

Suspensions

Requirements and Design Breakout Presentation
NSF Review of Advanced LIGO Project

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LIGO-G060216-00-R

LIGO advancedligo Suspension System Functions

US + UK = TOTAL
\$15.9M + \$6.4M = \$22.3 M

- Support the optics to minimise the effects of
 - » **thermal noise** in the suspension
 - » **seismic noise** acting at the support point
- Provide damping of low freq. suspension resonances (local control)
- Provide means to maintain interferometer arm lengths (global control) while at same time
 - » Not compromise low thermal noise of mirror
 - » Not (re)introduce noise through control loops
- Provide interface with seismic isolation system and core optics system
- Support optic so that it is constrained against damage from large motions
- Accommodate a thermal compensation scheme

Suspension Requirements (Test Masses)

- **Top-Level Requirements:**

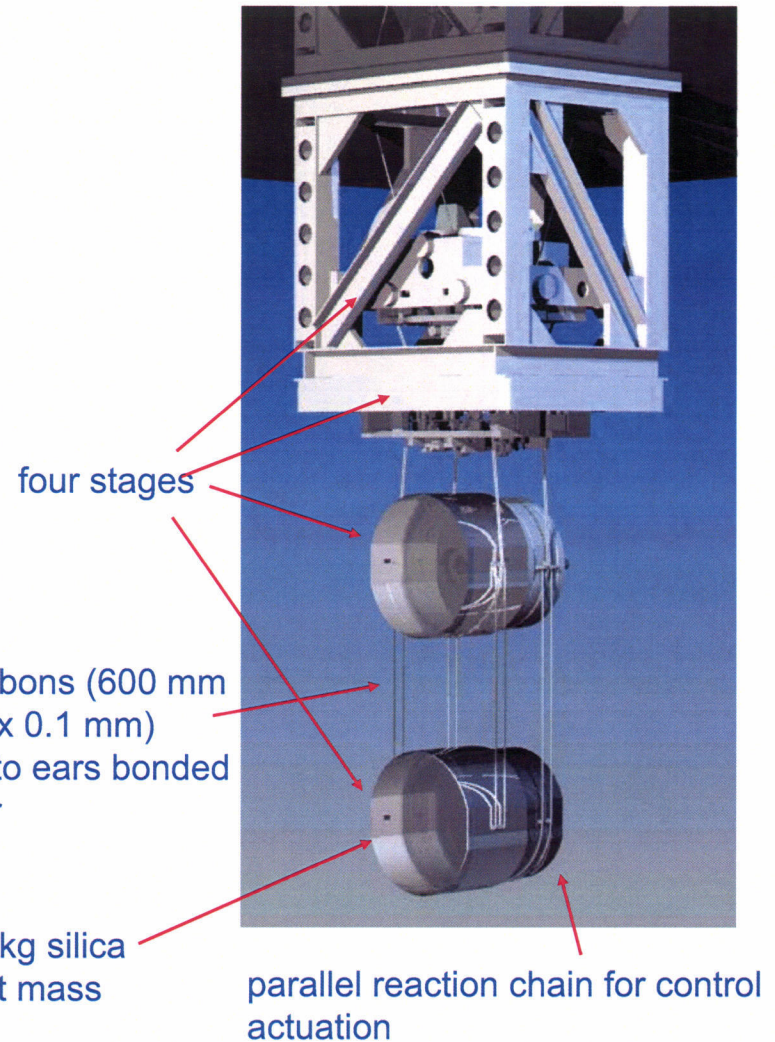
Requirement	Value
Suspension Thermal Noise	10^{-19} m/ $\sqrt{\text{Hz}}$ at 10 Hz (longitudinal) 10^{-16} m/ $\sqrt{\text{Hz}}$ at 10 Hz (vertical)**
Residual Seismic Noise	10^{-19} m/ $\sqrt{\text{Hz}}$ at 10 Hz (assumes seismic platform noise 2×10^{-13} m/rt Hz)
Pitch and Yaw Noise	10^{-17} rad/ $\sqrt{\text{Hz}}$ 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 up to 12 Hz

