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Quad Noise prototype PDR-3 overview
T060142-00-K

June 06

1. INTRODUCTION,

Past experience has shown that for any product design review (or almost any formal review) there are significant benefits to be gained from structuring the review documentation in such a way that it is readily approachable by someone who has little on no technical knowledge of the project. This document intends to provide that structure by outlining exactly what is to be reviewed, (and what is not), and then detailing how all the documentation is structured to allow relatively simple navigation.

2. WHAT IS BEING REVIEWED

Fundamentally PDR-3 is reviewing the fitness of the mechanical design of the quad noise ETM/ITM convertible prototype to satisfy the LIGO requirements. In short PDR-3 covers:

1. The mechanical design of all metal aspects of the quadruple suspension
2. The interfaces between the suspension and all relevant external systems.
3. The outline assembly procedure, and the outline assembly tooling
4. How the suspension achieves the necessary noise requirements
5. Have we learnt all we need to from the Quad controls prototype presently at LASTI

To help with the process of assessing compliance with the requirements and interface specifications, we have produced a compliance matrix document, E050317-02-K.

3. WHAT IS NOT BEING REVIEWED

1. The overall OSEM design and flag geometry (except changes since PDR#1 which are covered at this review).
2. Any aspect of the glass assembly apart from the interfaces with it (except changes since PDR#2 which are covered at this review).
3. This is not a complete review of the tooling – this will be much better done after the noise prototype build. However, an overview tooling document is included to make our intent clear.

4. SUSPENSIONS OVERVIEW

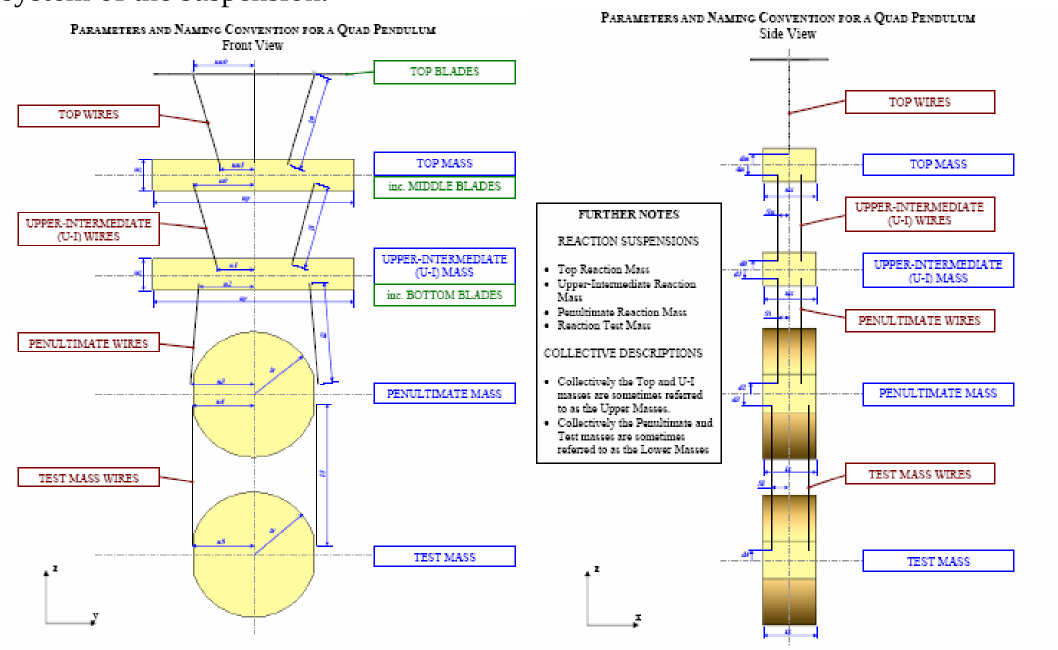
The baseline suspension design for advanced LIGO has a 4 stage pendulum suspended from a two stage active isolation table (SEI) on a one stage external isolation system (HEPI). These are all designed to interact together to deliver adequate levels of isolation across the working frequencies of advanced LIGO. The baseline suspension design was worked out by Norna Robinson and others in T010103-05. This documents outlines the principal suspension parameters required to deliver adequate isolation, this document was used (an earlier release) as the basis for both the Quad controls prototype and the mode cleaner. The scientific basis of this review is that the Controls prototype has been shown to perform as the model in

T010103 predicted, and thus it is sensible to take this design forward towards an assembly including glass masses.

