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A strategy to prove and provide monolithic suspensions

KA Strain, A.V. Cumming, W. Cunningham, G. Hammond, K. Haughian, J. Hough, R. Jones, R. Kumar, S. Rowan, K. Tokmakov, and M. van Veggel

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This is an internal working note
of the Advanced LIGO Project, prepared by members of the UK team.

Institute for Gravitational Research
University of Glasgow
University Avenue, Glasgow G12 8QQ,
Scotland UK

+44 (0) 131 440 5880

Department of Physics
University of Birmingham

+44 (0) 121 414 6447

Engineering Department
STFC Rutherford Appleton Laboratory
Chilton, Didcot, Oxon OX12 0NA
Phone +44 (0) 1235 44 5297
Fax +44 (0) 1235 445843

Science and Technology Facilities
Council (STFC)

http://www.ligo.caltech.edu/

1 Purpose of this document [1]

The change from original baseline ribbons to stepped fibres[2] has consequences for the design of the ears and welding procedure. This was anticipated, and work has been underway at Glasgow for some months including weld tests and FEA work on ears.

What was not fully anticipated was that there would be difficulties, of a type not previously seen, with the welding of the round fibres to "ribbon-type" ears. There is concern about even a small risk of damage to the LASTI Test Mass which is fitted with such ears. FEA has not yet revealed the cause of the observed weakness. Note that the problems do not exist with the ears designed from the start to be used with stepped fibres.

The tolerable level of risk of damaging the LASTI Test Mass is very small: there is no spare test mass. It is expected that the risk can be brought to acceptable levels either by symmetrising the welding of the existing ears (see below) or by inverting the mass and adding new ears, but either of these will take time to prove. This creates uncertainty in the schedule and so risks disrupting other aspects of the LASTI programme. This document reviews the situation and proposes a revised plan to prove and provide the monolithic suspensions for testing at LASTI, to provide assembly training, and for procurement of parts for the final assembly.

1.1 Summary of scope

The UK team is charged with:-

- delivery of all equipment needed to set up a fibre pulling, testing and welding facility
- assembly of a monolithic "noise prototype" suspension
- training of LIGO staff in the techniques required to repeat the assembly procedure reliably, and providing advice during assembly.

A fully-equipped fibre production facility is now in operation at LASTI. This is complete except for final calibration of the fibre pulling machine[3] and any necessary modifications of the weld-tooling such as may be needed to work with revised ears.

The other two items remain UK responsibilities that are to be discharged on a timescale that fits with the assembly and installation schedule for Advanced LIGO as a whole.

1.2 Review of recent progress with respect to fibres, ears and welding

Following a request for change, SYS agreed with a recommendation that stepped-fibres could replace ribbons to reduce technical risk. Stepped fibres have a long thinner central part and short thicker regions at either end, and are predicted to meet the Advanced LIGO noise budget for suspension thermal noise. The consequences of this change as *currently* viewed are:

- final suspensions can benefit from new ears that are much closer to the successful GEO ear than the more complicated ears that had been developed for use with ribbons. Such "GEO-style" ears are better studied and tested as a class, including long term testing in

[1] A draft version of this document was circulated to Advanced LIGO management. This version has minor editorial changes plus additional notes (as footnotes),

[2] RODA in circulation for signing, M080363-00

[3] That should be done in the week starting 20th October 2008. It is also planned to fit very high resolution encoders during November 2008, even though the existing encoders are adequate.

GEO, although at lower load.[4] Procurement and production of this ear design should be eased – as the ear is much simpler to fabricate than that needed for ribbons. Peak stresses in the system should be lower (than with the ribbon-ears), and the design is quite tolerant of slight variations in weld shape (the dilution factor is low and low thermal noise results instead from thermo-elastic noise cancellation)[5].

- final suspensions can benefit from butt-welding following a procedure derived from the one employed in GEO (with changes to allow for simplified welding if possible)[6].
- the LASTI noise-prototype monolithic assembly is more risky than originally anticipated. This is discussed in the following section.

