LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T050215-02-K 21st September 2006

Monolithic Stage Conceptual Design for Advanced LIGO ETM/ITM

C. A. Cantley[1], H. Armandula[2], M. Barton[2], G. Cagnoli[1], A. Cumming[1], D. Crooks[1], E. Elliffe[1], R. J. S. Greenhalgh[3], T. Hayler[3], A. Heptonstall[1], J. Hough[1], R. Jones[1], J. O'Dell[3], I. Martin[1], M. Perreur-Lloyd[1], N. A. Robertson[4,1], J. Romie[2], S. Rowan[1], K. A. Strain[1], C. Torrie[2], I. Wilmut[3]

[1] Institute for Gravitational Research, University of Glasgow

[2] California Institute of Technology, LIGO Project

[3] Rutherford Appleton Laboratory

[4] University of Stanford, Ginzton Laboratory

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

Institute for Gravitational Research

University of Glasgow
Kelvin Building
Glasgow G12 8QQ
Phone: +44 (0)141 330 3340
Fax: +44 (0)141 330 6833
Web: www.physics.gla.ac.uk/gwg

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/

Revision tracker

Rev 00	4th October 2005	Generated for Bonding, Ear, Ribbon/Fibre PDR
Rev 01	15th June 2006	Update for PDR-03
Rev 02	21st September 2006	Update to reflect mass material changes

Overview of modifications introduced in Rev 01

The key modifications introduced in this document are as a result of modifications to the ribbon end piece design, silica ear design and subsequent welding configuration. Due to these the beam access requirements for CO_2 laser welding have changed. Previously, during welding the beam was directed at the welding horn on each ear normal to the flat on the associated mass. The new approach with the new ear and ribbon designs requires access perpendicular to the flat on the mass (normal to the face of the mass).

Overview of modifications introduced in Rev 02

The key modifications introduced in this revision are:

- Material selection revisions for penultimate and reaction masses (Section 4).
- Insertion of Section 4.3 with brief description of reaction mass.
- More precise definition of the positional and angular alignment tolerances for ear bonding and ribbon welding (Sections 4.5 & 4.6).

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 was 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 the beam splitter suspension which also requires a monolithic lower stage using fused silica fibres.

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 fused silica ribbons. GEO 600 used cylindrical fibres. The use of ribbons will lead to further

[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.

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.

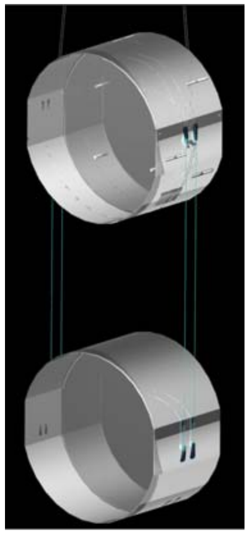

Figure 1 *Monolithic final stage suspension for the ETM/ITMs. The penultimate mass is suspended using steel wire loops from a metal mass above. The wire loops are provided with a clean break off using silica stand-off prisms which are silicate bonded to the flats on the penultimate mass. The test mass is suspended from the penultimate mass using silica ribbons CO_2 laser welded between silica ears which are silicate bonded onto the flats on the two masses.*

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].

[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.

[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 http://www.ligo.caltech.edu/~ctorrie/.

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 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]. Within Rev. 01 of this *Monolithic Stage Conceptual Design Document* we introduced minor changes to the ribbon design at the end pieces, but the baseline ribbon dimensions remain as described in the *Suspension System Conceptual Design Document.*

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 satisfied[1].