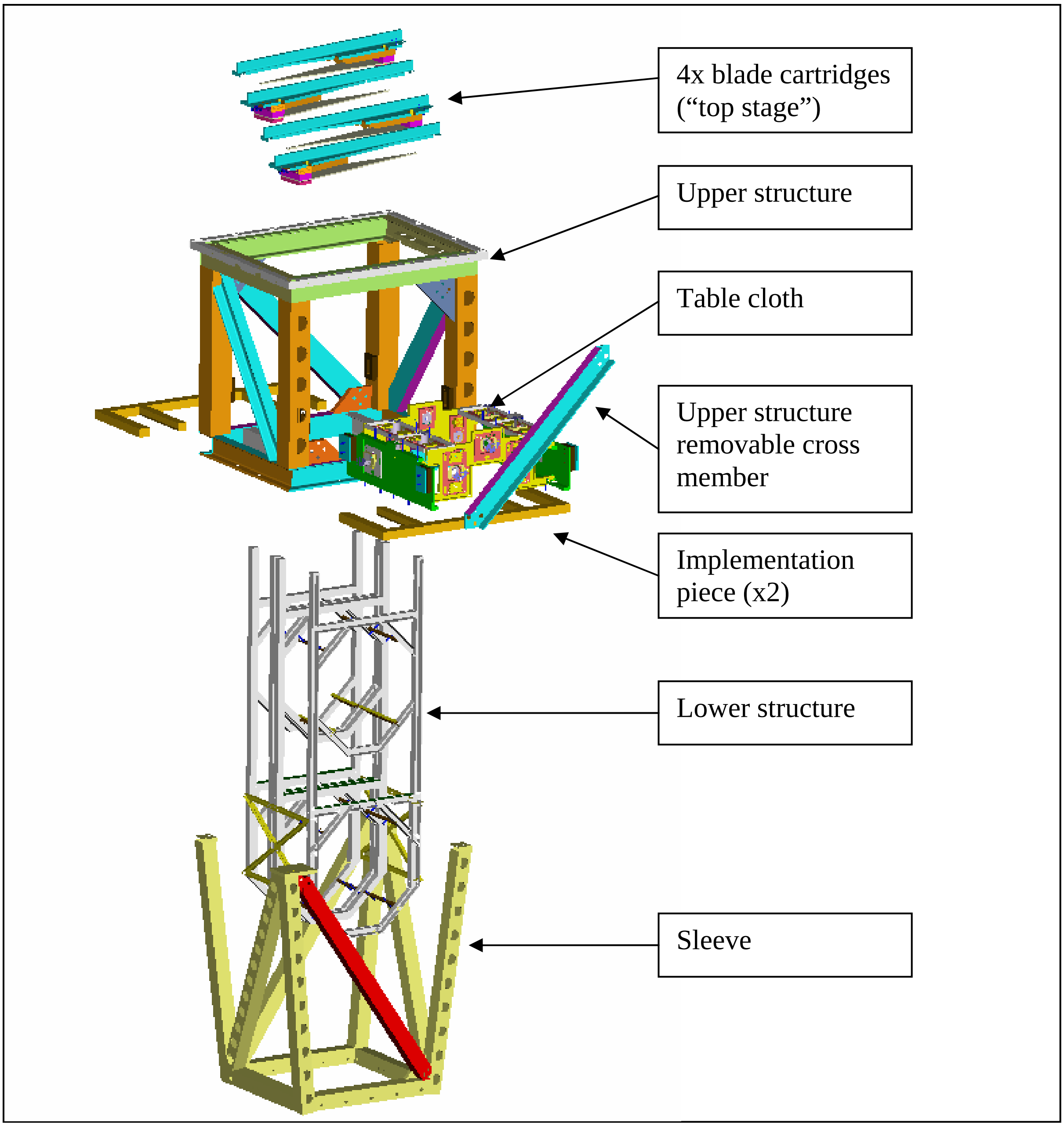
The noise prototype quad suspension has been designed so that it will be possible to convert the suspension from its initial ETM configuration to an ITM-like configuration with a thermal compensator plate and two ring heaters. It is intended that this should be possible by swapping out the bottom two masses. Since the design of the ring heater for the compensator plate is still conceptual this is clearly an area for more work during the noise prototype ETM build.

5. NAMING CONVENTIONS

When considering the suspension it is useful to bear in mind the naming conventions and co-ordinate system. In Mike Perreur-Lloyd's document T040072 he includes two useful diagrams (shown below) describing the naming convention and co-ordinate system of the suspension.

