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Monolithic Stage Conceptual Design for Advanced LIGO ETM/ITM

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1 Introduction

The suspension designs for Advanced LIGO are based on extension of the triple pendulum design developed for GEO 600. The GEO suspensions incorporated (quasi) monolithic silica final stages for enhanced thermal noise performance. The suspension technology applied in GEO 600, whilst within specification for GEO 600, must be further developed to meet the more stringent noise level targets of Advanced LIGO.

The target sensitivity for Advanced LIGO corresponds to a displacement sensitivity of 10^{-19} m/√ Hz at 10 Hz at each of the main mirrors (ETM/ITM), and falling off at higher frequencies as approximately $1/f^2$. To be more precise, the requirements call for the longitudinal thermal noise from the pendulum motion and the residual longitudinal seismic noise each to be at or below this noise level. Furthermore, any additional technical noise sources should be ≤ 1/10 of this figure[1].

The main mirror suspensions of Advanced LIGO (ETM/ITM) will be quadruple pendulums incorporating a monolithic silica final stage. The design requirements can be summarized as follows:

- the horizontal thermal noise should be 10^{-19} m/√ Hz or lower at 10 Hz, per test mass
- technical noise sources should be 10^{-20} m/√ Hz or lower at 10 Hz
- all pendulum modes that couple directly into the sensed direction should lie below 10Hz with exception of the highest vertical mode frequency which can be 12 Hz or lower and the associated roll mode which is expected to be about 1.4 times higher frequency[2].
- the fundamental violin mode frequency should be 400 Hz or higher.

The Advanced LIGO suspension system conceptual design document[3] provides full details of the overall suspension design concept and its performance requirements.

Here we focus on the conceptual design of the monolithic final stage for the main (ETM/ITM) suspensions of Advanced LIGO. This subsystem is the subject of review in the "Silicate Bonding, Ear, Ribbon/Fibre Preliminary Design Review" of October 2005. The same, or very similar, techniques will be applied in the detail design of any other suspensions requiring monolithic lower stages. This may include the beamsplitter and modecleaner suspension, but these are currently under consideration (TBD).

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[1] Fritschel et. al., "*Advanced LIGO Systems Design",* T010075-00-D.

[2] Fritschel, "*Low-Frequency Cut-off for Advanced LIGO*", T020034.

[3] Robertson et. al., "*Advanced LIGO Suspension System Conceptual Design",* T010103.

2 Overview of suspension design

The monolithic final stage will comprise of the following:

- A fused silica mirror forming the lowest stage of the pendulum which will be suspended on four vertical fused silica ribbons. GEO 600 used cylindrical fibres. The use of ribbons will lead to further improvements in the overall level of suspension thermal noise in line with the more stringent performance requirements of Advanced LIGO.
- The penultimate mass will also made of fused silica and identical in size and shape to the mirror.
- The silica ribbons will be laser welded to fused silica ears (prisms) that are silicate bonded[4] to flats on the sides of the penultimate mass and the mirror below.

Figure 1 shows a sketch of the monolithic final stage for the ETM/ITM suspensions.

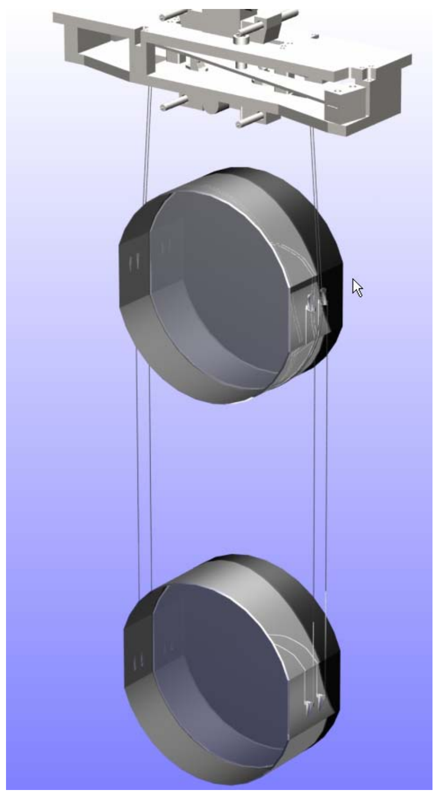

Figure 1 Monolithic final stage suspension for the ETM/ITMs. The upper intermediate (metal) mass from which the monolithic stage is suspended is also shown in this sketch. The penultimate mass is suspended using steel wire loops whilst the test mass is suspended using silica ribbons welded between the two masses. The stand-off prisms for the wire loops on the penultimate mass are not shown on this sketch.