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

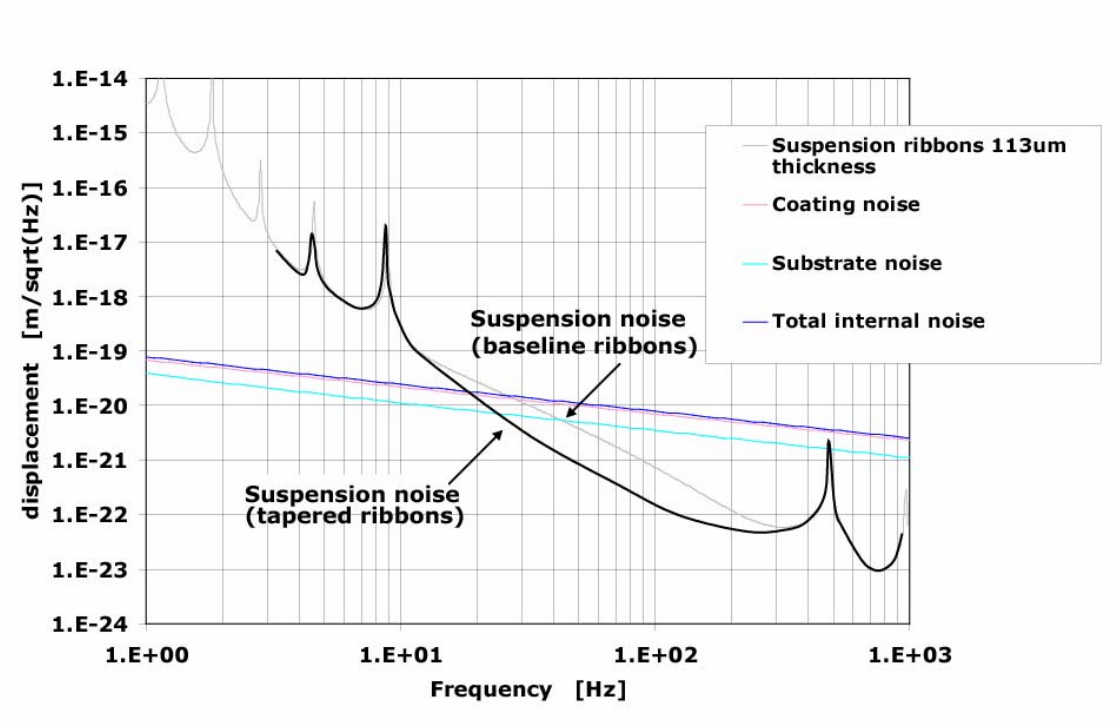

Figure 2 Suspension thermal noise curve and internal thermal noise curve for the coated 40 kg silica test mass. Note that thermal noise associated with the silicate bonded ears is not included.

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 $x10^{-17}$ rad/√ Hz which corresponds to 3.8 $x10^{-20}$ 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 $x10^{-9}$, mass radius 17 cm, mass thickness 20 cm, silica coating loss 1.2 $x10^{-4}$, tantala coating loss 1.6 $x10^{-4}$, transmission of the ETM 5 $x10^{-6}$, transmission of the ITM 5 $x10^{-3}$, spot size (waist) 5.5 cm.

---

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

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 baseline material for the ETM is the fused silica Heraeus Suprasil 312.

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

Both materials have density 2200 kg/m^3 yielding a mass of 39.6 kg (with flats cut).

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 $\lambda/10$ flatness specification for silicate bonding will be required on a reduced patch area within these flats (final area and position TBD)[11].

Four ITM substrates [9] [10] have already been purchased by the UK and delivered to Caltech in Jan 2006 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).

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 the fused silica Schott Lithosil QT. The penultimate mass dimensions and mass will be identical to the test mass (39.6 kg with diameter 340 mm and thickness 200 mm (with flats cut)).

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

[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

wire loop suspensions. Installation of such wire loops also presents a challenge and potentially could place the nearby silica ribbons/fibres under some risk of damage during assembly.

Based on these concerns an alternative concept was explored to reduce the potential for creak noise and facilitate a more straightforward and less risky installation[12]. The proposed concept involved the use of 'silica hooks' bonded to flats on the penultimate mass. With these arrangements drum ended wires or similar (e.g. 'wire with clamp') could be hooked into position and loaded under gravity. Clean wire break-off points would be provided using stand-off prisms silicate bonded vertically above the silica hooks.