1.3 Recent issues affecting the noise prototype suspension (monolithic installation)

The aim has been to deliver a safe and reliable monolithic suspension on a timescale that fits with the other activities at LASTI. We note however that some weld strength tests have been disappointing and that *some* ears have failed during testing in a way that is not yet fully understood based on FEA models. In particular the following concerns need to be dealt with through continuing (indeed accelerated) R&D:

- lap-welding: the "ribbon" ears were designed to accommodate lap welds. Welding round fibres by this method leads to a load that is further off-centre and tends to cause bending and hence cracking of the ear. While initial FE models suggested the stress should be within safe limits, higher stress during fibre-break events has been observed to lead to ear damage. Unfortunately the ear damage produced by this appears to be difficult to repair (in some cases). The remedy for this is to change to butt welding to keep the load more on-axis. Reducing the shear component by a factor of 2~3 should be possible and should suffice if shear stress is the cause of the failure.[7] Development of butt-welding was initiated to prepare for the revised ears, but its development for the noise prototype has been hindered by lack of ears with which to practice. It is currently felt that the noise prototype assembly is too risky with lap welding. Work in this area is currently underway, led by Hammond.
- fibres and welding: in very rare cases there have been signs of potential weakness near the welds, in the thick stock material. Although this may or may not be significant in static hanging, it likely represents a point weak point that could fail at, for example, the moment another fibre breaks or is broken. Although the probability that this effect would represent a long-term difficulty is small, as there is nothing essentially different from GEO where this issue was not seen, more work is needed to study it and make certain. Work is currently underway at Glasgow, led by Tokmakov

[4] Work is currently underway by Sorazu, Heng and Strain to derive glitch-rate statistics from GEO data by analysis of the violin-mode evolution on one or more masses where the violin-mode amplitude is close to the thermal level. Initial results are currently being checked and analysed.

[5] A document describing these effects is in preparation.

[6] A document describing the weld procedure will be released after the initial test programme is completed.

[7] FEA results showing this reduction have been obtained. These and other related results will be collected into a report.

- weld perfection: welds must be reliably strong and tested by design in such a way that inspection of a weld allows its potential strength to be assessed before loading. The inspection procedure needs further refinement. (Work underway at Glasgow.[8])

In summary, the over-riding concern is that even a small chance of ear failure may lead to damage to the LASTI Test Mass that takes some time to repair – this would clearly disturb the rest of the schedule. Noting that the assembly of the noise prototype does not duplicate the planned assembly for final suspensions, and that much of the "non-SUS" work at LASTI (i.e. most aspects of cavity locking, ESD, TCS) needs to progress in the near future, the following plan is proposed.

2 Proposed plan to prove and deliver monolithic suspensions

The proposed plan should meet all project milestones. It requires considerable additional effort from Glasgow, but this is already in place (over the past 3 months the effort has been steadily ramped up and is now about 5+ FTEs)[9], and is planned to continue until the job is done. This goes beyond the increase anticipated at the time of the change to stepped-fibres. The plan is described in terms of its main themes, with some overlap.

2.1 Ear design (final suspensions)

- FEA-based work plus welding tests using old GEO ears, to "scale up" the design for Advanced LIGO load and required weld-geometry (now that the suspension structure is finalised). This work is already underway with target for completion of **1st December 2008**
- Procure batch of test ears for welding tests, and undertake several 40kg builds using new dummy masses that are being procured. The target delivery date is **1st February 2009**
- Procure material and do rough preparation for final ears. The time span is **February-March 2009**[10]
- Review the new design and welding procedure, based on various test assemblies including at least two builds at LASTI.
- Procure final ears **April-August 2009** – approval of these would require, at minimum, assembly of suspensions at both Glasgow and LASTI including a "simulated installation" at LASTI (i.e. going through the motions of installation but onto a test stand, not into a tank).

[8] A document detailing the inspection procedure for welds will be released in due course.

[9] In detail: most of the research time of Hammond, Tokmakov, van Veggel, Cumming and Kumar, with significant input from Hough, Rowan, Cunningham, Jones, Strain. At least the first 4 named are to be available to work at LASTI when required.

[10] It has been realised that this can be brought forward with little risk, and material should be procured earlier than indicated.

2.2 Weld development (All activities span November 2008 to January 2009)

- Study butt welds for the existing ear shape to allow the possibility of safe use of the LASTI Test Mass as currently prepared (otherwise new ears will have to be bonded and the mass used upside-down, which is possible but entails a 4~6 week gap for preparation during which time there would be no working quad suspension at LASTI).
- Study butt welds for revised ears, with emphasis on control of thermal gradients, ease of welding and possibility to estimate strength from appearance.
- Decision on which approach is least risky is to be taken by the **end of January 2009**[11].