[4] Bonding technology based on hydroxide-catalyzed surface hydration. This was originally developed by D. H. Gwo at Stanford University as a robust method of bonding together parts of the Gravity Probe-B space telescope.

3 Design requirements

In determining the design requirements for the Advanced LIGO suspensions we make use of two main analytical tools:

- thermal noise design (*Maple* & *Matlab* code)[5]
- mechanical design and performance simulation (*MATLAB* code and *Mathematica* models) now encapsulated in *SIMULINK* within a suspension modeling toolkit structure[6].

3.1 Suspension thermal noise

The thermal noise performance is the critical driver for the design of the monolithic suspension stage. The baseline design for the ETM/ITM monolithic suspensions incorporates ribbons rather than fibres[7], so that the dilution factor, by which the pendulum loss factor is reduced from the value of the intrinsic loss factor of the suspension material, is increased. Moreover moving to ribbons of the same cross-section has the advantage of pushing up the frequency of the thermoelastic peak, which has the effect of reducing the loss in the critical 10 Hz region.

To achieve the target noise level at each of the test mirrors of 10^{-19} m/√ Hz at 10 Hz requires ideally that the highest vertical mode of the multiple pendulum should be kept below 10 Hz. Otherwise a peak in the noise spectrum will occur in the operational frequency band of the detector. This requirement has been reviewed and this limit has been relaxed to12 Hz[1]. This allows a fall-back fibre/ribbon design to be selected if there are problems with the thin ribbons proposed (see (b) below).

To keep the vertical bounce frequency of the monolithic stage low we use a combination of several factors:

a) the fibre/ribbon length is chosen to be as long as practicably consistent with ease of production, and whilst ensuring that the violin modes are of acceptably high frequency.
b) the fibre/ribbon cross-section is chosen to be as small as practicable, consistent with working at least a factor of 3 away from the breaking stress demonstrated for typical fibres/ribbons.
c) the penultimate mass is chosen to be as heavy as possible, consistent with the overall design characteristics of the multiple pendulum.

3.2 Ribbons versus fibres

A full discussion on the advantages of using ribbons compared to fibres is presented in the suspension system conceptual design document [3]. We have been considering minor changes to the ribbon design, but the baseline design remains as given in the suspension conceptual design document.

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[5] Reference G. Cagnoli (Glasgow) for further details.

[6] Reference C. Torrie/M. Barton (Caltech) and K. Strain (Glasgow) for further details. Examples can currently be found via C. Torrie's web page Hhttp://www.ligo.caltech.edu/~ctorrie/H.

[7] Dumbbell fibres are a fall back option – see Armandula, *"Ribbons/Dumbbell Fibers (Moving from Parallel to Serial Effort)",* T040223-01-D.

3.3 Thermal noise performance for ETM/ITM quadruple pendulum suspension

The method used for thermal noise modeling is fully described in the suspension system conceptual design document [3]. It takes account of the losses in the bulk material, the surface losses and thermoelastic effects.

Figure 2 shows the thermal noise estimation for the suspension and for the coated silica test mass. Note that the highest of the low frequency peaks occurs at just under 9 Hz. A displacement noise level of 10^{-19} m/√ Hz is reached at approximately 11.5Hz. The first violin mode occurs at about 490 Hz. Therefore the main design requirements (see Section 1) are met[1].

