Advanced LIGO Suspensions Subsystem Design Requirements Review

20 September 2001

Peter Fritschel, Norna Robertson, Janeen Romie, Phil Willems

Agenda

- ❑ Introduction – Peter F, 10 min
- ❑ Design Requirements – Phil W, 1 hr
- ❑ Conceptual Design – Norna R, 1 hr
- ❑ Testing and development plan – Janeen R, 15 min

Review Committee

- Members: Gabriela Gonzalez, Brian Lantz, Virginio Sannibale, Ben Abbott, Warren Johnson

- Charge:

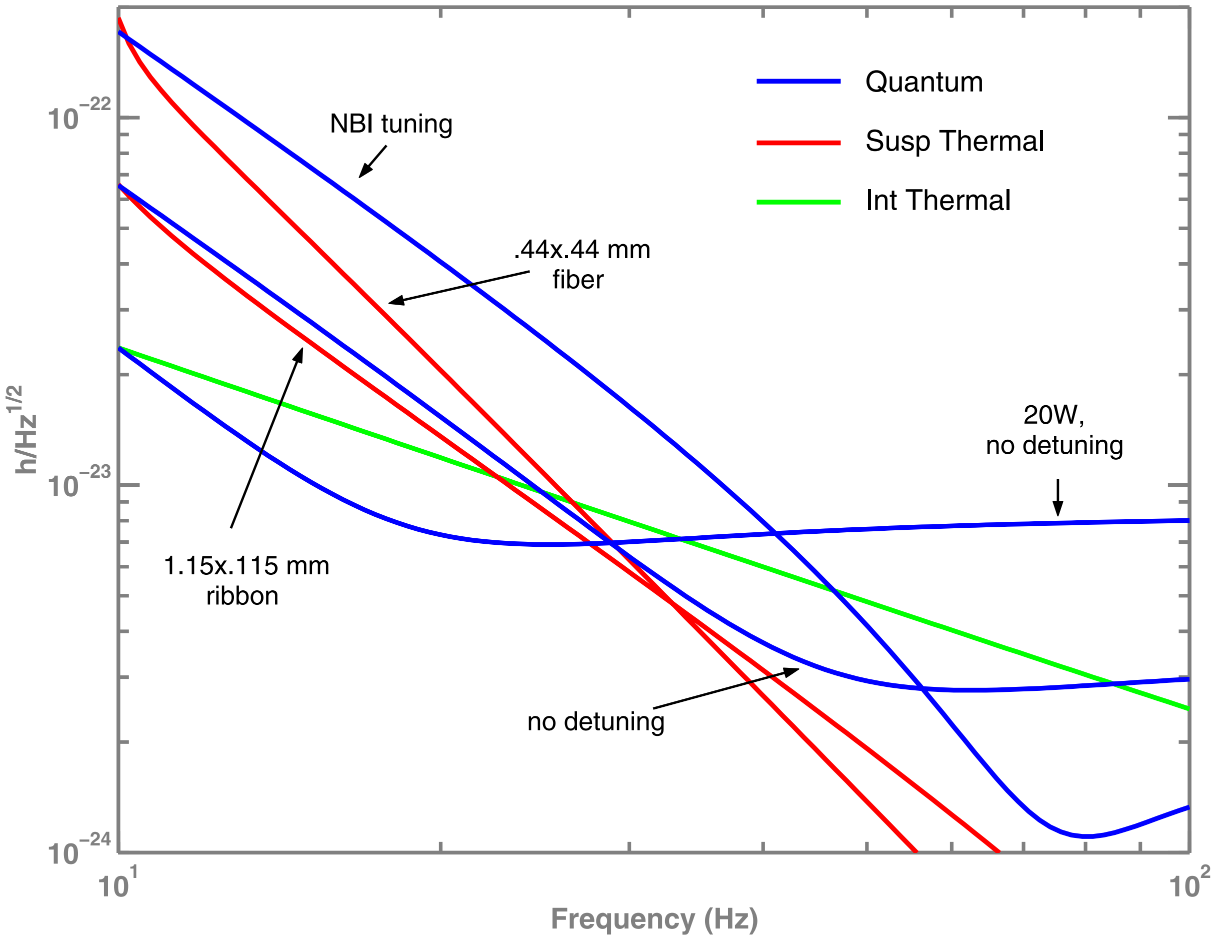
  • Determine whether the requirements identified in the Design Requirements Document are complete; advise whether the proposed requirement values are appropriate; if needed, recommend additional requirements to be specified; and recommend other appropriate actions. Some specific points to consider are:

    - definition of the scope and objectives
    - performance requirements
    - delineation of interfaces
    - physical and environmental requirements
    - documentation
    - testing requirements

  • Evaluate the conceptual design to determine if it is consistent with the stated requirements and sufficiently developed to proceed with the Preliminary Design phase.

Systems Design Update

- ❑ Factor of 2 increase in suspension thermal noise in Bench ⇒ low frequency performance:



➢ *circular fiber noise now dominates quantum noise when operated with no detuning*

Low Frequency Cutoff

- For this review:
  - Requirement is (continues to be)10 Hz, 1e-19 m/rtHz (forcing vertical 'bounce' mode of suspension below 10 Hz)
  - Suspension design team has been asked to present the technical risks, challenges, and tradeoffs associated with achieving a sub-10 Hz vertical mode
- Larger picture:
  - The various technical risks and possibilities, and the astrophysical source detection impact, continue to be analyzed
  - Plan is to pull this together in a 'Position Paper' within the next ~month

Suspension Design Requirements

Phil Willems, Caltech

Suspensions Design Requirements Review,
Sept. 20, 2001

Overview

- Requirements are presented here only for cavity optics in the HAM's and BSC's:
  - » Test masses
  - » Beamsplitter
  - » Power and signal recycling mirrors
  - » Folding mirrors in folded interferometer
  - » Mode cleaner mirrors
- Performance requirements are presented, along with physical justifications for those requirements.
- Outstanding issues are listed.

Test Mass Suspensions

- The test mass suspensions limit or nearly limit the detector sensitivity in much of the frequency range through thermal noise of the suspension and test mass, even with best available technology.
- For this reason, certain ‘requirements’ are in fact input parameters, and other noise sources are scaled to them. These parameters are shown in black type.
- Baseline is 40kg sapphire, 31.4cm diameter by 13cm thick. Input parameters will change if fused silica is chosen. Coating and polish thermal noise are also not figured into requirements yet.

Test Mass Suspensions, cont.

- For now it is taken as a requirement that the vertical bounce frequency be below 10Hz. Similar requirements on vertical bounce frequencies for other suspensions are linked to this requirement.
- Seismic noise input is assumed to be requirement output spectrum in SEI DRD.
- ‘Requirement’ for suspension thermal noise is probably too low; should it be revised?

TM Suspensions Requirements: Thermal Noise

Parameter	Value	Discussion
Longitudinal thermal noise due to test mass internal modes	5×10^{-20} m/√Hz at 10 Hz, falling roughly as 1/f	Figure 1; see section 3.2.1.2.1.
Longitudinal thermal noise due to pendulum motion	10^{-19} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	This needs revision to better reflect quantum noise and changes to Bench
Pitch thermal noise	5×10^{-17} rad/√Hz at 10 Hz, falling roughly as (1/f)	Requirement driven by offset of beam from center of mirror
Yaw thermal noise	5×10^{-17} rad/√Hz at 10 Hz, falling roughly as (1/f)	Requirement driven by offset of beam from center of mirror
Vertical transverse thermal noise	10^{-16} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Assumes vertical to longitudinal motion coupling of 10^{-3}
Horizontal transverse thermal noise	10^{-16} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Based on .001 coupling to longitudinal motion

TM Suspensions Requirements: Seismic Noise

Longitudinal	10^{-19} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Pitch axis	$4\text{x}10^{-17}$ rad/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Yaw axis	$4\text{x}10^{-17}$ rad/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Horizontal transverse	10^{-16} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	Assumes horizontal transverse to longitudinal motion coupling of 10^{-3}
Vertical transverse	10^{-16} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	Assumes vertical to longitudinal motion coupling of 10^{-3}

Recycling Mirror Suspensions

- Signal and power recycling mirrors have identical dimensions (26.5x10cm) and nearly identical noise requirements (assuming RF readout scheme, worst case for PRM). Therefore their requirements (and presumably design) are set in common.
- No source of noise in the RM suspensions is expected to set a fundamental limit to sensitivity. Therefore all noise- seismic, thermal, technical- is converted to equivalent longitudinal displacement noise and lumped together to set the requirement.

