# Update on Suspensions for Enhanced and Advanced LIGO

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**For the Advanced LIGO SUS team**

**LSC/Virgo meeting, MIT**
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# Advanced LIGO SUS Team

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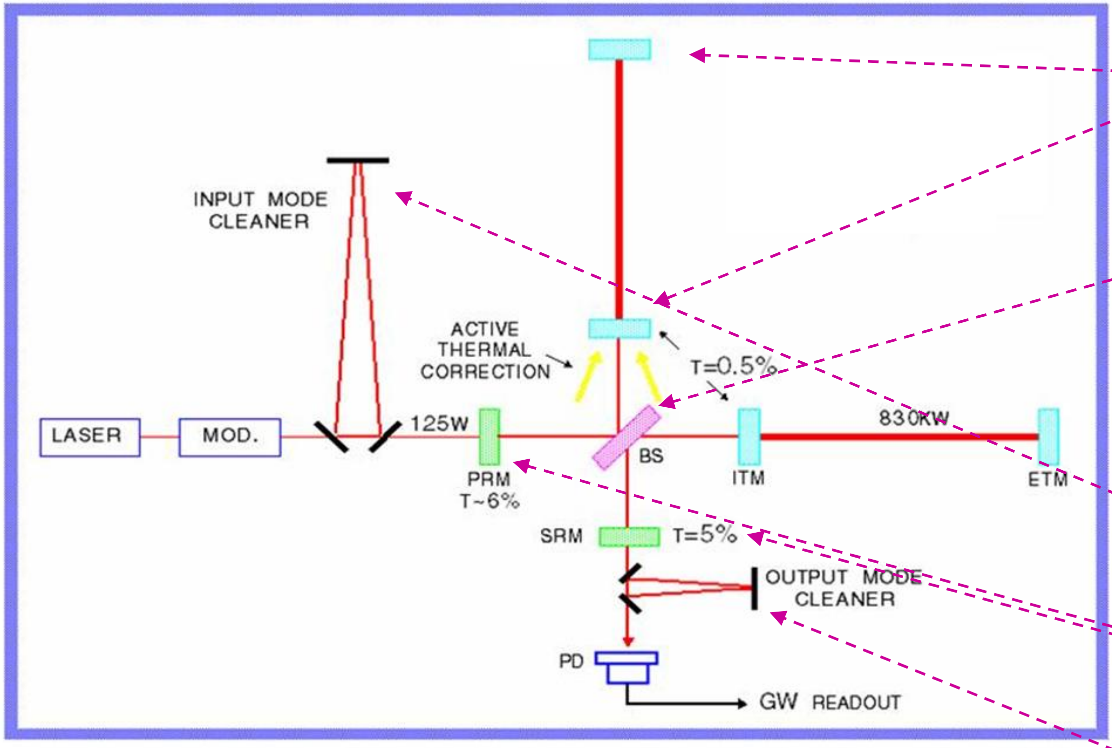
- LIGO LHO: B Bland
- LIGO LLO: J Romie
- University of Glasgow: M Barton, L Cunningham, A Cumming, A Heptonstall, J Hough, R Jones, I Martin, S Rowan, K Strain, C Torrie
- Rutherford Appleton Laboratory (RAL) : J Greenhalgh, T Hayler, J O'Dell, I Wilmut
- University of Birmingham: S Aston, R Cutler, D Lodhia
- University of Strathclyde: N Lockerbie