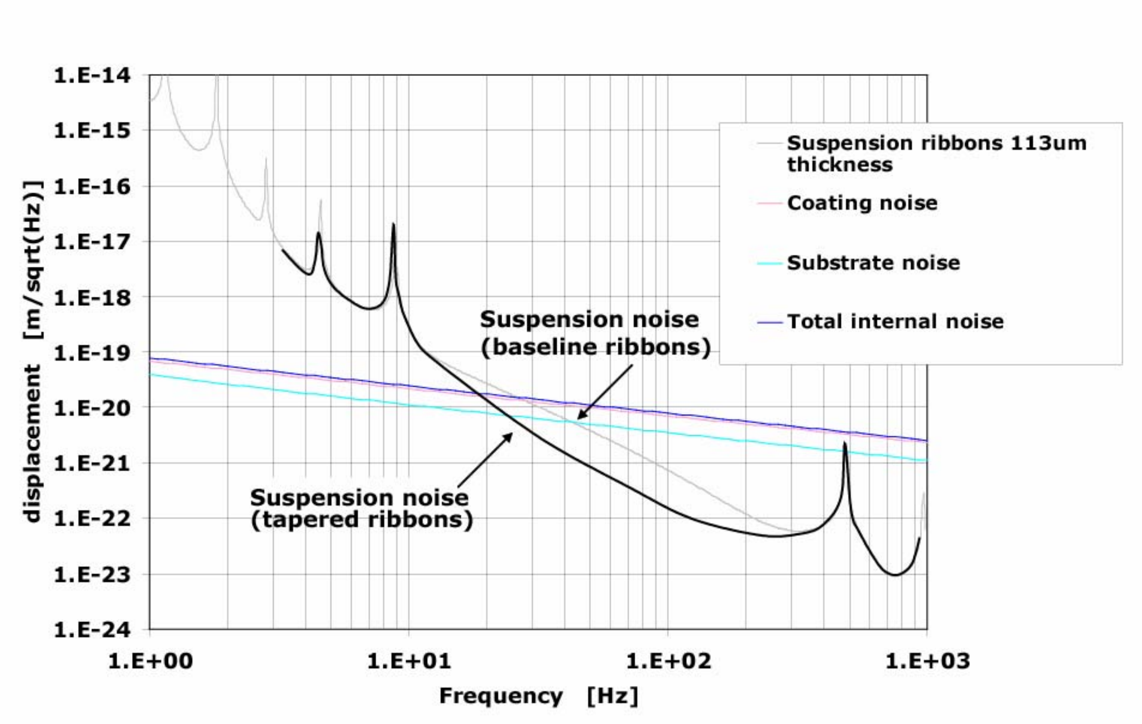

Figure 2 Suspension thermal noise curve and internal thermal noise curve for the coated 40 kg silica test mass. Note that thermal noise associated with the silicate bonded ears is not included.
The suspension thermal noise curve is derived by combining the longitudinal and vertical thermal noise contributions. The grey curve refers to ribbons of 113 micron thickness (aspect ratio 10) whereas the thick black curve is an estimation of the thermal noise if ribbons with tapered ends (heads) were used (linear dimensions at the ends twice as much as in the middle of the ribbon). A full analysis involving all degrees of freedom has not been carried out. Thermal noise from angular motions should be considered, and in particular noise due to pitch motion, since for this motion there is no dilution factor in loss compared to yaw motion. An order of

magnitude estimate was carried out for a previous design with 30 kg test mass[8] *which showed that pitch thermal noise would contribute less than* 10^{-19} *m/√ Hz at 10 Hz when the beam offset was less than 3 mm. The requirement on beam offset is 1mm. Updating the pitch thermal noise estimation for the current design gives a noise level of* 3.8×10^{-17} *rad/√ Hz which corresponds to* 3.8×10^{-20} *m/√ Hz for a 1 mm offset. This is lower than the longitudinal suspension thermal noise requirement of* 10^{-19} *m/√ Hz but not by as much as a factor of 10, the number used in setting the pitch requirement (TBC). A tighter specification on the beam offset would be needed to achieve that factor of 10.*
For the internal thermal noise of the test masses the following parameters have been used: silica substrate loss 5×10^{-9}*, mass radius 17 cm, mass thickness 20 cm, silica coating loss* 1.2×10^{-4}*, tantala coating loss* 1.6×10^{-4}*, transmission of the ETM* 5×10^{-6}*, transmission of the ITM* 5×10^{-3}*, spot size (waist) 5.5 cm.*

4 Preliminary design for ETM/ITM monolithic suspensions

A full description of the preliminary parameters for the quadruple suspensions is provided in Appendix D of the suspension system conceptual design document [3].

An overview of the key design features and main parameters for the monolithic stage is presented below.

4.1 Test mass

The test masses will be 39.6 kg with diameter 340 mm and thickness 200 mm [9] [10].

The proposed material for the ETM is Heraeus Suprasil 312 (TBD).

The baseline material for the ITM is Heraeus Suprasil 311. This is optically superior to Suprasil 312 but otherwise identical in mechanical/bonding properties.