- 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 $\sim 3e-7$, c.f. steel $\sim 2e-4$*
- Seismic isolation: use **quadruple pendulum** with 3 stages of maraging steel blades for enhanced vertical isolation
 - » *isolation @ 10Hz: quad $\sim 2e-7$, c.f. single stage $\sim 5e-3$*
- Control noise minimisation: apply damping at top mass and use quiet reaction pendulum for global control actuation

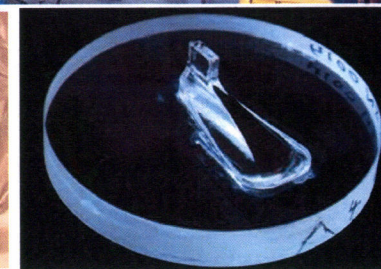
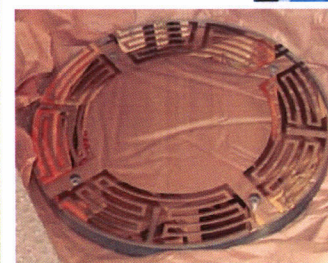
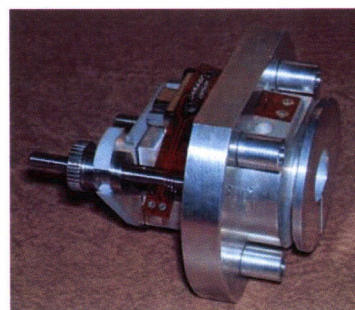
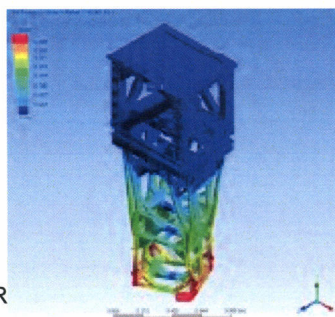
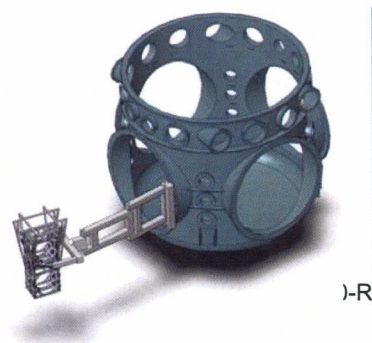
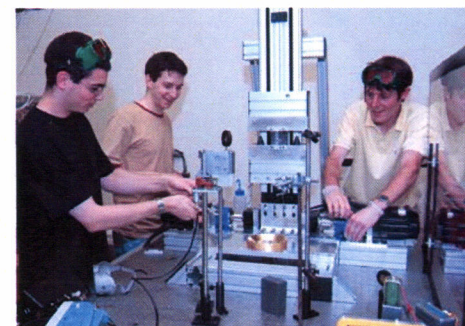
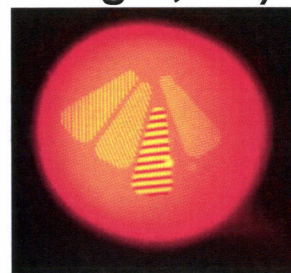
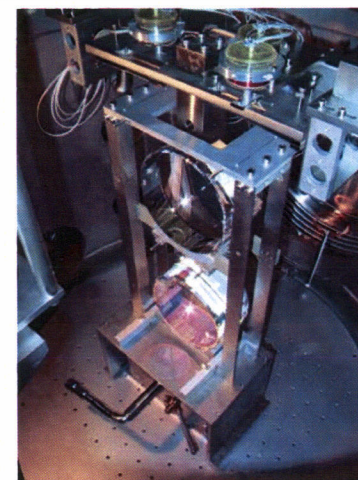
Other mirrors: triple, double, single pendulums as necessary from noise requirements