# Five Major Suspension Designs

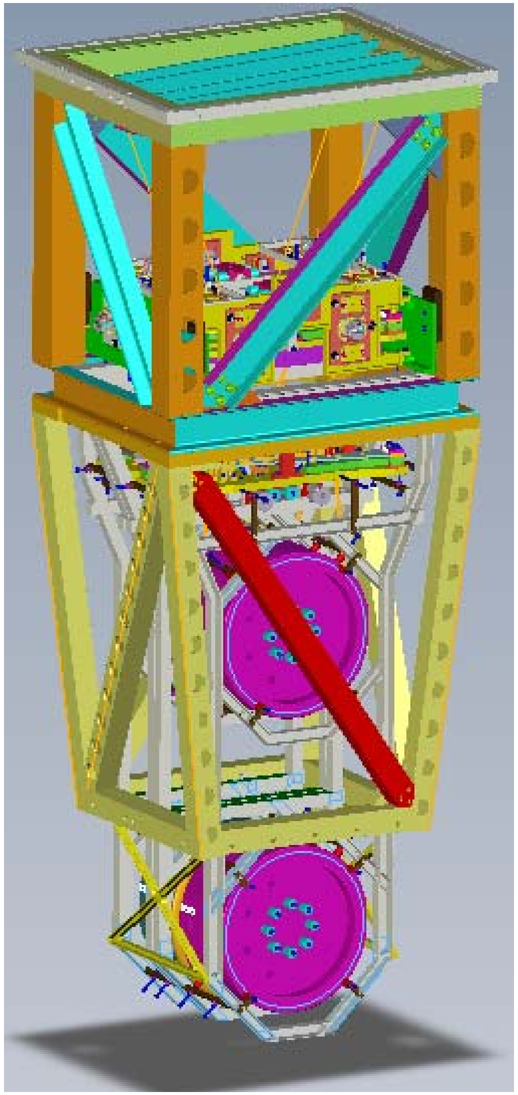



Advanced LIGO optical layout schematic

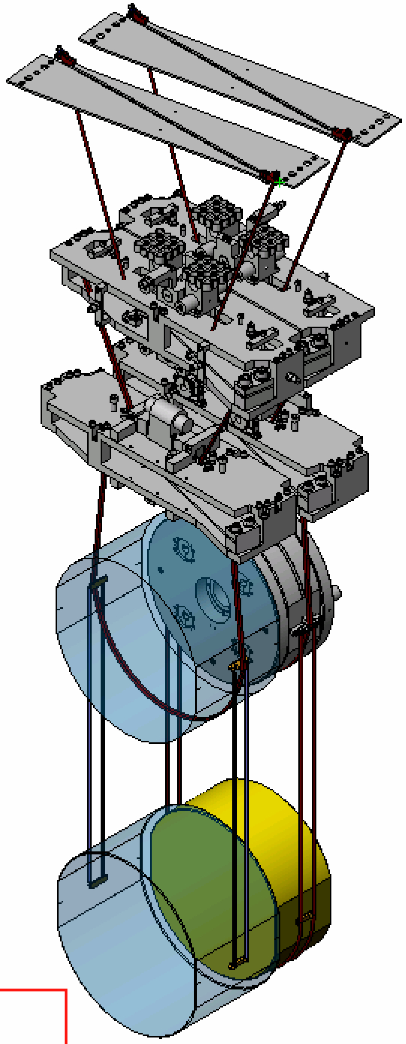
- Most sensitive optics in BSC chambers: UK deliverables
  - » Quadruple pendulum for Test Masses (ETM and ITM and reaction chains)
  - » Triple pendulum for Beamsplitter (BS) and Folding Mirror (FM)
- Other optics in HAM chambers: US deliverables
  - » Triple Pendulum for Input Modecleaner Mirrors (IMC)
  - » Triple pendulum for Power Recycling Mirror (PRM) and Signal Recycling Mirror (SRM)
  - » Double Pendulum for Output Modecleaner (OMC)

# Test Mass
# Quadruple Pendulum Suspension





- Key Design features
  - Monolithic final stage: 40 kg fused silica mirror (34 cm diam x 20cm ) on 4 fused silica ribbons (600mm x 1.1mm x 0.11 mm) for good thermal noise performance
  - 4 stages for longitudinal seismic isolation plus 3 stages of blades for vertical isolation
  - 6 degree of freedom damping (local control) at top mass for all low frequency modes (requires good mode coupling)
  - Parallel reaction chain for quiet global control actuation: electrostatic (ESD) at test mass, electromagnetic at upper stages (hierarchical)



Major noise requirements

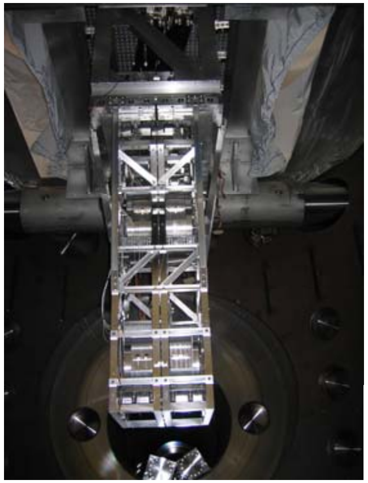
Suspension thermal noise 10^-19 m /√ Hz @ 10 Hz

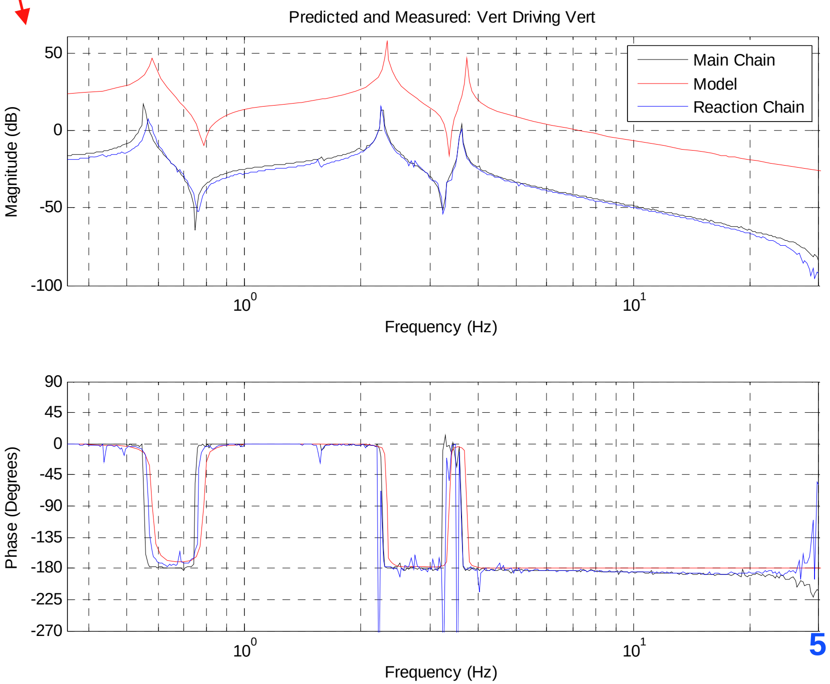
Residual seismic noise 10^-19 m /√ Hz @ 10 Hz

# Test Mass
# Quadruple Pendulum Suspension continued

- Current status
  - » All-metal "controls" prototype assembled at Caltech and tested at LASTI.

