Suspension Design for Advanced LIGO

Norna A Robertson
Stanford University &
University of Glasgow
for the LIGO Scientific Collaboration

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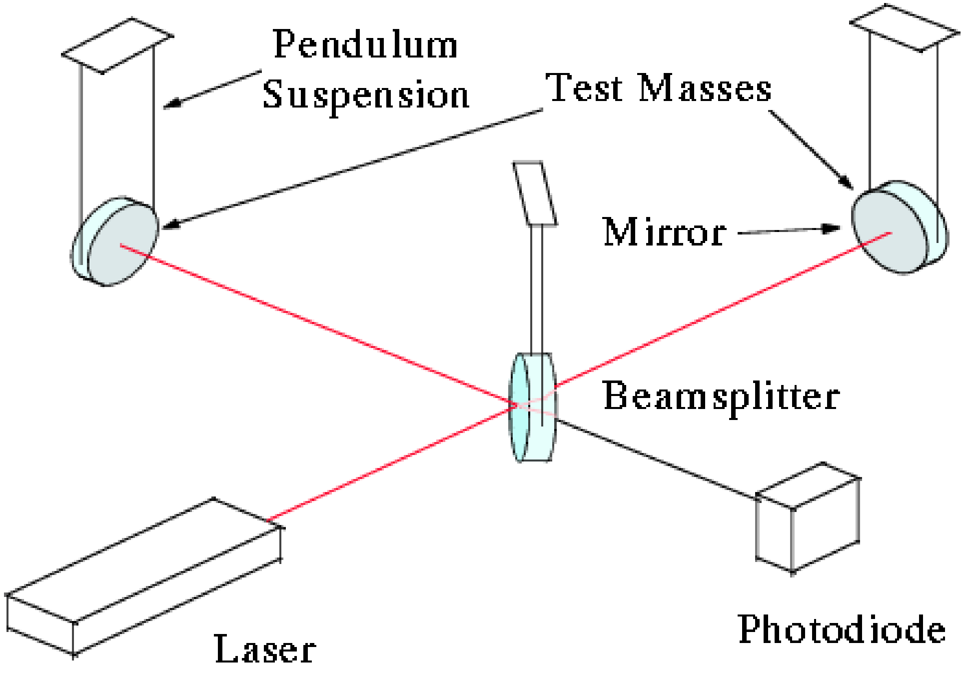
Topics to be Addressed

- Suspension requirements
- GEO 600 suspension design
- Advanced LIGO suspension design
- Current status and future work

Gravitational Wave Detection

- long baseline laser interferometry between *freely suspended* test masses using a Michelson Interferometer



Suspension Design for GW Detectors

- Requirements of suspension system:
    - support the mirrors (“test masses”) so as to minimise the effects of
        - thermal noise in the suspensions
        - seismic noise acting at the support point
    - allow a means to damp the low frequency suspension resonances (local control)
    - allow a means to maintain arm lengths as required in the interferometer (global control)

while at the same time

- not compromise the low thermal noise of the mirror
- not introduce/reintroduce noise through control loops

Thermal Noise

- Thermally excited vibrations of pendulum and violin modes of suspensions and of mirror substrates + coatings
- Important noise source in low to mid-range frequencies (10s to few 100s of Hz)

To minimise this noise source:

- use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise level off resonance
- in general operate away from resonances (exception - violin modes)
- take advantage of significant "dilution factor" to increase pendulum and violin Qs above that of suspension material

Seismic Noise

- Seismic noise limits sensitivity at low frequency - "seismic wall"
- Typical seismic noise spectrum at "quiet" site

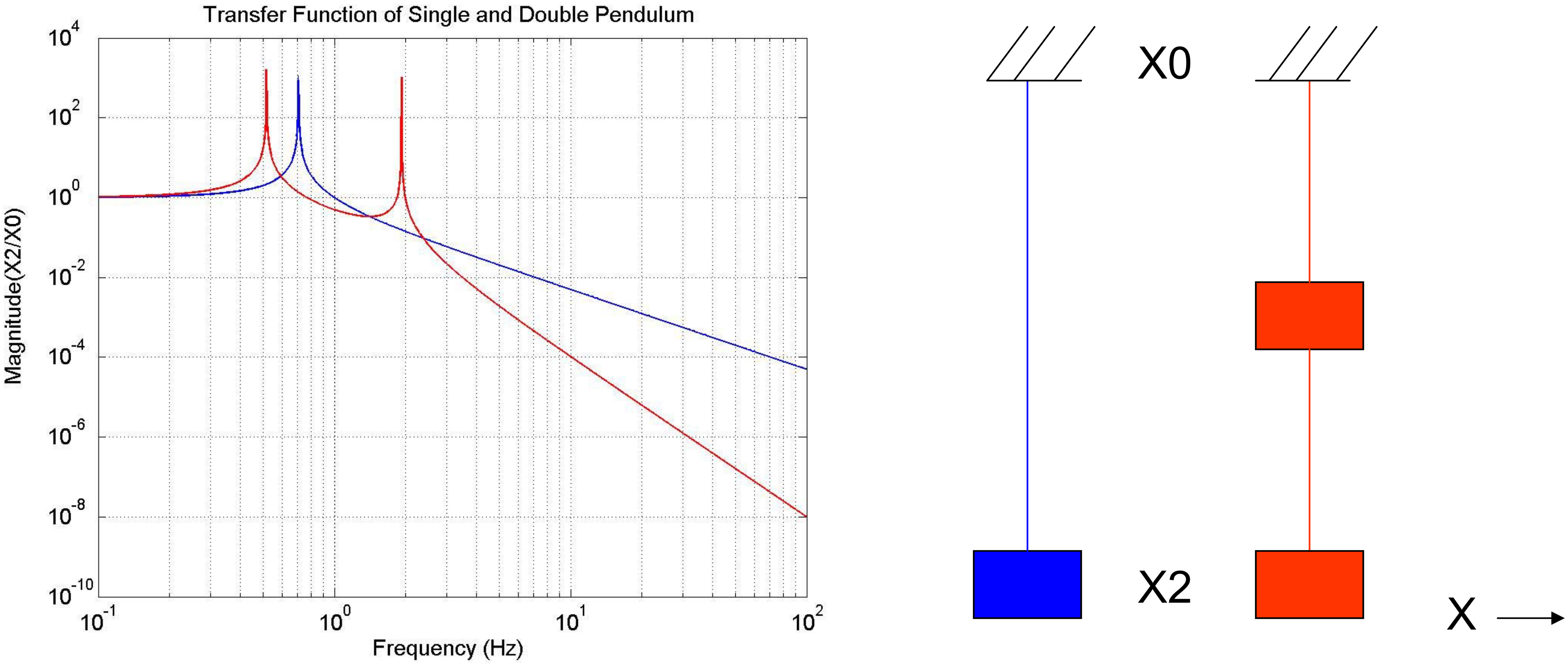
$$x(f) \approx \frac{10^{-7}}{f^2} m/\sqrt{Hz}$$

Thus large isolation required!