- **UK deliverables (Suspensions) - PPARC funded**
 - » **Test mass noise prototype suspension for LASTI* tests**
 - » **23 further suspensions: for all the test masses (quadruple pendulums) and for beamsplitters (triple pendulums) + spares**
 - » **Front end electronics for these suspensions and for modecleaner and recycling mirror suspensions**

- **US deliverables**
 - » **All other suspensions: for input modecleaner and recycling mirrors (triple pendulums) plus other optics**
 - » **All other electronics**

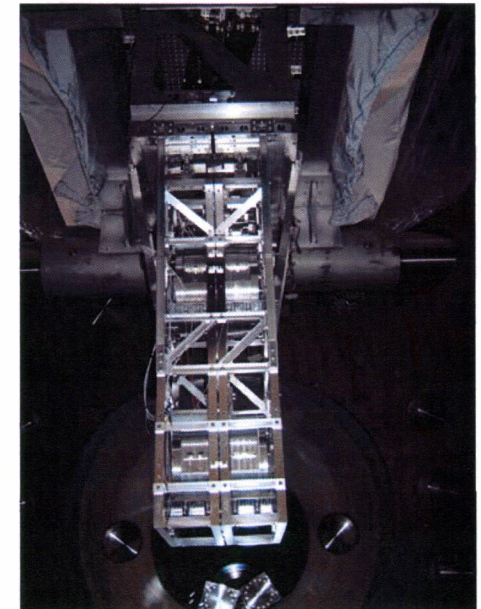
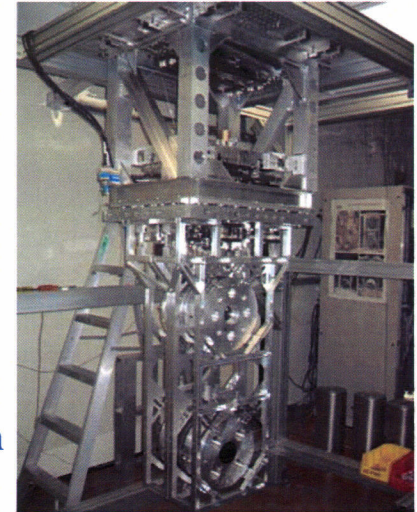
- **Suspension design based on GEO600 triple pendulums incorporating fused silica monolithic final stage (up to 10 kg masses): installed in 2001**
- **Further research and development**
 - » **Ribbon pulling and welding: development of CO₂ machine for repeatability, reliability – improved strength and performance**
 - » **Testing of ribbons and fibres (shape, strength, Qs)**
 - » **Silicate bonding and ear development**
 - » **Sensor and actuator development**
 - » **Support structure design for stiffness**
 - » **Installation fixtures**



- **Quadruple pendulum**

- » **“Controls” prototype (all- metal) constructed at Caltech and delivered in Feb 2006 to LASTI for full tests**
 - Test mechanical and control aspects
 - Design as similar to noise prototype as possible
- » **“Noise” prototype (full monolithic silica assembly)- development underway in UK, delivery to LASTI early 2007**
 - Essentially final design
- » **LASTI tests:**
 - Assembly, alignment and installation
 - Mode frequencies, transfer functions, damping (active and eddy current), comparison to model
 - Integration with isolation system and repeat above
 - Investigation of overall behaviour, coupled dynamics etc
 - Global control between two multiple pendulums, noise performance to LASTI limits

First assembly at Caltech



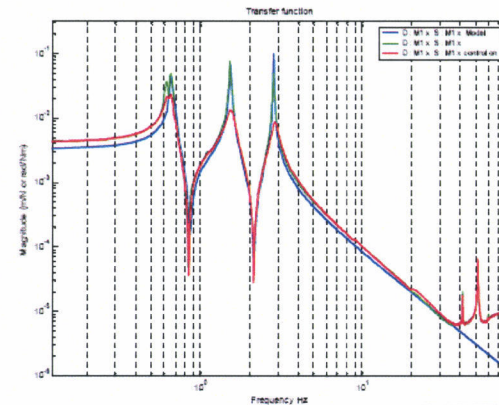
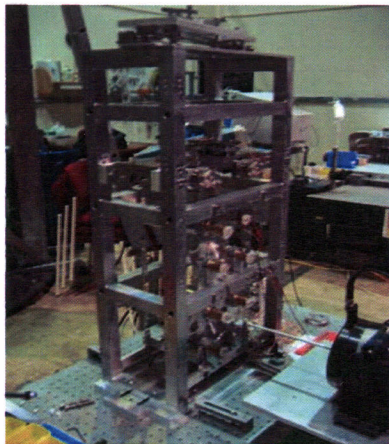
Installed in vacuum chamber at LASTI