Recycling Mirror Suspensions, cont.

- Vertical bounce need not be below 10Hz, but must be sufficiently narrow to be filtered from data without substantial loss of bandwidth. The same goes for suspension violin modes.
- Many DOF's have noise levels set by wedge angles in the optics. These angles are not yet fixed for the unfolded IFO's and are completely unknown for the folded IFO.

RM Suspension Requirements

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	4×10^{-16} m/√Hz at 10 Hz, falling to 1.5×10^{-17} m/√Hz at 100 Hz	See section 3.2.2.2.1 and the seismic isolation requirements
Pitch noise	4.4×10^{-14} rad/√Hz at 10 Hz, falling to 1.7×10^{-15} rad/√Hz at 100 Hz	Requirement driven by optical path length through wedged ITM
Yaw noise	2.7×10^{-14} rad/√Hz at 10 Hz, falling to 1×10^{-15} rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter
Vertical transverse displacement noise	2.2×10^{-13} m/√Hz at 10 Hz, falling to 8.3×10^{-15} m/√Hz at 100 Hz	Assumes coupling of vertical to longitudinal motion of .0018; see section 3.2.2.2.4
Horizontal transverse noise	4×10^{-13} m/√Hz at 10 Hz, falling to 1.5×10^{-14} m/√Hz at 100 Hz	See section 3.2.2.2.5

Beamsplitter Suspensions

- Beamsplitter suspension is not expected to limit sensitivity, so all noise sources are converted to equivalent longitudinal displacement noise and lumped together to set the requirement.
- Vertical bounce frequency must be below 10Hz.

BS Suspension Requirements

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	2×10^{-17} m/√Hz at 10 Hz, falling to 6×10^{-19} m/√Hz at 100 Hz	See section 3.2.3.2.1
Pitch noise	2.9×10^{-15} rad/√Hz at 10 Hz, falling to 8.6×10^{-17} m/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror and ITM vertical wedge; See section 3.2.3.2.2
Yaw noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter; See section 3.2.3.2.3
Vertical transverse displacement noise	2.2×10^{-15} m/√Hz at 10 Hz, falling to 6.7×10^{-17} m/√Hz at 100 Hz	Assumes vertical to longitudinal motion coupling of .009; see section 3.2.3.2.4
Horizontal transverse noise	2×10^{-14} m/√Hz at 10 Hz, falling roughly as 1/f	See sections 3.2.3.2.5

Mode Cleaner Suspensions

- The requirements here are for the input mode cleaner. The output mode cleaner requirements and configuration require analysis at the systems level and choice of readout scheme.
- Vertical bounce frequency need not be below 10Hz.

MC Suspension Requirements

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	$3x10^{-17}$ m/√Hz at 10 Hz, falling to $3x10^{-19}$ m/√Hz at 100 Hz	See section 3.2.5.2.1
Pitch noise	$3x10^{-14}$ rad/√Hz at 10 Hz, falling to $3x10^{-16}$ rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror
Yaw noise	$3x10^{-14}$ rad/√Hz at 10 Hz, falling to $3x10^{-16}$ rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror
Vertical transverse displacement noise	$3x10^{-14}$ m/√Hz at 10 Hz, falling to $3x10^{-15}$ m/√Hz at 100 Hz	Assumes vertical to longitudinal motion coupling of .001; see sections 3.2.5.2.4
Horizontal transverse noise	$3x10^{-14}$ m/√Hz at 10 Hz, falling to $3x10^{-15}$ m/√Hz at 100 Hz	See sections 3.2.5.2.5

Folding Mirror Suspensions

- These requirements are for the folding mirrors in the BSC's of the folded interferometer only.
- Mass and size of FM suspensions are constrained since they share their seismic platforms with the ITM's.
- Vertical noise requires knowledge of optics layout before requirements can be set.

FM Suspension Requirements

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	2×10^{-17} m/√Hz at 10 Hz, falling to 6×10^{-19} m/√Hz at 100 Hz	See section 3.2.4.2.1 and the seismic isolation requirements
Pitch noise	4×10^{-15} rad/√Hz at 10 Hz, falling to 1.2×10^{-16} rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror
Yaw noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter
Vertical transverse displacement noise	TBD	Vertical to longitudinal motion coupling TBD; see sections 3.2.4.2.4-5
Horizontal transverse noise	2×10^{-14} m/√Hz at 10 Hz, falling to 6×10^{-16} m/√Hz at 100 Hz	See sections 3.2.4.2.4-5

Control Requirements

- The local damping on the suspensions must:
  - » Be adjustable (to zero damping if possible for TM's)
  - » Not introduce noise above requirements if left on
  - » Reduce the Q of all suspension body modes (save vertical and roll of bottom mass) to 10

General Suspension Requirements

- This is mostly dull stuff, <u>except:</u>

  » "The Mean Time Between Failures (MTBF) for all in-vacuum components in all suspensions collectively shall be at least two years per interferometer. The MTBF for all extra-vacuum components collectively shall be at least six months. "

Outstanding Issues

- Do we shoot for 10Hz or not?
- Sapphire vs. fused silica
- Suspension thermal noise requirement for TM’s
- Output mode cleaner
- Optical layout drives many noise requirements; folded interferometer layout needed
- New materials must be qualified for use in the LIGO vacuum:
  - » Maraging steel
  - » Phosphor bronze
  - » PFA440HP Teflon
  - » Hydroxy-catalysis bonds?

Outstanding Issues, cont.

- Many ‘minor’ suspensions requirements are still not determined (though LIGO I suspensions should do):
  - » Steering mirrors
  - » Photodetector
  - » Faraday isolator? (probably not)
  - » Mode-matching telescope
- Compensator plates
- New materials must be qualified for use in the LIGO vacuum:
  - » Maraging steel
  - » Phosphor bronze
  - » PFA440HP Teflon
  - » Hydroxy-catalysis bonds?

Advanced LIGO Suspension Conceptual Design

Presentation at

Advanced LIGO Suspension Design Requirements Review

Norna A Robertson for the GEO Suspension Team

September 20th 2001

DCC number : G010379-00-D

Conceptual Design for Advanced LIGO

- Suspension design based on modified GEO 600 triple pendulum
- Key points in GEO design:
  - The fused silica mirrors (6 kg) form the lowest stage of a triple pendulum, and are suspended on 4 vertical fused silica fibres of circular cross-section to reduce suspension thermal noise.
  - The penultimate mass is also made of fused silica identical in size to the mirror.
  - The fibres are welded to fused silica “ears” or prisms which are silicate bonded to the flat sides of the penultimate mass and the mirror below. This technique preserves the high Q of the test mass – essentially one has a *monolithic fused silica pendulum*
  - Included in the triple pendulum are two stages of cantilever springs made of maraging steel to enhance the vertical seismic isolation.

