Silica suspension and coating developments for Advanced LIGO

Cagnoli G[1,2], Armandula H[3], Cantley C A[1], Crooks D R M[1], Cumming A[1], Elliffe E[1], Fejer M M[5], Gretarsson A M[6], Harry G M[4], Heptonstall A[1], Hough J[1], Jones R[1], Mackowski J-M[7], Martin I[1], Murray P[1], Penn S D[8], Perreur-Lloyd M[1], Reid S[1], Route R[5], Rowan S[1], Robertson N A[5,1], Sneddon P H[1], Strain K A[1]

[1] IGR - Physics and Astronomy, University of Glasgow, G12 8QQ Glasgow, UK

[2] INFN Sez. Firenze, via G.Sansone 1, 50019 Sesto F.no, Firenze, Italy

[3] LIGO Laboratory, California Institute of Technology, Pasadena CA 91025, USA

[4] LIGO Laboratory, Massachusetts Institute of Technology, Cambridge MA 02139, USA

[5] Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4088, USA

[6] Embry-Riddle Aeronautical University, 3700 Willow Creek Rd., Prescott, Arizona 86301, USA

[7] Laboratoire des Matériaux Avancés, Université Claude Bernard, Lyon, 69622, France

[8] Department of Physics, Hobart and William Smith Colleges, Geneva, New York 14456, USA

E-mail: `g.cagnoli@physics.gla.ac.uk`, `cagnoli@fi.infn.it`

Abstract. The proposed upgrade to the LIGO detectors to form the Advanced LIGO detector system is intended to incorporate a low thermal noise monolithic fused silica final stage test mass suspension based on developments of the GEO 600 suspension design. This will include fused silica suspension elements jointed to fused silica test mass substrates, to which dielectric mirror coatings are applied.

The silica fibres used for GEO 600 were pulled using a Hydrogen-Oxygen flame system. This successful system has some limitations, however, that needed to be overcome for the more demanding suspensions required for Advanced LIGO. To this end a fibre pulling machine based on a CO_2 laser as the heating element is being developed in Glasgow with funding from EGO and PPARC.

At the moment a significant limitation for proposed detectors like Advanced LIGO is expected to come from the thermal noise of the mirror coatings. An investigation on mechanical losses of silica/tantala coatings was carried out by several labs involved with Advanced LIGO R&D. Doping the tantala coating layer with titania was found to reduce the coating mechanical dissipation. A review of the results is given here.

1. Silica suspensions for the Advanced Detectors

The first generation of interferometric Gravitational Wave detectors (TAMA [1], LIGO [2][3] and Virgo [4]) use metal wire suspensions for the main optics. In contrast GEO 600 [5][6] uses fused silica fibres welded onto silica pieces called "ears", chemically bonded to the main fused silica mirror substrates. The last stage of the test mass suspension is hence "quasi monolithic", "quasi" referring to the use of silicate bonding.

Fused silica fibre technology has several advantages over the steel wire technology:

- silica fibres of the dimensions typically used in suspensions have a mechanical loss angle of about 3×10^{-7} [7][8][9] whereas the value for steel is around 10^{-4} [10] at best;

- the Young's modulus of steel (200 GPa) is about 3 times that of silica (70 GPa). Steel suspensions are more rigid than silica suspensions of the same dimensions, reducing the effect of "dilution dissipation" [11];

- frictional losses due to rubbing are completely avoided in the quasi monolithic suspensions using silica, whereas these losses are present in the break off points between steel wires and spacers. These losses affect both the pendulum and the internal thermal noise and they are difficult to quantify;

- thermoelastic loss in silica can, in theory, be canceled through careful design of the geometry of the suspension fibres used, however this has yet to be experimentally verified [12].

