Suspensions

Technical Status
NSF Review of Advanced LIGO Project
April 25-27, 2011, LLO

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LIGO

US + UK = Total
$15.8M + $7.8M* = $23.6M

Suspension System Functions

- Support the optics to minimise the effects of
  - » thermal noise in the suspension
  - » seismic noise acting at the support point
- Provide damping of low frequency suspension resonances (local control), and
- Provide means to maintain interferometer arm lengths (global control)
  - » while not compromising low thermal noise of mirror
  - » and not introducing noise through control loops
- Provide interface with seismic isolation system and core optics system
- Support optic so that it is constrained against damage from earthquakes
- Accommodate a thermal compensation scheme and other systems as required e.g. acoustic mode dampers, baffles, alignment fiducials, ancilliary tooling, vibration absorbers

*Total UK contribution = $14M
($6.2M development + $7.8M fabrication)

Suspension Requirements: Test Masses

- Top-Level Requirements:

Requirement	Value
Suspension Thermal Noise	**10^{-19} m/√ Hz at 10 Hz (longitudinal)** **10^{-16} m/√ Hz at 10 Hz (vertical)*#**
Residual Seismic Noise	**10^{-19} m/√ Hz at 10 Hz** **(assumes seismic platform noise $2x10^{-13}$ m/rt Hz)**
Pitch and Yaw Noise	**10^{-17} rad/√ Hz at 10 Hz (assumes beam centering to 1 mm)**
Technical Noise Sources (e.g. electronic noise, thermal noise from bonds)	**1/10 of longitudinal thermal noise for each source** **(since noise terms add in quadrature, each increases total by 0.5%)**

*assumes 10^{-3} coupling vert. to long.

#except for highest bounce mode peak which can be up to 12 Hz

Suspension Requirements (Other Masses)

In general, requirements are relaxed by two or more orders of magnitude compared to the test masses (End Test Mass/ETM, Input Test Mass/ITM)

- Beamsplitter/Folding Mirror triple suspension (BS/FM):
  - » 6.4×10^{-18} m/√Hz at 10 Hz
- HAM large triple suspension (HLTS):
  - » 1×10^{-17} m/√Hz at 10 Hz
- HAM small triple suspension (HSTS):
  - » 1×10^{-17} m/√Hz at 10 Hz when used in recycling cavities
  - » 3×10^{-15} m/ √ Hz at 10 Hz when used in input modecleaner
- Output modecleaner double suspension (OMC SUS):
  - » 10^{-13} m/ √ Hz at 10 Hz

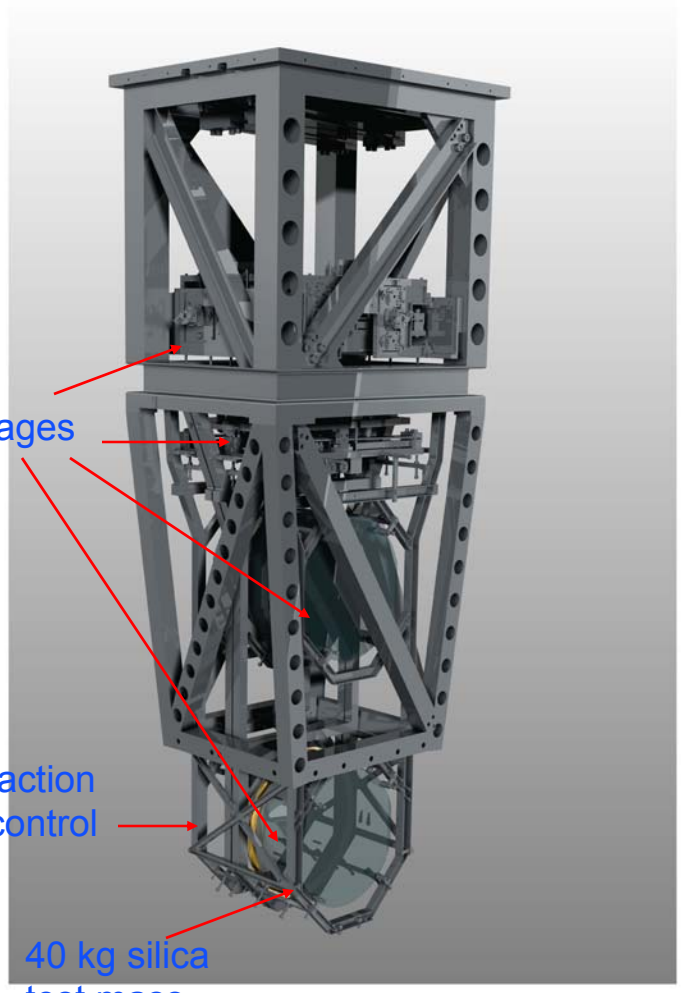
BS/FM seismic noise is product of suspension transfer function and residual noise on the two-stage BSC-ISI seismic platform

HLTS, HSTS and OMC seismic noise is product of suspension transfer function and residual noise on the one-stage HAM-ISI seismic platform

The HLTS and HSTS requirements assume equal contributions from the 3 mirrors in the recycling cavities.

