Investigation of Suspension Upgrades for Advanced Gravitational Wave Detectors

Kyung-ha Lee

(**Institute for Gravitational Research, SUPA University of Glasgow**)

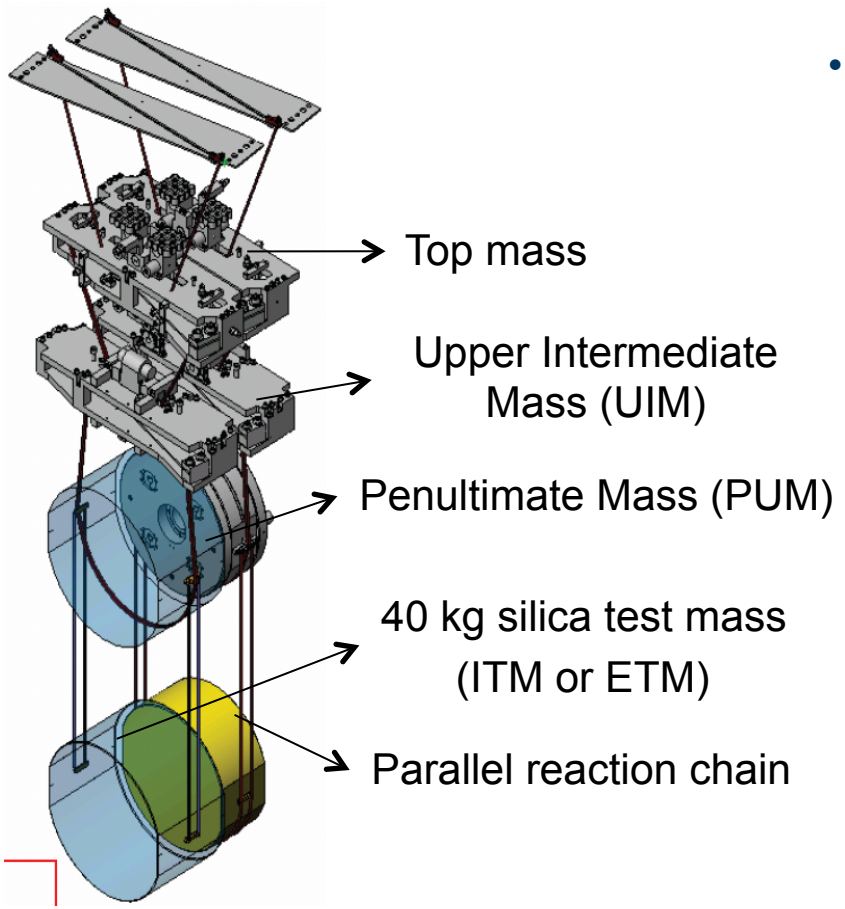
Alan Cumming, Liam Cunningham, Giles Hammond, Jim Hough, Russell Jones, Daniela Pascucci, Sheila Rowan, Brett Shapiro