Following initial investigation it was concluded that the silica hook concept would require extensive development. In addition to this it was identified that the drum ended wires which would be used in conjunction with the hooks would require extensive development due to early evidence of premature failure associated with current manufacturing practices (both in machining and in heat treatment).

Based on the new risks associated with, and timescales involved in, development of the silica hook system and taking account of the lack of evidence for the actual occurrence of creak noise using wire loops with conventional stand-off prisms it was decided to remain with the existing baseline design (an extension of the wire loop with stand-off prisms design used successfully in GEO 600).

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 baseline to suit ribbon/ear design) (TBD).

4.3 Reaction mass

The reaction chain is thinner than the main chain. Hence the dimensions of the reaction (test) mass are diameter 340 mm and thickness 130 mm. It is desirable for pendulum dynamics and control to have the reaction mass of similar mass to the test mass. Hence a heavy glass, Schott F2, is the material choice for the reaction mass. The density of F2 is 3610kg/m3 yielding a mass of 42.2 kg (with flats cut).

The reaction mass will have an electrostatic gold coating on it's inner face to allow the higher frequency feedback forces to be applied directly to the test mass.

4.4 Silica ears & ribbon interface

The silica ear design was been revised (change reported previously in this document Rev 01) from having an orthogonally aligned welding horn[13] to having a longitudinally aligned welding horn as illustrated in Figure 3.

---

[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.

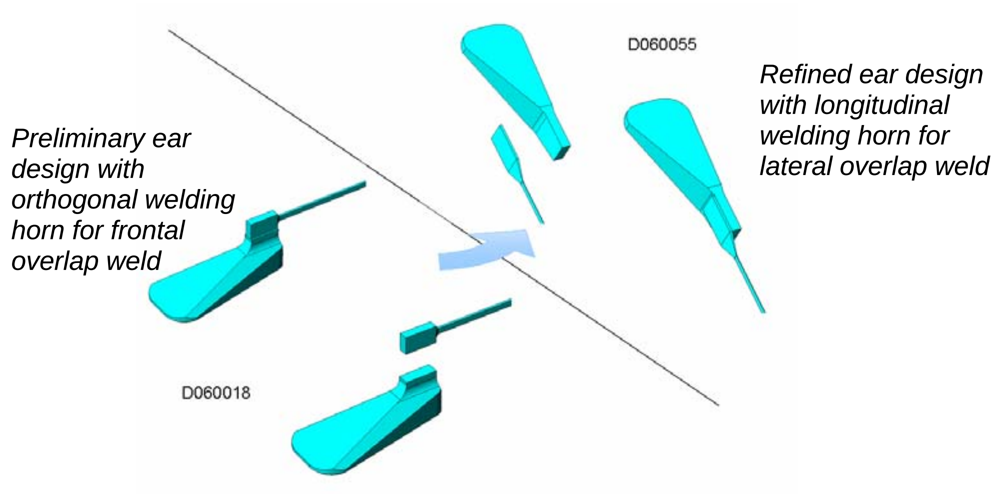

Figure 3 Refinement of ear from design with orthogonal welding horn (D060018) to longitudinal welding horn (D060055). Ribbon modifications are discussed in Section 4.6.

To produce the correct positioning of the ribbons with respect to the suspension the ears of the refined design are of two types A and B (left and right handed)[14] [15]. The refined ears accommodate lateral overlap welds between the horn and the ribbon end piece instead of a frontal overlap weld. Lap welding has an advantage over butt-welding with respect to alignment tolerances during assembly[16].

The modification in ribbon/ear design and interface has multiple benefits:

(a) Investigations into ribbon fabrication clearly highlighted that the optimum shape for the ribbon end pieces would be rectangular with cross-section dimensions 5 mm x 0.5 mm (aspect ratio 10:1 matching that of the ribbons). To produce ribbons with end pieces of smaller aspect ratio was considered to be problematic and add unnecessary complexity, risk and cost to the ribbon manufacturing process.