Conceptual Design for Advanced LIGO contd

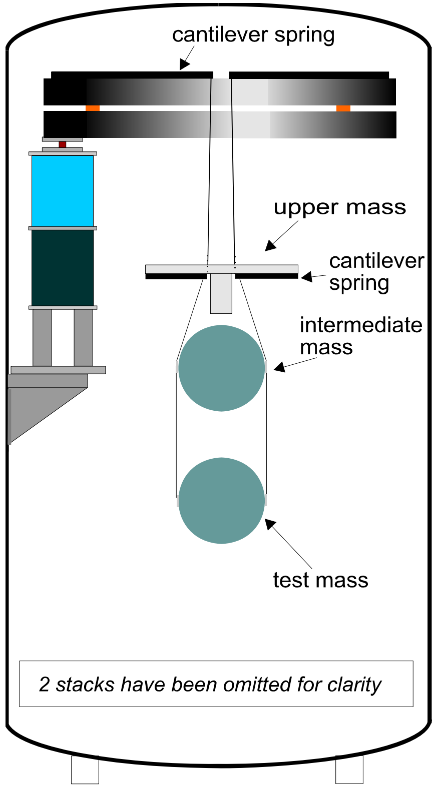
- Damping of all of the low frequency modes achieved by using 6 co-located sensors and actuators at the highest mass of triple pendulum

- DC alignment of mirror yaw and pitch done by applying forces to the actuators at the highest mass, with lower stages like a marionette

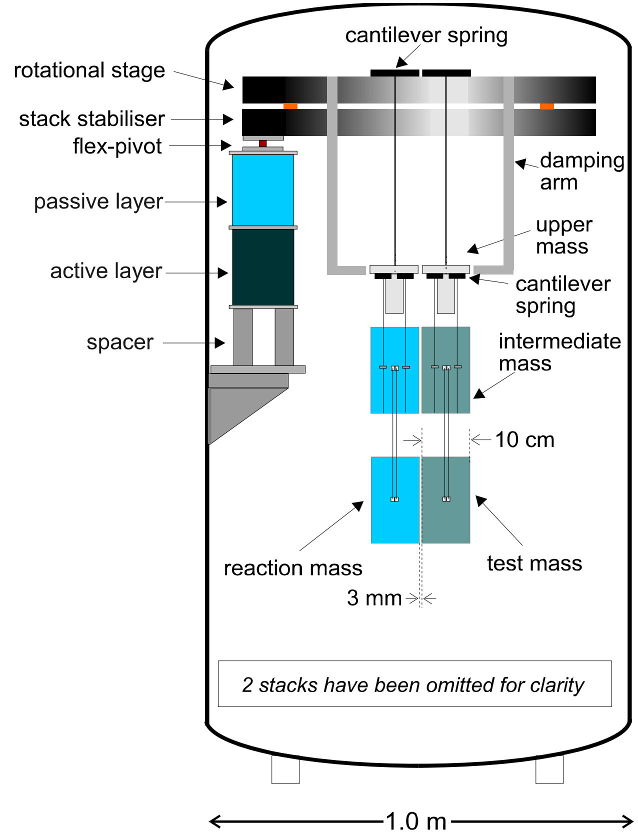
- Global control forces applied via a triple reaction pendulum, essentially identical in mechanical design to the main triple pendulum

- Global control carried out using a split feedback system:
  - large low frequency motions applied magnetically between the penultimate masses
  - small higher frequency signals applied electrostatically between the mirror and corresponding lowest reaction mass made of silica with a patterned gold coating.

