Suspensions and Isolation Systems for LIGO II

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Scope: the Transducer Mechanical Design

» this is a mechanical experiment!

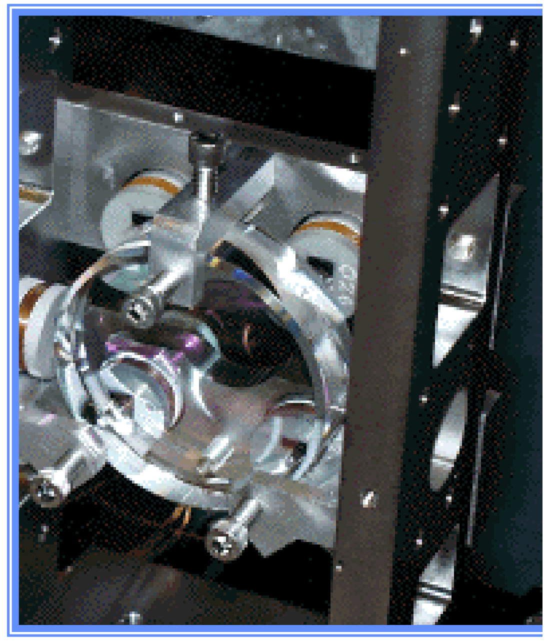
- **Top-Level Functions**
  - » realize a 'free test mass'
  - » provide isolation from seismic noise
  - » minimize thermal noise
  - » actuation to hold interferometer operating point

- **Organization of presentation**
  - » discuss suspensions, then isolation
    - – LIGO I
    - – concepts, physics driving requirements
    - – LIGO II concept, requirements
  - » planning: deliverables and milestones

Suspensions: Concepts

- **Objective: a mass free of all forces, free to follow the metric**
- **Principal challenges:**
  - » **Seismic noise**: combined isolation requirements on seismic isolation, suspension system
  - » **Thermal noise**: each mechanical mode of system in equilibrium with heat bath
    - – leads to brownian motion on, and off, resonance
    - – noise in our measurement band minimized when mechanical losses minimized
  - » **Radiation pressure**: fundamental and technical
- **Important interface: Optics**
  - » test mass is both an optic and inertial mass
  - » requirements placed on optical, mechanical performance