While the tensile strength of silica can be up to 2 times higher than steel [15], the strong dependence of this parameter on the application of a correct handling procedure requires the safety factor for silica to be much higher than for steel. In practice for steel wires the working stress in the current detectors is about 750 MPa, but for silica the same parameter drops down to 200 MPa. Still, silica suspensions have a thermal noise level that is about 12 times lower in amplitude than for steel wires. The calculation is carried out taking account of the dilution factor in the expression of the pendulum loss angle ϕ_{p}, considering the bending at both end of the fibres [11]:

$$\phi_{\mathrm{p}} = \phi_{\mathrm{mat}} \sqrt{\frac{E\,I}{T\,L^2}} = \phi_{\mathrm{mat}} \sqrt{\frac{E\,T}{4\pi\,\sigma^2\,L^2}} \qquad (1)$$

where ϕ_{mat} is the mechanical loss angle of the material related to structural and surface relaxations; E is the Young's modulus; I is the cross section moment of inertia; T is the tension and L is the fibre length and σ is the longitudinal stress in each fibre. The previous equation is adapted to the case when the pendulum motion causes the fibre to bend at the top and at the bottom. Thermoelasticity is neglected because for steel the peak is at hundreds of Hz whereas for silica it is almost totally compensated at the stress σ of 200 MPa [12]. The amplitude of thermal noise per square root of Hz is proportional to the square root of ϕ_{p}. Replacing the values of the parameters one can calculate the ratio of the thermal noise between steel wires and silica fibres. This ratio increases up to 19 if silica ribbons with an aspect ratio of 10 are used instead of circular fibres. Detailed calculations can be found in reference [13]

So far the production of silica fibres and their welding were based on using a hydrogen-oxygen flame. Whilst this technology met the specifications for GEO600 [5][6] there are limitation to this technology. The possible contamination, the limited control of fibre shape and the blowing of the fibre by the flame during the welding are the main limitations.

The idea of replacing the flame with a CO_2 laser beam (10.6 μm wavelength) came after the GEO 600 suspensions were installed. Advanced LIGO has been designed with the idea of exploiting, as far as possible, the performance of materials at room temperature and the requirements for the final suspension stage represent a challenge for the quasi monolithic silica suspension technology [14]. The flame based machines developed for GEO 600 may not be suitable for the Advanced LIGO requirements and the CO_2 laser is certainly a very precise technology for both fibre production and welding. It is worth mentioning that the Braginsky group at Moscow State University had the same idea in the 1980s for the production of very thin fibres (1 μm to 20 μm) [16] (compared with those required for Advanced LIGO 400 μm). In this work the fibres were pulled once the material was melted and the pulling time had to be shorter than the cooling time. The same technique has been used for the GEO 600 fibres with a diameter of about 250 μm diameter. Such methods of simple pulling do not allow much control of the fibre shape and the length repeatability is only within 5 mm. In order to improve on this

a different method of pulling has to be applied. Such a method known as "pulling and feeding" consists of maintaining a constant volume of melt material while the fibre is pulled. The negative rate of material pulled away is compensated by more material being melted, moving the heat along the stock material. The ratio between the diameters of the stock material and the pulled fibre is equal to the square root of the ratio between the pulling and the feeding speeds. At the LIGO group in Caltech [17] such "feed-pull" technique with a hydrogen-oxygen flame was used to produce silica fibres.

An R&D project for the development of a pulling and welding machine based on using a CO_2 laser technology commenced early in 2004. This is financed partly by an EGO grant and partly by a PPARC grant. The machine that is being developed consists of 3 motorized and controlled axes: one is vertical for the pulling of one fibre end, the other end being clamped on the machine base; the other axes - one vertical and one horizontal - are used for delivering the laser beam. In order to feed the molten mass with more material just the vertical axis is moved whereas for welding both vertical and horizontal are used. Figure 1 shows a schematic picture of the machine and reference [20] for a first status report on this project. The conceptual design of the machine is now complete and a first prototype is being replaced by the final machine. A picture and diagram are shown in Figures 2 and 3 respectively. The CO_2 laser pulling machine
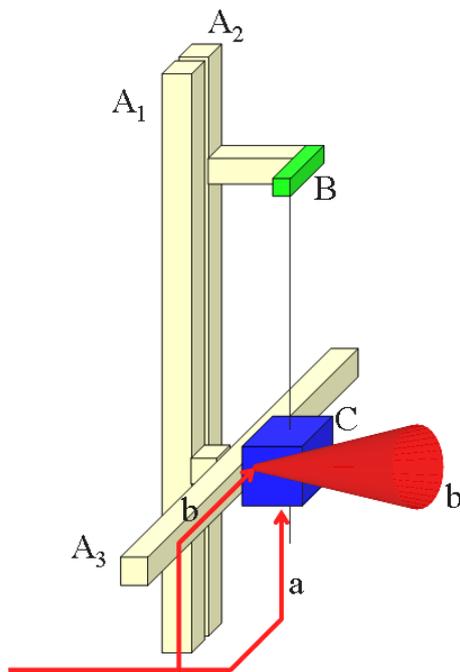