    Assembly technique, mode frequencies, transfer functions, damping (active and eddy current) investigated. Compares well with revised Mathematica/MATLAB models
  - » Lessons learnt re pitch and vertical modes: angled wires affect vertical frequencies and flexure lengths. Finite lateral blade compliance affects pitch.
  - » Currently modal damping and cavity locking between quad and input modecleaner triple pendulum is being investigated (including use of electrostatic drive)
  - » "Noise" prototype with full monolithic stage built at RAL and now under construction at LASTI (all-metal to start with)
  - » Development of techniques for assembly of monolithic stage underway at Glasgow : $CO_2$ welding and pulling machine, profiler and proof/bounce tester, jigs for silicate bonding
  - » OSEM and electronics builds ongoing (Birmingham and Strathclyde)

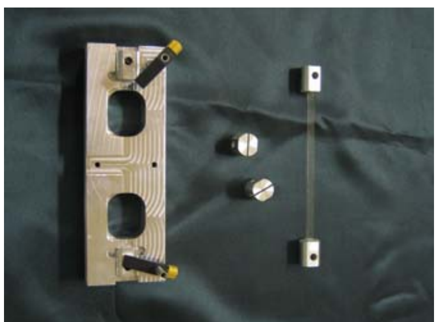


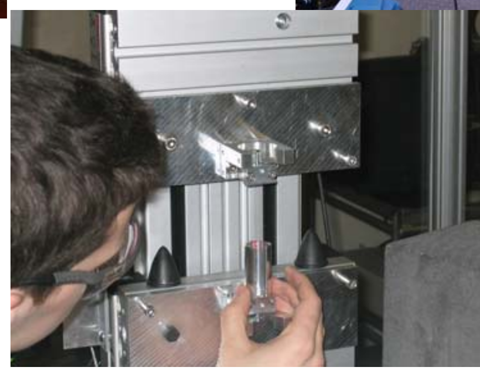


# Test Mass
# Quadruple Pendulum Suspension continued

Development work on monolithic assembly techniques at Glasgow

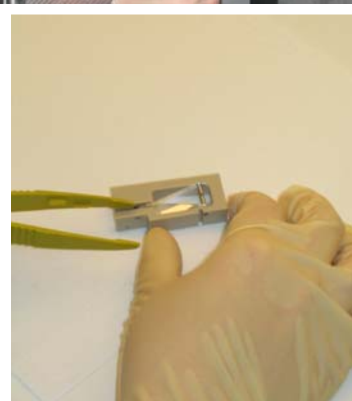
$CO_2$ ribbon puller/welder

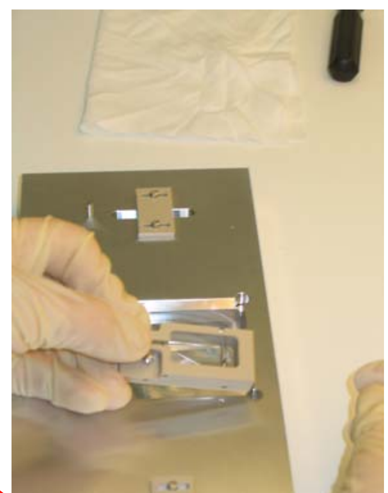




Preparing ribbon for pulling

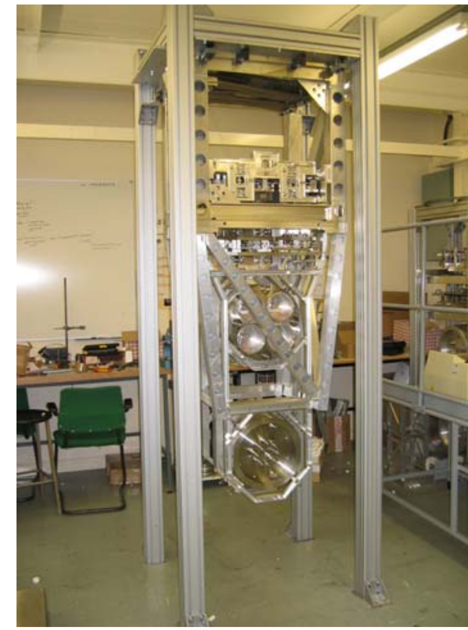