Design Concept: ETM and ITM

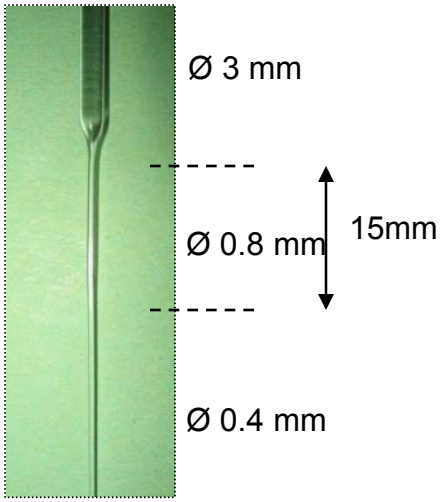
- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor
  - » *silica fibre loss angle ~ 3e-7, c.f. steel ~2e-4*
- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation
  - » *isolation @ 10Hz: quad ~ 3e-7, c.f. single stage ~ 5e-3*
- Control noise minimisation: apply damping at top mass (for 6 degrees of freedom) and use quiet reaction pendulum for global control actuation in a hierarchical way
  - » Coil/magnet actuation at top 3 stages
  - » electrostatic drive at test mass

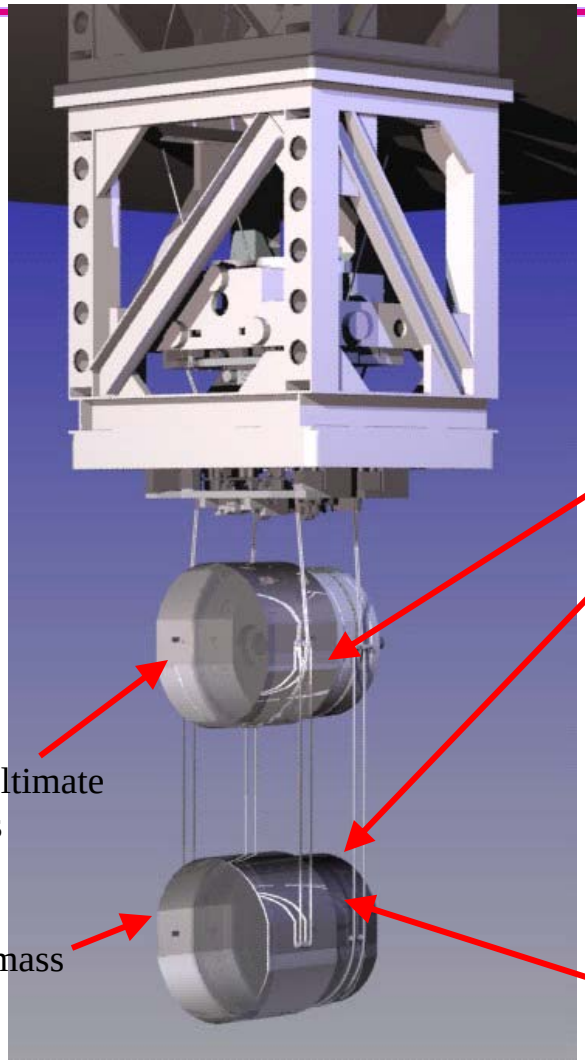


Design Concept: ETM/ITM
continued

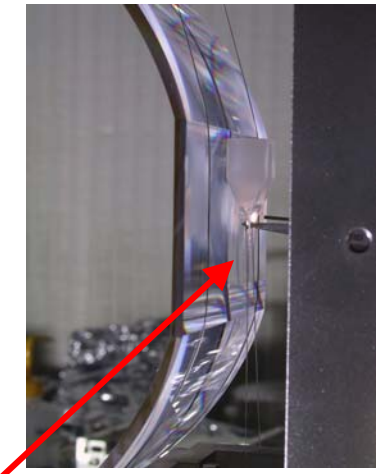
Monolithic stage

- 40 kg silica test mass suspended from 40 kg penultimate mass, also silica
- Four dumbbell shaped silica fibres (details below)
- Fibres welded to silica ears, bonded to the sides of the silica masses





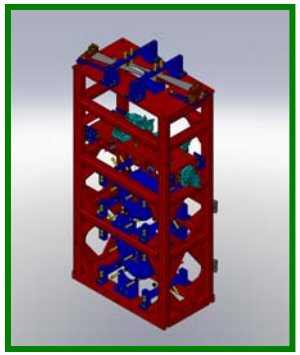
Ears silicate bonded to masses

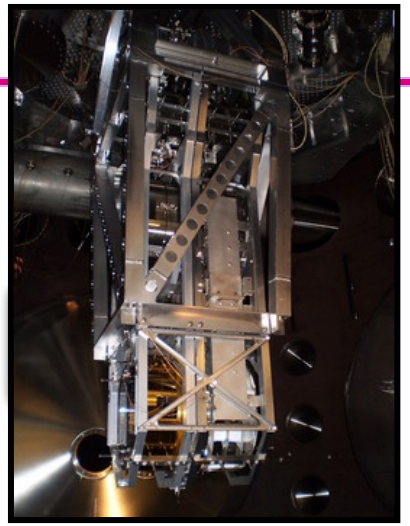


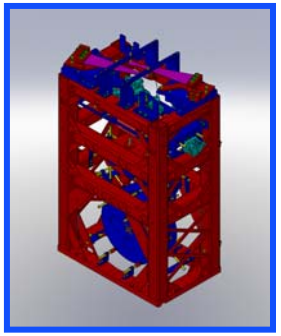
Silica fibres, length 600 mm diameter 400 μm, welded to silica ears