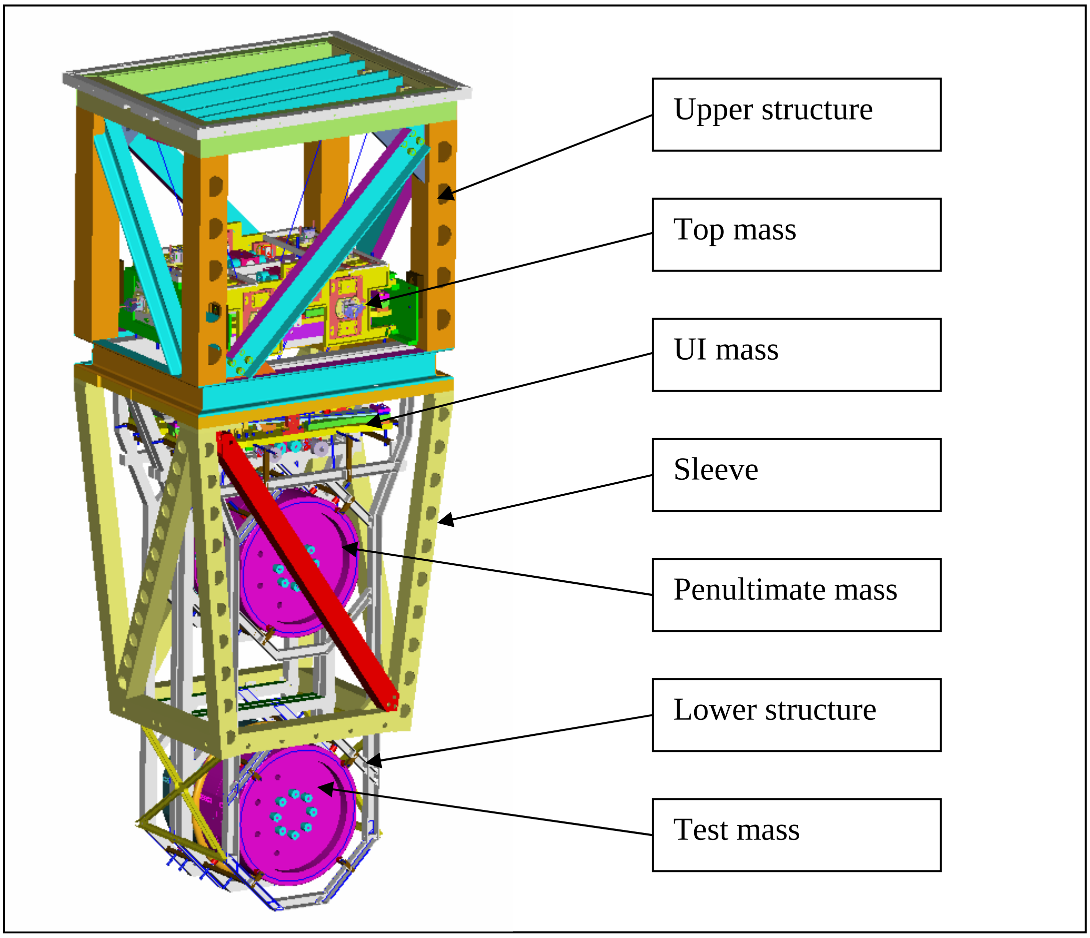


There are then several non-suspended systems which are named as follows:

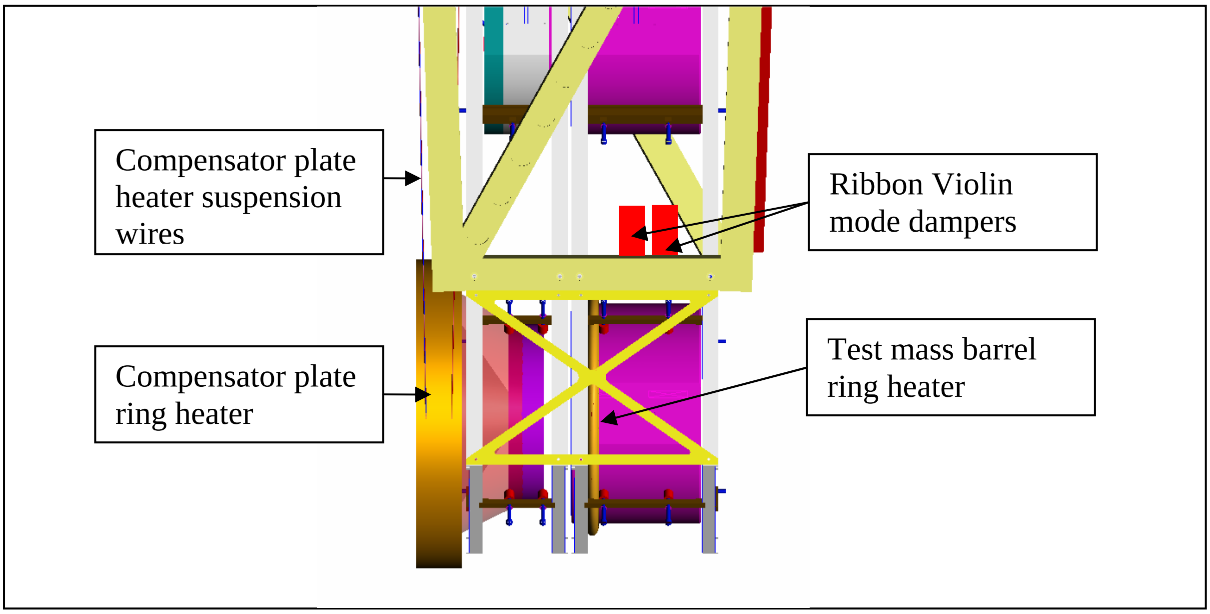


Note: The exploded view is for reference only and is not of the latest CAD model.

And when assembled appear as follows, note the masses are also shown to provide additional context.



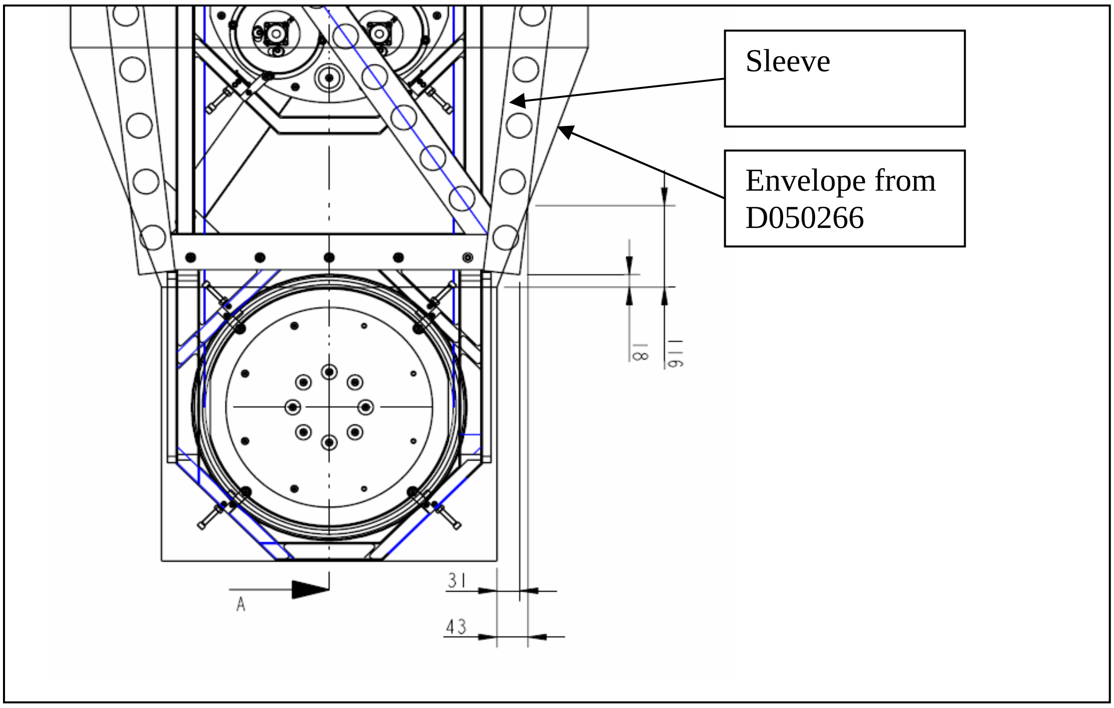
The compensator plate ring heater, the test mass ring heater, and the violin mode dampers are still being worked upon so their exact location and design is sketchy. They are shown below.