Prism strength testing





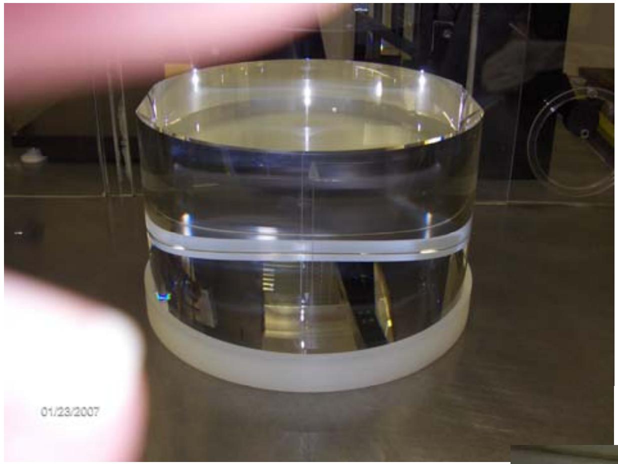
Ear bonding fixtures

Prototype quad at Rutherford Appleton Lab



# Test Mass
# Quadruple Pendulum Suspension continued

- Future work
  - » Full program of tests on noise prototype at LASTI over next ~9 months
    - – mechanical fit, installation and alignment
    - – interaction with seismic platform
    - – mode frequencies, transfer functions and damping
    - – thermal loading effects
    - – assembly and reinstallation with monolithic stage
    - – cavity tests incl. testing ESD
    - – violin mode damping
  - » OJEU (European Union) process for procurement of parts for final suspensions about to begin



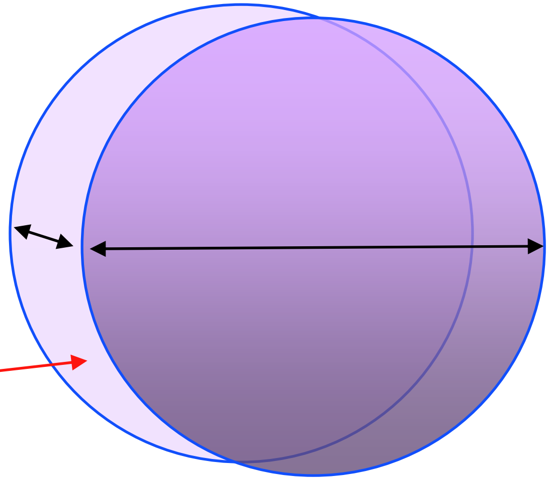

LASTI test mass

Prototype ring heater

Reaction mass with 4 quadrant gold coating for electrostatic drive (ESD)

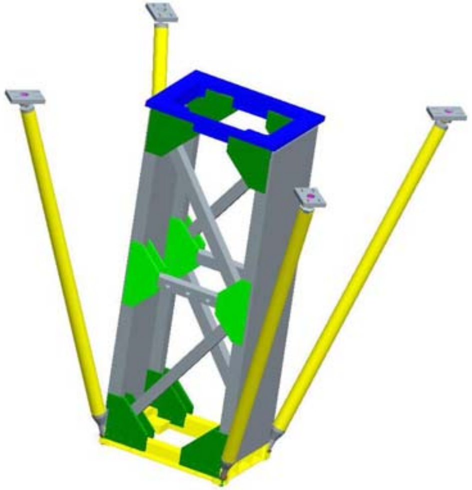
# Beamsplitter Triple Pendulum Suspension

- Design features
  - » Triple pendulum with two stages of blades
  - » Silica mass 370 mm diam x 60 mm thick (~15 kg)
  - » Horizontal wedge
  - » Wire suspension (change of baseline)
- Design challenges
  - » Extreme mass aspect ratio (plate-like)
  - » Long thin support structure