GEO 600 Main Suspension

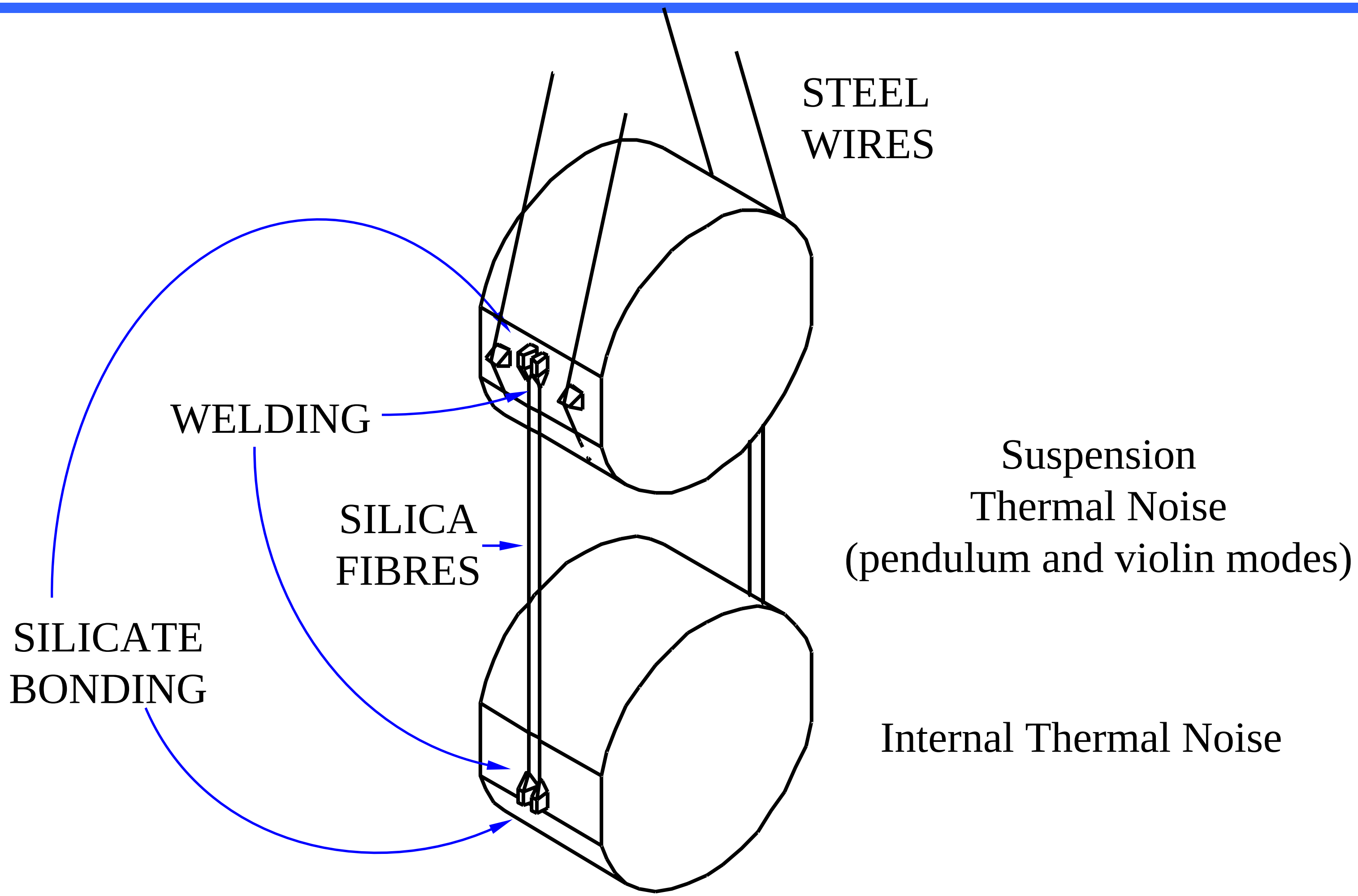


FACE VIEW

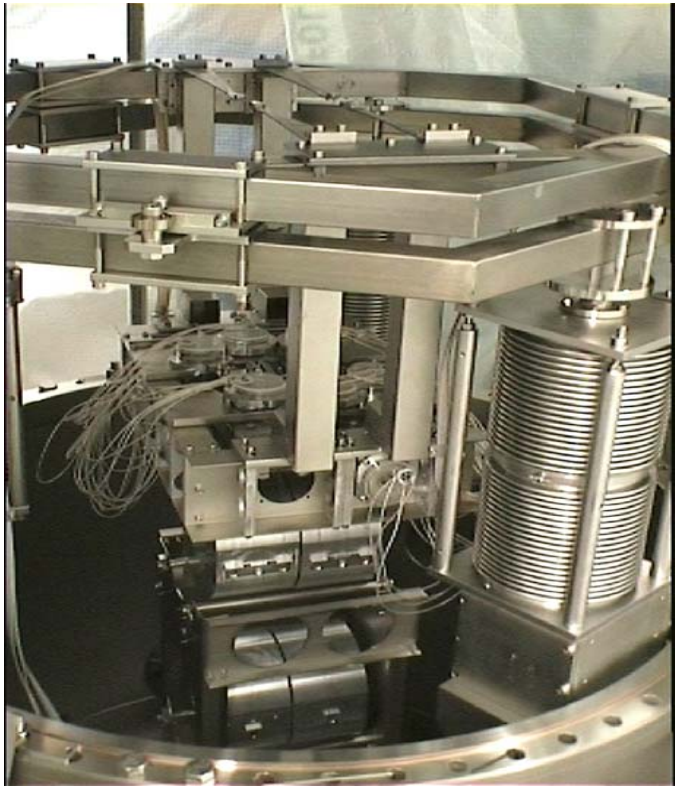


SIDE VIEW

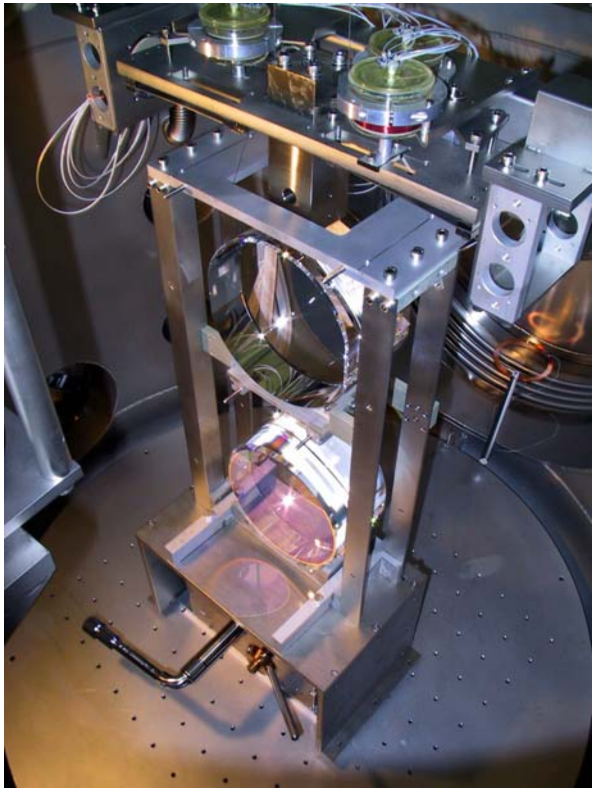
Monolithic Suspension - Detail



GEO Suspension System



Triple pendulum + reaction pendulum in situ (all metal)



Triple pendulum with monolithic final stage in situ

Baseline Design for Adv. LIGO
Main Mirror Suspensions

Modifications required to existing GEO design

- More stringent requirement on internal thermal noise performance:-

  sapphire rather than silica for mirror for improved internal thermal noise performance

- More stringent requirement on pendulum thermal noise:-

  use of *ribbons* rather than fibres

- More stringent requirements on reduction of seismic noise and local control noise (i.e. for damping):-

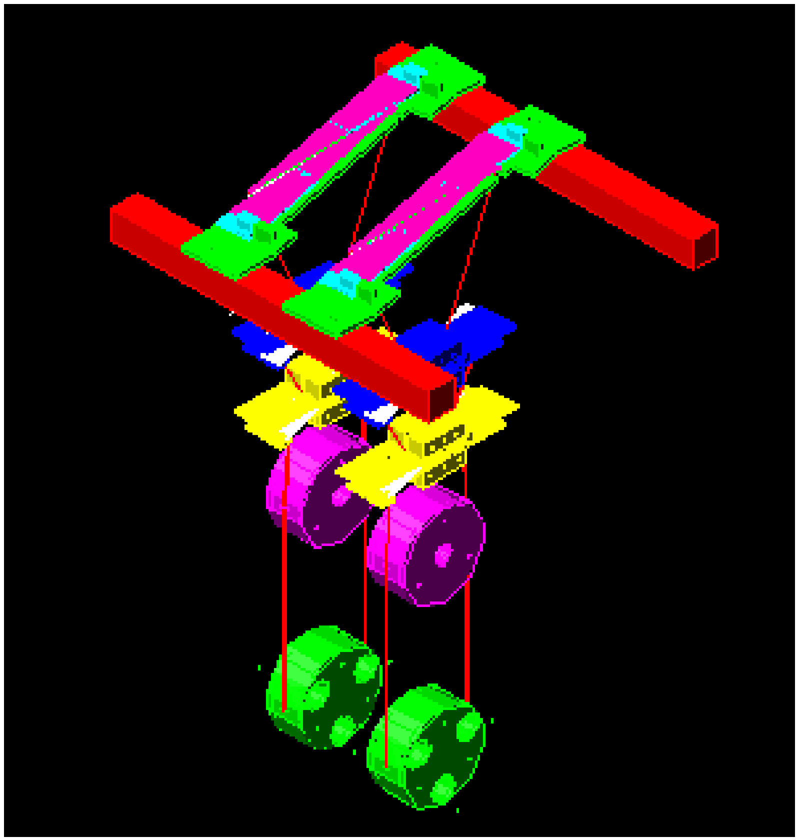
  change to *quadruple* suspension, with damping at topmost mass, and three stages of enhanced vertical isolation

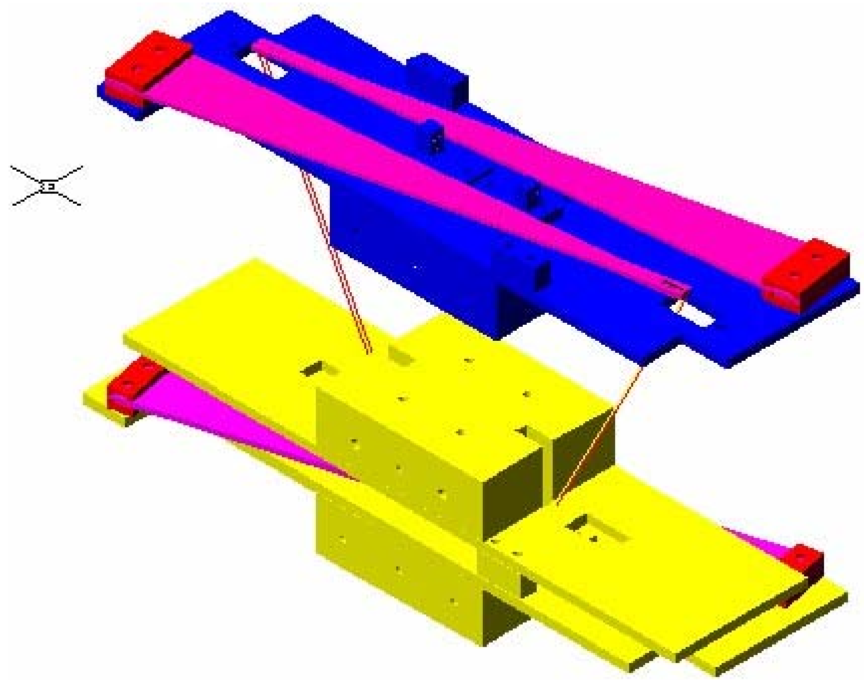
Design Description: Thermal Noise Issues

- To meet 10^{-19} m/rt Hz requires ribbons rather than fibres
  - Leads to issues of strength, reliability, loss, twists to avoid buckling

- To meet 10 Hz target for upper vertical mode –
  - use long fibre length in final stage (60 cm)
  - use fibre cross-section as small as practicable
  - use heavy penultimate mass

Design Description: Mechanical Design





Design Description: Control Issues

- Local Control Issues: Isolation of sensor noise involves
  - Sensor noise level
  - Isolation of sensor noise by multiple pendulum
  - Allowable level of residual motion (residual Qs)
  - Possibility for global actuation to take over (certain degrees of freedom)
- Possible alternative – eddy current damping
  - Fixed Qs OK?
  - Require diagnostic sensors and actuators as well?

