SILICA RESEARCH PLAN FOR ADVANCED LIGO

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Advanced LIGO has set as its design goal a range for detecting neutron star binary inspirals of 200 Mpc per interferometer, or 300 Mpc for the two-observatory array. In order to achieve this range, the noise sources in the central frequency regime of 10 — 1000 Hz must be minimized such that the thermal noise for the test mass substrate and coating is to be below the combined quantum noise of the laser.

The two candidates for test mass substrate material are fused silica and sapphire. The relative merits of these two materials are discussed in greater detail elsewhere. We provide here only a summary of the materials distinguishing features. Sapphire has the advantage of a larger Young's modulus, a higher density, and a lower mechanical loss in large samples. To its detriment, sapphire has significant thermoelastic noise at low frequencies. A high thermal conductivity reduces thermal lensing, but the nonuniform distribution of optical absorption may make corrections for thermal lensing challenging. We also have no experience with sapphire as an optical material, and thus there is an ill-defined but increased risk associated with sapphire.

Fused silica has a long history as a substrate material. It has low, uniform optical absorption and has negligible thermoelastic noise. However silica has a lower thermal conductivity that will necessitate a correction for thermal lensing. Silica also has a lower Young's modulus. Its lower density makes the volume of a suitably large mass a challenge for the system integration. And, until recently, it was thought to have a higher mechanical loss. Recent measurements, which have utilized annealing to reduce mechanical loss, have produced significant reductions in mechanical loss in fused silica. Fused silica rods (Heraeus Suprasil 312, 8 mm diameter) have been measured after annealing with $Q > 200$ million (Penn, Ageev, et alia). Additionally, careful measurements of an uncoated Initial LIGO spare optic (Heraeus Suprasil 312, 25 cm OD, 10 cm thick) have yielded Q's of 120 million for two modes at 11 kHz respectively (Willems).

These losses are to be compared with Q's of 200 million seen in various sapphire samples (Mitrofanov, Glasgow, Willems) including a similar result measured recently for several modes in a full-sized Advanced LIGO sapphire sample (Willems).

It should be noted that the results on the annealed fused silica rods indicate that the loss for this small sample remains entirely in the surface. Therefore larger samples, if properly annealed, may reveal losses at even lower levels. The measurements of $Q \approx 100$ million for the Initial LIGO-sized mass is entirely consistent with this model. An optic of that size would have a $Q \approx 2$ billion, if its loss was due entirely to the loss in a pristine surface. A surface loss increase by a factor 20 is consistent with other superpolished optics that have been measured (Gretarsson, Harry, Penn).

At some scale the bulk mechanical loss of fused silica can be expected to dominate the surface loss. However the bulk mechanical loss of fused silica has yet to be measured. Thus we do not know at what sample size this transition will occur.

These new results hold the promise that Advanced LIGO test masses could be made of fused silica with a loss $\phi \approx 5 \times 10^{-9}$. At that loss level the two substrate materials would be roughly comparable. Then the major difference in thermal noise for coated silica or sapphire optics would lie in the loss of the coating materials and how well the coating parameters matched those of the substrate.

Clearly, better knowledge of our ability to realize these low losses in Advanced LIGO-sized silica substrates would significantly help to make an informed decision on the substrate material. The challenge remains to achieve low loss in large, superpolished samples of fused silica, and to accomplish this goal within the time frame established for Advanced LIGO. While this research hold great promise, there remains much work to be accomplished within a short time.

Below are listed the main considerations of the fused silica research plan. Following that list is a proposed schedule for this work.

TIME TABLE: While the down-select decision on test mass substrates may happen as early as August 2003, it seems clear that the silica research will take approximately six months to see results on superpolished samples with V/S ratios of 12 cm and another six months to see results on LIGO-sized test mass optics. Significant results obtained within one year would still be within a time period where the Advanced LIGO design could be altered to take advantage of this new knowledge.

ANNEALING ATMOSPHERE: We should test whether the loss in an annealed sample are affected by the annealing atmosphere. It is sufficient to compare air, vacuum and argon annealing atmospheres.