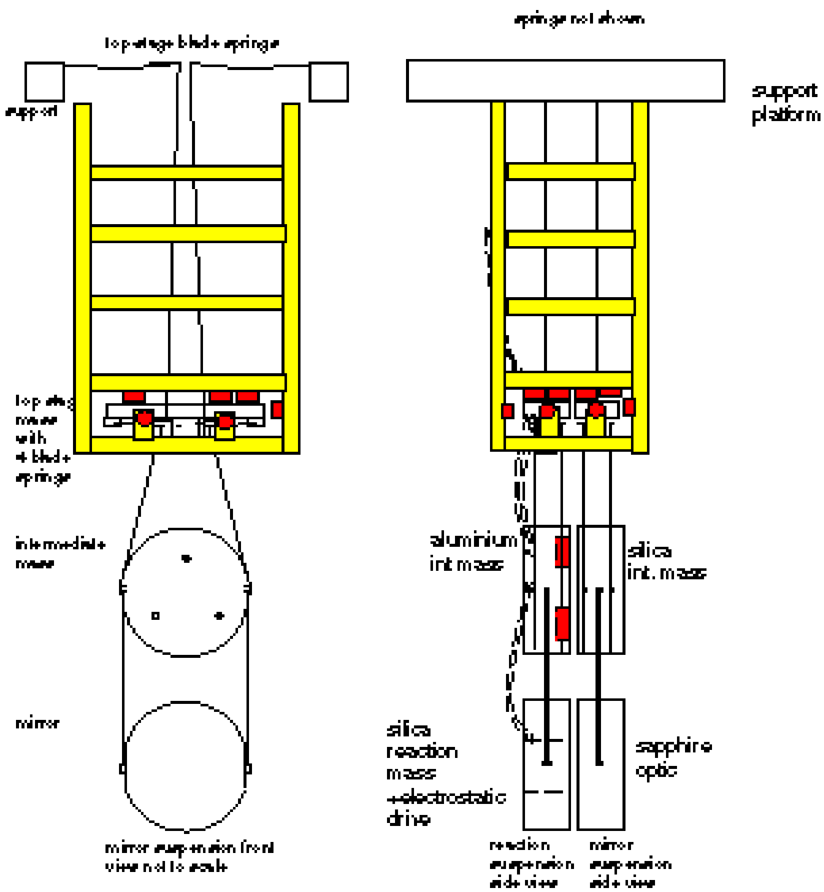
Suspensions: LIGO I Approach, Evolution

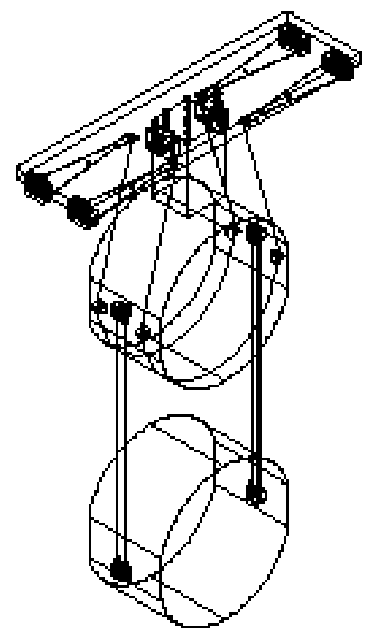


- **Design evolved from acoustic bar GW detectors**
  - » first used by Max Planck Garching Group for interferometric detectors
  - » a single wire loop around the mass
  - » magnets glued to mirrors, coils on frame to exert forces
- **Advantages**
  - » simple, robust, great deal of experience
- **Disadvantages**
  - » attachments increase mechanical losses, increase thermal noise, interact with EMI
  - » large forces required to maintain 'DC' alignment
- **Multiple pendulums a good solution**
  - » early work at MIT, Garching
  - » real engineering done for GEO 600 interferometer

LIGO II Suspension

- **GEO design; preliminary sketch**



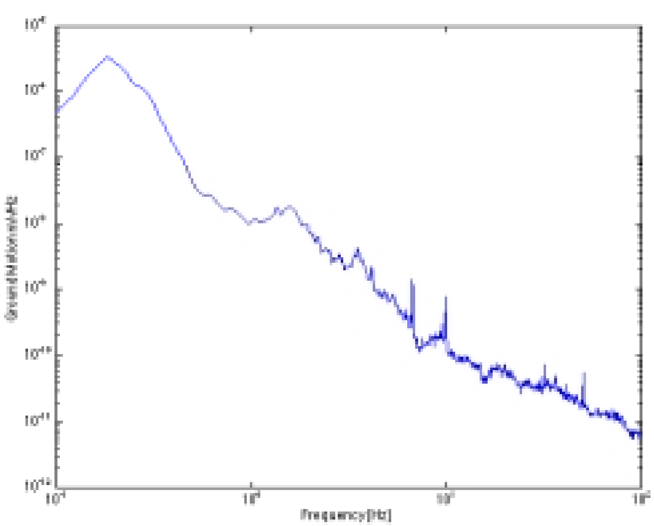


LIGO II Suspension

Suspension Parameter	Value
Test mass	30 kg, sapphire
Effective mechanical loss ‘φ’	5×10^{-9}
Penultimate masses	16 kg, fused silica
Upper masses	28 kg, stainless steel
Test mass suspension fiber	Fused silica ribbon, 4×10^{-7} m^2, 1:55 aspect ratio
Upper mass suspension fibers	Steel
Effective mechanical loss “φ”	3.3×10^{-8}
Approximate suspension lengths	0.4 m test mass, 0.35 m intermediate, 0.7 m top
Vertical compliance	Trapezoidal cantilever springs
Horizontal seismic transmission	10^{-6} at 10 Hz
Test mass actuation	Electrostatic (acquisition), photon pressure (operation)
Upper stage actuation; sensing	Magnets/coils; incoherent occultation sensors