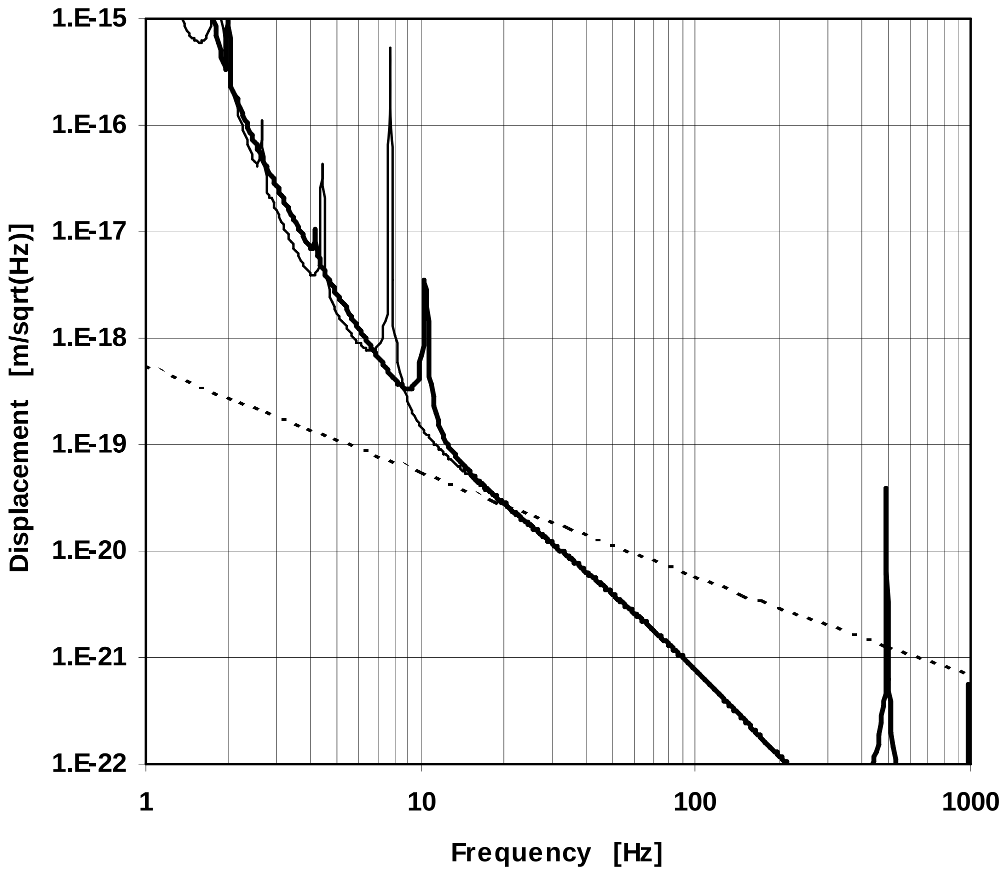
Design Description: Control Issues contd

- Global Control – general philosophy
  - Use of reaction chain + split feedback
  - Hierarchical signal and bandwidth (large low bandwidth signals higher up chain etc)
  - Magnetic actuators higher up, electrostatic or photon drive lower down
- Global control – issues
  - How much bandwidth and hence how many stages
  - Which mirrors need which type/level of drive
  - Final stage – photon drive?
  - Violin mode damping

Design Description: Other Design Issues

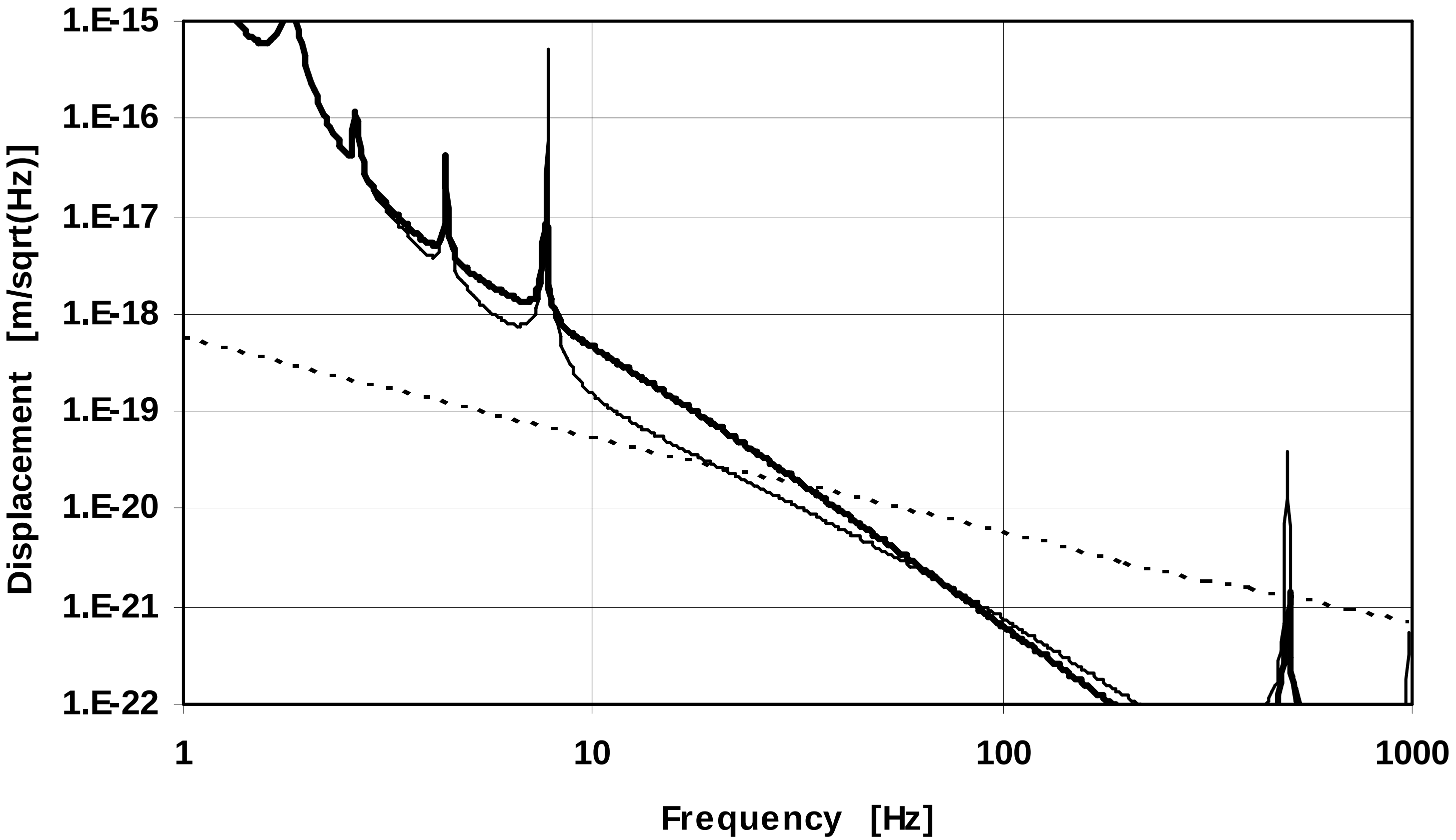
- Method of mechanical assembly – advocate full metal suspension built for all assemblies, then substitute mirror/fibre assembly
- Loading curved blades, and maintaining load during changes
- Clamp design
- Interfacing
- Handling
- Footprints