ANNEALING SAMPLE SUPPORT: During the annealing process, the samples will be oriented with the optical axis parallel to the vertical. In this way, any distortion that may occur should be axially symmetric. The sample will be placed on a support which it will contact the sample at the bevel only. An enclosed fused silica crucible has been purchased for annealing 7.5 cm diameter samples. The crucible's slanted sides support the sample uniformly around the bevel. This method will be tested for small samples before being used for larger samples. An alternate method consists of placing the sample on three sapphire spheres positioned to touch the sample only at the bevel. We will attempt to calculate the distortion that is likely to occur for a given sample and annealing schedule.

SURFACE FIGURE: It is important to understand the change in surface figure as a result of the annealing process. As mentioned above, we will attempt to model this change for

each sample and its annealing schedule. In addition, we will need to contract a metrologist to measure the surface character after polishing and again after the sample has been annealed. If our modeling is accurate and the measurements prove costly, we may choose to rely on modeling as a sole indication of sample distortion.

SURFACE POLISH & SURFACE CONTAMINATION: Surface loss is likely to be the dominant source of loss for all sample sizes utilized in this research program. Therefore it is important to know the contaminants deposited in the polishing process. We should also explore polishing methods, such as ion beam polishing, that are said to impart few contaminants into the surface.

OPTICAL ABSORPTION: Optical absorption in fused silica is known to be nearly uniform and relatively low (Lawrence). However, it has been shown that annealing can change the optical absorption in sapphire (Stanford). A similar test should be made for changes in optical absorption in fused silica due to annealing.

LOSS DEPENDENCE ON FUSED SILICA TYPE: Initial measurements reveal some dependence of loss based upon fused silica type. Early indications are that Suprasil 312 has the lowest loss. Both Suprasil 2 and 312 SV have comparable and significantly lower Q. The major difference in these fused silica types is their content of OH and Cl. Suprasil 2 has a high OH content (1000 ppm) and low Cl content (100 ppm). Suprasil 312 has moderate OH content (200 ppm) and moderate Cl content (200 ppm). Suprasil 312 SV has low OH content (< 1 ppm *). The Cl content is assumed to be high if the manufacturer uses HCl to remove the OH. We are inquiring with the manufacturer on this issue. Because the measurements of high Q's (above 30 million) are few, it is unclear at this point whether these early measurements indicate a real effect or a variation based on any number of other differences between the samples such as their manufacturing history. Strong variation in Q has been measured previously for samples that were nominally of the same fused silica variety (Syracuse). Nevertheless, this matter requires further investigation. Additionally, fused silica from Heraeus tends to yield higher Q's than the comparable material from Corning. This difference should be examined in order to determine how the two manufacturing processes result in different mechanical loss. The results should also inform our selection of materials for the Advanced LIGO end test masses. (* We are in the process of verifying this value with the manufacturer.)

SUSPENSION ISSUES: The suspension methods used for these experiments must meet two criteria. First, it must not present a limiting source of loss. Second, the suspension method cannot alter the sample, for example by changing the loss in the sample or surface character of the polished faces. A third consideration is that large optics will need to be tested with the Advanced LIGO suspension method. Therefore, it will be important to discover soon whether the annealing and repolishing process will adversely affect that suspension. Three suspension methods are considered to be low loss:

- a single, polished wire loop greased with lard (Willems/MSU method),
- a fused silica bob-fiber chain welded to the sample (Syracuse method), and

- a fused silica suspension welded to fused silica ears which have been silicate bonded to the sample (Glasgow/Stanford/AdvLIGO).