- Isolation required in vertical direction as well as horizontal due to cross-coupling effects
- Ultimately gravity gradient noise will limit low frequency performance: – LISA (and beyond) for low frequency detection

Seismic Noise contd

- Use multiple stages of isolation, e.g. combination of n-stage isolation stack + n-stage pendulum



Advantage of double over single pendulum of same total length

GEO 600 Thermal Noise Issues

- To reduce suspension thermal noise, GEO is pioneering fused silica fibre suspensions to support fused silica mirror
  - fused silica loss factor ~10^{-6} to10^{-7}, c.f. steel ~10^{-4}
- Fibres are welded to fused silica ears, bonded to sides of mirror - effectively making

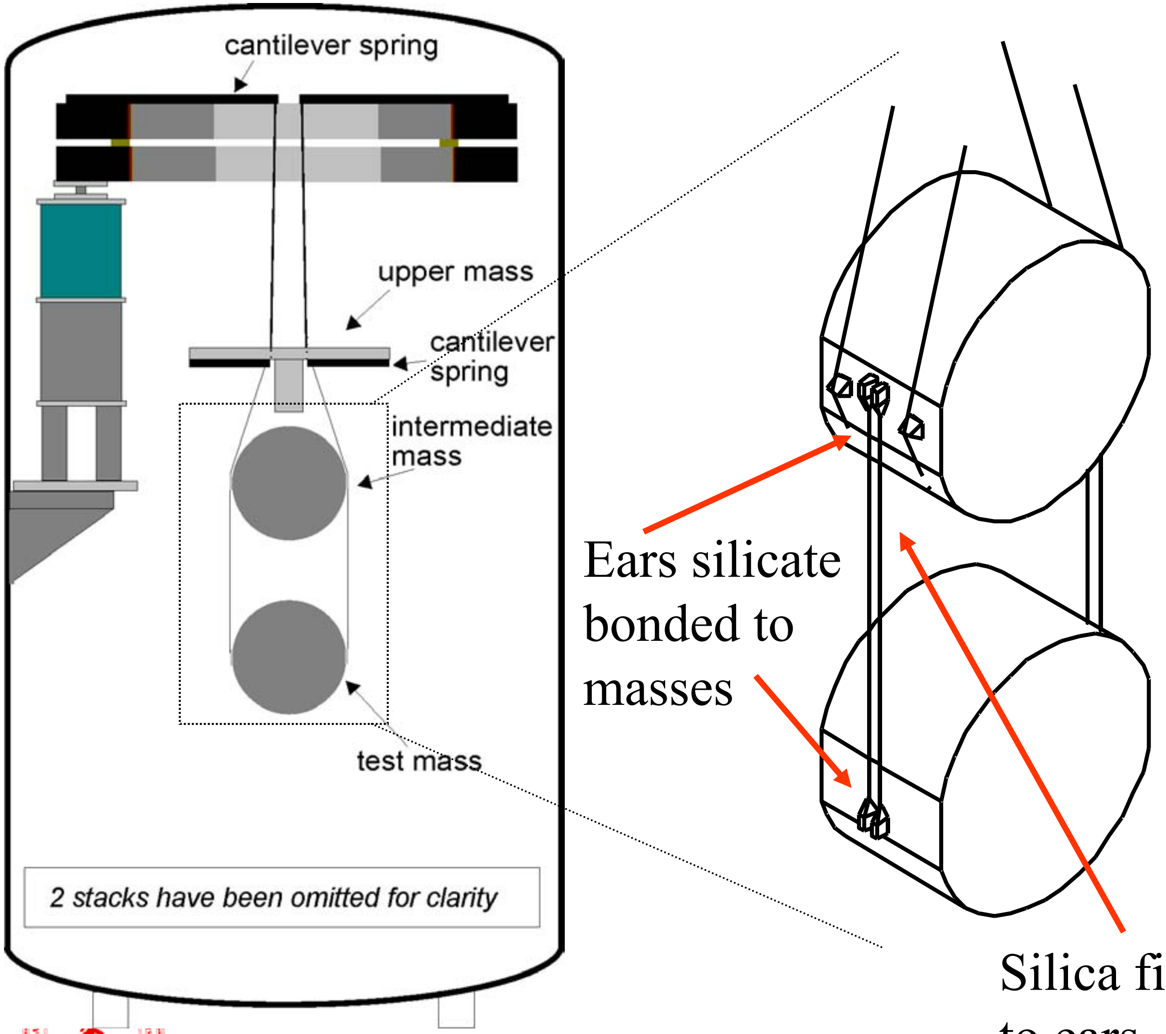
  monolithic fused silica suspension
- Bonding: GEO has developed low loss hydroxy-catalysis technique - “silicate bonding”

  based on work at Stanford for Gravity Probe B expt.

Summary of GEO 600 Suspension Design

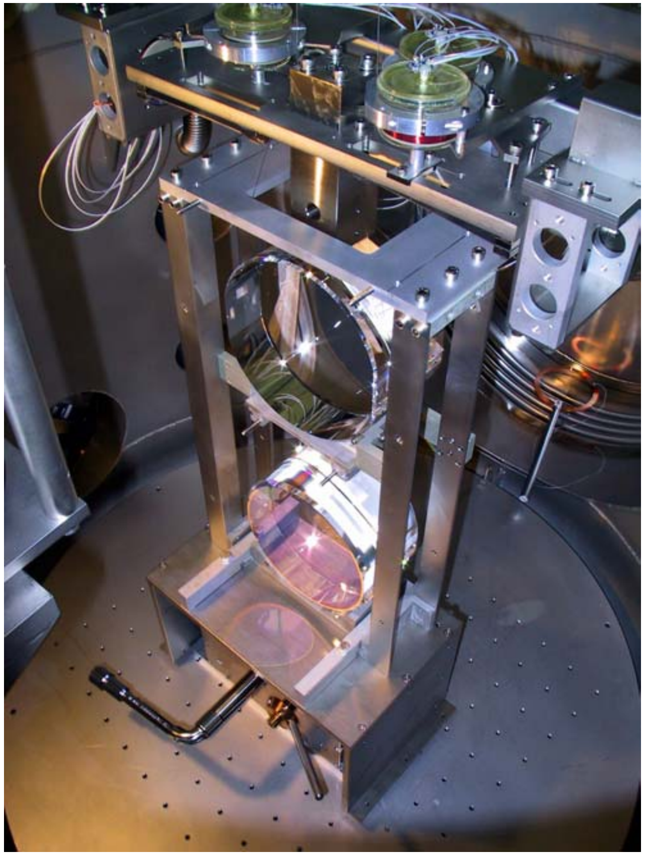
- *Monolithic fused silica suspension* as final stage of suspension for low pendulum thermal noise and preservation of high mirror quality factor
- *Triple* pendulum for horizontal isolation *+ 2 stages of maraging steel blades* for enhanced vertical isolation
- *Local control* for damping of all low frequency pendulum modes by 6 co-located sensors and actuators *on topmost mass* for sufficient noise isolation: requires modes observable at topmost mass
- *Global control* at penultimate mass and at mirror (electrostatic at mirror) using adjacent “identical” *reaction pendulum as quiet reference*