(b) To accommodate the revised ribbon end piece design the welding horn on the silica ears had to be modified from orthogonal to longitudinal alignment with the ear. This had several benefits. Due to the simplified shape the ear manufacturing process was simplified. The realignment of the welding horn also removed the stress concentration in the region between the welding horn and the ear proper.

(c) With the improved ear design an improved surface finish is achievable during the manufacturing process i.e. an inspection polish finish is achievable potentially removing any requirement for flame polishing. In earlier tests the overall strengths of the bonded ears,

---

[14] Jones, "*Noise Prototype Refined Ear - Type A*", D060055-02.

[15] Jones, "*Noise Prototype Refined Ear - Type B*",, D060056-02.

[16] Cantley et. al., "*Ribbon-Ear Interface for ETM/ITM Monolithic Suspensions*", T050118-00-K (requires revision)

whilst satisfactorily high for the Advanced LIGO application, were found to be ultimately limited by failure at the welding horn / ear interface. The refined ear design is anticipated to provide increased margin (at least a factor of two stress reduction). Furthermore, this modification reduces stress concentration effects without jeopardizing ease of welding and repair.

(d) The thinner dimension of 0.5 mm for the ribbon end piece makes CO_2 laser welding easier. The greater the thickness the more difficult it would be to uniformly melt the material to provide a strong weld. Welding tests have already indicated that the ribbon end piece and welding horn dimensions are within the optimum range. For the scenario where a ribbon repair has to be carried out, with the thinner ribbon end piece there is less material to remove and less potential for a resulting effect on the positioning and alignment of the replacement ribbon.

A 'single ear design' is the baseline for Advanced LIGO (one ribbon per ear) as opposed to the compound ear design employed in GEO 600 (two fibres per ear). The proposed ear pairs[14 15] (types A and B) for the two ribbons on each side of each 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.

It is proposed that the material for the penultimate and test mass ears will be Heraeus Suprasil 312.

4.5 Silicate bonding of ears

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 stress on the bonds as per GEO 600. The total bond area per test mass is limited here by thermal noise considerations[17] to 7.1 cm^2.

Shear tests carried out in Caltech[18] 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 the 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. The proposed separated (single) ears (1.77 cm^2 per ear) allow a large height to width ratio within the area constraints and along with the carefully designed triangular bond face these minimize peeling effects. Finite element modeling of the ears has been carried out and experimental strength testing is ongoing.

---

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

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

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[19] 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. Preliminary experimental measurements have been carried out to investigate the peak dynamic force on fibre failure. Initial results show the factor of three increase beyond static load is realistic but further verification is required. However, based on the work that has been carried out so far the residual risks are considered to be small.

A bonding procedure has been written for Advanced LIGO based on the GEO 600 bonding procedure[20]. Several test ears have already been bonded[21] [22] [23] and preliminary strength tests performed [24]. 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. These tests were performed on the preliminary ears which had the orthogonally aligned (protruding) 'horn' designed to accommodate the initial design of frontal lap-welding of the ribbon end pieces as shown in Figure 3. During strength testing of these ears failure occurred at the horn/ear interface due to stress concentration in this region which was further exacerbated by the poor quality ground finish. The modification of the horn alignment and the improved surface finish during manufacturing will lead to significantly improved intrinsic ear strength. Further bonded ear strength tests and analysis will be carried out when the next batch of refined ears become available (due date October 2006).

Development of the laser welding technique is ongoing and verification tests on laser weld strength continue. It is believed that the current configuration of 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 until further verification is carried out 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 preliminary 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 horn/ear interface for improved strength to enable the bonds to be tested to higher loads [21]. The degraded bonds on which interference fringes were observed were bonds between Heraeus Suprasil 312 and Suprasil 2. In the literature the mean co-efficient of thermal expansion for these grades of fused silica is identical e.g. 5.1 x 10^{-7}/K (0 to 100 ^{o}C). However,

---

[19] 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.