6. KEY SUSPENSION FEATURES

6.1 Overall dimensions and envelopes

Dennis Coyne provided an overall quad envelope drawing based on the controls prototype design in late 2005. The envelope drawing (D050266-00) has formed the basis for our structural design, and we have remained within the envelope almost entirely. The one area where we infringe the envelope is at the bottom of the sleeve structure. This can be seen on the GA drawing of the ETM and ITM assemblies. A detail of this is shown below.



The figure above shows the infringement when looking along the beam and is dimensioned on one side, the infringement in the side view is very much smaller with no more than 5mm protruding outside the envelope.

Looking at the drawings of the ITM it will be seen that the ring heater protrudes from both sides of the envelope as well as the bottom.

Other than the envelope infringements cited the quad is dimensionally correct complying with the conceptual design and the optic position in the envelope drawing D050266.

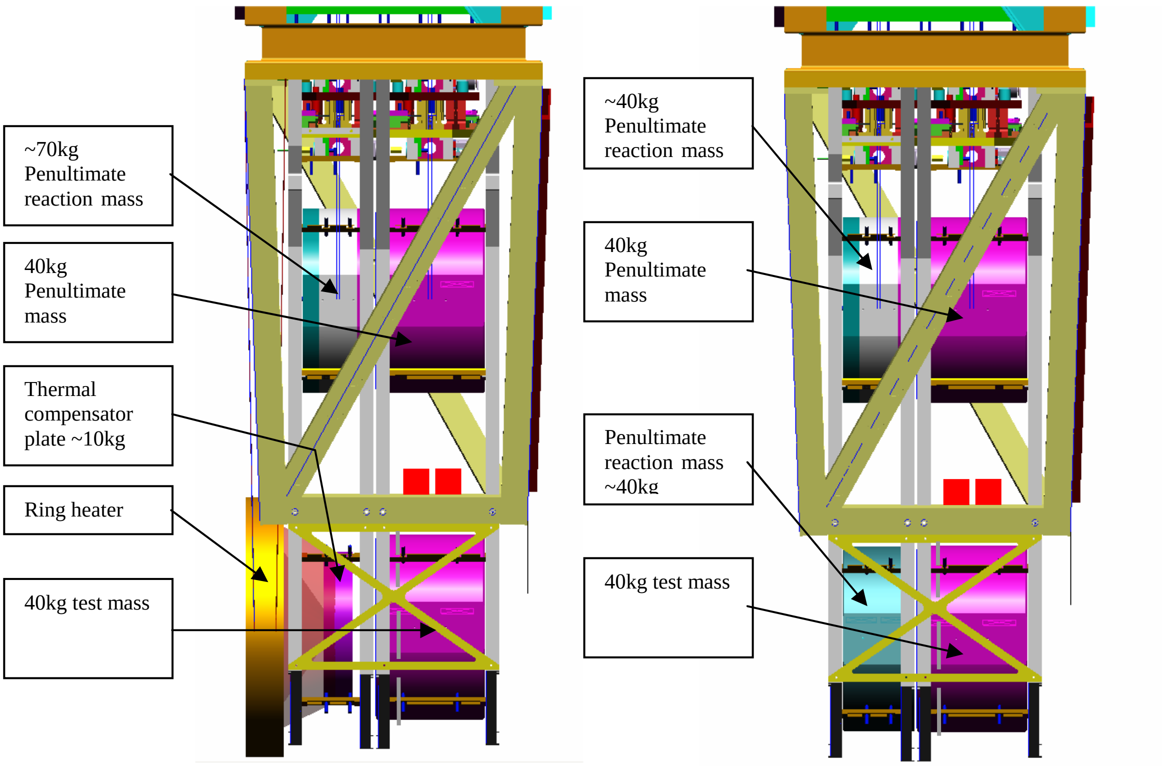
For reference the table below covers all the major dimensions of the quad suspension. Note all dimensions are nominal and in mm, all are to 0 decimal places

Overall dimensions z, y, x	1959, 710, 550
Optic table to optic CL	1742
Optics table to top mass CL	522 (vertical distance)
Top mass CL-UI mass CL	277 (vertical distance)
UI mass CL-Pen mass CL	341(vertical distance)
Pen mass CL-optic CL	602 (vertical distance)

Top mass mass	22.1kg
UI mass mass	22.0kg
Pen mass	40kg
Test mass	40kg
Overall mass with structure	375kg excluding dog clamps

6.2 ITM/ETM conversion

The quad noise prototype is in fact two suspensions in one design. By default most of the models and the first item to be delivered will be configured as an ETM. With minimal modifications it will be possible to re-configure the suspension to an ITM. This will be done by assembling the penultimate reaction mass in a heavier configuration, and replacing the test reaction mass with the thermal compensator plate. A ring heater will then be hung from a point higher up the structure, and will be able to heat the compensator plate appropriately. The two renderings in the figure below show the two configurations and list the differences.