GEO Triple Pendulum Suspension

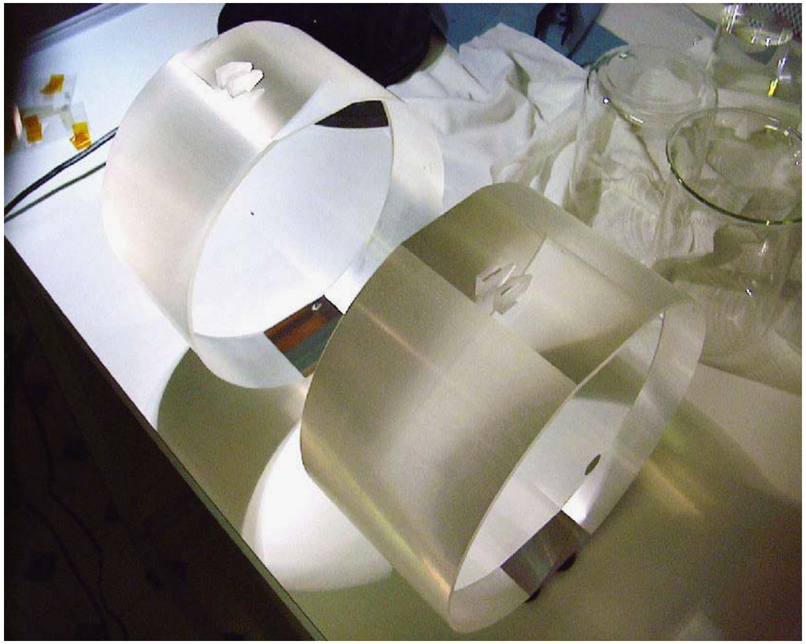


Ears silicate bonded to masses

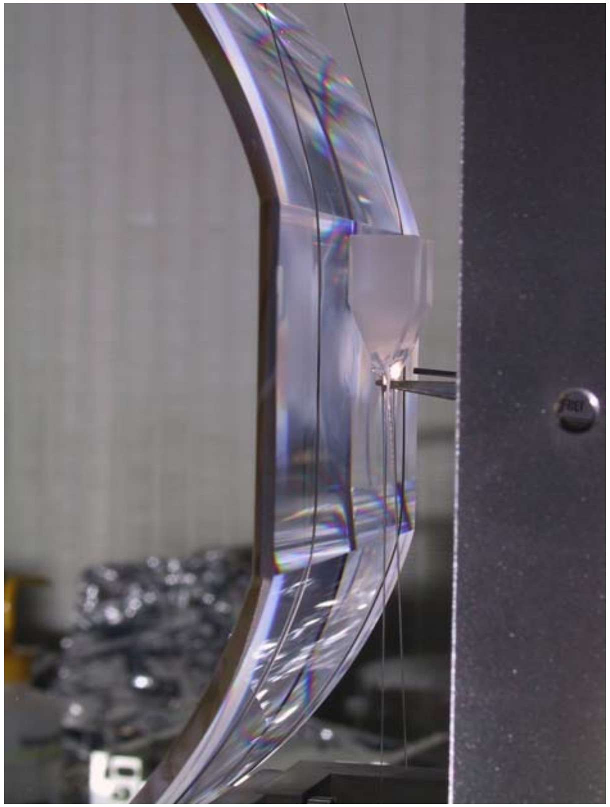
Silica fibres welded to ears



Monolithic Suspension - Assembly

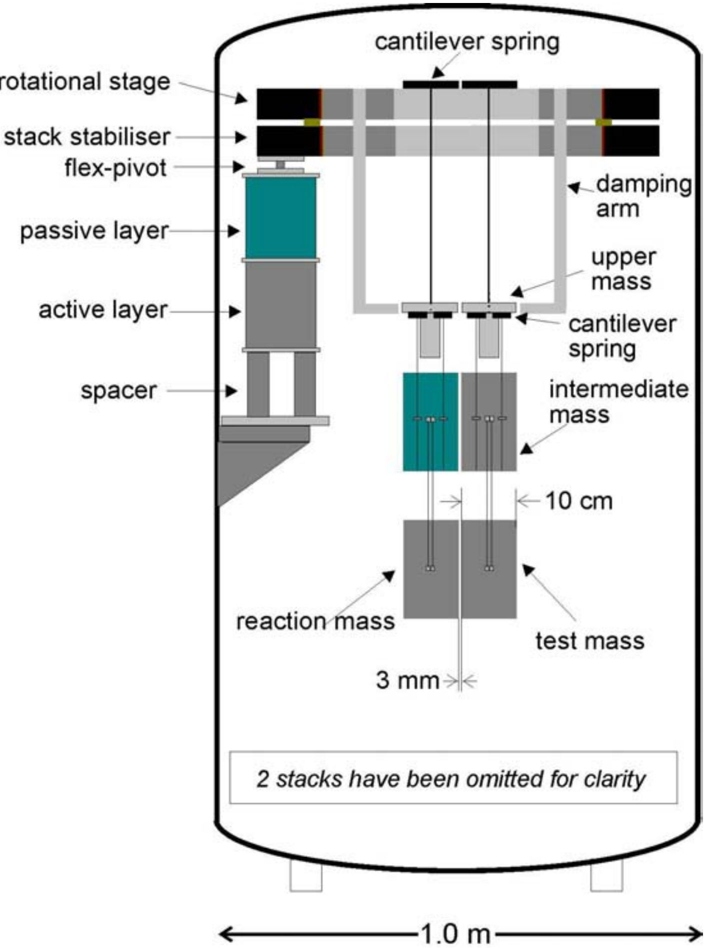


Bonding of ears

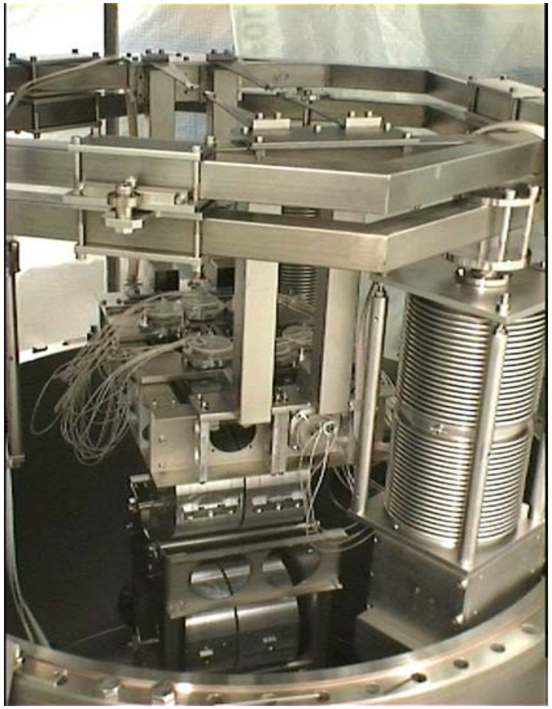


Welding of fibres

GEO 600 Suspension (side view)



Side view



Triple pendulum + reaction pendulum in situ (all metal)

Reaction mass with gold plated grid for electrostatic control

LIGO Suspension/Isolation Systems

- LIGO I has more conservative design than GEO
  - single pendulum with steel wire loop, magnets for local and global control attached to back of mirror
  - 4 layer passive isolation stack
- Advanced LIGO design (in-vacuum elements)
  - multiple pendulum based on modified GEO 600 triple pendulum (The SUS system)
  - two layer active noise reduction platform (The SEI system).

target sensitivity for main optics:

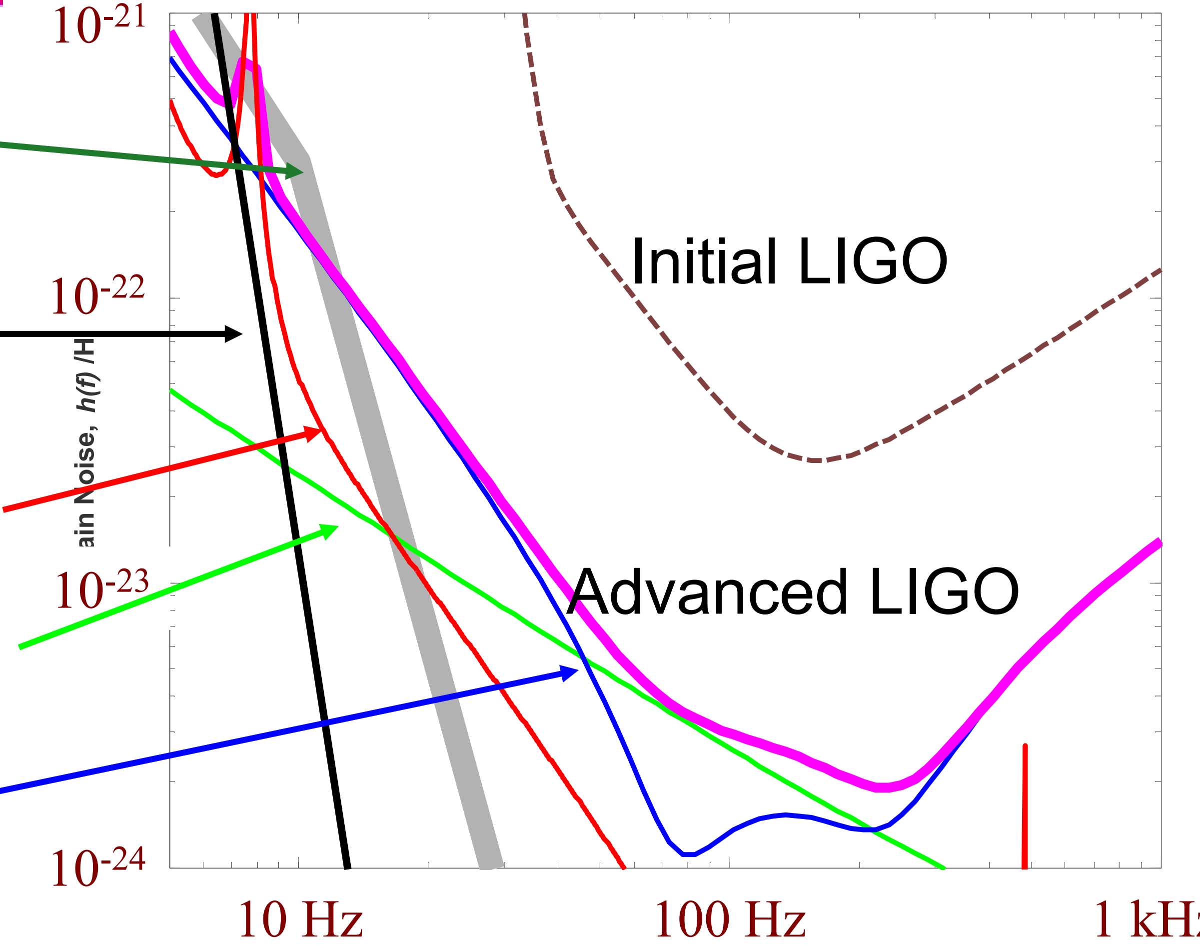
10^{-19} m/ √ Hz at 10 Hz

(h = 5×10^{-23} / √ Hz)

c.f. typical seismic noise level of ~10^{-9} m/ √ Hz at 10 Hz

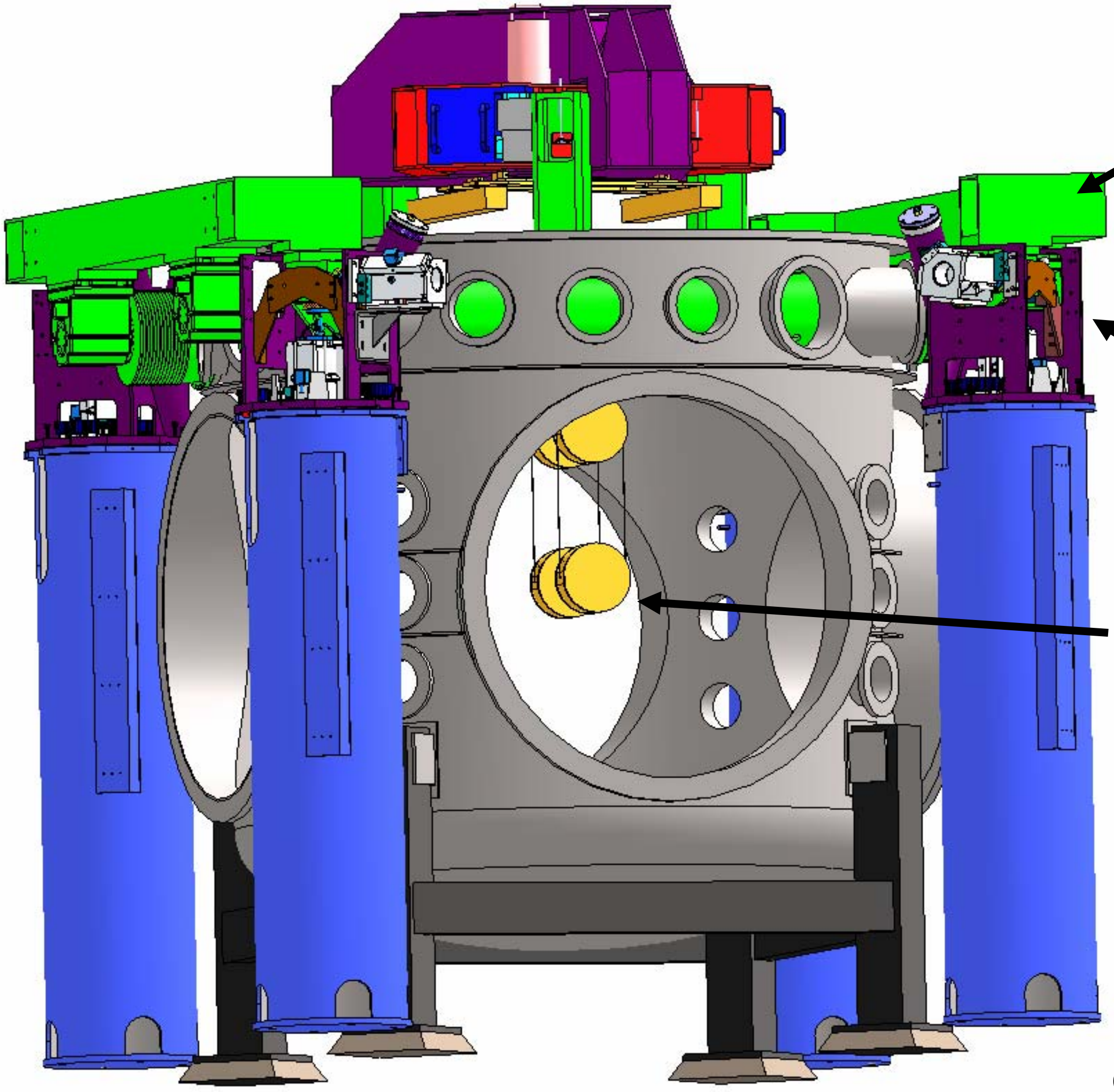
Projected Advanced LIGO detector performance

- Newtonian background, estimate for LIGO site ("gravity gradient" noise)
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



D Shoemaker/adapted

Advanced LIGO Suspension+ Isolation



active isolation platform

Hydraulic pre-isolator (HEPI)

quad pendulum

Corwin Hardham

Baseline Design for Adv. LIGO Main Mirror Suspensions

Modifications required to existing GEO design

- More stringent requirement on mirror thermal noise :-

  use *sapphire* rather than silica mirror for improved thermal noise performance
- More stringent requirement on pendulum thermal noise:-

  use of *ribbons* rather than cylindrical fibres*, to increase dilution factor
- More stringent requirements on isolation and on reduction of local control noise (i.e. for damping):-

  change to *quadruple* suspension, with damping at topmost mass, and three stages of enhanced vertical isolation
- Heavier mirror to reduce radiation pressure noise:-