Figure 1. Conceptual drawing of the CO_2 laser pulling and welding machine. A_1 to A_3 are the three motorized axes. A_2 carries the upper clamp "B" of the silica fibre. A_1 is the other vertical axis that together with A_3 is responsible for delivering the beam. During the fibre production A_3 is not activated and A_1 feeds the melt with more material by moving the beam downward. The block "C" is interchangeable depending on the operation the machine has to do. For pulling a circular fibres "C" consists of a unit that receives the laser beam from path "a" and makes it rotate around the melting point. During the production of ribbons and during the welding "C" becomes a device that uses an X-Y scanner (mirror galvanometers) to steer and dither the laser beam. In this case the laser beam comes in through the path "b" and the cone in the picture represents the scanned solid angle. During welding the axis A_3 is extensively used whereas A_2 is kept steady at the maximum height.

should open the possibility of producing fibres with a large cross section at the two extremes and gradually decreasing toward the middle [18]. The large cross section meets the criteria for the thermoelastic loss cancelation and at the same time reduces the increase of stress due to bending. The reduction of cross section in the middle, on the other hand, helps to keep the violin mode frequencies high and the vertical bouncing mode frequencies low.

Repeatability test has not been done yet. The diameter of the fibres pulled so far is very regular (5 μm of standard deviation against an average of about 400 μm over 85% of the total

Figure 2. Picture showing the status of the CO_2 pulling and welding machine. The two vertical axes are mounted whereas the horizontal one has been removed. On the machine base it is possible to see one of the gold coated conical mirrors that will be used for pulling circular fibres. As a temporary solution a mirror galvanometer mounted on a post is used to dither the laser beam for the production of silica ribbons. The periscopic system P and the galvanometer G are shown in the picture.
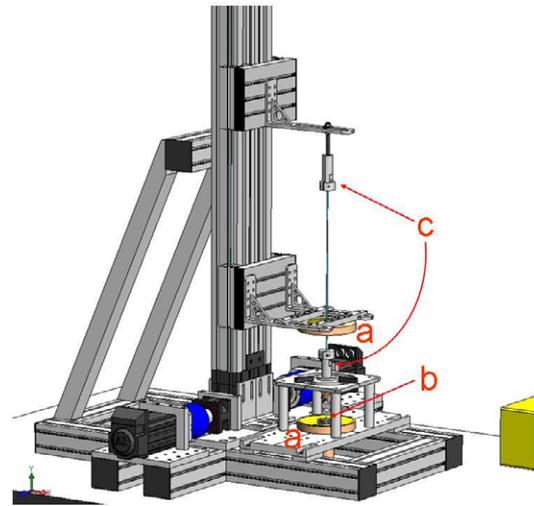

Figure 3. Rendering of the pulling machine. The configuration shown is for pulling circular fibres. The two conical mirrors "a", the rotating mirror "b" and the two clamps "c" are shown.

length of the fibre between the necks) and it depends only on the diameter of the stock material and on the speed ratio.