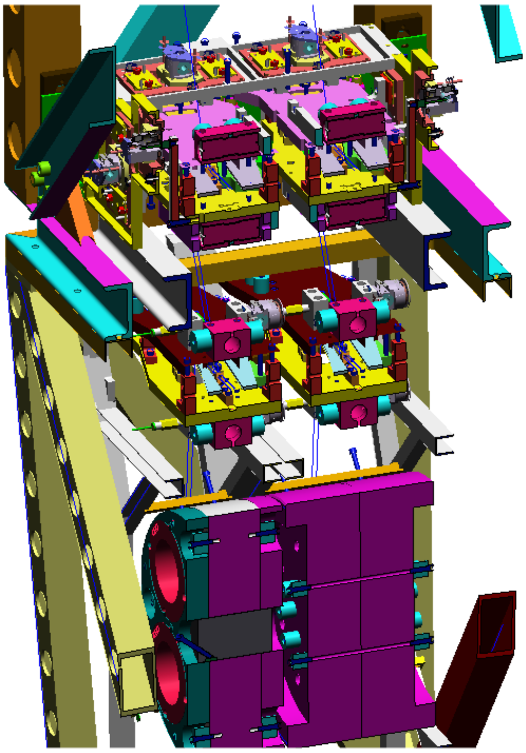
ITM configuration ETM configuration

One of the most noticeable features of the noise prototype design is that the test and reaction chain thickness are different. This decision was made quite early in the noise prototype design process as the most robust way to make a stiff structure that fell within the envelope given by D050266. The complete argument is available in T050077, but could be condensed as follows:

Having a thin (sapphire width) reaction chain allows the overall width of the combined chains to be as small as possible without having to consider making masses (specifically the top and UI) any smaller than in the controls. Keeping them the same diameter means that you don't need any additional wire lengths, or different geometry mass stops. Making the reaction masses thinner allows us to minimise non-suspended mass at the bottom of the chain and give us the most efficient form of cross bracing without exceeding our envelope.

6.3 Silica/Sapphire conversion

The other constraint that was connected to this decision is the requirement that we should be able to convert back to sapphire masses as easily as possible. Looking at a cross section through the centre of the chain it can be seen that the all metal masses and the top stage of the quad have a large separation. This is to allow these units to be moved closer together should the decision be made to switch back to a sapphire mass.



If it was decided to revert to sapphire rather than silica the following would be needed to convert the present ITM/ETM structure:

- The top of the upper structure would need reworking to allow the top stages to go closer together.
- The sides of the tablecloth would need to allow the masses to be closer.
- The lower structure faceplates would need to be assembled differently to allow for different mass widths.
- The lower structure faceplates and stops would need to be re-worked to allow for smaller diameter masses.
- The penultimate reaction mass would need re-thinking to ensure we could make a ~70kg mass to pair with the compensator plate. To do this it might be necessary to make it square for example.
- It might be desirable to re-work the sleeve to provide a stiffer structure; this would be possible since the members could be at a greater angle.

6.4 Material selection in vacuum

Following is a full list of materials used in the Quad, in some cases quantities are given.

Stainless steel, various grades	Used extensively in suspended masses
Aluminium alloy, various grades	Used extensively in structure
Maraging Steel, blades only	Blades and some clamps only
Magnet material	Magnets only
Nickel (plating the magnets)	Small quantity
Flourel, earthquake stop compliance	40 stops up to 15mm diameter by 15mm long
Silica, masses, ribbons, stop tips	
Brass	Possible use in locking fixture (T050227-00-K 2.7) and adjusting cams
OSEM materials	See section 5.1 of T050111-01-K; all materials are approved or pending approval.

A specification for the welding of the upper structure is in discussion with a proposed manufacturer. The fine detail has yet to be agreed.

6.5 Structural frequency requirements

The one known area where the present design does not conform to the design requirements is that of the structural frequency. This is also the area in which we have deviated most from the controls prototype design, our aim being to improve performance. Our proposed structure has a predicted overall frequency (by FEA) of ~94 Hz. This is below the requirement of 100Hz, especially when allowance is made for the real structure to perform worse than the FEA prediction.

However, it is anticipated that the performance will in fact be acceptable on the basis of the following arguments.

Tests were made on the controls prototype structure at the ETF in Stanford; they are described in G060007-00.pdf and G060065-00.pdf. What they showed was that it was likely to be possible, but difficult, to control the SEI when loaded with the controls prototype structure with a minor infringement of science requirements. That structure had a measured natural frequency of ~65Hz when bolted to the ETF table and a calculated frequency (by FEA) of 84Hz. The conclusion of the ETF work was that it would be desirable to increase the natural frequency of the structure by 10-20 Hz, and that it may also be necessary to add a passive damping strut.