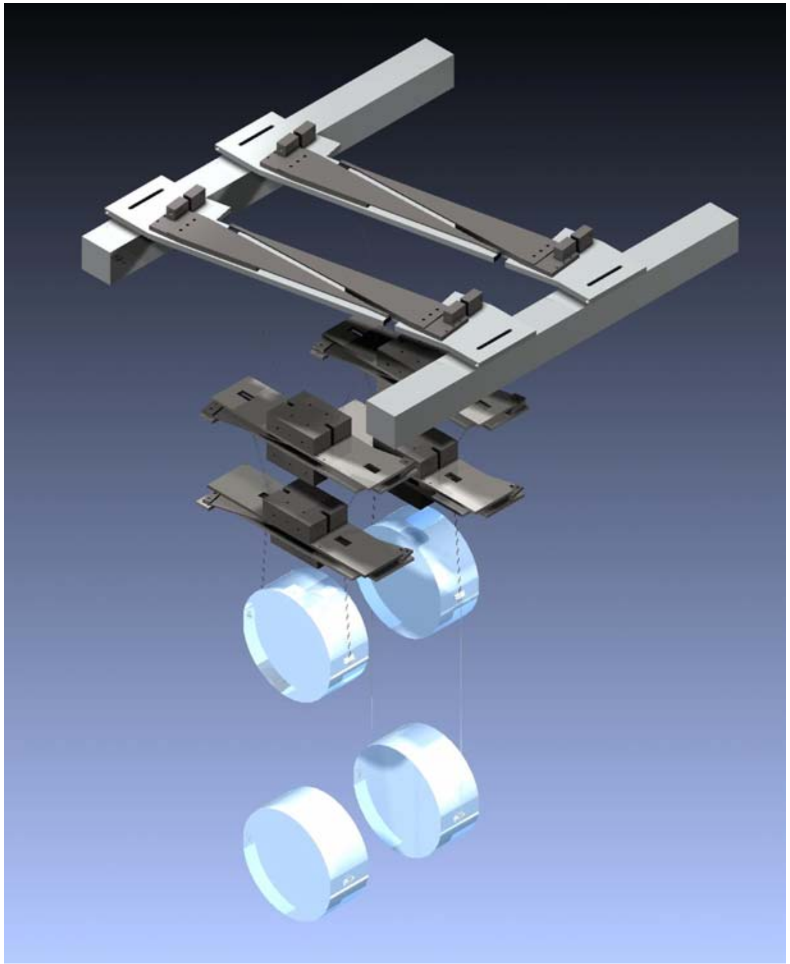
  increase to *40 kg*

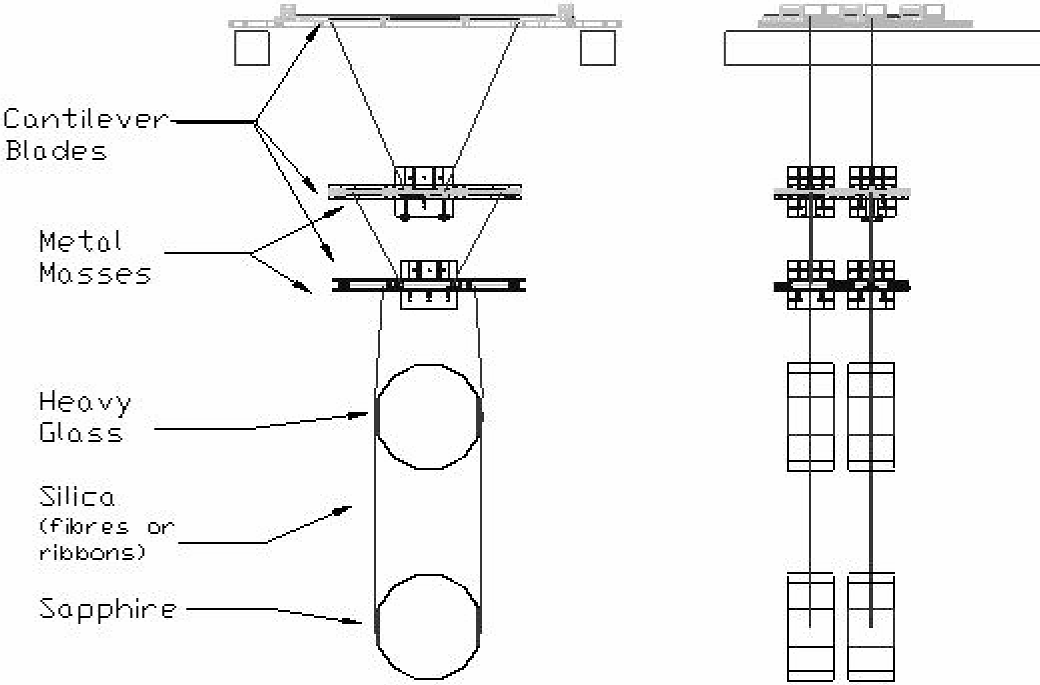
* alternatively use dumbbell fibres with thicker ends optimised to minimise thermoelastic damping (Willems)

Final (Lowest) Stage Design

- Requirements
  - noise performance 10^{-19} m/ √ Hz at 10 Hz per test mass
  - highest vertical mode < 12 Hz
  - violin mode fundamental frequency > 400 Hz
- Parameter choices
  - Fibre length as long as practicable consistent with ease of production
  - Fibre cross-section as small as practicable consistent with safety factor > 3 away from breaking stress
  - Penultimate mass heavy enough to achieve vertical mode <12 Hz
- Ribbons or dumbbell fibres can meet requirements