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

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

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

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

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

there is some indication that the co-efficient of thermal expansion can be influenced by OH content and these two grades of silica have quite different OH contents[25]. Whilst there is potential for a small degree of bond heating during fibre welding, the protrusive horn shape has been designed such that radiative cooling should be relatively high and heat transmission to the bond through conduction should be minimal. Flame polishing by contrast requires even and prolonged heating over the body of the ear and horn. The requirement for flame polishing of the welding horns has been removed due to the refinement of the shape of the ears and the improved surface finish achievable during manufacturing. Hence the risk associated with this effect is considered to be negligible.

A long term load test was 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 [26] with the maximum in-service load being 10 kg. This bonded ear was successfully loaded until 19th May (9 months) when the ear had to be unloaded then reloaded due to a necessary re-location of the experiment during the IGR lab refurbishment. A few hours after relocation the ear failed at the site of the locating groove on the extended test horn. This in itself was not of concern since the locating groove and extended test horn were there only for the purposes of loading using a wire loop (avoiding the requirement for welding) and the groove produced an obvious region of stress concentration. The loading and unloading of the wire may also have led to deformation of the wire and repositioning of the wire could have exacerbated the induced stress. We plan to set up two or three more long-term loading tests in the near future once the Glasgow Silica Lab is fully reinstated following refurbishment.

It is proposed that the same ear designs (type A and B) will be used on the penultimate mass (orientated at 180^{o}). There is no restriction on bond area from thermal noise considerations at this mass. Since the wire loops 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, which is unlikely based on the evidence to date) (TBD).

Figure 4 shows the proposed ear arrangement on the penultimate mass.

[25] 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).

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

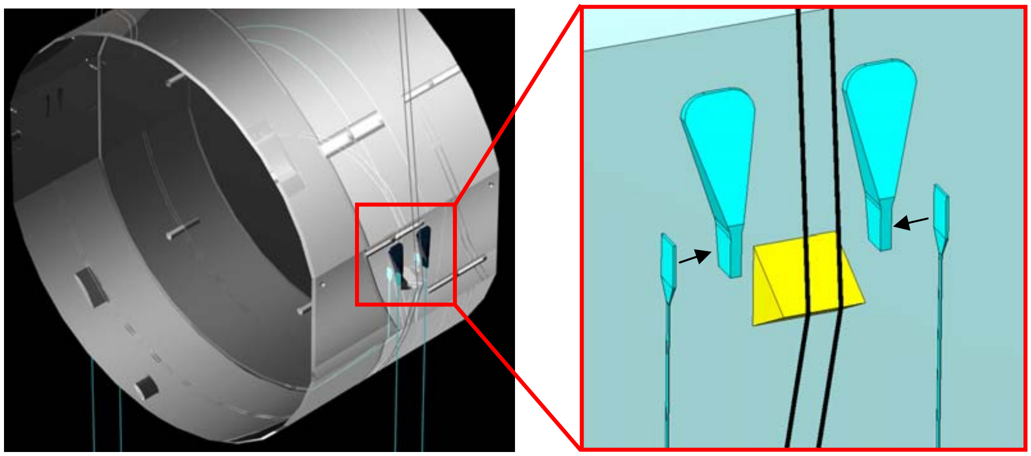

Figure 4 Ears bonded to penultimate mass with ribbons welded in place. Note that the break-off prisms for the wire loops suspending the penultimate mass are also shown in this sketch.

The ear position and angular alignment requirements for bonding have been calculated [27]. 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. Since the ears are no longer a reference during welding then a suitably precise fixture for holding the ribbons/fibres will be designed and tested.

An initial concept for a fixture for precision bonding of the ears on to the optics was previously generated[28]. It is now planned that RAL will design an ear bonding jig for each mass/ear configuration. To this end RAL have recently been given a hands-on tutorial at Glasgow where they performed some silicate bonding to give them practical insight into the requirements for the jig.

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 4.6 below). The revised Advanced LIGO bonding jig should have no problem in achieving these tolerances.