Overview

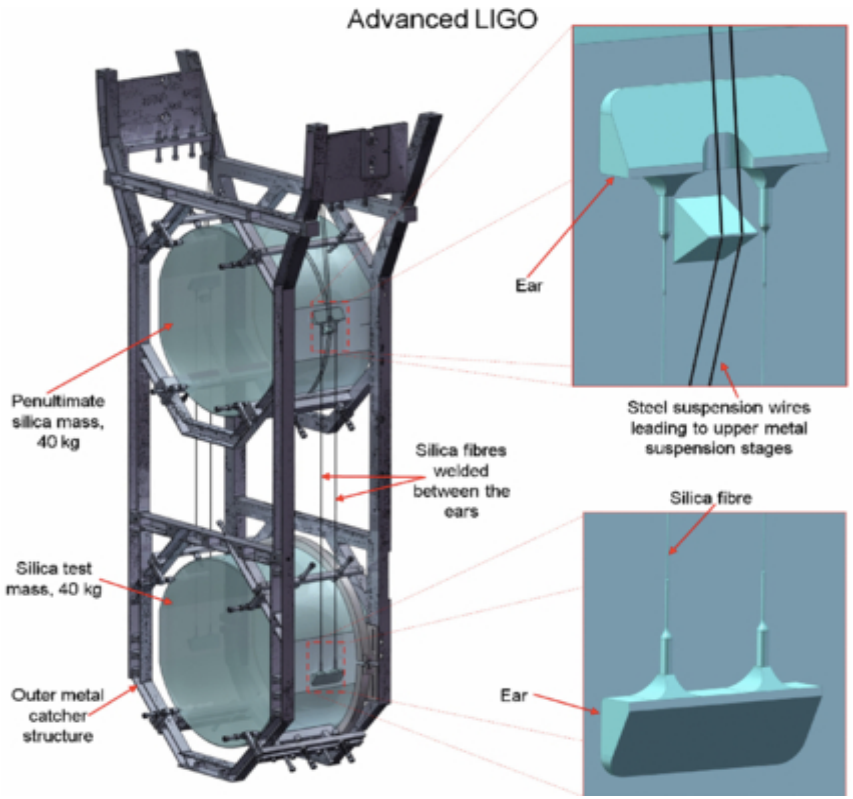
- Current aLIGO quadruple pendulum suspension
- Motivation for warm upgrades to the aLIGO suspensions
- MATLAB Modeling
- Strain enhancements with warm upgrade scenarios (40, 80 kg)
- Research development for warm upgrades in Glasgow
- Summary

Current Suspension System

- Seismic noise reduction
  - Quadruple pendulum system



- Thermal noise reduction
  - Final stage is monolithic fused silica suspension
- Nulling thermoelastic noise
  - Fused silica fibres are pulled in dumbbell[1] shape



1. C. Bell et al., Class. Quantum Grav. 31 (2014) 065010 (12pp)

Motivation for Warm Upgrades

- Fluctuation-Dissipation Theorem: $S_x(\omega) = \frac{4k_B T}{\omega^2} \Re\left[\frac{1}{Z(\omega)}\right]$
- Cryogenic condition : Being pioneered in KAGRA.

  ➔ Requires more significant changes in detector infrastructure
- Warm Upgrades:

  Sensitivity gains can be achieved by changing
  - Mass of the mirror
  - Length of the suspension (final stage length, total suspension length)
  - Stress in the fibre

- Variables used in these simulations:
  - Mass
    - Test mass: 40 kg, 80 kg
    - Mass arrangement for upper masses: optimised using approximation from T1300786[2] by Dr. Brett Shapiro to minimise longitudinal seismic isolation
  - Length
    - Final stage length: 0.6 m, 1.1 m
    - Total suspension length: 1.6 m, 2.14 m
  - Stress in fibre: 770 MPa, 1.54 GPa

2. B Shapiro et al, LIGO III Quad pendulum conceptual design optimization, Technical Report LIGO-T1300786, LIGO Collaboration, 2014

MATLAB Modeling

- Noise terms considered:
  - Suspension Thermal Noise
    - 5 mm fibre stock with dilution, D, calculated via FEA[3] by Dr. Alan Cumming