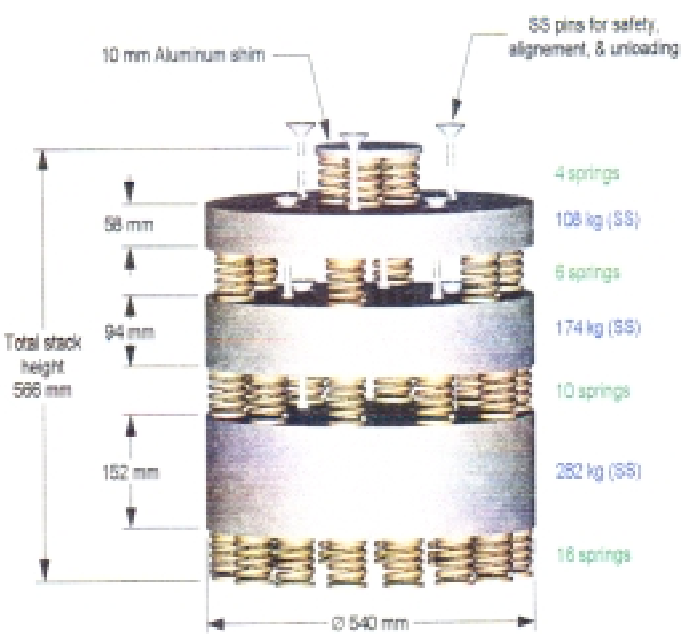
Isolation: Concepts

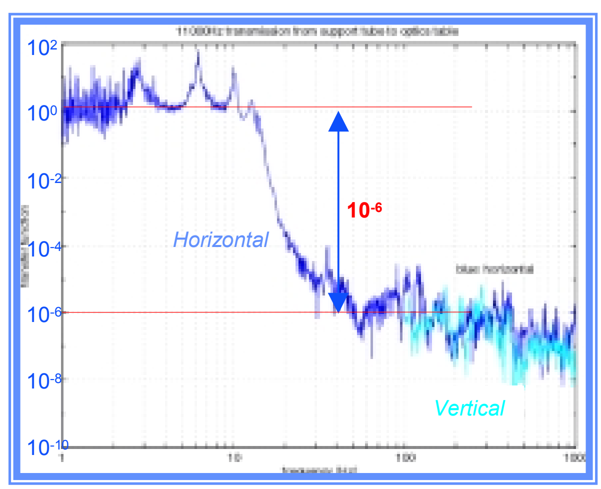
- **Direct coupling in detection band**
  - » very steep slope, so effectively establishes a 'cutoff' frequency
- **Indirect effect of low frequencies**
  - » interferometer works well when held to operating point
  - » typically a small fraction of a light wavelenth; e.g., 10^{-14} mrms
  - » disturbance concentrated at microseismic peak, 0.16 Hz



Isolation: LIGO I Approach, Evolution

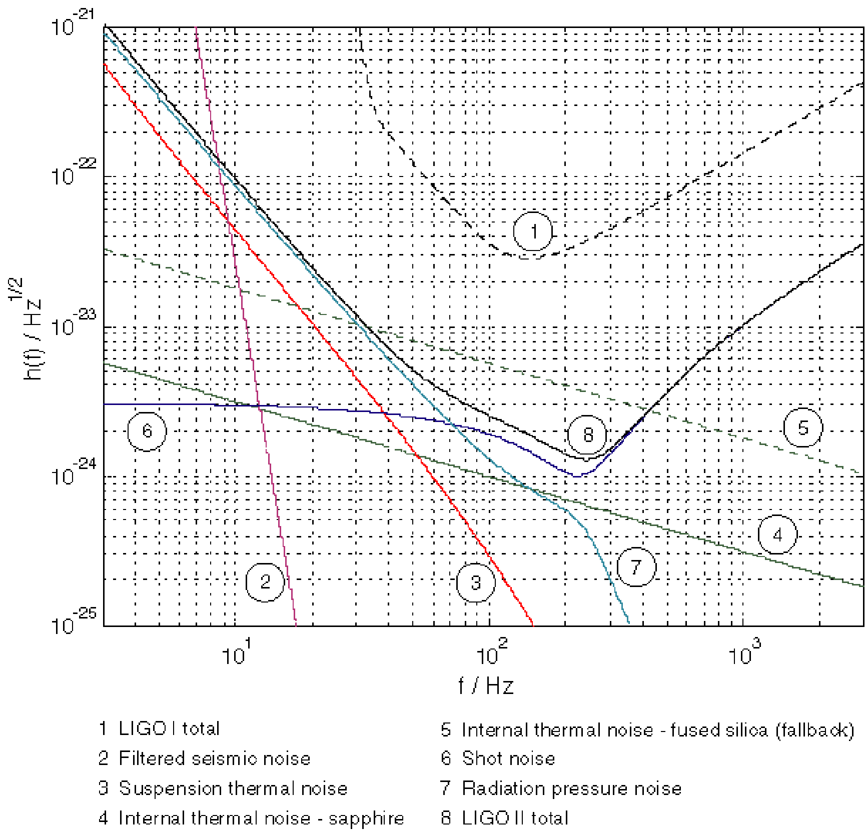
- **Passive low-*Q* oscillators in series**
- **Advantages:**
  - » Nominally simple, wealth of experience
- **Disadvantages**
  - » relatively high cutoff (f_0 goes as compression^2)
  - » difficult to damp internal resonances well