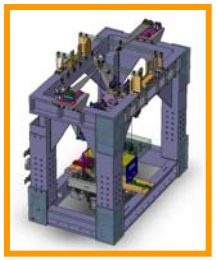
Design Concept: other suspensions

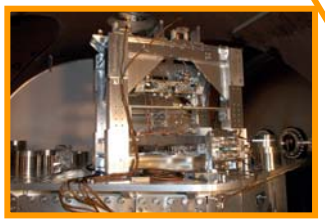
Similar concept to ETM/ITM suspension but with reduced number of stages, use of wire suspensions, and no reaction chain

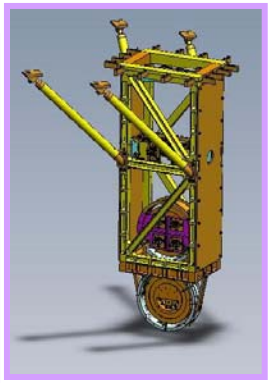












Subsystem Project Organisation: who does what - UK/US split

- UK deliverables (Suspensions): STFC* funded
  - » Test mass noise prototype suspension for LASTI tests
  - » 23 further suspensions: for all the test masses (quadruple pendulums) and for beamsplitters/folding mirrors (triple pendulums) + spares
  - » Front end electronics for these suspensions and for all other suspensions (except single pendulums)
  - » BOSEMs*
- US deliverables
  - » All other major suspensions: for input modecleaner and recycling mirrors (triple pendulums, two designs), output modecleaner (double pendulum)
  - » Total number = thirty suspensions plus spares
  - » All other electronics plus cabling (cabling parts delivered by UK)
  - » AOSEMs (re-engineered LIGO 1 style OSEMs)
- Institutions involved:
  - » UK – University of Glasgow, Rutherford Appleton Laboratory, University of Birmingham, University of Strathclyde
  - » US – staff at all US sites (Caltech, MIT, LHO, LLO)

*STFC = Science and Technology Facilities Council

*OSEM = optical sensor and electromagnetic actuator

Suspension Development Progress
(preceding project activity)

- Full monolithic suspension successfully carried out May 2010
- Monolithic final design review held in September 2010
  - » completed development work for ETM/ITM suspensions
- HAM Large Triple Suspension final design review held April/May 2010
- Blade characterisation and comparison of final round of prototypes from 3 vendors completed June 2010 and vendor chosen
  - » completed development work for HAM suspensions

Response to Comments from NSF Reviews in 2010

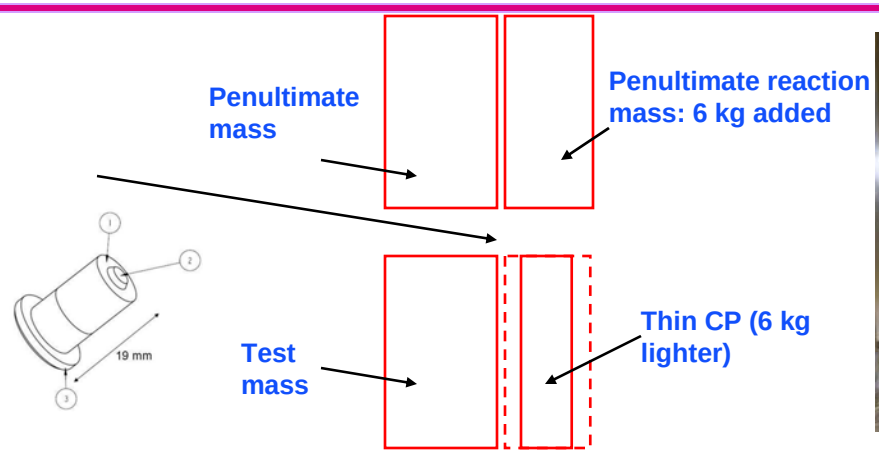
- April 2010
  Recommendation 3.2-1: Place a high priority on LIGO systems engineering to reach final resolution on the outstanding Suspensions design requirements. Specific open issues include the need for violin mode sensors, the possible adjustment to the gap of the compensation plate, changes to the reaction mass design, the possibility of tuned mass dampers on the test mass, and the possible use of stiffening bars on the mounting frames. As the suspensions move into production and assembly, delaying these decisions will have a progressively larger impact on cost and schedule for this subsystem.
  - **1. Violin mode sensors** (VMS): decision taken not to implement VMS in form prototyped by UK. Background: if violin modes get excited we might need to sense and damp. However the need has not been demonstrated and we can use Arm Length Stabilisation (ALS) system as a sensor if required.
  - **2. Changing the gap and design of compensator plate, CP** (the reaction mass for the ITM): To mitigate enhanced gas damping noise in small gaps, decision taken to increase gap between ITM and compensator plate from 5 mm to 20 mm by reducing thickness of CP by 30 mm (effectively removing 15 mm from each side).
    - redesign & fabrication of parts to compensate for reduced mass by adding to penultimate reaction mass
    - redesign and fabrication of earthquake stops between masses for larger gap

    For the ETMs, more complicated geometries are being considered, where the gap is small for the electrostatic drive electrode annular area to achieve enough drive, but large in the central region to reduce the damping, design to be finalised after experience with the one arm test at LHO.
  - **3. Tuned mass dampers:** Suspensions group has agreed with Systems/ISC (RODA signed) on positions on the barrel of test mass which can be utilised for acoustic mode dampers if required
  - **4. Stiffening bars:** Suspensions group is working with Seismic and Systems groups on details of bars (struts) for beamsplitter/folding mirror structures which fit layouts in different vacuum tanks. Vibration absorbers have been developed and fabricated for use with all types of suspension structures