Quadruple Suspension for Advanced LIGO

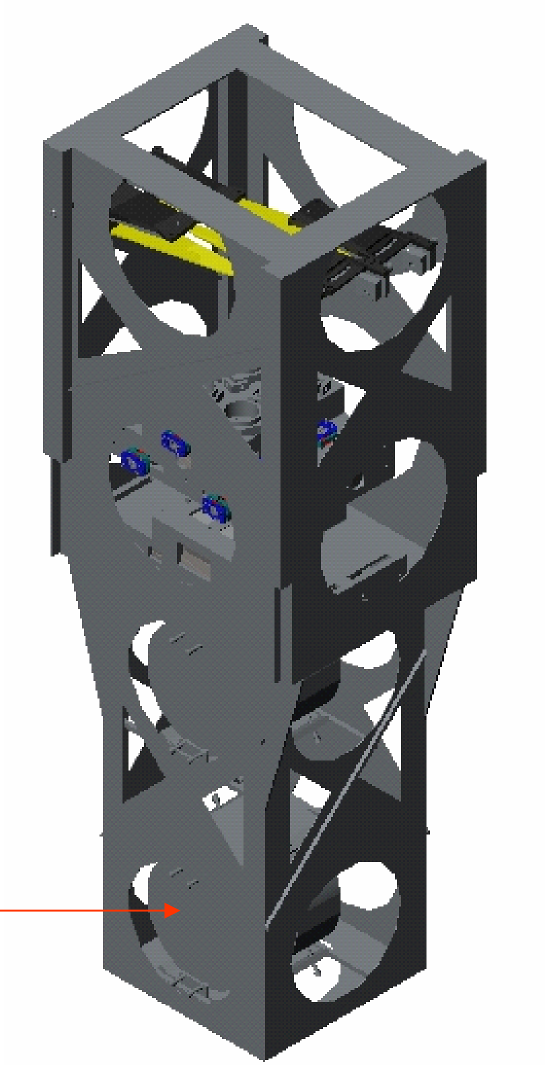




Quad Pendulum inside Support Structure

Weight ~ 400 kg

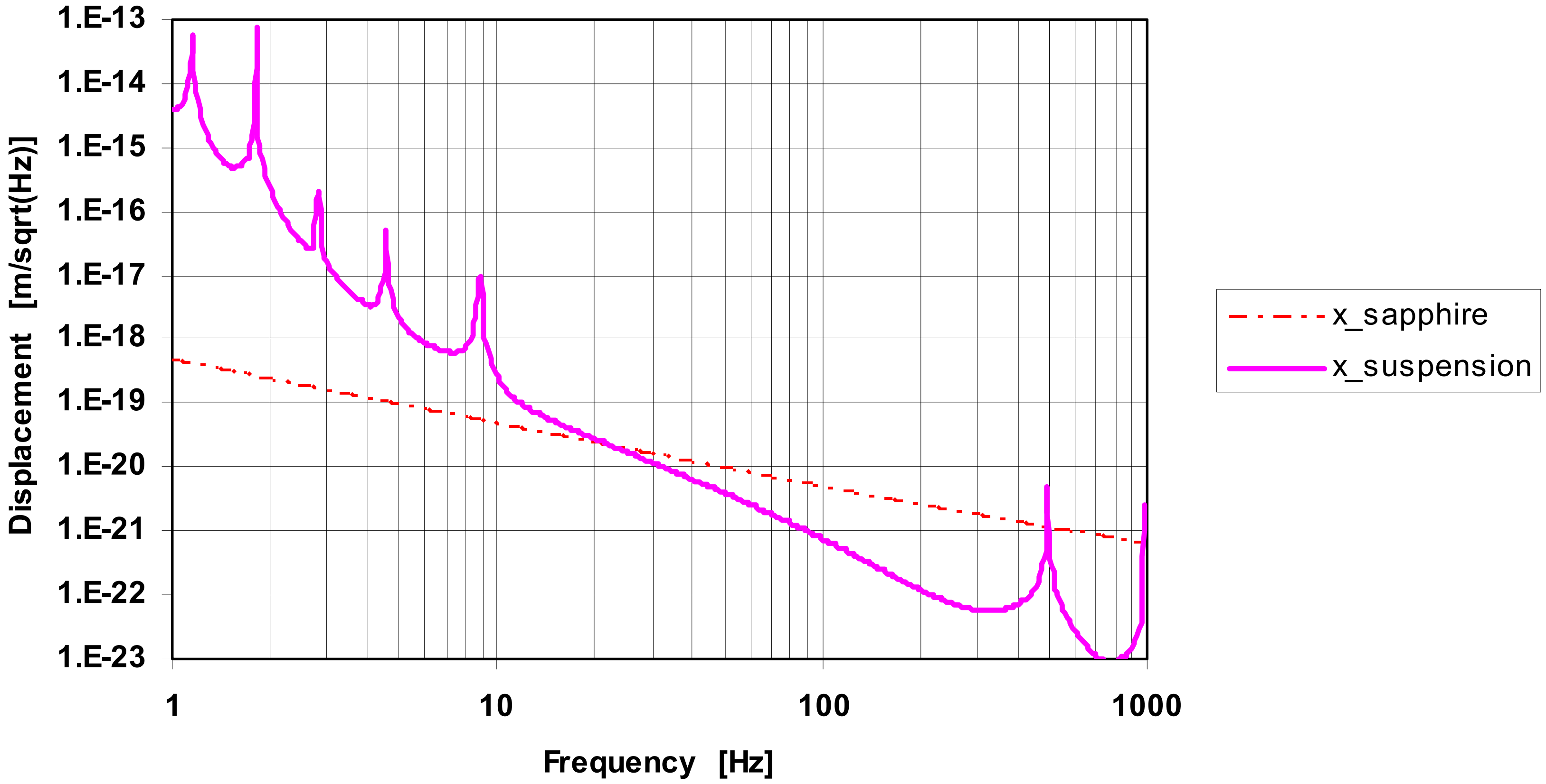
Height ~ 2 m



mirror

D Coyne, C Torrie, M Perreur-Lloyd

Thermal Noise Estimate



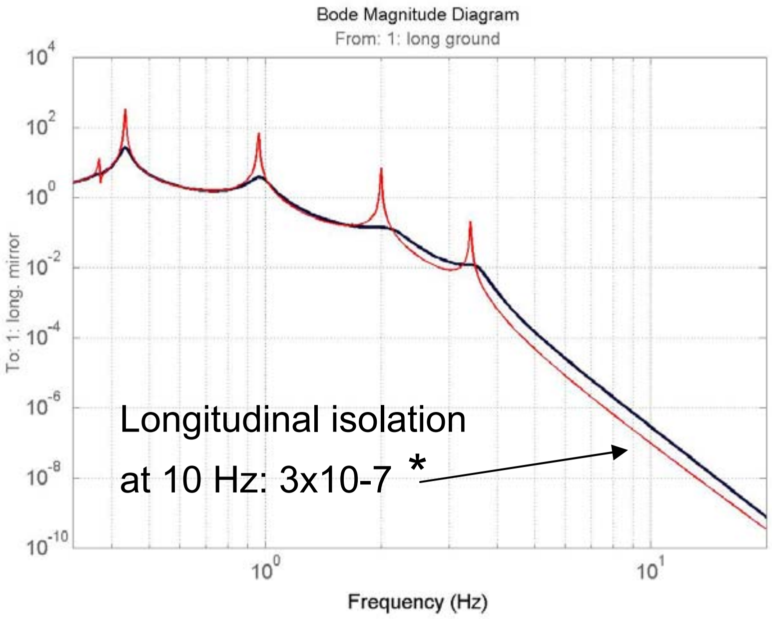
Magenta: suspension thermal noise estimate

Red: sapphire internal noise estimate (no coatings)

Final stage: 60 cm silica ribbons 1.1 mm x 0.11 mm

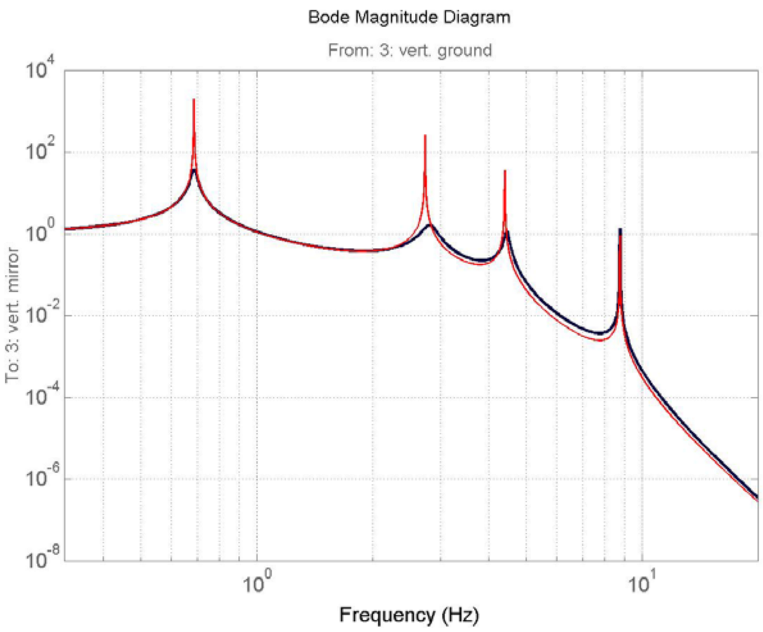
Vertical bounce mode: 8.8 Hz, first violin mode: ~490 Hz