Flats of height 95 mm and width 200 mm will be polished on the sides of the test masses for silicate bonding of the ears. The λ/10 flatness specification for silicate bonding will be required on a reduced patch area within these flats (area and position TBD)[11].

Four ITM substrates [9] [10] have recently been purchased by the UK for early coating runs. Assuming the substrates meet the required specification they will be re-polished and installed in one of the detectors. For this reason they have been oversized in thickness to accommodate at least two polishes (thickness 204 mm).

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[8] Robertson, *"Baseline Suspension Design for LIGO II – Update – LSC presentation Aug 2000",* G000295.

[9] Billingsley, "*Fused Silica Blank Input Test Mass",* D050337-A-D

[10] Billingsley, *"Specification for Fused Silica Blank Input Test Mass",* E050071-C-D

[11] Document in preparation: Cantley et. al., *"Recommended surface specification for ETM/ITM flats"*, T050116-00-K

4.2 Penultimate mass

The penultimate mass is chosen to be as heavy as possible, consistent with the overall design characteristics of the multiple suspension. This improves the performance of the local damping.

The proposed material for the penultimate mass of both ETM and ITM is Suprasil 312 (TBC). The penultimate mass dimensions and mass will be identical to the test mass (39.6 kg with diameter 340 mm and thickness 200 mm).

The baseline proposal is for the penultimate mass to be suspended using two wire loops with silicate bonded stand-off prisms providing low loss break-off points. The wire loops will be positioned at +/- 3 mm from the centre of mass along the direction of the beam axis.

The wire loop method has successfully been employed in the GEO 600 suspension of the penultimate masses and in Initial LIGO for suspension of the test masses. However there is some (uncorroborated) concern that creak noise due to slippage/twisting of the loops may be intrinsic to wire loop suspensions. Installation of such wire loops also presents a challenge and potentially can place the nearby silica ribbons/fibres under some risk of damage during assembly.

Based on these concerns an alternative concept is currently being explored which may reduce the potential for creak noise and facilitate a more straightforward and less risky installation [12]. The proposed concept involves the use of 'silica hooks' bonded to flats on the penultimate mass. Drum ended wires or similar (e.g. 'wire with clamp') can be hooked into position and loaded under gravity. Clean break-off points are provided for the wire using stand-off prisms silicate bonded vertically above the silica hooks. It is moderately likely that we will move to this alternative design, subject to extensive testing.

For either option the flats on the penultimate masses will be as per the flats on the test masses (95 mm x 200 mm with a reduced $\lambda/10$ patch area (area/location dependent on option)) (TBD).

4.3 Ears and bonding

The preliminary design for the ears is complete[13]. It is a single ear design (one ribbon per ear) as opposed to the compound ear design employed in GEO 600 (two fibres per ear). The proposed ear pairs for the two ribbons on each side of the mass will be silicate bonded to the flats on the masses such that they are separated by +/- 15 mm from the centre of mass along the beam axis. This separation was chosen as the minimum reasonable separation to provide access for laser welding. The flats for silicate bonding on both the masses and the ears will be polished to $\lambda/10$ as discussed in Section 4.1 and Section 4.2..

The size of the bond area is limited by consideration of the thermal noise introduced to the test mass using the 10% technical noise limit set in the systems design document[1].

Simple scaling up from the bonds used in GEO 600 based on the increased mass from 10 kg to 40 kg would require a total bond area of 24 cm^2 per test mass to maintain the same level of average

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[12] Wilmut, Cantley, *"An Alternative to Wire Loops for Suspension of Penultimate and Reaction Masses"*, T050219-00-K.

[13] Perreur-Lloyd, "*Noise Prototype Test Mass Preliminary Ear (Triangular Face)*", D050169-08.

stress on the bonds as per GEO 600. The total bond area per test mass is limited here by thermal noise considerations[14] to 7.1 cm^2.

Shear tests carried out in Caltech[15] on sodium silicate (1:6) bonds (that were only three days old and not fully cured) showed at worst around ~ 4.3 MPa breaking stress and up to ~6.3 MPa. Hence at face value a bond area limit of 7.1 cm^2 is acceptable since the resulting average stress levels on the bonds will be at least ~ 8 times lower than the typical measured breaking stress for these types of sodium silicate (1:6) bonds. However the effects of bond peeling on strength must be considered.