The first two methods have been demonstrated to provide no loss limit for *Q*'s of more than 200 million. The mechanical loss in silicate bonds has been measured and is estimated to not limit *Q*'s of that level (Glasgow). However, the highest *Q*'s measured for bonded samples are 28 million for a pendulum mode with a silica mass, 27 million for an internal mode of a sapphire mass, and 3.8 million for an internal mode of a silica mass. These lower values do not necessarily indicate any problem. Because bonding is a very time consuming process, it has not been chosen as the suspension method for experiments exploring very low loss in materials. Nevertheless, since bonding is scheduled to be the suspension method is Advanced LIGO, it is important to demonstrate that a bonded sample can achieve a *Q* above 100 million.

Another consideration is that while the first two methods have the advantage of not being affected by the annealing process, they are not suitable for Advanced LIGO. It would be advantageous to use the bonded suspension in our tests since any test mass must eventually be characterized for that suspension. If the bonded suspension did present some unforeseen problem, then it would be best to discover that problem as soon as possible.

Tests are currently underway to test the effect of annealing on a bonded sample. An early test in this research plan should be to verify that a high *Q* sample retains its low loss when a bonded suspension is applied.

In this research plan, for any given sample size the experimenter may choose to use any of the known low loss suspensions. However, for each size of optic there should be a measurement of a sample with a bonded suspension annealed at the optimized conditions.

ANNEALING OF THE MIRROR COATING: There exists a separate research program dedicated to minimizing the mechanical loss associated with the test mass mirror coating. The goal of that research effort is to minimize the loss in the coated test mass by minimizing the loss in the coating materials and to optimally match the characteristics of the coating to those of the substrate. That coating research has shown that the low temperature (< 600° C) anneal of the coating can significantly alter the loss in the substrate. We need to test whether the loss in an optimally annealed substrate will be adversely affected by the anneal performed after the optic is coated.

ANNEALING OVENS:

LSC COLLABORATORS:

Syracuse: 1 fiber oven with inert atmosphere

1 small (ft^3) oven, air

MIT: 1 small oven, air

Glasgow: 1 medium oven with inert atmosphere

HWS: The NSF has given preliminary approval to purchase a vacuum annealing oven

COMMERCIAL OVENS:

Solar Atmospheres: research-grade, vacuum oven, does NASA work, in Pittsburgh

Syracuse Heat Treating Corp.: high quality vacuum ovens, local, ($70/hr)

OTHER:

French: large sample oven, vacuum (?)

RESEARCHERS:

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SAMPLES REQUIRED:

POLISH	TYPE	SIZE	NUMBER
Commercial	7980	2.5 cm OD, 1 m long	2
Commercial	312	2.5 cm OD, 1 m long	2
Commercial	312 SV	2.5 cm OD, 1 m long	2
Superpolish a/o Ion Beam	312 SV	7.5 cm OD, 2.5 cm thick	9
Superpolish	312 SV	15 cm OD, 6 cm thick	5
Superpolish	312 SV	LIGO I, 25 cm OD, 10 cm thick	1

EXPERIMENTS:

ANNEALING TEST:

- Compare the loss for three samples with equivalent annealing schedules in atmospheres of Air, Argon, and Vacuum.
- Determine the optimal cool down rate for a given maximum temperature. This rate should be a function of the sample geometry only. Therefore the optimization for smaller sized samples can be performed using rod samples while the large samples will be cylindrical optics.
- Determine the loss as a function of maximum temperature and optimized cool down rate. The cool down rate is said to be the critical variable for alleviating stress in the sample. We need to determine the best cool down rate for a given peak temperature. Because surface character is likely to change with annealing, and since we do not know our ability to correct for this change without introducing loss, we should know the best loss achievable for a given maximum temperature.

SURFACE CHARACTER:

- Compare the surface character before and after each annealing. This measurement includes a determination of the optical figure (Caltech?) and a test for surface contamination (Charles Evans & Associates (CEA), www.cea.com). At this juncture, it appears that surface contamination may be best performed on these samples with either SIMS (Secondary Ion Mass Spectroscopy), RBS (Rutherford

Back Scattering) or FTIR (Fourier Transform Infrared Spectroscopy). A detailed consultation with CEA is required.
- Determine distortion as a function of maximum temperature and integrated heating. Models of this distortion should be compared to the measured values to determine the necessity of similar measurements for all samples.
- Determine if polishing (possibly ion beam polishing) can restored the surface to acceptable optical quality without increasing mechanical loss.