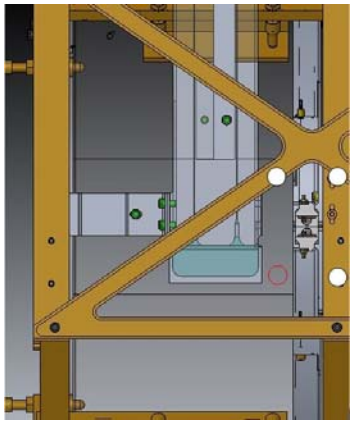
See following pages for further info on items 2 to 4

Resolution of April 2010 Comments

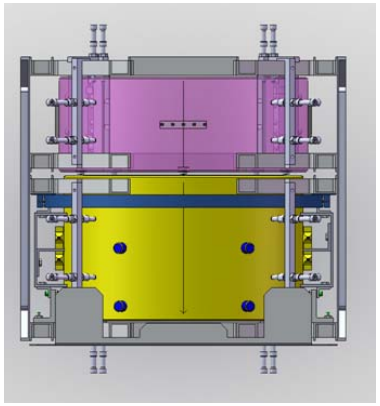
- Changes to accommodate thin CP
  - » Gap changes from 5 mm to 20 mm
  - » 6 kg added to penultimate reactior mass
  - » Revised design of bump stops for wider gap



- Tuned mass damper positions chosen and reserved (white circles on side, blue circles on top of barrel)

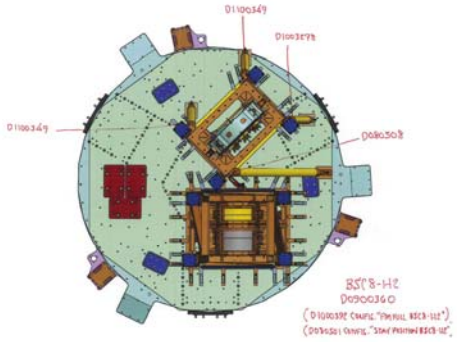


Side view



Top view

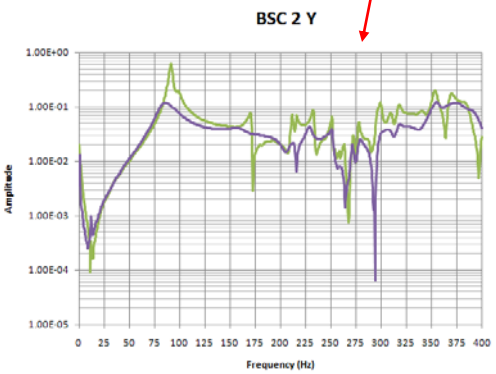
- Struts and Vibration Absorbers
  - » Struts used with beamsplitter /fold mirror (intrinsic part of the design)
  - » Different layouts required in different tanks (Systems)

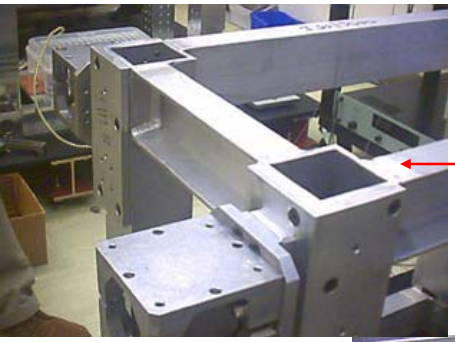


Resolution of April 2010 Comments
continued

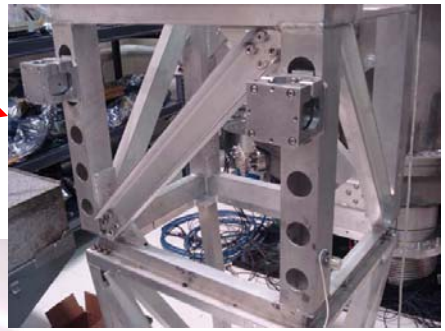
- Vibration Absorbers, proposed by Seismic and Systems groups, has been accepted as solution for damping all suspension structures (in SUS and AOS)
  - » simple to assemble and install
  - » add minimum mass to the structure
  - » no footprint on the optic table
- Testing underway: collaboration of Seismic+Systems+Suspensions

Transfer functions for BS/FM structure with absorbers

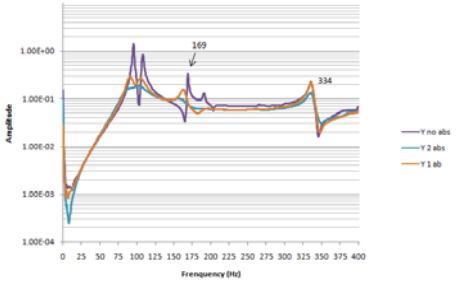




Absorbers on prototype OMC-SUS, HLTS and quad structures



Transfer functions for first article HSTS structure with absorbers



Response to Comments from NSF Reviews in 2010, continued

- **December 2010**

  Mirror coating and suspension noise

  We continue to support the idea of an ongoing, and perhaps increased, research effort to study the science and technology of the thermal noise in optical materials and the fabrication and processing methods. This should include basic material science and theoretical analysis to develop a deeper understanding of the fundamental science and ultimate physical limitations. Risk reduction and performance improvement research and development on mirror coatings should continue through aLIGO.

  - Suspension research ongoing in LIGO. Note that this is funded from the LIGO operations grant. Areas include
    - Investigation of how losses in fibres vary with polishing
    - Possible use of silica (or silicon) blades in final stage of suspension: breaking strength tests underway
    - Experiments to place limits on creak in maraging blades
  - Suspension research for risk reduction and enhancements also underway in the LSC community.