LIGO II Isolation

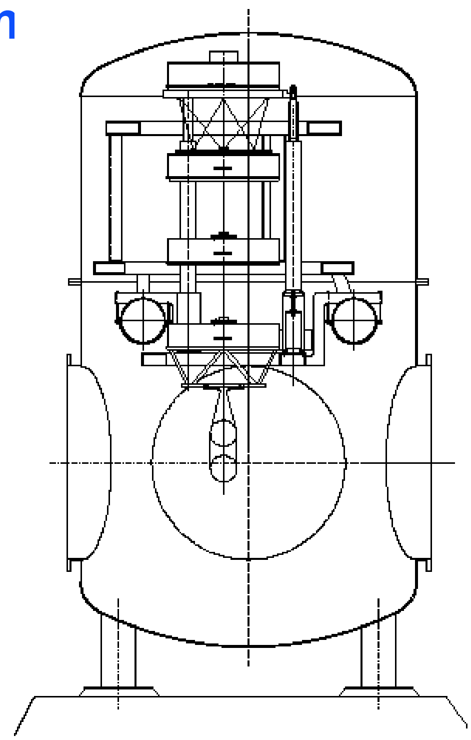
- **Requirements**
  - » The 'brick-wall' cutoff is to be significantly below the frequencies of best overall sensitivity (~100 Hz): thus, 10 Hz cutoff.



LIGO II Isolation

- **Requirements** continued
  - » The rms motion of the test mass while the interferometer is locked is to be less than 10^{-14} meters.
  - » The rms velocity of the test mass is to be small enough that the interferometer can acquire lock (order of 10^{-14} m/sec)
  - » The system will fit and into interface to the existing vacuum chambers and can be tested in the LIGO/MIT Advanced System Test Interferometer Facility.
  - » The system will interface to the GEO suspension design and interferometer layout.
- **Two designs may meet requirements:**
  - » **'Soft'** approach: low natural resonant frequencies, based on VIRGO design
  - » **'Stiff'** approach: servo controlled platform, experience at JILA, MIT, Stanford