Another important part of the research activity is dedicated to the development of silica ears. These pieces should support 10 kg with a good safety factor and they need to have a contact surface no greater than 7.1 cm² in total per test mass in order to limit their contribution to the thermal noise in the test masses [19]. The peeling effect has been recognized as one of the main causes of failure of the silicate bonding, therefore the ear has been designed with the triangular bond shape as shown in Figure 4. Some samples have been machined from Suprasil 2 and their strength tested (see Figure 5). The weakest point of the ear is the ankle that is almost a right angle. The first sample tested had ground surfaces (apart from the $\lambda/10$ polished surface that was bonded onto a Suprasil 312 flats) and resisted up to a force of 93 N. The next sample was flame polished in our laboratory after being bonded and it resisted up to 368 N before failure again at the right angle ankle. Clearly the cause of the failure of the first sample was the presence of cracks on the surface due to the ground finish. Future ears will have an inspection polish finish and the stress concentration will be reduced using a larger radius at the ankle. Another sample was flame polished and loaded with 12 kg as shown in Figure 5 for a long term strength test.

2. Investigation on coatings

The initial LIGO mirror coatings of alternating quarter wavelengths layers of silica and tantala have a mechanical loss of 2.4×10^{-4} [21]. This level of mechanical loss will make the coating thermal noise the dominant source of noise in the mid frequency range in Advanced LIGO as shown in Figure 6. Using the interferometer noise simulation code BENCH [22] it is possible to
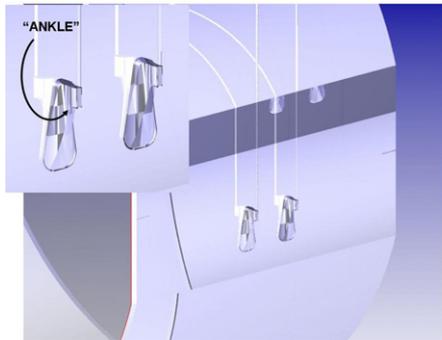
Figure 4. Rendering of two ears attached to a silica mass. The triangular shape of the ears has been designed for the reduction of the peeling effect due to the high shear stress. The height and width of the ears are respectively 25 mm and 12 mm. The fibre head is lap welded to the ear.
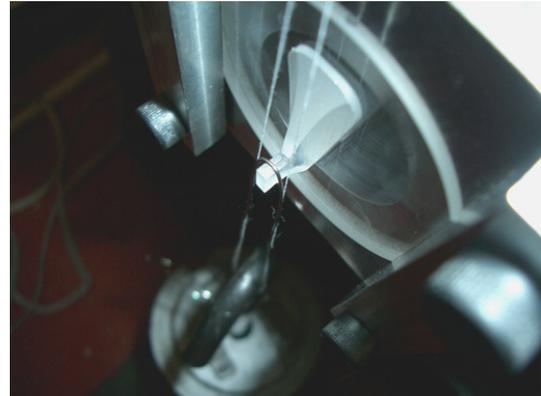
Figure 5. Top view of an ear bonded on a disk and loaded with 12 kg. The hook holding the mass is placed on the same position where the fibre head will be welded. Clock stopping wires are in place to record precisely the time of the eventual breaking.
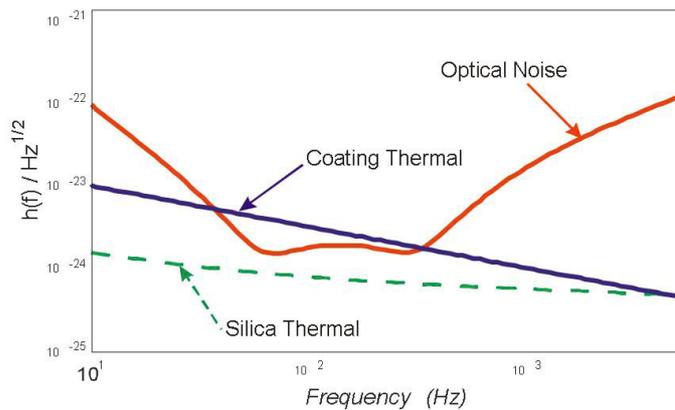

Figure 6. Square root of the power spectral density in h of some fundamental noises in Advanced LIGO. The calculation has been done with the code BENCH [22]. The mechanical loss angle used for the coatings is 2.4×10^{-4} [21], a value that makes the coating thermal noise the main limitation to performance at mid frequencies.

estimate the maximum distance at which a neutron star binary can be detected and this distance is 160 Mpc. In order to increase this limit up to 200 Mpc as in the Advanced LIGO goal the loss angle of the coatings need to be reduced to about 5×10^{-5}. In this estimation there is an uncertainty in the contribution coming from the thermoelastic effect in the coatings because the thermo-mechanical properties of materials like tantala are not well known. In general, in order to reduce such noise contribution the thermo-mechanical properties of coatings and substrates need to be as well matched as possible [23].