2.3 LASTI Noise prototype modification

- Prepare for the immediate installation of the noise prototype, revised to have a metal final stage, to allow all the "non-suspension" objectives to be met (i.e. cavity tests, ESD, CP suspension, TCS). It is thought that this can be planned for and parts fabricated within 5-6 weeks[12]. Metal break-off prisms would be needed for the LASTI Test Mass, there is possibly a need for a revised jig to allow the prisms to be mounted and probably a need for revised wire loops – nothing else should be required. Glasgow and RAL (wire loops) can provide the necessary parts. The installation is planned for January to allow the "noise prototype" to be installed and other work to continue.
- Look for a natural gap in the LASTI schedule for noise prototype silica suspension installation and assembly training sometime during 2009 (we suggest during the Summer)[13].
- We suggest that "one or two" LIGO staff become familiar with mechanical aspects of quad suspension at initial installation in December. This can be achieved by regarding the (now much lower risk) December installation as a practice run.

In detail the changes to the noise prototype are:

- new wire loops (needs a revised wire jig for new length and this sets end Nov as earliest install date as RAL activity must not start until 3rd November because they are 100% committed to BS/FM work till then)
- break-off prisms (like CP design with detail changes, designed so that wires clear ears). This is a Glasgow activity but requires design check by LIGO staff. This aspect should be faster than the new wire loops, a bonding jig may be needed (this is being investigated, the existing one may suffice)[14]
- minor rebalancing of metal penultimate mass (as part of the "triple-hang" test) – marginally extends the work needed for that test

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[11] As the new ears must be under test by then it is almost certain that they will be chosen for the LASTI TM too.

[12] RAL was consulted on the timescale for provision of wire-loops and jigs, and on the suitability of the existing penultimate mass to suspend the LASTI test mass. Subsequently a target date of 12th January has been set to start the process of installation (i.e. all parts at LASTI well before then).

[13] It turns out that HAM installation work creates just the gap we need, currently scheduled for August 2009.

[14] A prism design is under review, the bonding jig requires only a new "holder", also under review.

- while an initial "think through" does not reveal any other issues/conflicts, a more formal assessment of this is required

2.4 Suspension tests

- Procure an additional "test setup" (i.e. duplicate tooling now available at LASTI so that there is a set at Glasgow). Target date is **Mid November 2008**
- At the appropriate time and place (probably Glasgow, probably **December**), attempt to butt weld on "ribbon type ears" using existing test parts.
- Carry out a first test suspension with revised ears (40kg, Glasgow). Target date is **End February 2009**[15]
- Further test suspensions (at least one more at Glasgow and 2 at LASTI). Target date is **Prior to Monolithic Installation** (Spring/Summer 2009 – exact date depends on scheduling of the installation as these tests will involve training of LIGO staff)

2.5 Re-planning LASTI work

The programme for the fibre/welding lab at LASTI is clearly perturbed by this change. It is proposed that there be some final setting up of the pulling machine etc. such that they are all tested and "signed off" as working with the proviso that there may need to be adaptations (UK to provide) based on continuing R&D described in this document. It is hoped that, particularly with respect to the mechanical assembly of suspensions and welding associated with the new ears that LIGO staff can remain involved such as to keep up with developments and give rapid feedback on practicality, perhaps studying the possibility of butt-welds to the existing ears. Over the timescale envisioned, however, it is not expected that the LASTI "fibre/welding" facility will be kept in continuous operation. A detailed schedule will need to be put together in the near future, so this aspect will require to be monitored.

3 Summary

To deliver well-tested new ears and reduce the risk of failure when welding the LASTI Test Mass, requires further R&D. The most efficient approach seems to be to postpone the monolithic aspect of the noise prototype installation until the modified designs and refined methods have been well tested, in the meantime the LASTI programme can continue with a metal suspension of the test mass. This should minimise further delays to the overall programme at LASTI. The aspects of LASTI tests that would be delayed by this are confined to the aspects of cavity locking tests that rely on high-Q modes and the violin-mode damper functionality testing. It is necessary to look closely at the effects of retiming of these.

[15] Initial planning for LIGO staff to participate in these tests is underway.