LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Bonding, Ear, Ribbon/Fibre PDR - Response to Committee Report

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1 Introduction

Reference is made to T050245-00-R *"Advanced LIGO Suspension Ribbon/Fibre/Ear/Bonding Preliminary Design Review Report"* written by the Review Committee in May 2006. Here we provide responses to the points raised within the report.

Reference should also be made to the main review documents which have recently been updated to reflect design modifications made since the October 2005 PDR.

T050215-01 *"Monolithic Stage Conceptual Design for Advanced LIGO ETM/ITM"*

T050213-01 *"ETM/ITM Monolithic Stage Fabrication and Assembly"*

2 Committee's specific suggestions for research concentration – status update

An extract from the detailed report from the committee T050245-00-R is given below in *italics*. Specific suggestions made by the committee for research concentration are given below in ***bold italics*** along with the status update from the SUS group in plain text.

Detailed Report (extracted from T050245)

The preliminary design review of Advanced LIGO Suspension subsystem Ribbon/Fiber/Ear/Bonding issues was held October 31, 2005, following a preliminary meeting of the review team where they discussed the documents and compiled questions. These questions were addressed by the suspension team at the review.

It is clear to the review committee that much thought and effort has gone into the overall suspension design and that work on suspension filaments and connections is progressing well along a carefully chosen path. The committee brought up a number of issues after reading the provided support material, primarily in the categories of thermal noise, welding, fallback plans, and strength/stability. All issues were addressed by the suspension team to the satisfaction of the committee. In many cases, the practical experience using similar suspensions in GEO 600 lay to rest many concerns that might otherwise be troubling. Particular issues that were brought up by the committee and addressed included:

- *Concerns about the art and practice of flame welding. The GEO 600 experience here is directly transferable to the advanced LIGO case and gives no cause for concern. Prior consultation and continuing work with professional glass blowers also makes this a non-issue.*
- *Effects of thermal diffusion differences between laser and flame welding.*
- *The ability to fallback to either flame welding as a connection method and/or dumbbell ribbons should problems arising with tapering*
- *Strength of silicate bonds and ears connections and the ability of these connections to survive a single wire breaking or other catastrophic events.*
- *The ability to achieve required geometrical tolerances on ribbons with laser drawing.*

The committee felt that in many cases further research and planning was necessary to address some issues, but that the suspension team had adequate (and typically detailed) plans to do so. Particular areas that need further research and have plans in place are:

Develop requirements (in collaboration with ISC team) on positioning of the optics.
STATUS:
Some discussions have taken place and the details for the ETM noise prototype are reasonably well understood. However, this area of design requires focused attention within the next month or two to determine the details for the range of suspension types. Correspondence requires to be set up between the SUS, ISC and COC teams.

Effects of violent impacts (including likely installation effects) on stability of silica suspensions. Evaluation of requirements of earthquake stops spring constant in light of impact effects.
STATUS:
This is covered as part of PDR-3 in June 2006. Reference can be made to the following documents.

http://www.eng-external.rl.ac.uk/advligo/_review/documents/structures/T060053-00-K.pdf (calculations, part 1)

http://www.eng-external.rl.ac.uk/advligo/_review/documents/overview/T060098-00-K.pdf (calculations, part 2, ongoing)

http://www.eng-external.rl.ac.uk/advligo/_review/documents/overview/T060139-00-K.pdf

Thermal noise effects of silicate bonding. In particular, directly measuring the mirror thermal noise effects of a silicate bond using an existing prototype interferometer, possibly the TNI or Glasgow interferometer, should be explored.
STATUS:
No action taken to date. Correspondence requires to be set up between TNI, COC and SUS.

Thermal noise effects of tapering of filaments, flame welding, and laser welding. The recent paper on suspension thermal noise from laser welded fibers addresses many inadequacies in our knowledge. It would also be desirable to explore the direct measurement of suspension thermal noise in a prototype interferometer, to allow for more direct research on effects from bonding, welding, tapering, etc, although this may not be feasible. Analysis of data from existing gravitational wave interferometers, particularly GEO, for thermal noise information should be pursued.
STATUS:
Analysis of the flexure position and thermal noise of ribbons with tapers of length between 3 mm and 5 mm with linear, exponential and square root profiles have commenced (P. Willems with input from G. Cagnoli). This work will continue in conjunction with the further

development of fabrication techniques for tapered ribbons with the Glasgow CO_2 laser pulling machine.
Plans for the direct measurement of thermal noise in a prototype interferometer have not been progressed (see comment above).
Analysis of data from existing gravitational wave interferometers for thermal noise information has not been pursued.
Correspondence requires to be set up between TNI, COC and SUS to address the two points above.

Possible non-Gaussian noise from silicate bonding, welding, and/or silica hood connections. This is another area where work with an existing prototype and GEO data can be potentially useful
STATUS:
The investigation of non-Gaussian noise from silicate bonding, welding and/or silica hood connections in a prototype interferometer has not been progressed (see comments above).
Correspondence requires to be set up between TNI, COC and SUS.