Beamsplitter aspect ratio ~ 6 to 1

Prototype bolted structure at RAL

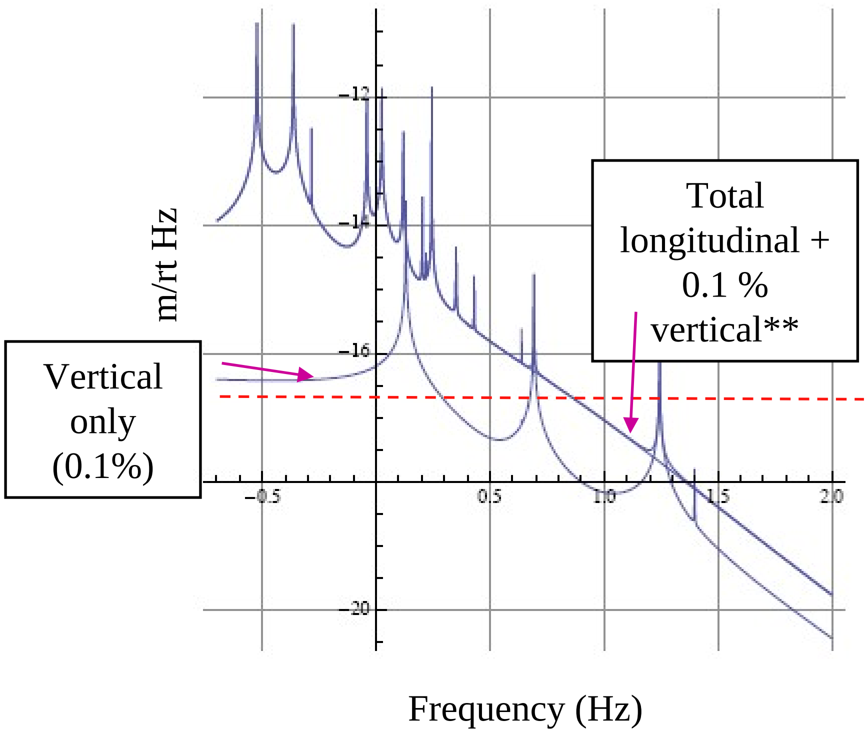


Struts to stiffen structure

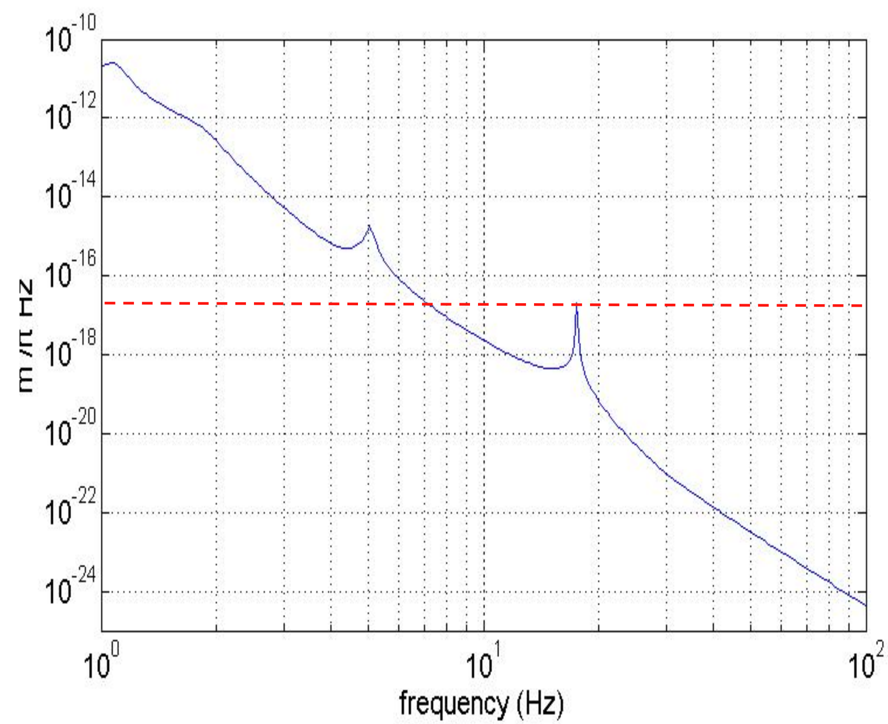
# Beamsplitter Triple Pendulum Suspension continued

- Noise requirement: 2 x 10^-17 m/√ Hz at 10 Hz (--------)
- Noise estimates shown below, assuming 0.1% coupling from vertical

**Thermal noise estimate**




**Seismic noise estimate***



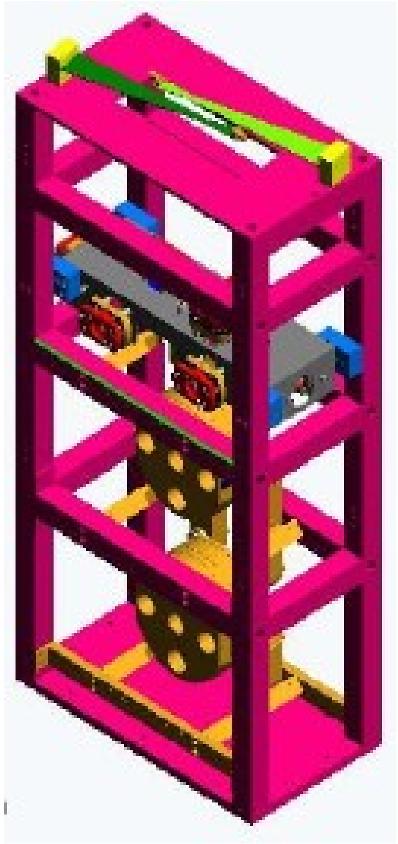

- **Current status: at conceptual design stage**

**added quadratically

*Assumes 10^-11 m/rt Hz @ 1 Hz and 2 x 10^-13 m/rt Hz @ 10 Hz at suspension point

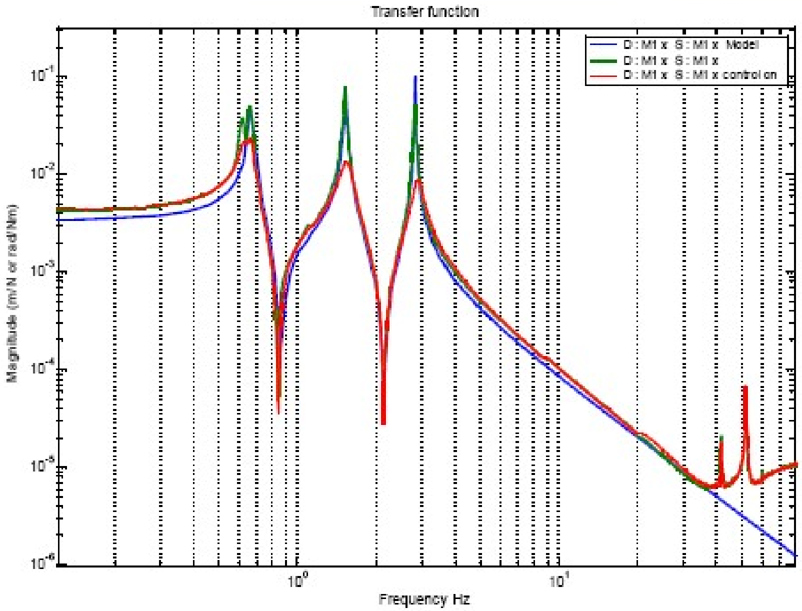
# Input Modecleaner
# Triple Pendulum Suspension