If a compound ear was adopted, working with an allowable bond area per flat of 3.55cm^2 and using a ribbon separation of 30 mm would necessitate a compound ear with an unacceptably large width to height ratio which would amplify peeling effects. Using the proposed separated (single) ears (1.77 cm^2 per ear) allows a large height to width ratio within the area constraints and along with the chosen triangular shaped bond footprint this reduces peeling stresses. FE modeling of the ears is underway and the results will be verified experimentally in the near future.

One potential disadvantage of this design is that in the event of a ribbon failure the single ear may be subject to a dynamic stress level much higher than its static operating stress level. An upper limit[16] for this may be considered as a factor of 3 with a compound ear design reducing this by 50% to a factor of 1.5. However in the event of such a failure scenario on a single ear system the integrity of the bond would not be compromised by this level of dynamic stress. The operating static stress on each bond will be ~0.55 MPa hence the upper limit would be a dynamic stress of ~ 1.7 MPa. Based on the work that has been carried out so far [15] the residual risks are considered to be small.

A bonding procedure already exists based on the GEO 600 bonding procedure[17]. Several test ears have already been bonded[18] [19] [20] and preliminary strength tests performed [21]. Initial results are very encouraging with the bonded ears strength tested up to x 3.7 working load (~ 2.1 MPa) without failure of the bond. The preliminary ears have a protruding 'horn' designed to accommodate lap-welding of ribbons since this has an advantage over butt-welding with respect to alignment tolerances during assembly[22]. During strength testing the horn failed in the preliminary test ears due to stress concentration in the horn region which was exacerbated by the poor quality ground

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[14] Cantley et. al, "*Ear Bond Area Limit for ETM/ITM Optics from consideration of Thermal Noise",* T050216-00-K.

[15] Private communication. Data measured at Caltech by H. Armandula in 2001 on unbaked sodium silicate bonds.

[16] For confirmation a simple experiment is being planned in Glasgow to measure the peak dynamic stress upon failure of one element of a four element suspension.

[17] Armandula, *"Silicate Bonding Procedure (Hydroxide-Catalysis Bonding)",* E050228-00-D

[18] Rowan, Hough, Cantley, *"Bonding & Visual Inspection of Preliminary Test Ears (Serial Number 0001-0004)",* T050209-00-K

[19] Rowan, Hough, Cantley, *"Bonding & Visual Inspection of Preliminary Test Ears (Serial Number 0011-0014)",* T050121-00-K

[20] Armandula, Cantley, Rowan, *"Bonding & Visual Inspection of Preliminary Test Ears (Serial Number 0005, 0006, 0015-0016)",* T050120-00-K

[21] Cantley et. al., *"Bonded Ear Strength Tests (Serial Numbers 0001, 0002, and 0011 to 00140",* T050211-00-K

[22] Cantley et. al., "*Ribbon-Ear Interface for ETM/ITM Monolithic Suspensions",* T050118-00-K.

finish. All future ears will be inspection polished. Hence minor design are modifications required to the ear design itself, after which further bonded ear strength tests are to be carried out. Modifications have been implemented to the shape in region of horn to reduce stress concentration effects without jeopardizing ease of welding and repair. This has been achieved by using a larger radius at the horn/ear interface and along with the smoother inspection polish finish this should push the breaking strength of the ear even higher. The risks associated with the details of the ear design are considered to be small.

The precise detail of the horn to accommodate the laser welded ribbon head will be optimized as the development of the laser welding technique and verification tests on laser weld strength progress. It is believed that a lap-weld will be simpler to redo in the event of a ribbon repair being required. However, there is some risk associated with the lap-weld technique and we retain the butt-weld approach, successful in GEO 600, as a fall-back.

The effect of heating on the bond integrity requires further investigation. Slight degradation of the bonds was evident following flame polishing of the test ear horns during initial strength testing. Flame polishing was carried out to remove the rough ground finish and micro-cracks in the region of the horns for improved strength to enable the bonds to be tested to higher loads [21]. However, the bonds on which fringes were observed were between dissimilar substrates (hybrid bonds between Suprasil 312 and Suprasil 2) and it is not anticipated that this effect will be a problem on like-to-like bonds with matching co-efficient of thermal expansion[23]. Additionally, whilst a small degree of bond heating may occur during fibre welding, it is believed that the horn shape is such that radiative cooling should be relatively high and that the heat transmitted to the bond should be minimal. Hence the risk associated with this effect is considered to be small.