Quadruple Pendulum: Thermal Noise



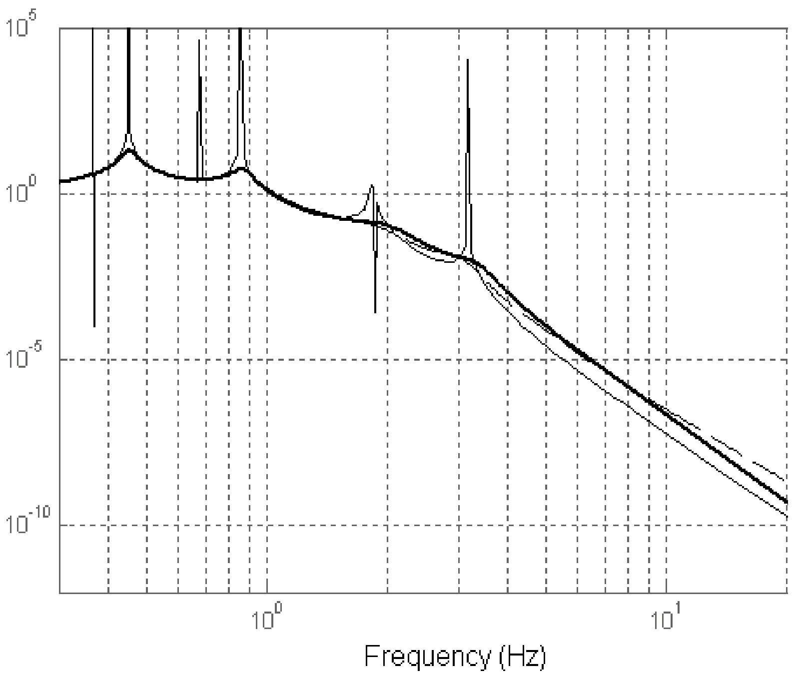
light solid curve – baseline, heavy solid curve – light penultimate mass, dotted line – sapphire internal thermal noise

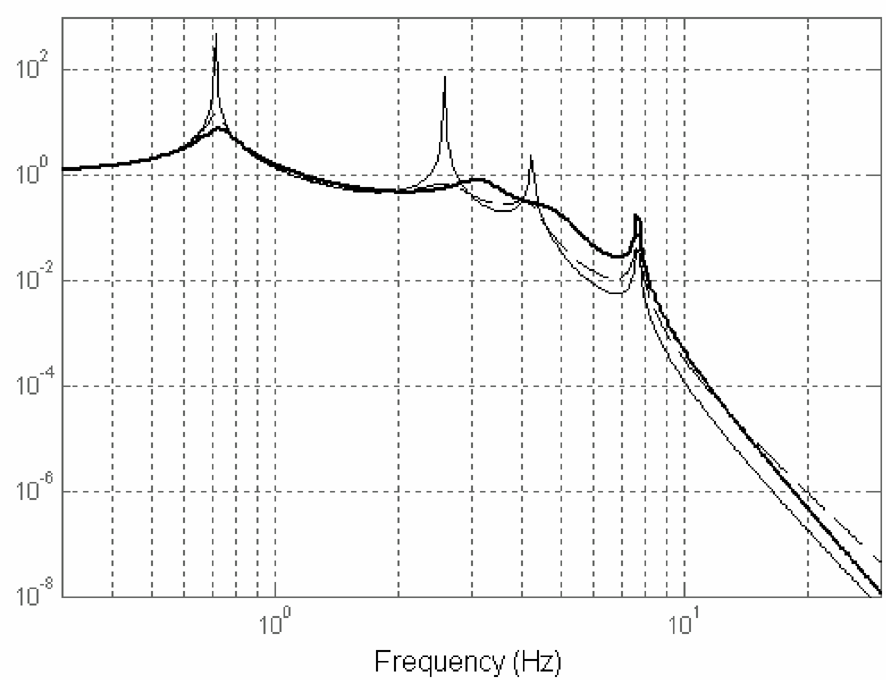
Quadruple Pendulum: Thermal Noise



Light solid curve – baseline, heavy solid curve – circular fibres, dotted curve – sapphire internal

Quadruple Pendulum: Isolation





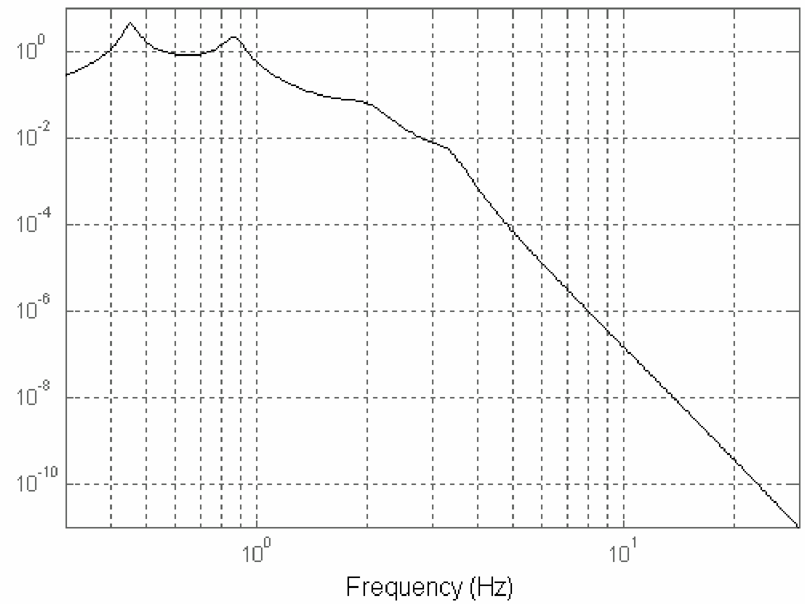
Longitudinal isolation
At 10 Hz: 2×10^{-7}, damped

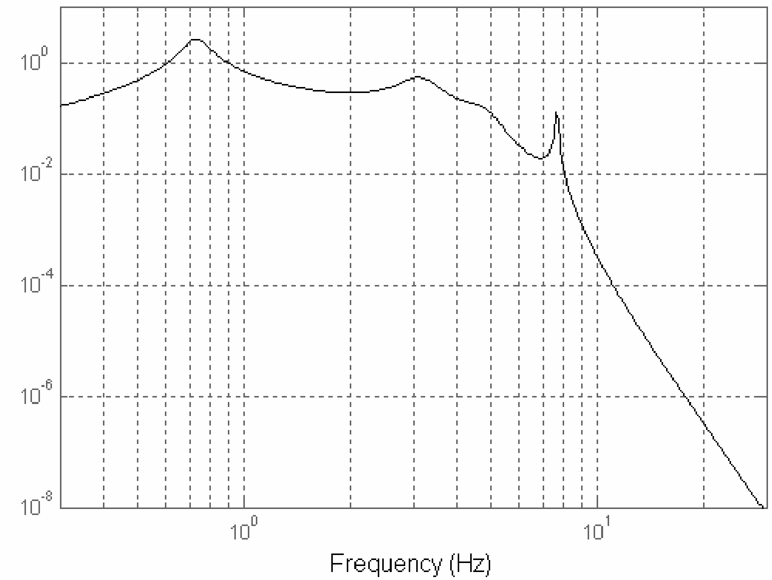
Vertical isolation
At 10 Hz: 4.5×10^{-4}, damped

Heavy line – with local controls, light line – without, dashed – eddy current damping