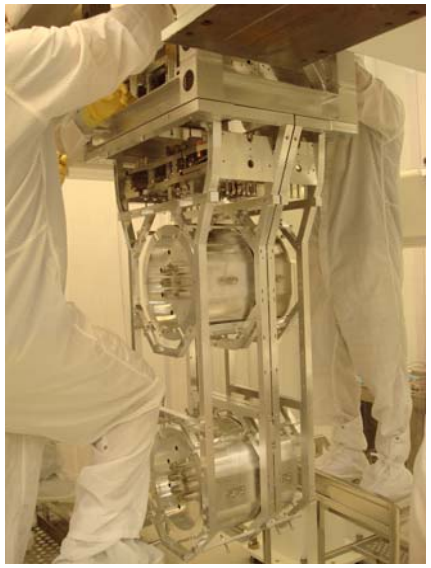
LIGO

Technical Progress - Highlights

- Assembly and test of quadruple suspensions with metal dummy masses underway at LHO and LLO
- Preparations for monolithic fused silica work underway at LHO (where first needed)
- Sub-assembly work of beamsplitter/folding mirror metal parts underway at LHO and LLO and first full assembly at LHO (where first needed)
- Sub-assembly work underway on HSTS suspensions at LLO (where first needed)
- First batch of ~100 production blades for HSTS and HLTS characterized at LLO
- ~ 350 (out of 400) AOSEMs and all BOSEMs (~670) in hand
- All UK electronics delivered to US
- Cable routing worked out, cabling ordered and some already received
- US electronics builds well underway

Quad Assembly Work

- Essentially all suspension parts now delivered from UK (RAL)
- Assembly and testing underway at LHO and LLO
  - » 5 suspensions assembled in metal form + subassemblies of remaining 7 + spares)
- Containers for quad storage delivered
- Recent finding: rebuild using heavier dummy masses to reflect actual optic weights gave lower first pitch frequency than required. All other (21) low frequency modes as modeled and all modes damped
  - » Fixed by increasing effective “d” values (vertical breakoff points with respect to centre of mass)
- Lessons learned from first builds have been recently reviewed (see later)



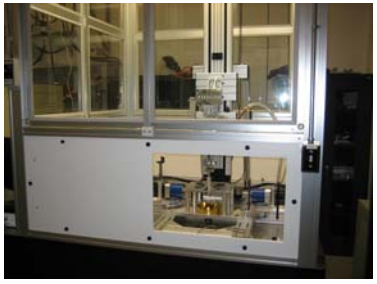
Monolithic Aspects of Quad Suspensions: Bonding, Fibre Pulling, Welding

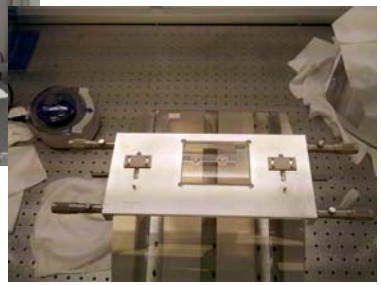
- Successful full monolithic hang at LASTI in May 2010 following test hangs at Glasgow and LASTI
  - » Violin mode measurements tie up well with thermal noise modeling
  - » LASTI suspension being used in cavity locking tests to investigate hierarchical control, in modal damping work and in charging experiments
- Training sessions for LIGO staff by Glasgow staff on silicate bonding, fibre pulling and welding held at Glasgow, MIT and LHO (~ 25 person weeks for LIGO staff so far)
- Fibre pulling equipment including ancillary testing apparatus shipped from LASTI to LHO
- Bonding and fibre pulling labs and two movable welding stations assembled at LHO
- Bonding of four penultimate masses and bonding of first test mass for single arm test completed

Full presentation on monolithic work is available (G1100425)