- Design features
  - Triple pendulum with two stages of blades
  - Silica mass: 150 mm diam. x 75 mm thick (~3 kg)
  - Wire suspension
- Noise requirement: originally 3 x 10^-17 m/√ Hz at 10 Hz (relaxation of this requirement has since been proposed)
- Current status
  - prototype fully characterised at LASTI
  - currently being used for cavity tests with quad prototype

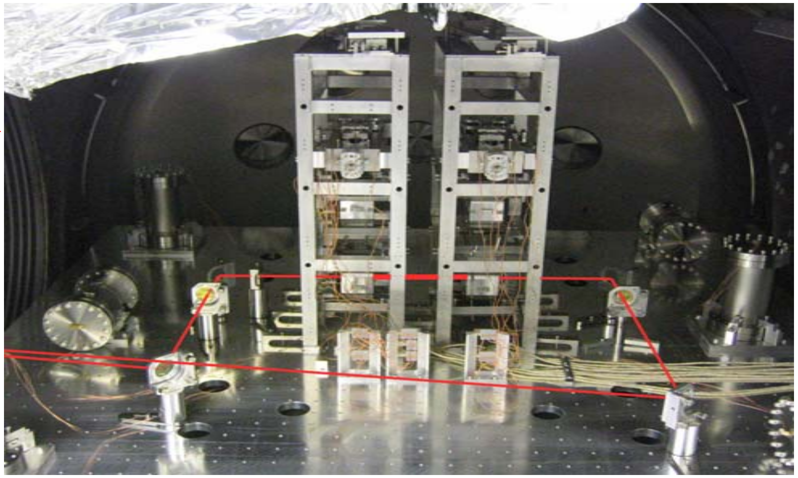


# Input Modecleaner
# Triple Pendulum Suspension continued

- Characterisation and comparison to MATLAB model
  - » Mode frequencies, transfer functions, active damping
- More recent work: test of independent modal control with a state estimator for damping - minimises sensor noise re-injection (L Ruet)
  - » relies on good model
  - » tested using second modecleaner triple pendulum as quiet reference
- Final design prototype testing & review: late 2008

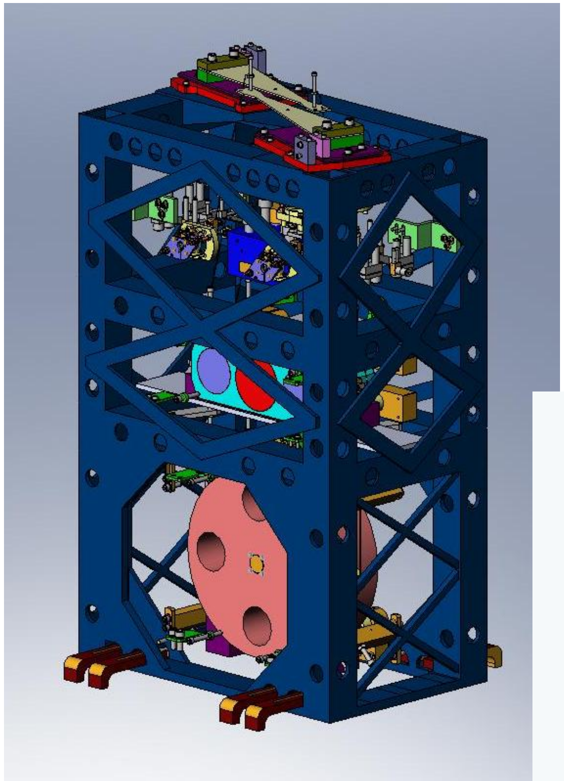


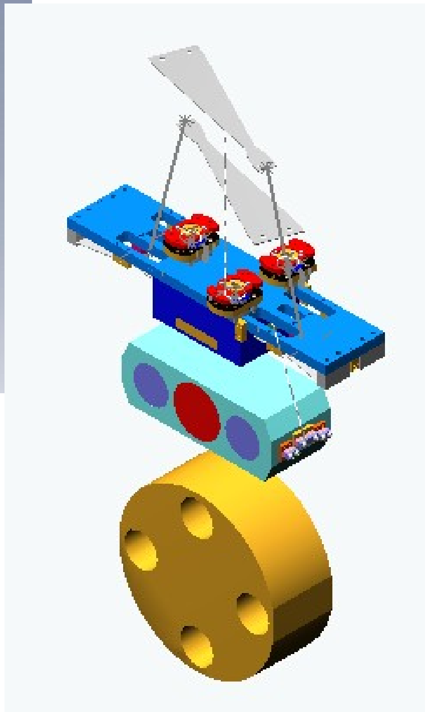

Longitudinal transfer function at top mass
Blue: model, green: damping off, red: damping on