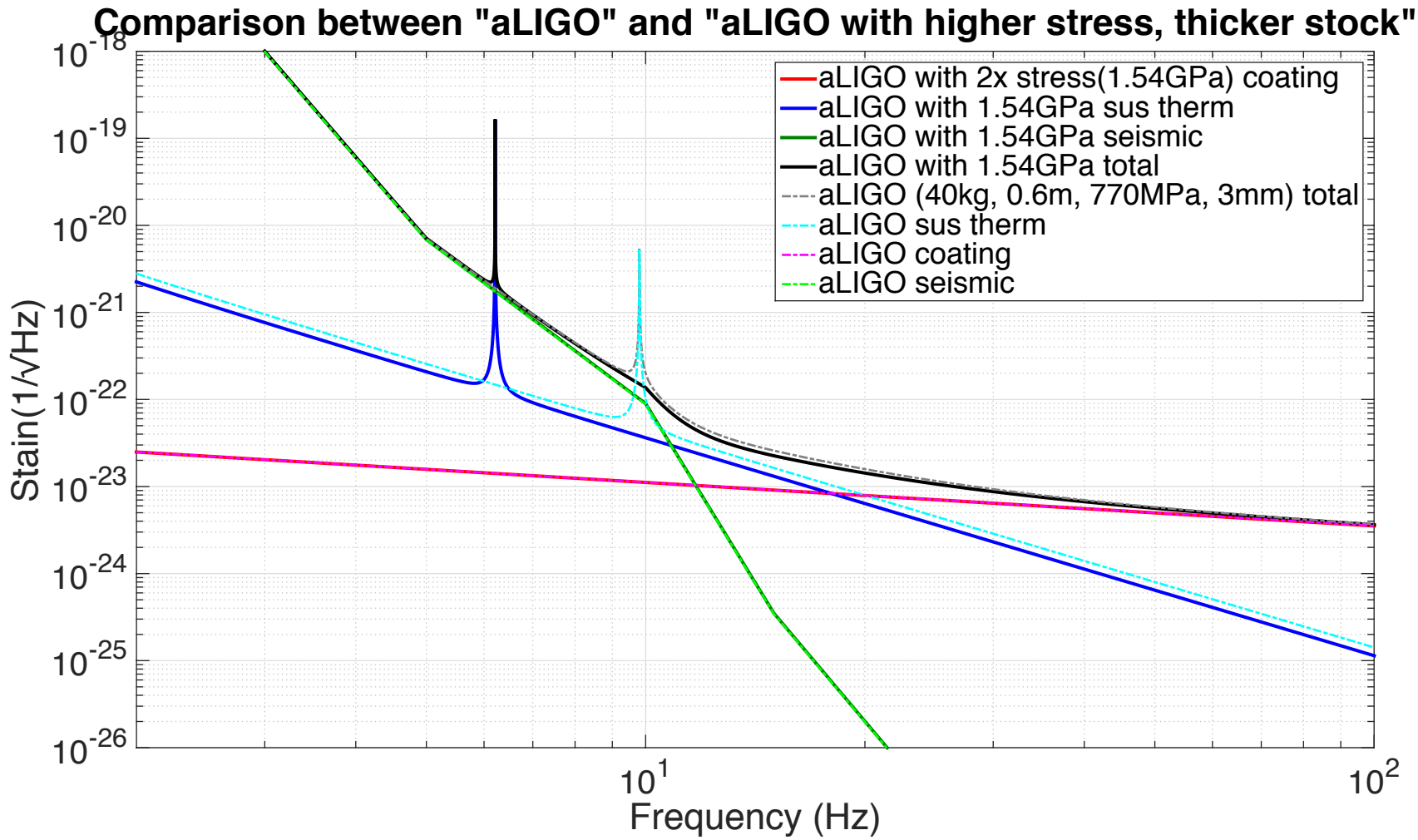
$$\phi_T = \frac{1}{D}\left[\phi_S + \phi_{Bulk} + \phi_{Thermoelastic}\right]$$

  - Coating Brownian Noise
    - Optimized aLIGO coating layers (Ta_2O_2 + SiO_2)
    - Finite test mass correction by Somiya and Yamamoto, Phys. Rev. D 79 (2009)[4]
  - Seismic Noise
    - Transfer function estimate by Shapiro et al (T1300786)[2]
    - Used BSC requirements

$$\frac{x_4}{x_g} = \frac{g^4}{(2\pi f)^8}\frac{1}{L_1L_2L_3L_4}\frac{(m_1+m_2+m_3+m_4)(m_2+m_3+m_4)(m_3+m_4)m_4}{m_1m_2m_3m_4}$$

3. A Cumming et al, Finite element modelling of the mechanical loss of silica suspension fibres for advanced gravitational wave detectors, Class. Quantum Grav. **26** (2009) 215012
4. K Somiya and K Yamamoto, Coating thermal noise of a finite-size cylindrical mirror, Phys. Rev. D 79 (2009) 1-13