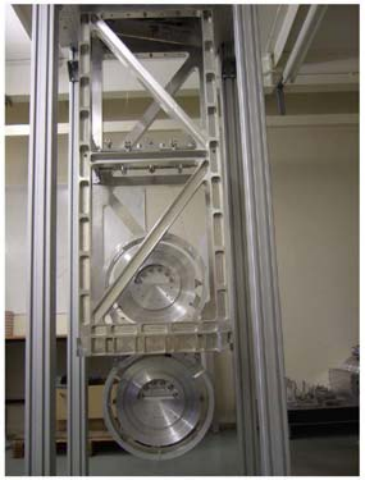


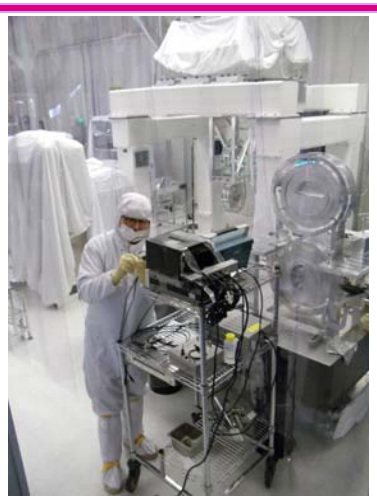


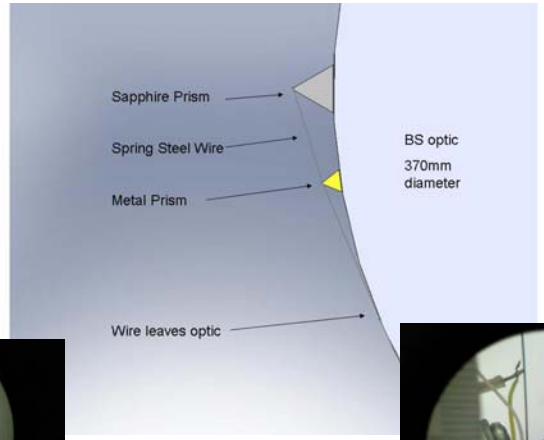



Beamsplitter/Folding Mirror (BS/FM) Triple Suspensions

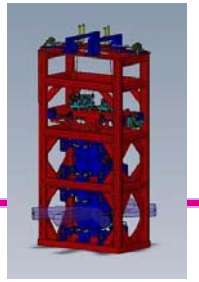
- One folding mirror suspension with dummy mass required for single arm test at LHO in H2 (optic not needed and not yet available)
  - » Suspension assembled at LHO and under test
- Double prism placement study carried out – use correctly placed second prism to minimise thermal noise for wire suspension.
  - » Assembly jig revised to accommodate correct position
- Ongoing work with Systems to arrange layout of struts for different tanks (as previously mentioned)
- Ongoing work with Systems to finalise procedures for replacing dummy optic with glass optics in situ and to develop any necessary tooling



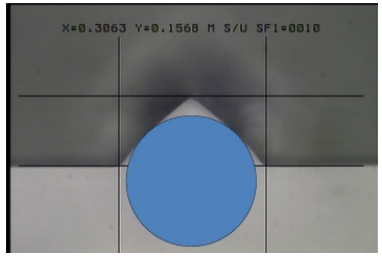


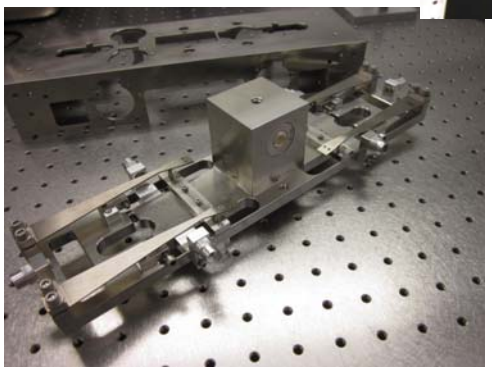


HAM Large Triple and Small Triple Suspensions (HLTS, HSTS)



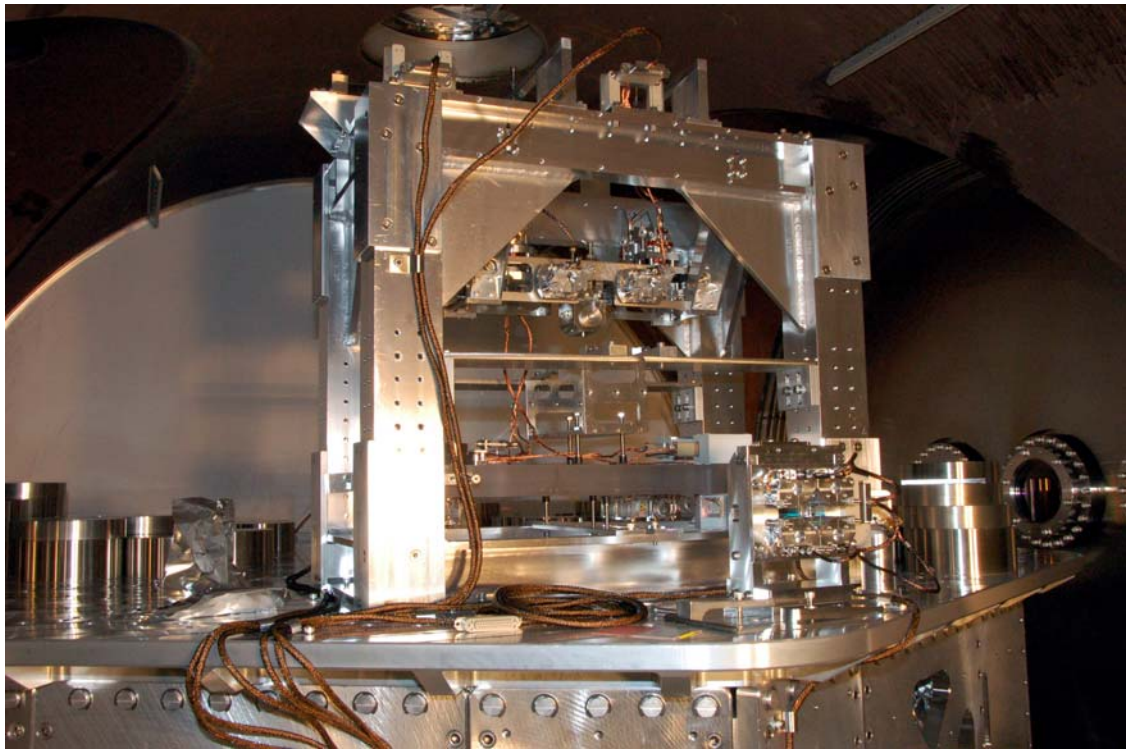
- First ~ 100 blades arrived (HSTS and HLTS) and have been characterised at LLO. Now undergoing clean and bake
- HSTS machined parts all delivered to both sites. Initial dirty assembly of one set to check parts. Clean and bake underway. Helicoiling and clean assembly started at LLO.
- Delivery of HLTS machined parts to both sites underway (>50 % received)
- Sapphire prisms for HSTS and HLTS manufactured and received and HSTS ones undergoing clean and bake at Caltech
- Welding contracts for stainless steel support structures underway . Some problems –see later