A long term load test has been set-up with one of the bonded ears loaded to 12 kg since 19th August 2005 [21]. Proof testing of the ear bonds to a factor of 1.2 over the maximum in-service load is an Advanced LIGO requirement [24] with the maximum in-service load being 10 kg. Further long-term loading tests are planned.

It is proposed that similar ears (orientated at 180^{o}) will be used on the penultimate mass where there is no restriction on bond area from thermal noise considerations. Since the wire loops (or alternatives [12]) must pass between the ears on the penultimate mass and access may be restricted it is likely that the ears will not be scaled up significantly (unless strength testing indicates that a higher safety margin is required) (TBD). It is very probable that the same ear design will be used in both locations, this is the baseline.

Figure 3 shows the proposed ear arrangement on the penultimate mass.

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[23] There are some indications that the co-efficient of thermal expansion is influenced by OH content. Suprasil 311 & 312 have an OH content of approximately 200 ppm whilst Suprasil 2 is specified as < 1000 ppm. (Private communication from David Bright of Heraeus).

[24] *"Universal Suspension Subsystem Design Requirements Document",* T000053-03-D

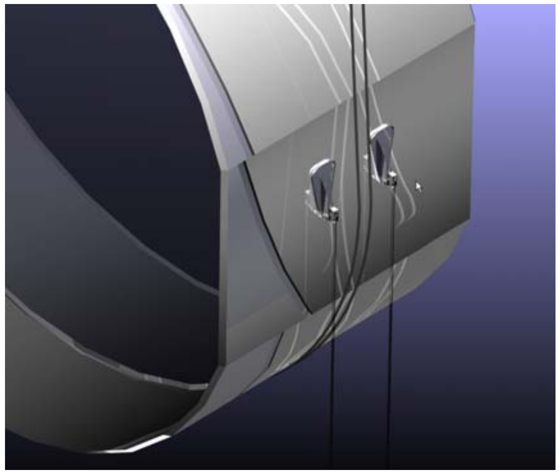

Figure 3 Ears bonded to penultimate mass with ribbons welded in place. Note that the break-off prisms for the wire loops suspending the penultimate mass are not shown in this sketch.

The ear position and angular alignment requirements for bonding have been calculated [25]. The ears are treated as attachment points for welding rather than a reference for the positioning of the ribbon/fibre head. This is justifiable since in the case of ribbon/fibre replacement the ear loses any referencing task therefore it is better to design the system such that the ears are simply attaching points. If the ears are no longer a reference during welding then a suitably precise fixture for holding the ribbons/fibres must be designed and tested.

A concept for a fixture for precision bonding of the ears on to the optics has been generated [26]. Based on the experience from GEO 600 it is easy to reach a precision of ± 0.1 mm and ± 2e-3 radians in linear and in angular positioning of the ears. These values are perfectly compatible with the welding requirements (see Section 4.4 below). The proposed Advanced LIGO fixture [26] should achieve these tolerances.

It is proposed that the ear material for each mass will be chosen to be identical to the substrate material. This removes the requirement for additional testing of hybrid silicate bonds [23]. We do not expect significant differences in the performance of bonds on different materials, but every material in use will be tested (except that we assume Suprasils 311 and 312 are identical for the purposes of bonding).

4.4 Ribbons and welding

Ribbons of cross-section 1.13 mm x 113 μm and length 600 mm are the baseline for Advanced LIGO. It is proposed that the H-pieces that were previously considered as potential welding interface pieces between the ribbons and the ears will not be used [22]. Instead it is proposed that the

[25] Cagnoli, *"Ear Position and Angular Alignment Requirements for Advanced LIGO Optics",* T050208-00-K

[26] Romie, Cantley, Armandula, *"Concept for Fixture for Alignment of Silica Optic Ears on Advanced LIGO Optics",* T050205-00-D

ribbons will be produced with thickened heads (1.5 mm x 3 mm) (TBD) for welding directly to the horns on the ears as illustrated in Figure 4. This reduces the overall number of welds in the system.

Figure 4 *Sketch of preliminary ear for test mass showing triangular footprint to minimize bond peeling effects. The horn has been designed to accommodate lap-welding of the thickened ribbon head. The design details of this horn have yet to be optimized. The ear shown has since been modified to increase the radius at the horn to minimize stress concentration in this region.*
Note that similar ears (orientated at 180^o) will be used on the penultimate mass with no technical noise restriction on bond area.