Quadruple Pendulum: Sensor Noise

Transfer functions : sensor to mirror





Longitudina
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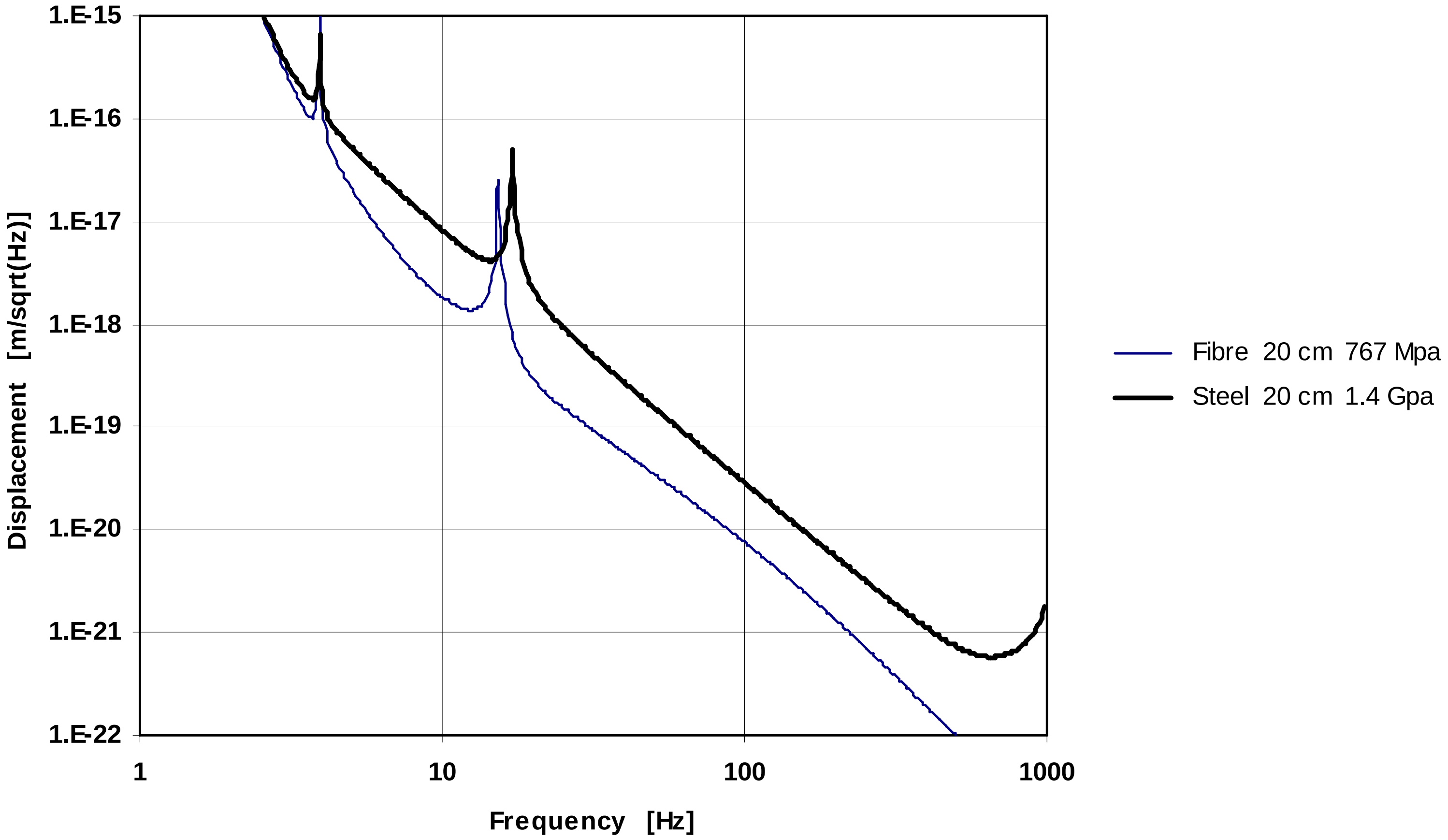
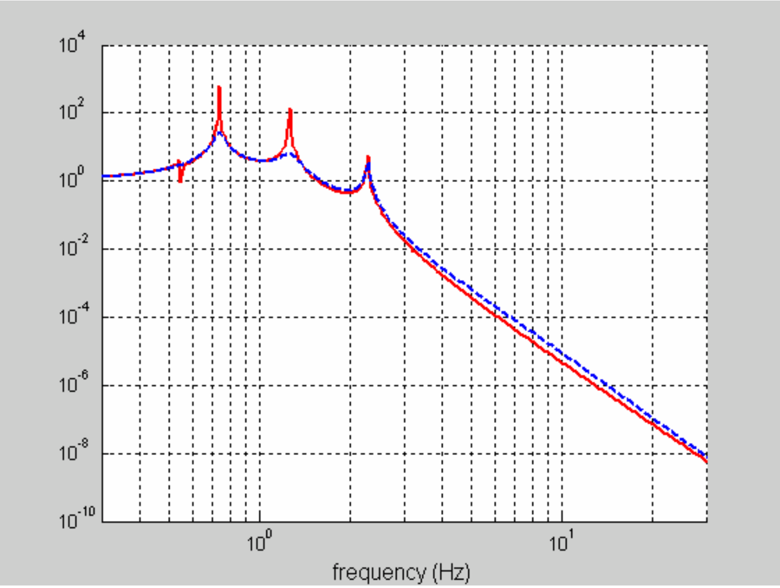
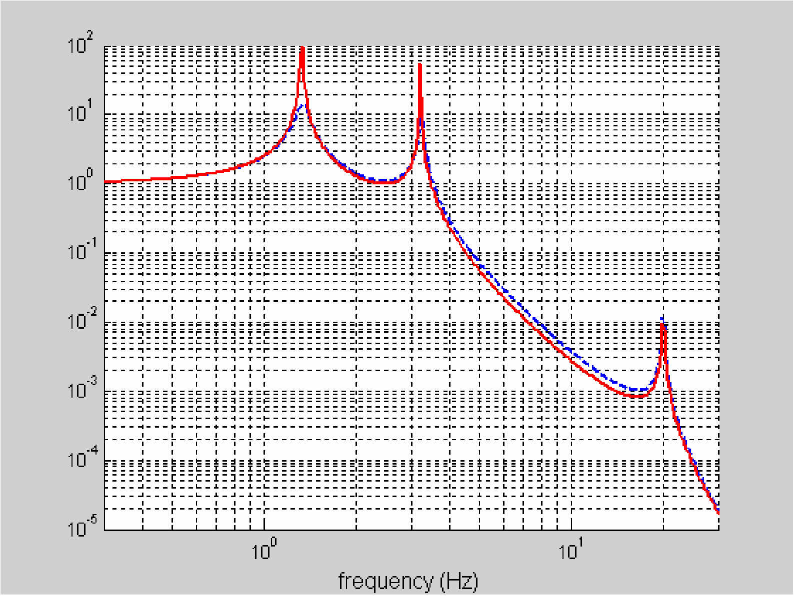
Vertical