In order to increase the frequency of the structure, we have substituted a welded "sleeve" structure in the place of bolted "outriggers" that were present in the controls prototype design. Careful measurements made on parts of the structure at Caltech (see T050237-03.pdf) showed that the measured performance of the welded upper structure matched the FEA predictions much better than was the case for the bolted lower structure. Our expectation on this basis is that by making the primary structure welded, rather than bolted, we will be producing a structure that matches the FEA predictions rather better than did the controls prototype. The change from bolted to welded construction should yield an improvement of at least 10Hz all other things being equal. At the same time, by judicious lightwieghting of the structure we have improved the predicted frequency by about a further 10 Hz, and so we have good reason to believe that the structure will deliver the required 10-20 Hz improvement. The arguments are developed more fully in T060088-00-K. We have made a prototype of the new "sleeve" arrangement and are preparing to test it both freestanding and fixed to the upper structure. We hope to have early results by the end of June 2006. Depending upon the outcome of these tests we may then seek to repeat the ETF tests with the new structure. The real proof will not come until the noise prototype is mounted on the seismic table at LASTI, and we propose to defer any decision about passive damping struts until that time.

6.6 Assembly overview

Although there is a dedicated assembly document that goes into considerable detail a very much abridged version can be seen below. This is intended to give a flavour rather than be comprehensive.

1. Dirty assembly with metal masses (RAL)
    a. Blade characterisation and selection
    b. Tooling assembly
    c. Wire production
    d. Mass assembly
    e. Assemble and align suspension with OSEMs? Note characteristics.
    f. Trial fit of trial pig tails.
    g. Complete strip down
2. Cleaning
    a. Clean in-vacuum components
    b. Clean tooling
3. Clean assembly with metal masses (RAL)
    a. Re-assemble tools
    b. Re-make clean wires
    c. Re-assemble everything,
    d. Fit Clean OSEMs and pig tails, check alignment
    e. Partial strip down to masses & structure for shipping
    f. Ship to LASTI
4. Metal assy at LASTI
    a. Re-assembly of tooling if required
    b. Trial metal assy at LASTI (to ensure no problems due to shipping; check alignment)
    c. Remove lower structure
5. Clean assembly with glass (LASTI)
    a. Split lower structure
    b. Remove metal masses
    c. Install glass masses
    d. Weld ribbons etc. (including proof test)
    e. Re-join lower structure
    f. Re-install lower structure to upper structure
    g. Test, align, etc.
    h. Separate lower from upper

i. Install upper to tank.
j. Install lower to tank
k. Install sleeve to tank
l. Final alignment-commission

6.7 Ring heater interface

There are currently planned to be a ring heaters on the tests masses of the ETM and ITM and a ring heater on the thermal compensator plate. We are still in discussion over the details of the ring heaters, in particular the sleeve design interferes with the most recent ring heater design (of around may 2006) and we are seeking the best way to resolve this. There are some concerns about the effects of the heat load on the structure from the ring heaters. These, together with the thermal effects of the OSEMs, are explored in T060115-01-K. In any event we are planning to support the ring heaters (as well as the nearby baffles) by suspension wires, in order to avoid the deleterious affect that their mass would otherwise have on the structural performance. The details will emerge as the design of the ring heaters firms up.

6.8 Violin-mode damper interface

The violin mode dampers are still at an early stage of design – see further discussion in T020215-01-K. Currently the interface consists of ensuring that some space is available. Suitable fixing holes will be added as late as possible before manufacture.

6.9 Wire routing

On the controls prototype the wire harness was routed from the test mass to the UI mass via the penultimate mass and then on to the upper structure. This was all done on the reaction chain since that is where all the active components are housed. It should be noted that shielded cable was used from the penultimate mass upward. On the noise prototype this provided the basis for the baseline solution.

We propose to route the test mass cables from the ESD centrally up to the Penultimate mass, here they will pick up the Penultimate mass OSEM cables (which will not be shielded) we will then pass on up (central to the chain where possible) to the UI mass. Since there is very little open space around the UI mass the wires may pass through the middle of the UI mass (there is sufficient available space but at present no hole). From the UI mass we would ideally like to transfer the cable directly to the upper structure. Presently we are investigating the stiffness of the cables to see if we can get sufficient attenuation to do this. Once we have real stiffness measurements from prototype cables we will work through a similar procedure as has been done for the HAM-SAS system recorded in T060038-00-D. Initial investigations suggest that this bypassing the top stage will be acceptable.

Having done some initial routings we are confident that the wiring should not provide any significant routing problems, and the only significant change needed may be to add a 12mm hole through the UI mass.

7. CONTROLS PROTOTYPE RESULTS

By following the design, manufacture and assembly process of the controls prototype very closely we aim to have incorporated all the “lessons learned” into the design of the noise prototype where feasible. The document T060039-00 gives an excellent and thorough review of the assembly process as it was carried out in practice with many suggestions for improvements which we have implemented as far as possible.

A document has been produced, "Summary of Controls prototype data" (T060134-00-D), which gives the key technical results from the controls prototype.

8. MAJOR CHANGES FROM THE CONTROLS PROTOTYPE

Below is a list of all the major mechanical changes from the controls to the noise prototypes. Clearly there are also changes in material of test masses etc these are not listed since it assumed they are well understood.