POLISHING TEST:
- If the surface figure of an optimally annealed optic is outside of LIGO requirements, then have the sample repolished and measure how the *Q* changes in the process.
- Investigate whether there exists a cost-effective source of ion-beam polishing that can polish LIGO-sized masses.
- Compare ion beam polished with superpolished samples. Determine which polishing method yields lower loss initially and after annealing. Using the data from the surface tests described above, try to isolate contributing factors to the surface loss.

OPTICAL ABSORPTION TEST:
- Investigate whether the optical absorption has changed in magnitude or distribution due to the annealing process.

SUSPENSION TEST:
- Investigate whether annealing a sample with silicate bonded fused silica ears increases the loss or weakens the bond.
- Measure a high *Q* sample with a bonded suspension either by bonding an ear on a sample of known high *Q* or by bonding an ear on a sample of identical dimensions and material to a high *Q* sample.
- Unless a significant problem is detected, we will proceed by using the silicate bonded suspension for the remainder of the tests.

EXPERIMENTAL SCHEDULE:

1) Initial Annealing Test: (6 months – runs concurrent with tests 2–4)

Using rod samples, optimized annealing curves and annealing atmospheres can be determined for Suprasil 312, Suprasil 312 SV, and Corning 7980. These results will be scaled by the sample size ratio to provide an initial guess for the optimized annealing conditions of the larger optic samples.

2) Bonding test: (≈1.5 months)

A fused silica ear will be bonded to a sample of known high *Q*. The sample will then be remeasured to prove that the bond did not spoil the high *Q*. Additionally a bonded sample will be annealed and tested to ensure that the bond was unaffected by the anneal and that the loss did not increase.

3) Polishing test: (3 months)

Four 7.5 cm x2.5 cm disk samples will be used; two will be superpolished and two will be ion beam polished. The surface figure, surface contamination, and *Q* will be measured initially. There will be two anneals, one to 600° C and the other to 900° C with appropriate, though not yet optimized, cool down rates. The *Q*, surface figure, and surface contamination will be measured before and after annealing. The temperature range is chosen as the likely bounds of the peak annealing temperature. This test will reveal the range of surface distortion and the spread of surface contaminants due to annealing. The test will also demonstrate whether a given polishing method is better suited for achieving low loss in fused silica.

4) Surface character test: (3 months)

Use the optics from the previous test. Repolish the optics using their respective polishing techniques to correct for the distortions from annealing. Remeasure the surface character, the surface contamination and and the Q. Determine which polishing method, if any, is suited to repairing the distortions from annealing.

5) Optimal Annealing Test: (6 months)

a) Prepare the samples using the optimized polishing technique determined above. Measure the surface character, surface contamination, and Q. Use three samples for three cool down rates. Assume that the optimized cool down rate is the rate used for the 8 mm rod sample scaled to the thickness of the disk. Then choose a minimum and maximum rate that is a factor two greater than and less than the optimal rate. Anneal the samples to 900° C maximum temperature and apply the three cool down rates to the three samples. Measure the surface character and Q. Determine the optimal cool down rate for this geometry.

b) Use two more samples. Measure the surface character, surface contamination, and Q. Use the optimized cool down rate and peak temperatures of 600° and 750° C. After annealing measure the surface character and Q. Determine the loss as a function of peak temperature.

c) Repeat parts a) and b) for a 15 cm x 6 cm disk sample, to determine the optimal annealing process for this larger sample. Use the results from test 2 to determine how to repolish (if necessary) the optic to obtain the lowest loss sample with the require surface character. Remeasure the Q of the repolished optic.

d) Test on a LIGO I optic. Measure the surface character, surface contamination, and Q. Scale the above results for this larger sized sample. Choose an optimal annealing curve and anneal. Measure the surface character and Q. Repolish if necessary and measure the new surface character and Q.