# Recycling Mirror Triple Pendulum Suspension

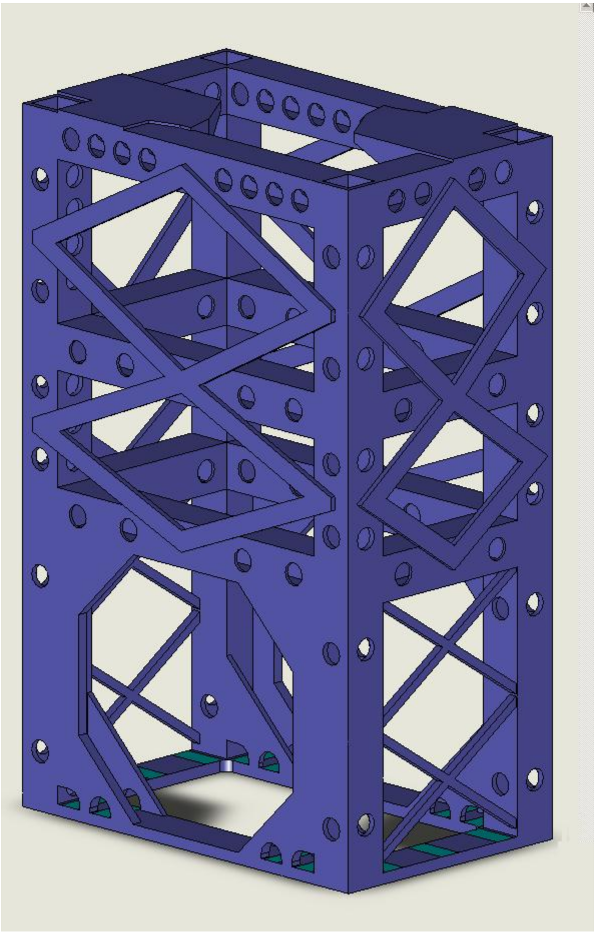
- Design features
  - Triple pendulum with two stages of blades
  - Silica mass: 265 mm diam. x 100 mm thick (~ 12 kg)
  - Wire suspension
- Noise requirement
  - 4 x 10^-16 m/√ Hz at 10 Hz
- Current status
  - detailed design work now underway
  - prototype assembly: early 2008





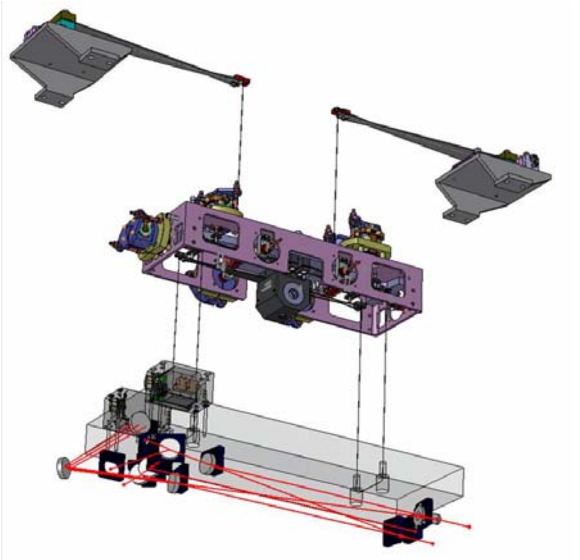
# Recycling Mirror Triple Pendulum Suspension continued

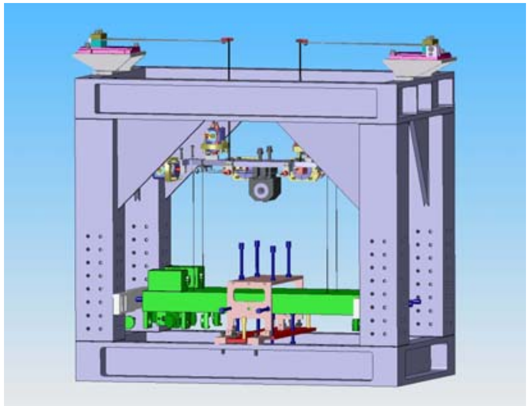
- Design Challenges
  - Meeting height restriction with large mirror: middle mass “squashed”
  - Meeting total mass budget (~ 120 kg) and 150 Hz lowest structural resonant frequency with steel structure
    - Stainless steel structure used to ease welding issues
  - Access for assembly and adjustment
    - Mock-up of suspension underway.



# Output Modecleaner Double Pendulum Suspension

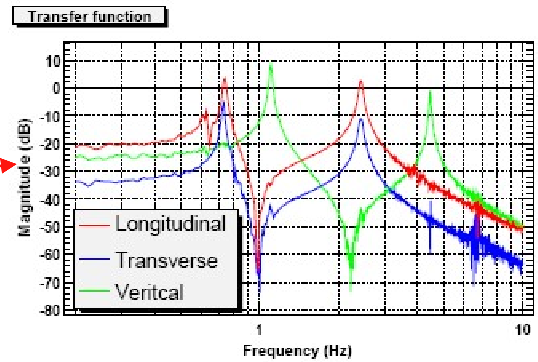
- Design features
  - » Double pendulum with two stages of blades
  - » Silica optical bench 450 mm x 150 mm x 40 mm (~6 kg)
  - » Steel wires
- Requirements
  - » Double pendulum isolation and 6 DOF active damping
  - » Pendulum frequencies 0.8 to 2 Hz (guideline)
- Current status
  - » Prototype with metal bench under test
- First Installation
  - » In Enhanced LIGO, end of 2007