Output Modecleaner (OMC) Double Suspensions

- Already successfully implemented in Enhanced LIGO at both sites - can reuse those units for first installs
- Machined parts and structures in hand for third unit, blades to come
- Minor mods carried out to structure design to allow use of vibration absorbers
- Structure design also used for the output Faraday isolator (AOS)
- Problems experienced with welding of new structures (see later)



OSEMs and Electronics

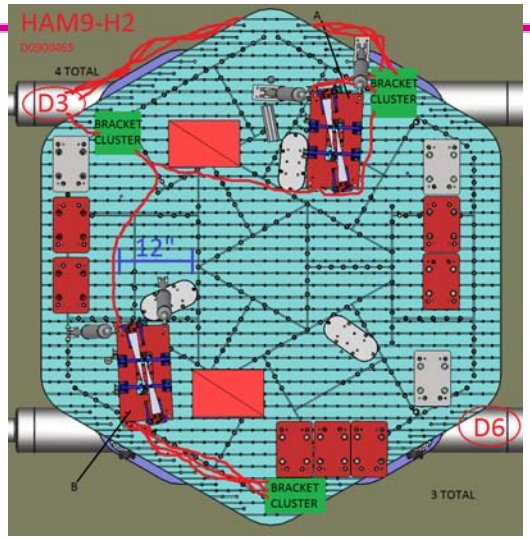
- BOSEMs = Birmingham OSEMs (~670), all delivered and majority already through baking and RGA testing. Also automated test equipment supplied.
  - » BOSEMs deliver much larger force (~ 2N/A) compared to iLIGO OSEMs (~ 0.016 N/A) - for use with heavier suspensions
- AOSEMs (~ 400)
  - » revised design of iLIGO OSEMs for ease of manufacture: body of carbon loaded peek+ flexicircuit + micro-D connector
  - » used at lower stages in suspensions
- UK electronics (coil drivers, satellite amplifiers, electrostatic drive amplifiers)
  - » tested in UK, delivered and tested again here
- US electronics (AA and AI filters, binary input chassis, racks etc) - builds and testing underway

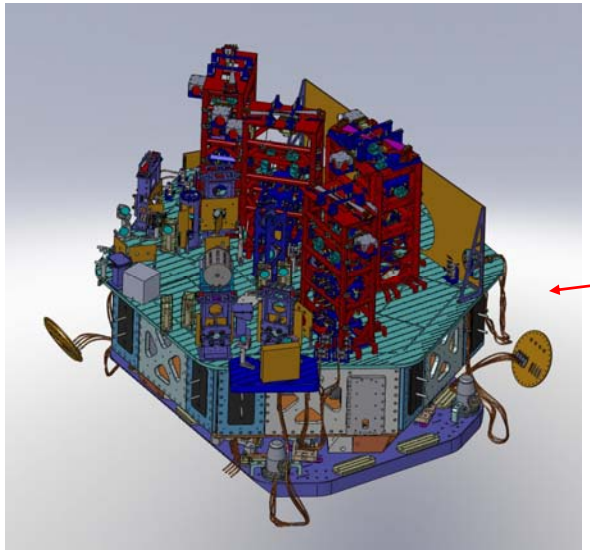
All UK deliveries were completed by end March 2011



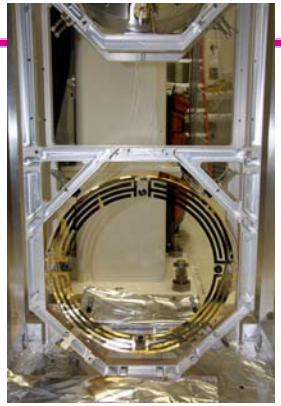


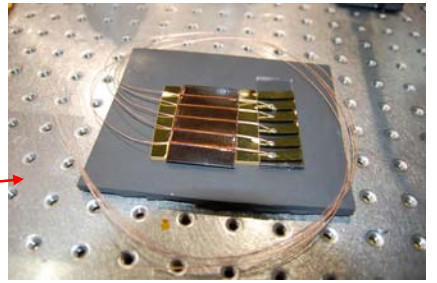

Cabling and Layouts

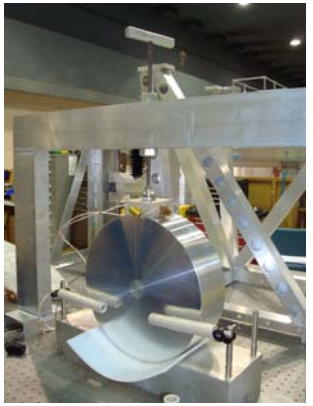




- Cables: (in vacuum and ex vacuum) - orders now all placed and some already arrived
- Testing of routing cables up suspended quad reaction chain carried out on LLO training quad
- Routing of cabling up/down all suspensions and across tables has been carried out (10 chambers per interferometer for SUS)
- Work on choice of cabling and method of attachment to gold coating (ESD) has been carried out
- Work with Systems on layouts. HAM 2 is especially difficult “Manhattan skyline” (3 x HSTS, 1 x HLTS, 4 x HAM Auxiliary suspensions etc) - work in progress
- Systems work on spacers for correct heights, dogclamps for fitting in awkward places, installation tooling, interface issues