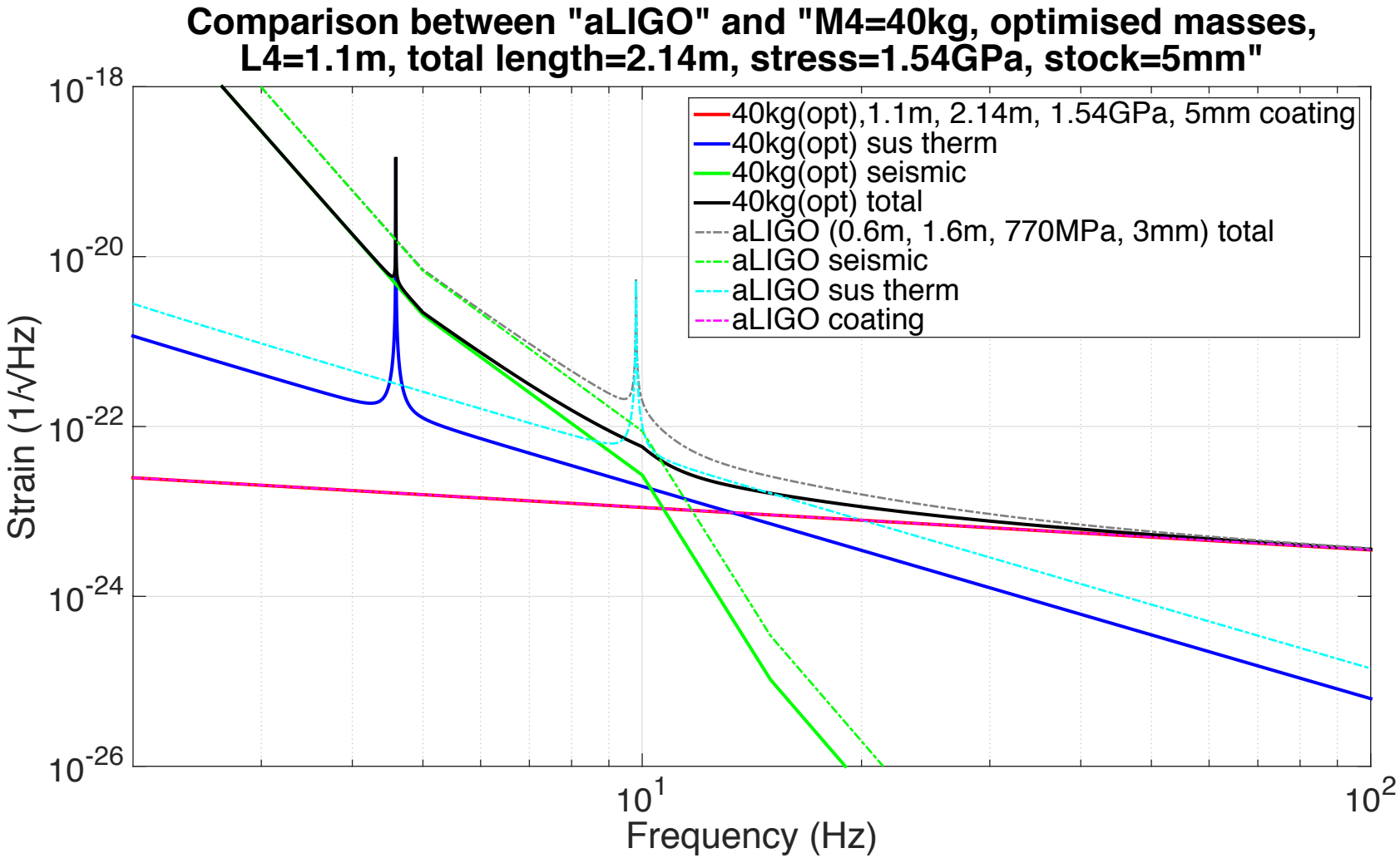
Upgrade #1: aLIGO with 2x stress



- Minimal Upgrade: Higher stress