Research on the effect of long term loading in both vacuum and air on micro-cracking in silica. Examine existing plans and procedures for transport and storage of silica suspensions in light of any insights to determine if additional planning is necessary
STATUS:
The plan for the transport and storage of silica exists but has not yet been formalized. It is planned that the fibres and ribbons will be stored in an inert moisture free environment; the storage times will be kept to minimum and special containers will be designed to transport the fibres within the detector site. The plan is for the fibres/ribbons to be fabricated as local to the chamber as possible. There are plans for C. A. Cantley (Glasgow) to visit LASTI and LHO later this year to progress with the interfacing of the CO_2 pulling and welding machine infrastructure requirements.

Continuing work with laser welding, including the planned development and assembly of the noise prototype for LASTI. This includes the need for further testing on lap welding, rather than the butt welding which GEO used.
STATUS:
A refined ribbon end piece and ear welding horn has been developed to further improve the ease of assembly, strength of the welded pieces and ease of repair (refer to T050215-01 for further details). The initial development phase of the CO_2 laser pulling and welding machine is now complete. Further work is about to commence to further develop the machine and its interfaces to specifically suit LASTI and Advanced LIGO. As part of this there will be an intensive programme of ribbon fabrication/testing and welding characterization/testing.
Results from overlap welding tests to date are very encouraging and there is no concern over the feasibility of this method for application to Advanced LIGO. From both an assembly and a repair perspective it has many advantages over the butt-welding technique applied in GEO 600.

The material to be used in penultimate mass. This may require studies of effects of silicate bonding on other types of (cheaper) glass. Needs to be done along with planning for the suspension method for the penultimate mass, whether silica hooks or wires.
STATUS:
The material selected to be used for the penultimate mass of the noise prototype is HOQ310 (fused quartz). Glasgow have significant experience with silicate bonding of this material and no special bonding tests are required.
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. These are an extension of the wire loop with stand-off prisms design used successfully in GEO 600 and also in Initial LIGO. The Initial LIGO designs will be looked at in detail and extrapolated for the Advanced LIGO design.

Details of the necessity and method for violin mode damping. The ongoing plan involving modeling and integrating the GEO experience should be encouraged.
STATUS:
A programme is underway to evaluate the requirement for damping of the ribbon violin modes. An initial assessment of these is presented in T050108-00-K *"Advanced LIGO ITM/ETM Suspension: Is Violin Mode Damping Required?"* and more details are given in T050267-01-K *"Advanced LIGO ITM/ETM suspension violin modes, operation and control"*.
The conclusion to date is that active damping of the violin modes should work, but a design study for a sensor is required to find the best approach.
Passive damping does not seem to offer a practical solution for damping of the most important, lower order modes. This is primarily due to the properties of the Advanced LIGO ribbons, particularly the high tension in them. Passive damping does not reduce the damping time sufficiently (i.e. to less than of order days) without also introducing unacceptable amounts of thermal noise in the bounce mode.

Keeping the spread in violin mode frequencies down below 5% is desirable for filter design. The GEO experience may not be directly relevant here as Teflon coating was used in GEO, which is only being considered for Advanced LIGO, so some additional research may be required.
STATUS:
In GEO 600 the spread in violin mode frequencies of the uncoated fibres was ± 3.5% and ±4.2% for the first and second modes. Teflon coating reduced these figures to ± 0.5% and ± 0.4% respectively. However passive Teflon damping will not be used in Advanced LIGO (see above).

The dimensional tolerance of the GEO 600 fibres was ± 2.1%. In Advanced LIGO consideration of the allowable roll (± 2 mrad) and pitch range (± 20 mrad) yields a maximum allowable error in bounce frequency of ± 2.8% which in turn yields a ribbon dimensional tolerance requirement of ± 1.9%.
Due to the improved laser fabrication technique the dimensional tolerance will easily be kept to within ± 1.9% and is likely to be reduced far below this following further development. Furthermore, stringent characterization and selection procedures will ensure the spread in violin mode frequencies can be kept to within the required ± 5%.

The necessity for annealing ribbons after welding to equalize stress across the weld.
STATUS:
There will be two laser welds per ribbon. Interface pieces are no longer being used therefore minimizing the number of welds in the overall suspension. Tension equalization in the ribbon/welds will be performed using the laser in a similar way to the procedure conducted in GEO 600 with the flame welding torch. Further work and further development of the procedure will be performed within the next month or two.

Further development of the optical profiler to be used to characterize ribbons after being drawn.
STATUS:
In its current configuration the profiler can measure ribbon width to ± 0.7% and thickness to ± 1%. The profiler is currently being taken into its next phase of development with improved optical set up and more precisely engineered and precision controlled mechanical components. This should result in further improvements in accuracy.