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advancedligo Suspension Development Status (other mirrors)

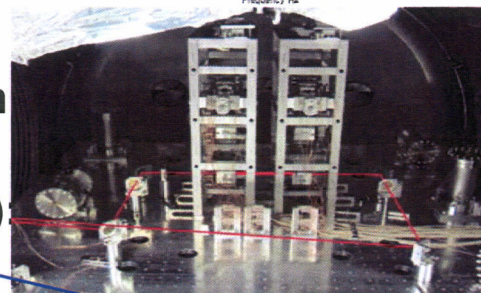
- Triple pendulum for modecleaner mirrors: controls prototype designed, constructed and fully characterised at LASTI, design based on GEO recycling mirror suspension



- Ongoing tests using quiet cavity set up between two triple pendulum suspensions

- Other suspensions (extensions of existing designs)

- » Recycling mirror (triple) – full design carried out
- » Beamsplitter (triple) – conceptual design carried out
- » Output modecleaner (double) – conceptual design underway
- » Mode matching telescopes, steering mirrors etc (single) – modified LIGO 1 suspensions



Points raised by panel

- **Importance of integration of full scale prototype suspension with the active seismic isolation system.**
 - » This is scheduled to take place starting early 2007 at LASTI.
- **Attention required to avoid introduction of sensor noise into observation band**
 - » Modeling shows use of strongly filtered active damping for lower frequency modes plus eddy current damping for higher modes can meet requirements. Also work on modal damping technique looks promising.
- **Full modeling of system encouraged**
 - » MATLAB and Mathematica models extensively used, and updated to incorporate findings from lab investigations.
 - » Quad model exported in state space form for incorporation into the Advanced LIGO end-to-end model.

- **Continuing research and development – large team (~45) involved from USA and UK (LIGO Lab, Stanford U, Glasgow U, Rutherford Appleton Lab, Birmingham U, Strathclyde U) + input from wider LSC**
- **Weekly telecons, face-to-face meetings and personnel visits**
- **Interface control documentation between UK and relevant subsystems**
- **Preliminary Design Reviews (PDR), recent and upcoming**
 - » **PDR - Electronics (July 2005)**
 - » **PDR - Ribbons, Fibres, Bonding (October 2005)**
 - » **PDR - Triple Pendulums (June 2006)**
 - » **PDR - Quadruple pendulums (July 2006)**
 - all significant design risks retired, based on controls prototype installed & tested at LASTI
 - approval for fabrication of the noise prototype
- **Final Design Review**
 - » **Follows full testing of noise prototype at LASTI**
 - Integrates fused silica fibres & R&D for bonding & welding processes
 - Includes coupled dynamics investigations with stiffer structural frame

- **Challenge: assembly and suspension of monolithic stage (scaling up from 10 kg to 40 kg), repair procedure**
- **Mitigation:**
 - » experience with GEO design and expertise from GEO
 - » continuing extensive testing at every step in development process
- **Challenge: noise performance cannot be fully tested in laboratory**
- **Mitigation:**
 - » minimise risk through modelling
 - » gain understanding of underlying physics
 - » explore use of lower noise alternatives (e.g. maraging steel wires for upper stage)
- **Challenge: support structure resonances may compromise isolation platform performance/ require use of complex control laws for each chamber**
- **Mitigations:**
 - » further finite element analysis
 - » trial structure for testing
 - » use of stiffening/damping struts