Coatings should have also a very low optical absorption to minimize the effect of thermal lensing from the optics. The overall optical loss expected from the coating is less than 0.5 ppm and the degree of homogeneity of such loss is also relevant if the aim is to avoid high order aberrations [24].

Early investigations [21][25][26] have shown that the mechanical losses come mainly from the tantala layers of the coatings and they are associated with structural relaxations inside this material rather than boundary effects. The method of measurements and the models used for the data analysis are explained in the previous references.

With the idea of freezing the relaxation in tantala, to forbid the transition of atoms, the LMA group in Lyon have tried to dope this material with titania (TiO_2). The optical properties of the doped coating are similar to the undoped one although the optical absorption is somewhat large (about 1 ppm for coatings with relative concentration of titania below 50 and 3 ppm for the other [27]). However the mechanical loss changes significantly as is shown in Figure 7.
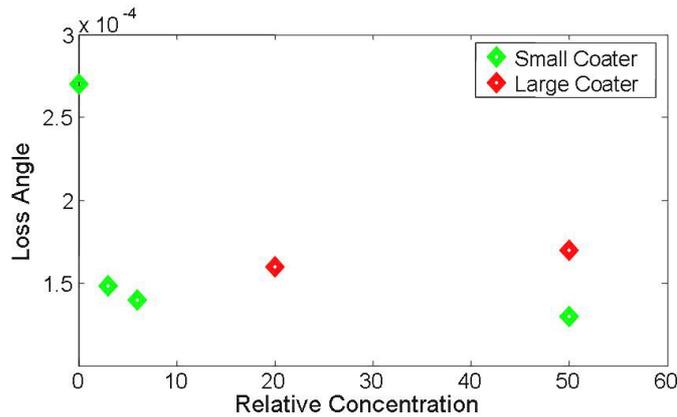
Figure 7. Plot of the coating loss angle versus the relative concentration of titania doping of tantala. The coatings were made at LMA in Lyon with two different coaters. The data show a rapid decrease of the loss with small concentrations of the dopant whereas at larger concentrations the mechanical loss seems to reach a plateau. Relative concentration expresses the fractional change of index of refraction assigning 0 and 100 to respectively pure tantala and pure titania.

The lowest loss measured is $\phi = (1.3 \pm 0.1) \times 10^{-4}$ that correspond to a relative concentration of 50. The relative concentration is related to the index of refraction of the doped material. A concentration of 50 means that the index of refraction of the doped tantala is exactly half way between the pure tantala and the titania values.

A possible explanation of the relatively large loss in tantala may come from the fact that the deposition of the coating happens in an environment deficient of oxygen. The layer is formed then with a large number of metastable states where the oxygen atoms of the layer can hop between adjacent sites. Possibly the titania forbids these transitions.

Future plans are to experiment with different dopants and materials. In another direction, an annealing cycle has been found at CSIRO that reduces the mechanical stresses accumulated during the coating deposition.

3. Conclusions

For the silica suspension development considerable progress has been made on the construction of a pulling and welding machine based on the CO_2 laser and the design and testing of new silica ears to be silicate bonded onto the mirrors. The machine development is well on track for a completion date at the beginning of 2006.

For the coatings, after the initial improvement due to the titania doping, research is being carried out to investigate alternative coatings that may reduce the mechanical losses by another factor 2 or so (rare earth oxides as dopant). Further improvements may come also from the results of investigation from other groups working on flat-top laser beams [28] and on different distribution of coating layer thickness [29].

4. Acknowledgments

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