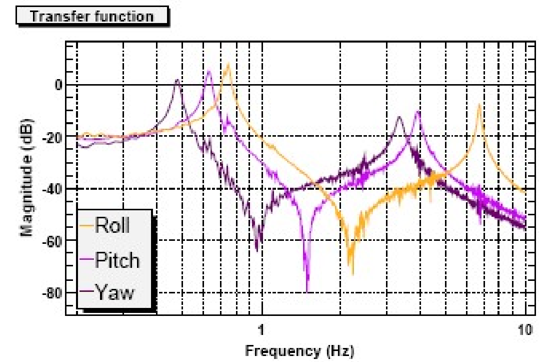


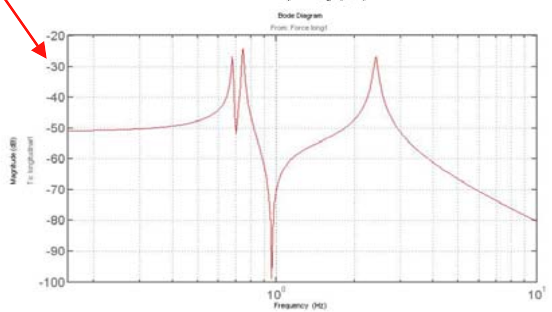


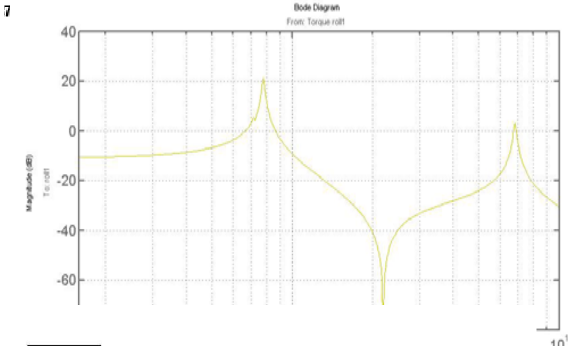
# Output Modecleaner Double Pendulum Suspension continued

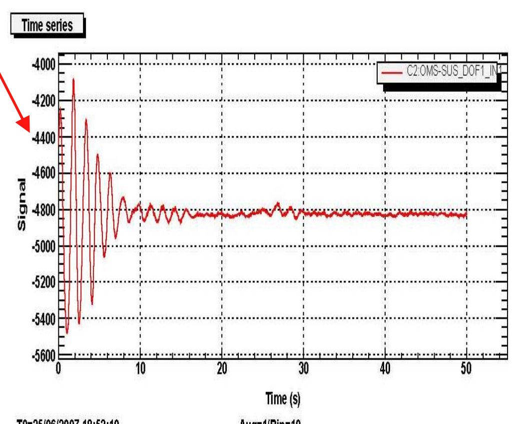
- Characterisation
  - » Mode frequencies: from 0.5 Hz (lowest yaw mode) to 6.7 Hz (highest roll mode)
  - » Transfer functions: measured and modelled (actuating and sensing at top mass)
  - » Damping (long. and vert. shown)
- Other tests
  - » Structural resonances
    - – lowest ~148 Hz with ~4 kg non-suspended mass attached
  - » OSEM design from UK
    - – Works well

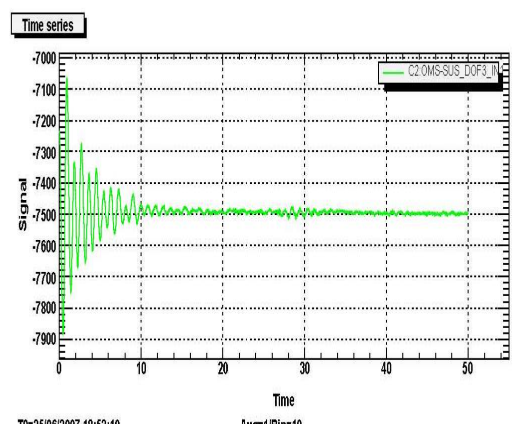


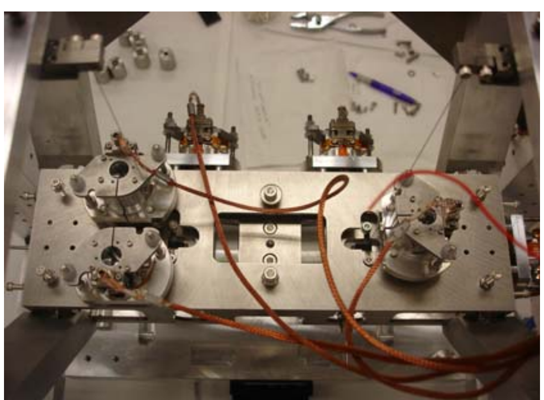







# Conclusions

- All major suspension designs underway
- Common features:
  - » multiple pendulums with blades for vertical isolation
  - » active damping at top mass
    - – designs based on GEO 600 design
- Distinctive features:
  - » Test mass quadruple pendulum: monolithic silica final stage with silicate bonding and silica ribbons, and use of reaction chain for global control
  - » All – different masses, sizes, requirements
- Status:
  - » prototypes of test mass quad, input modecleaner triple and output modecleaner double already tested
  - » others to follow
- Outlook:
  - » Promising!