➔ Only the fibre geometry is changed

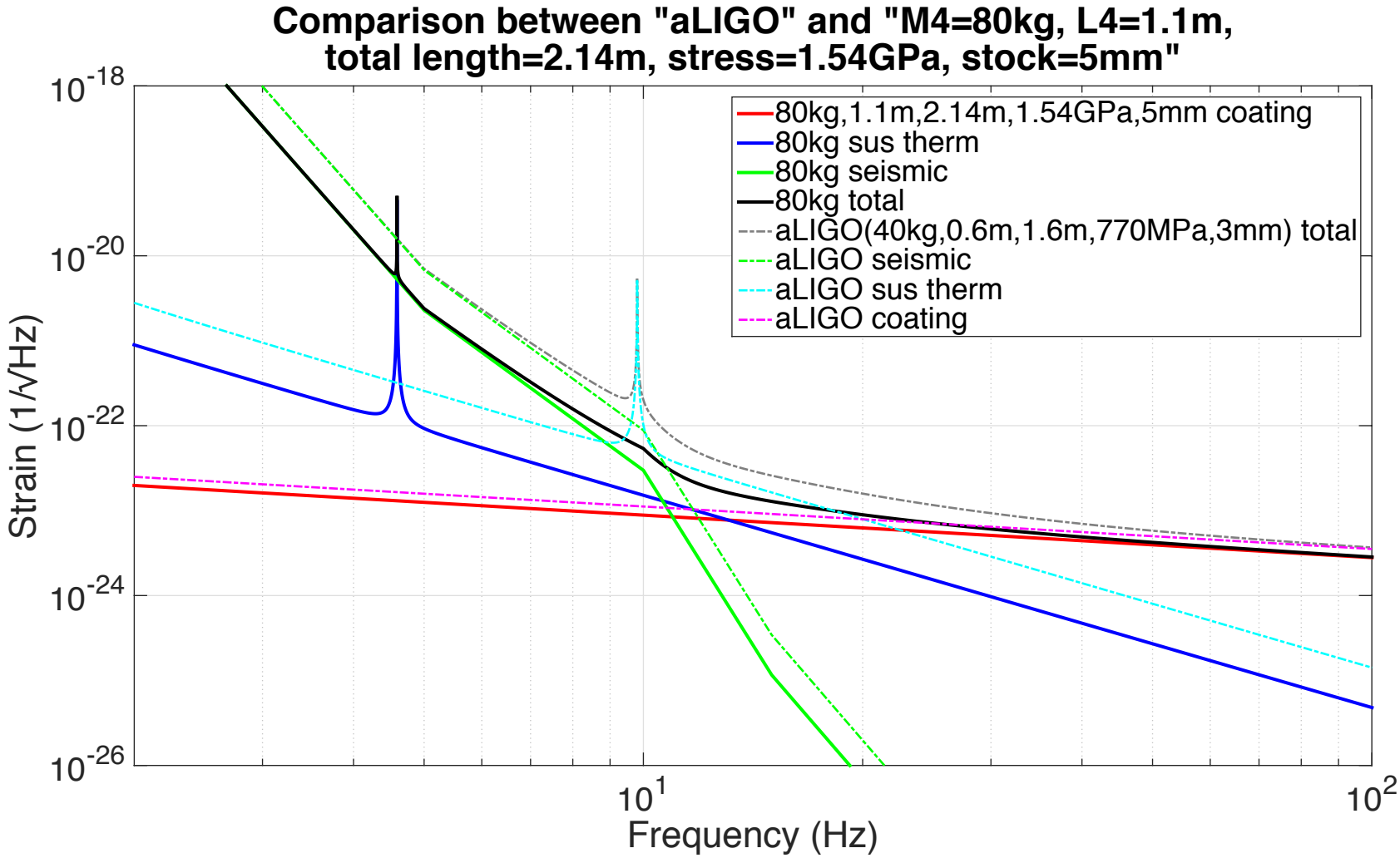
Upgrade #2: 40kg (opt), 1.1m, 2.14m, 1.54GPa