Longitudinal and Vertical Transfer Functions (MATLAB model)



Longitudinal isolation at 10 Hz: 3x10-7 *

Longitudinal TF



Vertical TF

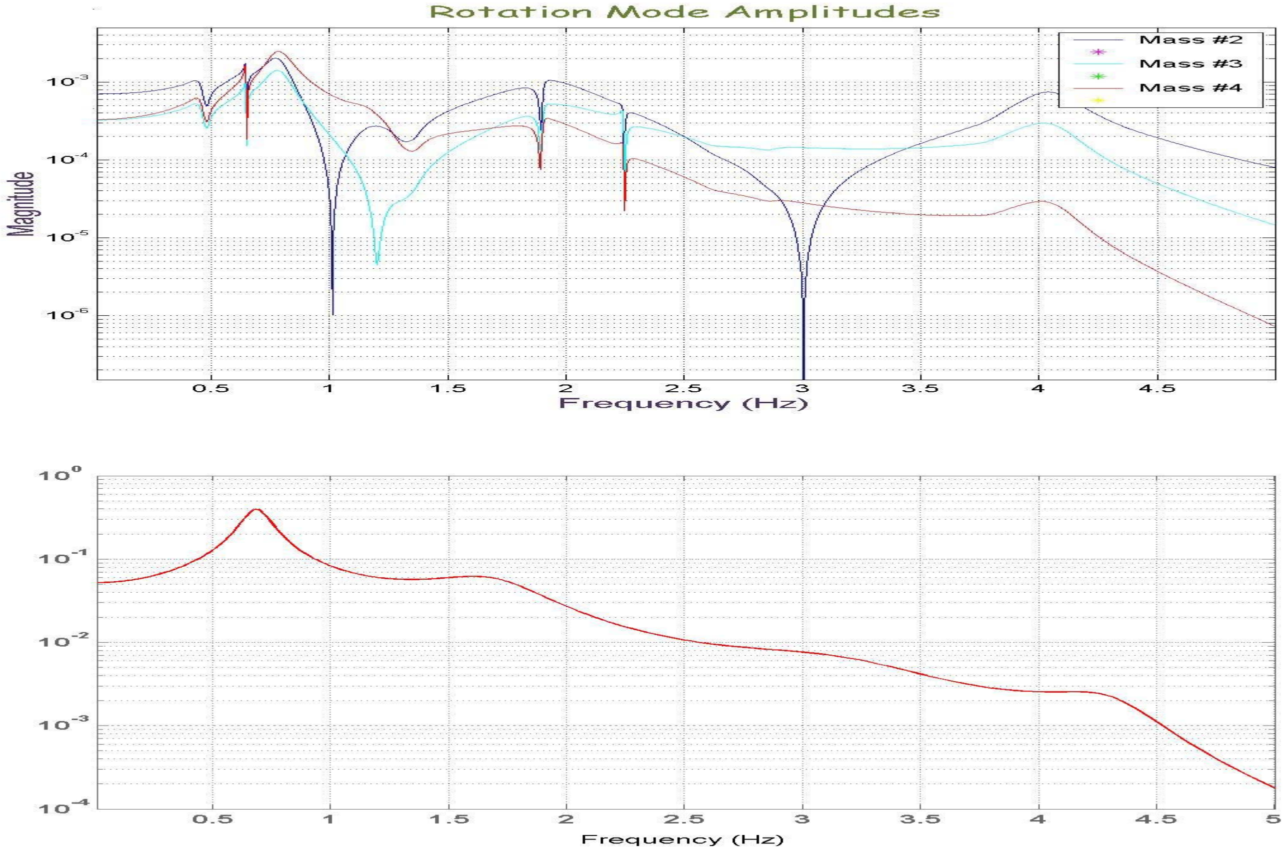
*Combine with isolation system residual noise level of 2x10^-13 m/√ Hz to achieve target sensitivity

Black curve: with active damping
Red curve: without

First Prototype Quadruple Suspension

Prototype all-metal quadruple suspension designed in Glasgow, tested at LIGO MIT.

MIT Quad: Damped Yaw Modes

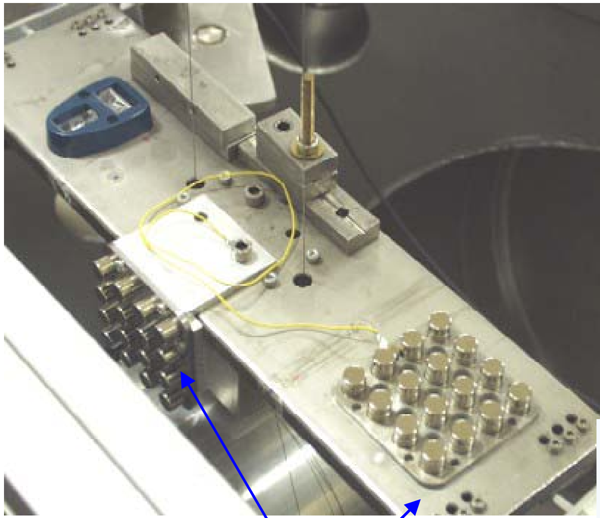


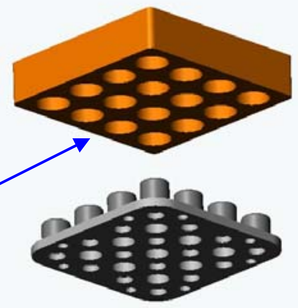
Transfer function from torque at top mass to angular displacement of mass 4 (“mirror”). Top: data, bottom: MATLAB model

Experimental data: R Mittleman

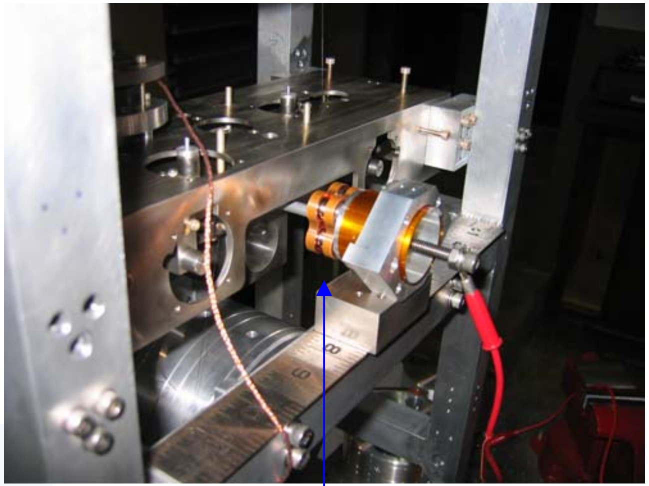
Eddy Current Damping

- Low noise alternative to active control (optical shadow sensors/coil actuators)
- Tests on triple pendulums (Glasgow & Caltech), single pendulum (Caltech)

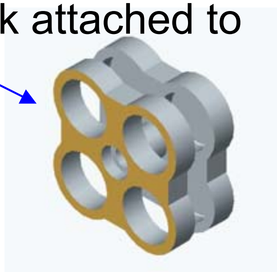




Glasgow: Two 4x4 NdFeB magnet arrays on mass move inside Cu blocks mounted on support (not shown in picture).