It has been found that shear stress due to shape imperfections is crucial in limiting the breaking strengths of silica fibres and ribbons. The development of a CO_2 laser technique to pull ribbons of suitable cross-section and length for Advanced LIGO is well underway[27]. This includes development of an optical profiling machine for measuring the dimensional tolerances in the fabricated ribbons/fibres [28]. The development work in these areas further reduces the small risk of excess shear resulting from imprecise fabrication.

It has been considered whether ribbon twists are required to avoid buckling effects as the mirror swings. Work has shown that ribbon twists to avoid buckling effects are not required for the Advanced LIGO ETM/ITM suspensions [29]. Hence the ribbons can be aligned as represented in Figure 3 without placing any special restrictions in alignment/handling of the suspension once the ribbons are welded in place.

The dimensional tolerances required for the Advanced LIGO ribbons have been calculated [30]. These are ± 1.9% in each of width, thickness and length. These are comparable with those tolerances achieved using the flame fabrication techniques of GEO 600 of ± 2.1%. The implication of this is that the flame fabrication technique used in GEO 600 could be used as a fall back to laser

[27] Cantley et. al., *"Update on Development of A CO2 Laser Machine for Pulling and Welding Silica Fibres and Ribbons"*, T040213-00-K.

[28] Cumming et. al., *"Optical Profiling Device for Dimensional Characterisation of Ribbons/Fibres",* T050207-00-K

[29] Hough, "*Buckling of Ribbon Fibres as used in the Suspensions of Gravitational Wave Detectors",* T030252-00-K.

[30] Cagnoli, Cantley, *"Ribbon Tolerances and Alignment Requirements for Advanced LIGO Optics"*, T050212-00-K.

fabrication assuming we use slightly more stringent selection during fibre/ribbon characterization. Our baseline for Advanced LIGO is, however, the CO_2 laser welding technique.

The most stringent welding alignment requirement for the optics of Advanced LIGO has been calculated to be ± 0.8 mm parallel to the beam axis [30]. Again this level of welding tolerance could be achieved using either the CO_2 laser technique or the flame welding technique assuming suitably precise welding assembly tooling is designed. This is considered to be easily achievable.

Silica fibres can be as strong as high tensile steel. Typical fibres produced for GEO 600 had test strengths of 3 ± 1.5 GPa. Recent measurements for flame pulled ribbons gave an average breaking stress of 2.6 GPa (range 2.0 GPa to 4.4 GPa over eleven samples) which when compared to an operating load of ~ 0.8 GPa for Advanced LIGO gives at least a factor of 2.5 safety margin[31]. It is anticipated that the more refined technique of laser pulling will achieve even higher strengths [27].

We are currently investigating failure mechanisms in silica ribbons to establish whether there is a requirement to protect the optic from debris in the event of a ribbon failure (TBD).

A program is underway to evaluate the requirement for damping of the ribbon violin modes. The following options require to be explored:

1. ribbon coatings (not necessarily the Teflon used in GEO 600; risks are unwanted damping at low frequency, vacuum contamination and weakening of the ribbons)
2. passive (tuned) dampers on the penultimate masses (requires design work)
3. active damping sensing either penultimate mass or ribbons, actuating penultimate mass or ribbons

Each of these methods requires urgent attention to determine which is/are practicable. An initial assessment of these is presented in a technical note[32]. Further work is underway to assess the best method of damping the ribbons. We have not yet chosen a baseline design (TBD).

4.5 Assembly

Full details of the proposed assembly procedure are given in the fabrication and assembly document for the monolithic stage[33].

In this document the critical assembly processes are presented. In summary these are:

1. Bonding
2. Ribbon/fibre fabrication & using CO_2 laser machine + characterization/testing
3. Refined '3 & 1' assembly
4. Welding + proof testing

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[31] Heptonstall et. al., "*Production and Characterisation of Synthetic Fused Silica Ribbons for Advanced LIGO*", T050206-00-K.

[32] Strain, *"Advanced LIGO ITM/ETM Suspension: Is Violin Mode Damping Required?"*, T050108-00-K

[33] Jones et. al., "*ETM/ITM Monolithic Stage Fabrication and Assembly*", T050213-00-K.

Proof testing of the assembly to a factor of 1.2 over the maximum in-service load is an Advanced LIGO requirement [24]. The maximum in-service load is 40 kg on the test mass and penultimate mass bonds. A concept for a loading clamp device to perform proof-testing on the assembled monolithic stage has been generated[34].