Triple Pendulum: Thermal Noise



Triple Pendulum: Isolation



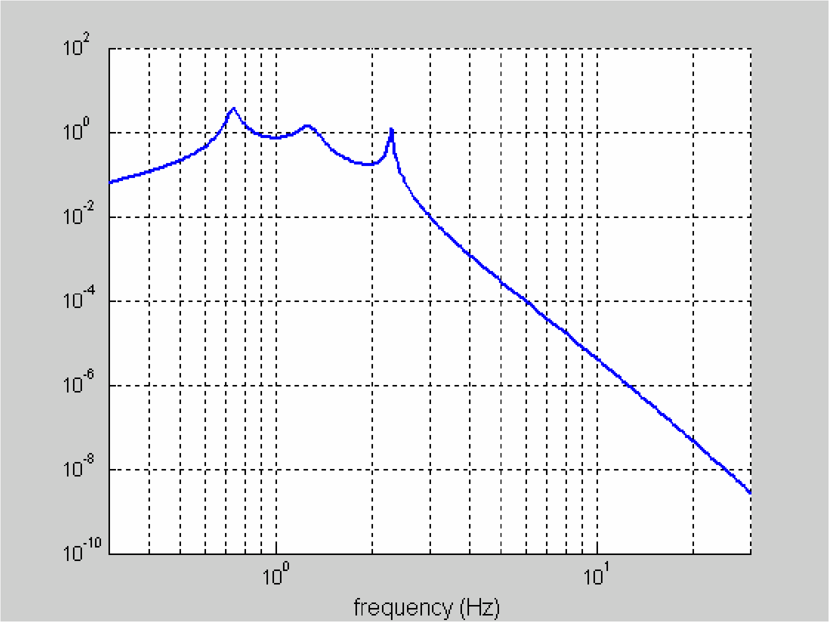


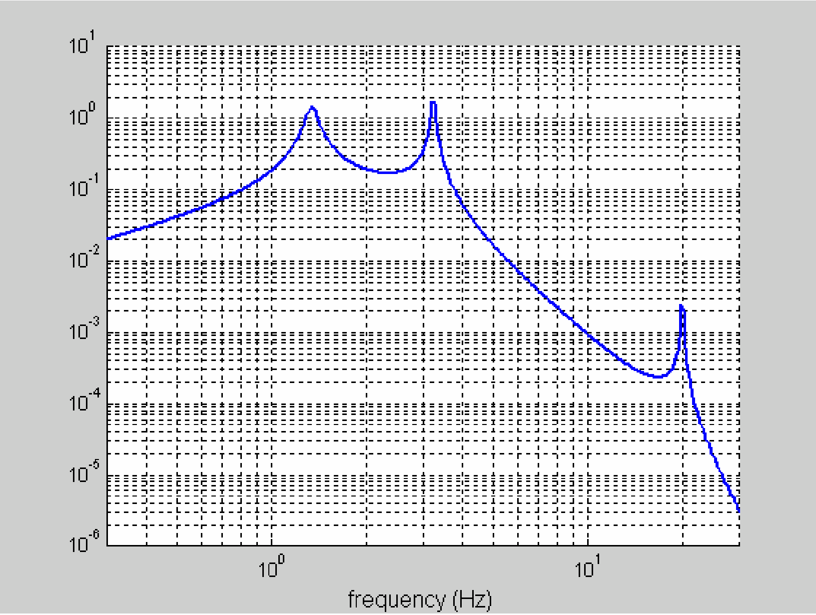
Longitudinal without (red, solid) and with (blue dotted) local controls
At 10 Hz: 9 x 10^{-6} damped

Vertical without (red, solid) and with (blue dotted) local controls
At 10 Hz: $4x10^{-3}$ damped

Triple Pendulum: Sensor Noise

Transfer functions : sensor to mirror





Longitudinal
At 10 Hz: 4×10^{-6}

Vertical
At 10 Hz: 10^{-3}

Areas of Research

- Ribbon manufacture (strength, reliability, loss)
- Bonding of silica to sapphire and heavy glass
  - Losses
  - Strength
  - Final design of silica ears
- Coating losses
- Bonding and welding tests with 40 kg masses
- Availability of sapphire with all desired properties

Key Issues to be Resolved

- Choice of material for main mirrors (sapphire vs. silica) and size (mass, dimensions)
- Low frequency cut-off (the 10 Hz vs. 13 Hz question)
- Control philosophy
  - lengths of reaction chains required
  - violin mode damping
  - degree of residual local damping
  - type of local damping

AD. LIGO SUSPENSIONS DESIGN REQ. REVIEW

ADVANCED LIGO SUSPENSIONS DEVELOPMENT PLAN AND TESTING

Janeen Romie

September 20, 2001

SUS. DEVELOPMENT PLAN

- Suspension development is a collaboration between LIGO Lab, the GEO600 Project and the LSC.
  - » Development Plan, LIGO-M000202-A
- Prototypes will be tested at LASTI.
- Suspension development is divided into two parts:
  - » Suspension component research (e.g. fiber and welding research) and
  - » Overall suspension design (e.g. suspension modeling and blade design)

- Research effort separated into the Conceptual Design Phase, the Preliminary Design Phase and the Final Design Phase.

SUS. DEVELOPMENT PLAN

- RESEARCH AND DEVELOPMENT ISSUES
  - » Fused silica vs. Sapphire for test mass material.
  - » Ear attachment to silica and sapphire.
  - » Ribbons vs. Fibers
  - » Sensor and actuator design research w.r.t. noise requirements.
  - » Suspension design w.r.t. resonant frequency requirements.
  - » Electronic noise and electrostatic charging requirements.

SUS. DEVELOPMENT PLAN MILESTONES

- Conceptual Design: 1Q00 – 3Q01
- CONTROLS Prototypes delivered to LASTI: 1Q02-3Q02
  - » Prototypes to be delivered: 1 ETM, 1 RM (the more complicated, either PRM or SRM) and 1 MC2
- SUS Preliminary Design Review: 4Q02
- NOISE Prototypes delivered to LASTI: 2Q03 - 3Q03
  - » Prototypes to be delivered: 1 ETM, 1 ITM, 1 MC1, 1 MC2, 1 MC3, 1 SRM and 1 PRM
- SUS Final Design Review: 3Q04
- Begin Production Procurement: 3Q04
- SUS Assembly begins at sites: 4Q04
- SUS Installation starts: 3Q05

SUS. DEVELOPMENT PLAN PRELIMINARY DESIGN

- Preliminary Design starts after the successful completion of the conceptual design phase – 3Q01 through 4Q02.
- GEO and LIGO Lab will develop four Advanced LIGO suspensions designs: a BSC quad pendulum suspension, two HAM Cavity Optic triple pendulum suspensions (one for RMs and one for MC mirrors) and HAM Auxiliary Optics suspensions, nominally based on LIGO 1 suspension designs.
- Controls Prototypes are designed, fabricated, delivered, assembled and tested under the preliminary design phase.

SUS. DEVELOPMENT PLAN CONTROLS PROTOTYPES

- To demonstrate mechanical and controls requirements, but not all noise requirements.
- Aluminum masses and metal suspension wire.
- Design, documentation and assembly a collaboration between LIGO Lab and GEO.
- All procurement is by the LIGO Lab.
- Tested at LASTI by LIGO Lab with support from GEO.
- One BSC and one HAM Cavity prototype at Caltech for stand alone, early testing.
- Controls prototypes will be tested alone for form, fit and function along with fixture design checkout.
- Controls prototypes will be installed in LASTI vacuum chambers for integrated controls testing.

SUS. DEVELOPMENT PLAN FINAL DESIGN

- Final Design starts after the successful completion of the preliminary design phase – 4Q02 through 3Q04.
- LIGO Lab will lead the design work in close collaboration with GEO and will incorporate data from LASTI tests.
- Noise Prototypes are designed, fabricated, delivered, assembled and tested under the final design phase.
- Noise prototypes may be reworked Controls prototypes.

SUS. DEVELOPMENT PLAN NOISE PROTOTYPES

- To set the limits on the thermal and excess noise in Advanced LIGO suspensions.
- Sapphire or fused silica test masses along with fused silica fibers or ribbons.
- LIGO Lab responsible for all design, documentation and procurement of materials for prototypes.
- Tested at LASTI by LIGO Lab.
- One BSC and one HAM Cavity prototype at Caltech for testing.
- Prototypes will be tested alone for form, fit and function along with assembly, installation and transport fixture design checkout.
- Prototypes will be tested in LASTI interferometer configurations to analyze thermal noise, suspension control, and interferometer lock acquisition and operation.