Recall the material for the ears for the penultimate and test masses will be Heraeus Suprasil 312. The ETM test masses will be Suprasil 312 with the ITM test masses Suprasil 311. Suprasil 311 and 312 have the same co-efficient of thermal expansion and are identical for the purposes of bonding. The penultimate masses in each case with be Schott Lithosil QT with co-efficient of thermal expansion the same as the Suprasils at 5×10^{-7}/K (25 to 100 ^{o}C). Hence there should be no issues with bonds between these different types of fused silica forming the monolithic stage.

---

[27] Cagnoli, *"Ear Position and Angular Alignment Requirements for Advanced LIGO Optics"*, T050208-01-K

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

4.6 Ribbons and welding

Ribbons of cross-section 1.13 mm x 113 μm and length 600 mm are the baseline for Advanced LIGO. The H-pieces that were previously considered as potential welding interface pieces between the ribbons and the ears will not be used [22]. Section 4.4 has already provided some details on the refined ribbon end piece and ear welding horn arrangements. Figure 5 shows the refined arrangement. The ribbon end pieces will be 5 mm x 0.5 mm cross-section resulting from the ribbon being pulled from a monolithic silica slide of the same cross-section. The ribbon ends will be laser welded directly to the longitudinally aligned horns on the ears using a lateral overlap weld as illustrated in Figure 5. Hence the overall number of welds in the system is minimized.

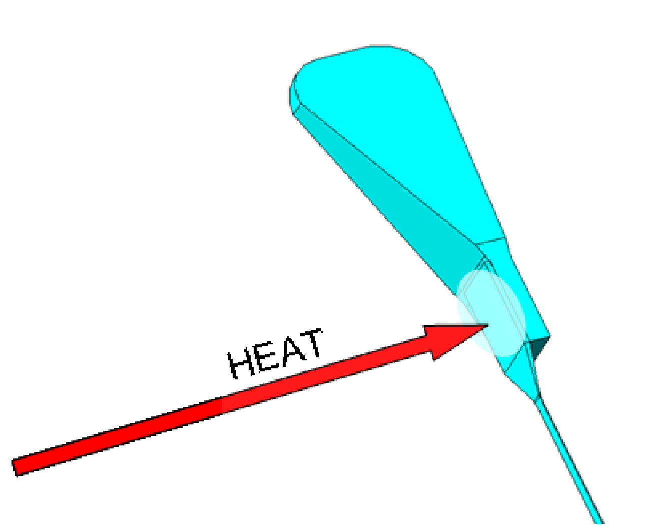

Figure 5 *Sketch of refined ear for test mass showing triangular footprint to minimize bond peeling effects. The longitudinally aligned horn has been designed to accommodate lateral lap-welding of the ribbon end piece (5 mm x 0.5 mm cross-section). The ears are left and right-handed (types A and B) to achieve the correct positioning of each ribbon axis with respect to the suspension reference. Note that for convenience similar ears will be used on the penultimate mass. Even though it has no technical noise restriction on bond area there is no requirement to scale up the bond area since there is sufficient margin already present in the bond strength.*

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[29]. This includes development of an optical profiling machine for measuring the dimensional tolerances in the fabricated ribbons/fibres[30]. The development work in these areas further reduces the small risk of excess shear resulting from imprecise fabrication.

[29] Cantley et. al., *"Update on Development of A CO_2 Laser Machine for Pulling and Welding Silica Fibres and Ribbons"*, T040213-00-K (requires revision)

[30] Cumming et. al., *"Optical Profiling Device for Dimensional Characterisation of Ribbons/Fibres"*, T050207-00-K (requires revision)

It has been considered whether ribbon twists are required to avoid buckling effects as the mirror swings. Work has shown that ribbon twists are not required for the Advanced LIGO ETM/ITM suspensions [31]. Hence the ribbons can be aligned as represented in Figure 4 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 [32]. These are ± 1.9% in each of width, thickness and length. These are comparable with those tolerances already achieved using the cruder 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 fabrication assuming we use slightly more stringent selection criteria during fibre/ribbon characterization. However, our baseline for Advanced LIGO is the improved CO_2 laser welding technique.