Upper structure	• No significant changes
Top stage	• Nominal position reference provided for blade adjusters
Top mass	• Blade tip z position adjuster added • Blade stops installed to base plate rather than top plate • Robust datum added local to blade tip • Increased removable mass added • ECD arrays re-arranged to damp 5 degrees of freedom • Top wire lateral (x) adjuster removed • Un-paired magnets shielded
Tablecloth	• OSEMs, ECD arrays and stops added to single adjustment unit. • Structural frequencies increased • Nominal position reference provided for top masses and tablecloth to upper structure
Implementation ring	• Adjustment mechanism removed • Just works as a shim now • Very light weight
Lower structure and sleeve	• Stiffness increased • Lower structure no longer designed to self support from below • More complex stops installed to cope with glass • Structure designed to allow welding • Can be assembled as either ITM or ETM suspension • Accommodates ring heaters and violin mode dampers
UI mass	• Blade tip z position adjuster added • Blade stops installed to base plate rather than top plate • Robust datum added local to blade tip

	• Increased removable mass added
	• OSEM x-z adjusters re-designed
	• Shielding magnets added to actuator magnets
Pen Re mass	• Convertible ITM ETM design implemented
	• Finer gradations on addable removable mass added
	• LIGO 1 OSEMs used, adjuster added
OSEMs	• Come with D shell connector to allow individual removal
	• Provide greater actuator force
	• Use magnetic mount for flag to prevent damage if knocked

9. KEY CHANGES TO AREAS PREVIOUSLY REVIEWED

9.1 Key changes from PDR#1

The changes are laid out in T060137-00-K (OSEMs) and the effects are reflected in the updated T050111-01 (OSEMs) and T050112-01 (electronics). The ESD design has changed significantly and the updated document T050110-01 reflects this. The latter two documents can be had from the Birmingham website. A significant amount of work has gone into updating the most relevant interface document, E050160-01.

Key items are:

- OSEMs
  - Removed 1064 nm filter
  - Doubled the length of the coil
  - Modified pinouts
- Electronics
  - Little change on sensor electronics
  - More precise noise limits (on output and input) now defined
  - Additional bandwidth required on the PU stage
  - Tell-backs now more comprehensively defined
- ESD
  - See full document on Birmingham website.

9.2 Ongoing OSEM emitter life tests

There have still been no failures in the overcurrent OSEM emitter life tests. Here is the latest commentary:

```
The manufacturers (Optek) quote that for our conditions of current
(35 mA), and at 25 degrees Celsius, the typical degradation in
optical output over 10000 h of operation is < 6%, and is < 24% at the
3-sigma level.

Running 24 devices at their maximum allowable current of 100 mA I
find a degradation of < 35% over 10000 h.  The present fit to my
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measured data does not indicate that the intensity will fall below
50% at any time, although there is a slow evolution in the fitting
parameters towards a time-constant even longer that the current value
of approximately 10000 h.
```

From this we conclude that:

- We have run the LEDs at ~300% of the design current for a total of 240,000 hours with no failures.
- Extrapolating the best fit we can make to the performance in the tests suggests that output will not drop as low as 50% of the initial output, which we would regard as a failure, on timescales of ~10 years.
- We do not expect failure of emitters to be an issue for advanced LIGO.

9.3 Key changes from PDR #2

The changes are laid out in the updated documents. That page also contains a link to a document responding to the formal review report of May 2006.

Key items are:

- The ribbon end pieces have been modified to further improve compatibility with the ribbons and ease welding.
- The ears have been redesigned for a lateral overlap rather than frontal overlap weld and to streamline the shape for further increase in strength.
- The approach route for the welding is now from the front of the mass rather than from the side.
- The material of the penultimate mass will be HOQ310 (subject to successful procurement).
- The material of the reaction mass will be F2 or F2 Chinese (subject to successful procurement).

10. SCHEDULE

Document T060126-00-K shows the present noise prototype schedule. It is our belief that it is possible to ship the noise prototype (unassembled) to LASTI in early Feb 07. This makes the following assumptions:

- If we are able use the spare controls prototype blades from Caltech we can probably do a lot of initial assembly sooner rather than waiting for the longest lead time item. These have the advantage they have already been characterised.
- If we do receive left over controls prototype blades early the final thing we will do before cleaning will be a suspend with the proper blades to make sure we don’t have any unexpected problems.
- We could use a slightly modified marionette frame if we don’t have structures right away to make sure everything works. And can be assembled stably.
- Structures and Blades are assumed to be longest lead time items. If this is not the case we may have problems.
- This schedule allows only one month for cleaning, including shipping both ways. It is very likely that this will require us to perform the cleaning at a contractor in the UK.

