments

2.10.1 Requirement

2.10.2 Basis

2.10.3 Status

> Creep in a sapphire/silica bond has been observed by Helena and
>
> myself for modestly heated sapphire/silica bonds (35C) and heating to 125C and
>
> back carries substantial risk of breakage. Experiments are ongoing.

2.10.4 Comparison with fused silica

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

2.10.5 Action needed

2.11 Alignment of Crystal Axis

2.11.1 Requirement

> Need to specify a control on allowable loss due to alignment birefringence

2.11.2 Basis

2.11.3 Status

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

-D
2.11.4 Comparison with fused silica

No alignment necessary with fused silica

2.11.5 Action needed

Compare Q of different axis optics as suspended by fiber

2.12 Suspension issues, actuation/size

2.12.1 Requirement

2.12.2 Basis

2.12.3 Status

2.12.4 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.

2.12.5 Action needed

2.13 Servo Control, Resonances

2.13.1 Requirement

2.13.2 Basis

2.13.3 Status

2.13.4 Comparison with fused silica

2.13.5 Action needed

-D

2.14 Cost

2.14.1 Requirement

2.14.2 Basis

2.14.3 Status

2.14.4 Comparison with fused silica

Fused silica input masses are ~1.5x more expensive than sapphire. FS 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 fs ITMs. The bottom line is that there is no huge difference.

2.14.5 Action needed

2.15 Delivery

2.15.1 Requirement

2.15.2 Basis

2.15.3 Status

Crystal systems currently has one furnace "fit" 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.

2.15.4 Comparison with fused silica

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

2.15.5 Action needed