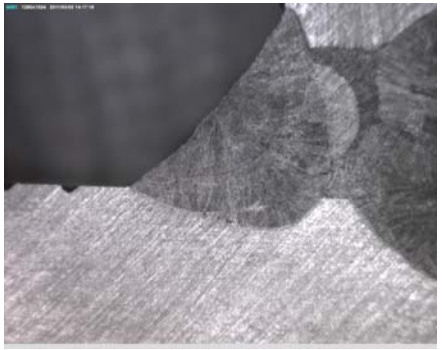






Technical Issues

- Unplated SmCo magnets (used to reduce Barkhausen noise) found to shed particulates: being replaced by Ni-plated versions.
- Steel music wire - recent batches found to have rust and dark spots and lower tensile strength than acceptable
  - » New wire ordered, specifications/requirements tightened
  - » Inspection guidelines written and sets of inspection tooling supplied to the observatories
- Welded support structures – continuing problems with quality of welds and general production to our strict requirements
  - » OMC-SUS aluminium structures: small pits in welds required grinding with dremel tool to remove and subsequent electropolishing to clean up
  - » HSTS stainless steel structures: vendor unable to produce full penetration welds with initial design. Iterations required on weld prep. after checks using FEA. First article provisionally approved with feedback to vendor.
  - » HLTS stainless steel structures: first RFQ received no acceptable bidders; had to go for second round with consequent schedule delay
- Quality of finish on some parts from UK vendors found not acceptable for UHV – electropolishing required
- RODA agreed to minimise use of magnetic steel fasteners in AOSEMs and BOSEMs for reduced Barkhausen noise
  - » replace key fasteners with 316 stainless steel fasteners. This has required retrofitting in US of some of UK BOSEMs



LIGO Quad and BS Suspension Assembly Reviews

- Several telecons held recently to look critically at how builds have been proceeding
  - » lessons learned for improving procedures or tooling, or if necessary aspects/parts of the suspension design.
- Prioritised task list with assignments prepared and work underway
  - » flag redesign for BOSEMs to improve assembly process and relax tolerance on alignment for minimising cross-coupling
  - » add pitch adjustment on upper intermediate mass to help alignment process
  - » various tooling/holes to aid blade adjustments and overall alignment
  - » address abrasion of bolt heads in high torque locations
- Testing: characterise cross-coupling of the suspension by test. Concern that asymmetries in mechanical assembly leads to cross-coupling in the dynamics which complicates the control
  - » development of OSEM cross-coupling minimisation procedure
  - » MATLAB scripts being generated for automated transfer functions
  - » modeling using Mathematica to look at cross-coupling
  - » building on systems –identification (sys-id) carried out on LASTI monolithic suspension
  - » development of SVN (revision control system) for storing and sharing models, scripts, results
  - » input and support from ISC group/commissioners and expansion of testing team

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Challenges, Risks, and Mitigations

- Challenge: assembly and suspension of monolithic stage, repair procedure

  Mitigation:
  - » experience with GEO design and expertise/support from GEO-Glasgow team
  - » successful monolithic hang at LASTI
  - » training of US staff by UK team
- Challenge: fabrication of stiff structures with suitable footprints which are UHV compliant. Stiffness required since structure resonances may affect isolation platform and require use of complex control laws.

  Mitigation:
  - » use of struts for stiffness (on BS/FM) and vibration absorbers to reduce quality factors of resonances (on all types)
  - » Comprehensive specification for welding provided to vendors, weld samples required for approval, measurements of first articles, QAME involvement at every stage

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Challenges, Risks, and Mitigations

- Challenge: follow-up from major assembly review could have schedule impact

  Mitigation:
  - » prioritisation into essential changes for first quads and changes/tooling for further builds
  - » support from staff from other groups
- Challenge: input from ISC group and assembly review has highlighted need for more sys-id on quad assemblies, may have schedule impact

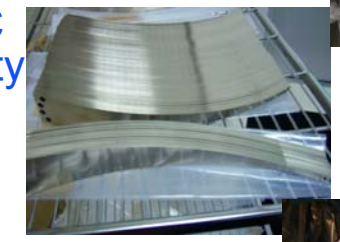
  Mitigation:
  - » input from ISC/commissioners
  - » development of better tools and better understanding of requirements
- Challenge: Absence of key personnel through illness, accidents (outwith work) and other personal circumstances: SUS has experienced such losses amounting to several person-months in the past 6 months

  Mitigation:
  - » redistribution of tasks, help from other subsystems, hire more staff

Suspensions: Next 6 Months

- Implement actions from recent assembly reviews for quad and beamsplitter/fold mirror (improve procedures and tooling, address design issues)
- Develop and implement full testing program for the quads with input from ISC group
- Single arm test at LHO – requires 1 x ETM, 1 x ITM and 1 x FM
  - » First test of bonding, fibre pulling, welding procedures in situ
  - » First test of cartridge installation (Seismic +Suspensions)
- Short Michelson test at LLO – initially requires 5 HSTS (3 x IMC plus 2 x recycling cavity mirrors plus 1 x HLTS for recycling cavity mirror)
- Ongoing assembly and testing of other suspensions and associated electronics.
- Total required = 47 suspensions (excluding spares)
  12 x ETM/ITM, 5 x BS/FM, 21 x HSTS, 6 x HLTS, 3 x OMC-SUS






Summary: Suspensions work is a success-oriented program which continues to be challenging. SUS teams in US and UK are working well together to maintain progress and achieve objectives