The most onerous welding alignment requirement for the optics of Advanced LIGO has been calculated to be ± 0.8 mm parallel to the beam axis [32]. 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. Based on the GEO 600 experience this is considered to be easily achievable with a precision of ± 0.1mm and ± $2x10^{-3}$ radians in linear and angular positioning of the ears achievable using a GEO style jig. The Advanced LIGO ear bonding and ribbon welding jigs should be designed to meet these positional and angular tolerances as these will easily cover the requirements.

Silica fibres can be as strong as high tensile steel if handled carefully. 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[33]. It is anticipated that the more refined technique of laser pulling will achieve even higher strengths [27].

A program is underway to evaluate the requirement for damping of the ribbon violin modes. An initial assessment of these is presented in a technical note[34]. Further work is underway to assess the best method of damping the ribbons[35]. A brief update is provided here:

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). Status – due to the properties of the Advanced LIGO ribbons, particularly the high tension in them, unfeasibly

---

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

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

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

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

[35] Strain, Cagnoli, *"Advanced LIGO ITM/ETM suspension violin modes, operation and control"*, T050267-01-K

large thickness of coating would be required (> 10 μm). This would introduce an unacceptable level of thermal noise in the pendulum bounce mode.

2. passive (tuned) dampers on the penultimate masses. Status - this has been demonstrated as theoretically possible but practically very difficult. To obtain reasonable coupling would require twelve high Q tuned dampers (at least 10^5) and detuning due to temperature drifts would prove to be highly problematic.
3. active damping sensing the ribbons, actuating penultimate mass or ribbons. Status – this should work and a design study for a sensor is underway to find the optimum approach (TBD).

4.7 Assembly

Full details of the proposed assembly procedure are given in the fabrication and assembly document for the monolithic stage[36]. This was previously updated to Rev 01 in conjunction with Rev 01 of this conceptual design document.

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

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 and is being progressed[37].

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 current design features and corresponding parameters. The baseline design has been presented along with a small number of options still under consideration. The baseline design is complete except for a method of damping violin modes

[36] Jones et. al., "*ETM/ITM Monolithic Stage Fabrication and Assembly*", T050213-01-K.

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

(considered low risk). The bonding, ears, ribbon/fibre development plan[38] 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.

The majority of development areas are in a mature state and the preliminary design review of the monolithic stage took place successfully in October 2005. Rev 01 to this document took place in preparation for the June 2006 review (update for PDR-3) of the overall suspension system. Rev 02 took place in September 2006, mainly triggered to record a change to the fused silica material choices for the penultimate and reaction masses.

Final design decisions will be made pending 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 and 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, penultimate masses and corresponding ears will be fused silica (Suprasils 311/312, Lithosil QT and Suprasil 312 respectively). The reaction masses will be F2 heavy glass.
2. *Ear Design*
   Continued development of the ears has brought about an improvement to the shape of the welding horn, driven by the ribbon welding requirements and also by the requirement to reduce the stress concentration in the region of the horn. Silicate bond strengths are considered to be more than adequate for the loading in Advanced LIGO. Additional long term load tests will be set up on the bonded refined ears when they arrive.
3. *Assembly and Installation*
   The assembly and installation procedure is considered to be mature for this stage in the project. This will be further developed to reach final design including the completion of repair procedures.

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

4. *Laser Welding*
   Flame welding is a proven technique. However further intensive development of laser welding is required. This includes continued testing of weld strength and repeatability. The effect of heating from welding on the integrity of the bond could also be further investigated but this is considered to be a very low risk concern. A suitably precise fixture for laser welding must be designed. The tolerance requirements for this are not considered to be onerous.
5. *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

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

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 lateral overlap welds to the ears. The allowable range of taper shapes has already been determined and the shape will be optimized in the near future.

6. *Ribbon/Fibre Violin Mode Damping*
The development of a suitable technique for damping of violin modes is underway but require to be accelerated for application to the noise prototype. At present the noise prototype design 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 noise prototype design, monthly ALUK Project Management Committee meetings and six-monthly ALUK Project Advisory Group and OverSight Committee meetings.

Our 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 continue to guide our recommendation of any changes from the current baseline.