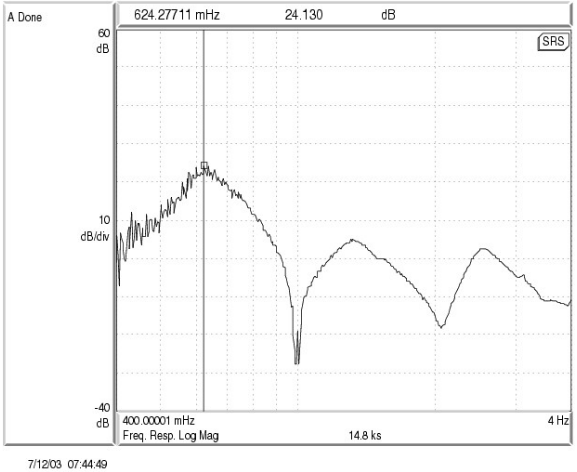


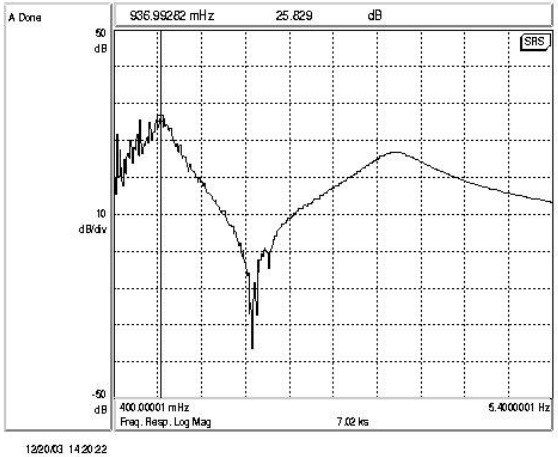
Caltech: One 2x2 magnet array mounted on support sits inside lightweight Cu block attached to moving mass.



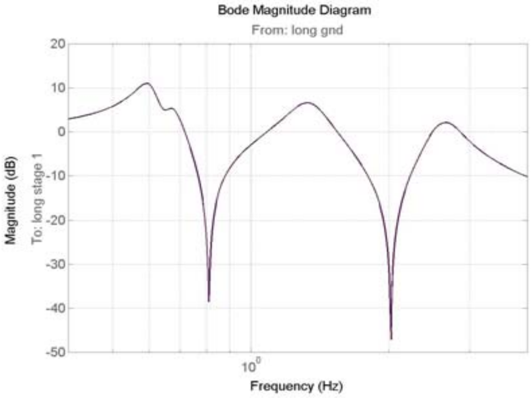
(M Barton, C Cantley, M Plissi, K Strain, C Torrie, NAR)

Some Eddy Current Damping Results

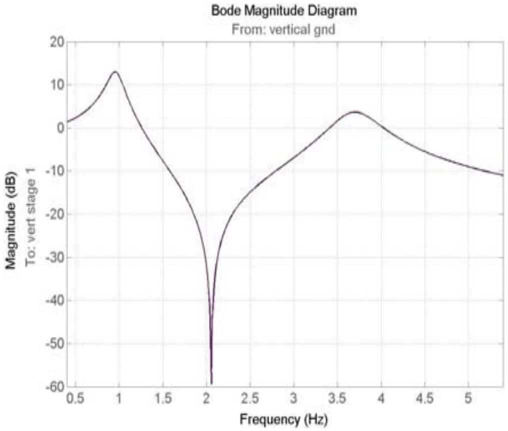




Experimental transfer functions (Glasgow prototype)



MATLAB model



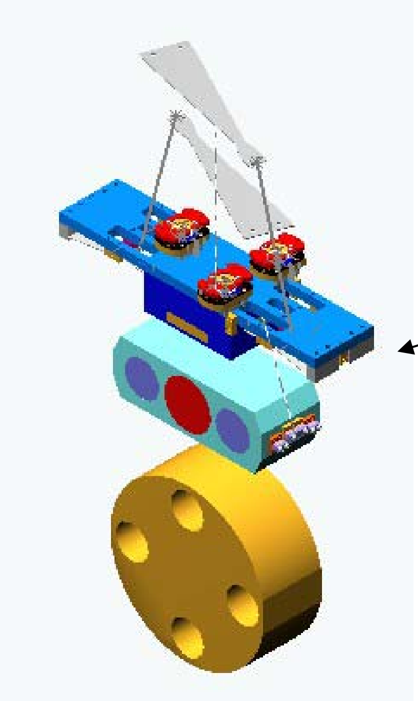
longitudinal

vertical

(M Barton, C Cantley, M Plissi, K Strain, C Torrie, NAR)

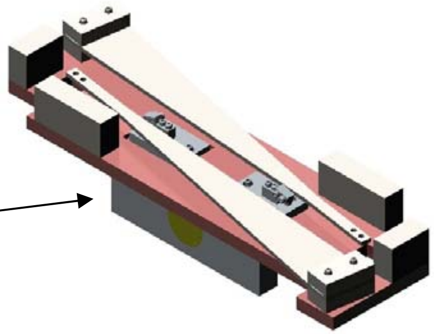
Current Status

- PPARC (UK) have awarded ~$12M grant to Glasgow, Rutherford Lab and Birmingham to develop and fabricate the quadruple suspensions + analog control electronics for Advanced LIGO
- Modecleaner triple pendulum prototype assembled at Caltech. Frequencies agree well with theory and all low frequency modes damped. Delivery to LASTI May 2004



- Recycling mirror triple pendulum prototype : detailed design done in Solidworks

- Test mass quad pendulum prototype: modelling underway. Some detailed design work already done. Aim to deliver prototype to LASTI by Jan 2005



Future Work

- Continuing design, modeling, construction and testing. Some issues still to be resolved, e.g.
  - test mass material (sapphire or silica)
  - design of fibre and ear attachments (losses, strength, reliability)
  - details of damping (low noise sensors, eddy current …..)
- Integration with other subsystems in Adv. LIGO, and overall system integration, such as
  - interaction with seismic platform: mass loading, footprint, layout, magnetic coupling…..
  - interaction with core optics and optical layout
  - control topology
- Evolution of prototypes to be tested at LASTI (MIT):
  - all-metal "control" prototypes,
  - "noise" prototypes with fibre suspensions and "real" mirror

→leading to final design

Suspensions Team

- **LIGO LAB**: CIT: H. Armandula, M. Barton, J. Heefner, J. Romie, C. Torrie, P. Willems. MIT:P. Fritschel, R. Mittleman, D.Shoemaker LHO: B. Bland, D. Cook LLO: J. Hanson, J. Kern, H. Overmier, G. Traylor
- **GEO600**: GLASGOW: G. Cagnoli, C. Cantley, D. Crooks, E. Elliffe, A Grant, A. Heptonstall, J. Hough, R. Jones, M. Perreur-Lloyd, M. Plissi, D. Robertson, S. Rowan, K. Strain, P. Sneddon, H. Ward UNIVERSITAT HANNOVER: S. Gossler, H. Lueck
- **STANFORD UNIVERSITY**: N. Robertson (also GEO/Glasgow)
- **RUTHERFORD APPLETON LABORATORY**: J. Greenhalgh, I. Wilmut
- **THE UNIVERSITY OF BIRMINGHAM**: S. Aston, C. Castelli, D. Hoyland, C. Speake
- **STRATHCLYDE UNIVERSITY**: N. Lockerbie