The concepts are presented and the key development work required to reach final design are:

1. Approach to precision alignment of ribbons/fibres for welding
2. Approach to beam delivery for welding
3. Approach to beam delivery for relieving stress at weld locations
4. Materials issues: compliance (micrometric displacement) within bearing pads during the welding process
5. Finalise approach to testing of monolithic chain

5 Conclusions and future development strategy

The conceptual design of the monolithic final stage of the ETM/ITM quadruple pendulum suspensions has been presented along with details of the preliminary design features and corresponding parameters. The baseline design has been presented along with a small number of options currently under consideration. The baseline design is complete except for a method of damping violin modes (considered low risk). The bonding, ears, ribbon/fibre development plan[35] has been generated. This document provides a summary of the main development milestones required for various aspects of the design that will lead to the conclusion of the final monolithic suspension stage design.

Whilst the majority of development areas are in a relatively mature state satisfying the requirements for triggering the preliminary design review (PDR) there are several areas where further intensive development will be required to conclude to final design.

Final design decisions will be made pending the conclusions of the PDR and, following the next phase of development, the conclusions of the Final Design Review (FDR).

Design areas considered to be in a relatively mature state, of low risk and where only modest an planned ongoing development is required are:

1. *Silicate Bonding.*
   It is proposed that ear material will be chosen to match substrate material throughout the suspension. The test masses and penultimate masses will be Suprasil. The reaction masses can be made from heavy glass or standard fused silica (TBD).
2. *Ear Design*
   Continuing development of the ears will require minor improvements to the shape of the horn, driven by the welding requirements and also by the requirement to reduce the stress concentration in the region of the horn. The bonded 'ear strength tests' will provide the

[34] O'Dell, Cantley, Jones, *"Concept for Variable Load Clamp for ETM/ITM Monolithic Assembly",* T050214-00-K

[35] Cantley et. al., "*Silicate Bonding, Ears, Ribbon/Fibre Status/Research and Development Plan*", T040170-00-K.

platform for continued evaluation of silicate bond strengths. Additional long term load tests will also be set up.

3. *Assembly and Installation*
   The assembly and installation procedure is considered to be relatively mature for this stage in the project. This will be further developed to reach final design including the completion of repair procedures.
4. *Alternative to Wire Loops*
   The concept of using silica hooks with break-off prisms to reduce the risk of creak noise in the penultimate and reaction mass suspensions will be further investigated.

Design areas where it is considered that more intensive development is required to minimize risks and to reach final design are:

5. *Laser Welding*
   Flame welding is a proven technique. However further intensive development of laser welding is required. This includes testing of weld strength and repeatability. The effect of heating from welding on the integrity of the bond must also be further investigated but this is considered to be a low risk concern. A suitably precise fixture for laser welding must be designed. The tolerance requirements are not considered to be onerous.
6. *Ribbon/Fibre Manufacture using CO_2 Laser System*
   Development of the technique for laser fabrication of ribbons and fibres will continue. Dimensional tolerances and repeatability will be tested, strength will be further tested and loss measurements will be made. There are no serious concerns in this area and the risks are diminished since flame fabrication techniques are already proven and in their existing state are almost good enough for application to Advanced LIGO. Only minor development of these would be required as a fall back. The baseline ribbon design is satisfactory and as an option to ease assembly we have tapered ribbons with thickened ends (TBD).
7. *Ribbon/Fibre Violin Mode Damping*
   The development of a suitable technique for damping of violin modes requires to be accelerated for application to the noise prototype. At present designs will move forward with provision for application of an active damping technique. We note that the requirement for such damping is independent of the choice of ribbon/fibre and that the suspension structure is being designed to accommodate any of the options under consideration.

The development progress in each of these areas is intensively tracked on an ongoing basis by the frequent telecons on controls/noise prototype design, monthly ALUK Project Management Committee meetings and six-monthly ALUK Project Advisory Group and OverSight Committee meetings.

It is planned that following the recommendations of the PDR a detailed development plan will be drafted to address the specific areas of concern. This will exist over and above the more general development plan generated within the UK (ALUK) project.

Out plans are driven primarily by the need to meet noise performance goals, and secondarily concerns of reliability, ease of assembly and ease of repair. These principles will guide our recommendation of any changes from the baseline.