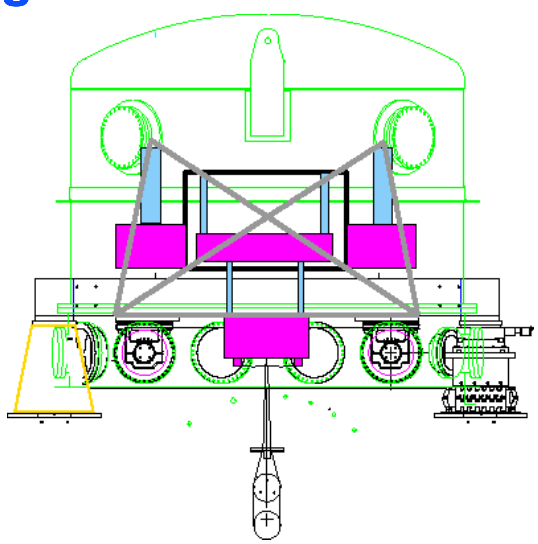
LIGO II Isolation: 'Soft' approach



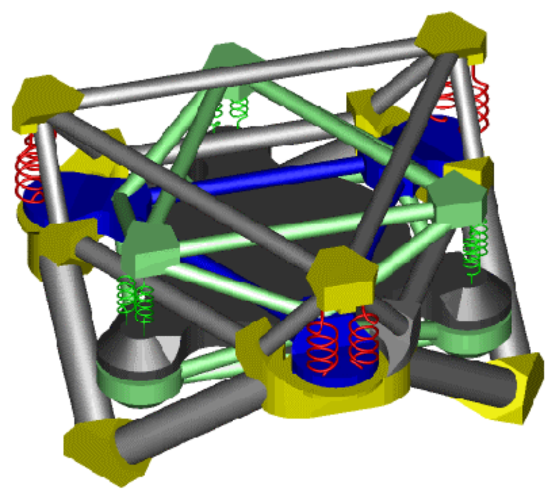
- **RMS motion reduction from inverted pendulum**
  » resonant frequency 30 mHz
  » reduces rms motion, also at microseismic peak
- **Horizontal attenuation from pendulums**
  » two stages, 0.75 Hz each
- **Vertical attenuation from balanced spring forces**
  » three stages, 0.1-0.3 Hz
- **Contols approach: damping, positioning**
  » attenuation provided by low natural frequencies
  » controls used to set operating point
  » controls and magnetic dampers used to control modes

LIGO II Isolation: 'Stiff' approach

- **Principal Isolation through active feedback**
  - » motion sensed with accelerometers
  - » actuation via voice-coil/magnets
  - » multiple input, multiple output digital servo



- **Two nested stages**
  - » each active in 6 degrees of freedom
  - » each with unity gain ~20 Hz
  - » suppression at 0.16 Hz of
- **Final passive stage**
  - » additional pendulum suspension



LIGO II Isolation: Selection process

- **Parallel development of both approaches**
  - » Definition of proposed system
    - – a specific configuration for both types of vacuum equipment chambers ('HAM' and 'BSC')
  - » 3d modeling
    - – attenuation of complete system as advertised?
    - – all mechanical modes under control?
  - » Protoyping of parts/systems
    - – isolation, creep, robustness
    - – teaming
- **Formal set of criteria established**
  - » committee of Lab, LSC, External experts in interferometry, isolation, suspensions
  - » objective: make the right decision in a constructive way
- **Deadline: recommendation by April 1, 2000**
  - » documents available here, on web

The LIGO II LSC Suspension/Isolation Working Group

- **Principal interests in suspensions:GEO, Moscow, Penn State, Syracuse, Stanford**
- **Principal interests in isolation: Caltech, JILA, LSU, MIT, Stanford**
- **Roughly 35 persons, 12 institutions**
- **Deliverables and milestones established**
  - » see LSC White Paper
- **Principal R&D tasks to enable LIGO II:**
  - » Test Masses: materials and processes
  - » Suspension fibers: processes, integration
  - » Overall suspension design
  - » Isolation systems: approach, design
  - » Control systems/hierarchy
  - » Modeling of parts and whole
  - » System test: at LIGO II sensitivity levels

Summary

- **Significant improvements in isolation, suspension are planned for LIGO II**
- **Much enabling R&D has taken place since initial LIGO I design**
- **No fundamentally new or untested notions in LIGO II design, but…**
- **Significant extrapolations needed in many domains**

- **Work to be done!**

Enhanced R&D Program

- **Lab Project schedule linked to R&D program**
  - » many subsystems brought through the design process by LSC groups, in and out of Lab
  - » schedule requires significant progress before earliest possible MRE funding
- **Specific areas of increased activity:**
  - » Sapphire development
    - industrial crystal growth tests
    - optical polishing tests
    - coating tests
    - birefringence tolerance tests
  - » Seismic isolation development and systems tests
    - completion of testing facilities
    - development of high sensitivity displacement sensors
    - prototype system construction and test
- **Additional funds in the R&D program before the MRE funds are necessary to meet the LIGO Lab schedule**