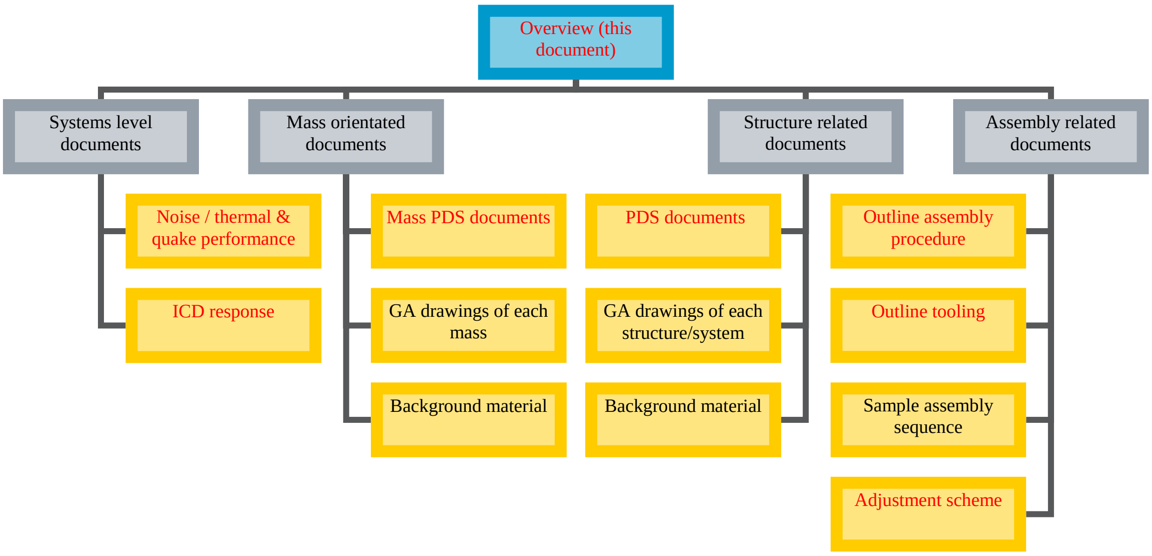
11. DOCUMENTATION ORGANISATION

11.1 Top-down document organisation

Since such a lot of documentation is involved in the Quad design we have attempted to produce a road map of the documentation. The hope is that from this road map the reviewers will be able to extract the information most relevant to their expertise and interest.

All the documentation for this review can be accessed via the CCLRC Advanced LIGO website[1] some of the documentation here is linked from the DCC and other sources and our aim is to update the links as the documentation migrates to the DCC after the review is complete.

The overall documentation structure is as follows:



For anyone approaching this document for the first time a PDF file of each of the four subheadings can be downloaded from:
http://www.eng-external.rl.ac.uk/advligo/_review/review.htm
For those working off line four top level PDF files contain the items listed in red and provide the majority of the core material. Complete material can be found at the above link along with links to all relevant DCC documents etc.

11.2 Key overview documents

Since most people will be initially interested in the overview or systems level documentation here is a short guide to the material.

Document	Number	Description
Mass budget	T060141-00-K	Mass breakdown of the whole Quad.
List of changes made from Controls Prototype to Noise Prototype	T050104-03-K	A document that started describing the proposed changes in the noise

[1] http://www.eng-external.rl.ac.uk/advligo/_review/index.htm

		prototype and now review the final decisions
Adjustment scheme	T050103-00-K	A description of the adjusters present in the suspension, and what they do.
Noise prototype Schedule	T060126-00-K	The schedule for the delivery of the noise prototype.
Technical noise sources	T060099-01-K	A run down of all known technical noise sources.
Thermal considerations	T060115-01-K	An investigation into the thermal considerations within a suspension
FEMA	T060116-00-K	A “first look” failure modes analysis for the noise prototype design.
Compliance matrix	E050317-02-K	A summary of the ICD requirements relevant to us and how we meet them
Earthquake stop overview	T060139-00-K	The layout of the stops and how they are used
OSEM & ECD magnet attachment PDS	T060122-00-K	A description of how the various magnets in the quad will be attached into place.
OSEM design document change log	T060137-00-K	The changes to the Birmingham OSEMs since PDR#1
ECD requirements for Quad suspensions	T050093-00-K	Reference: various documents on magnet specification for the noise prototype quad.
ETM/ITM magnets at top mass	T050105-00	
Magnet strength considerations	T050271-00	
Increase strength in PM/UIM actuators	T060001-00	
Investigation into Vac-seal flag attachment	T060017-00-K	Reference: A study of the strength of the magnetic attachment of flags
Conceptual design document	T010103-05-D	Reference: The original quad conceptual design document
ETM/ITM envelope	D050266-00	Reference: The quad envelope requirements

12. POSSIBLE CHANGES FOLLOWING THE NOISE PROTOTYPE BUILD

Although the noise prototype is intended to be a final article prototype there are a few areas of the design that we would like to reserve the option to change. These are detailed below along with explanations.

1. Reduce the implementation ring range: A smaller implementation ring will increase the stiffness of the structure and will simplify manufacture. On paper we believe we need a 6mm range, however, taking on board the experience of the controls prototype (where a 28mm range was only just adequate) we will also use a 28mm implementation ring with the intention of reducing it to closer to 6mm after we assemble the noise prototype.
2. OSEM adjusters: The noise prototype uses a new style of OSEM adjuster. These have been prototyped and worked very well, This may not translate to practice though. If this is the case the previous method of adjustment has been retained. It is intended to remove the initial adjustment mechanism if the new one works as well as we believe it will. This will allow two complex components (of the same material) being amalgamated.
3. Top mass pitch adjuster: On the controls prototype there was an adjuster which moved the wire attachment, this pitched the whole chain. The base line noise prototype does not have this adjuster. If work with the marionette (a simple single chain suspension) or the noise prototype demonstrates that removing this adjustment was wrong it will be re-instated in a very similar form to that used in the controls prototype.
4. Top stage interface to upper structure. Depending on the outcome of discussions with manufacturers it may prove economic to combine the interface pieces in the current design with elements of the upper structure rather than making them as separate parts.
5. The assembly sequence will almost certainly change depending on our experiences with the noise prototype assembly. This may result in very minor hardware changes.
6. The UI mass may have a hole added to the centre to simplify the cable routing on the reaction chain.
7. Further work on ring heater design and tests may reveal the necessity to add thermal control (heaters) to the structure. It is not yet clear that this will be required.