- Higher stress & Optimised mass arrangement

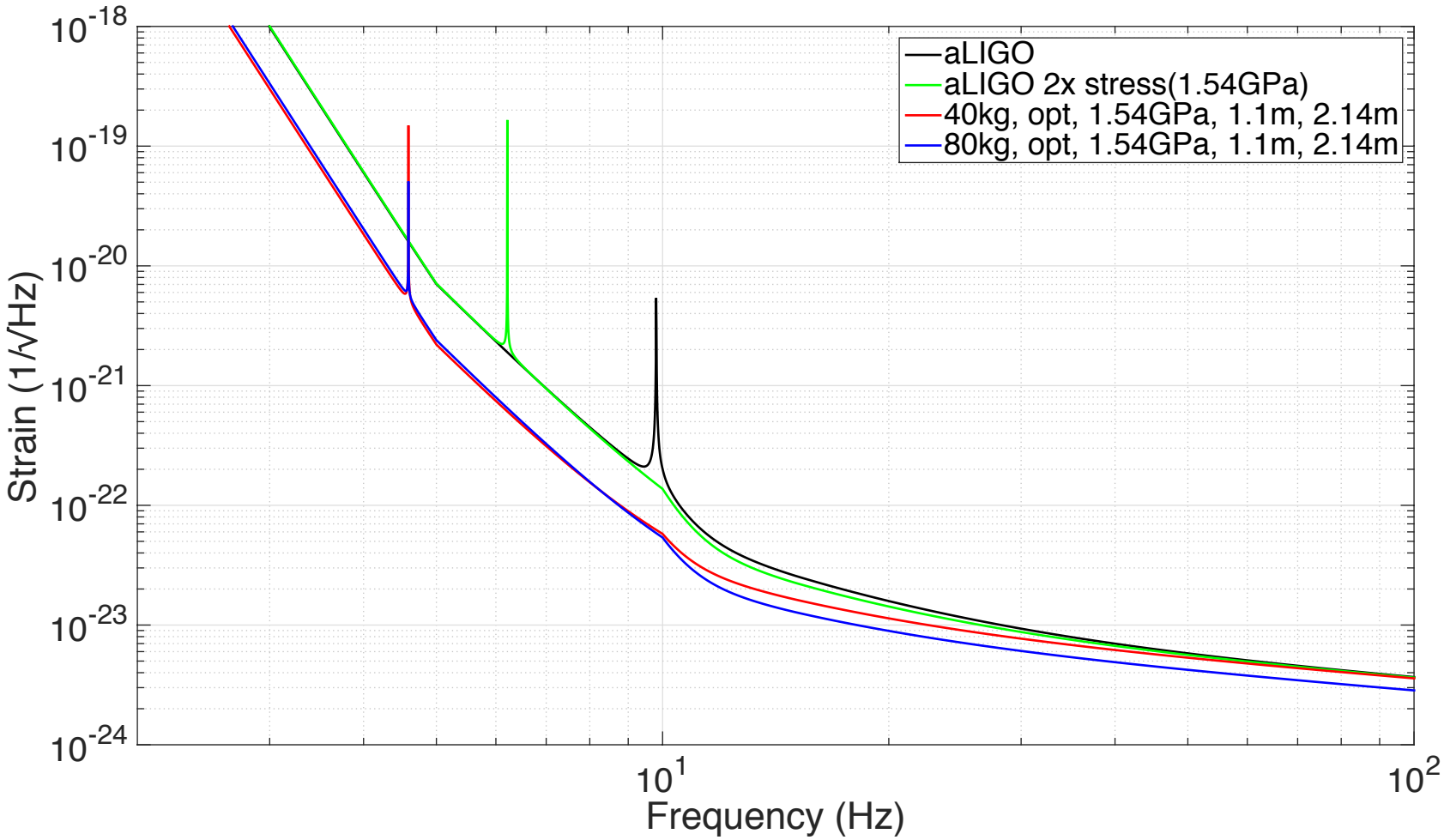
➔ Requires modifications to the suspension structure

Upgrade #3: 80kg (opt), 1.1m, 2.14m, 1.54GPa



- Higher stress & Optimized mass arrangement & Heavier test mass
  ➔ Requires more substantial modifications to the suspension structure and penultimate/test masses.

Prediction of Warm Upgrade Scenarios

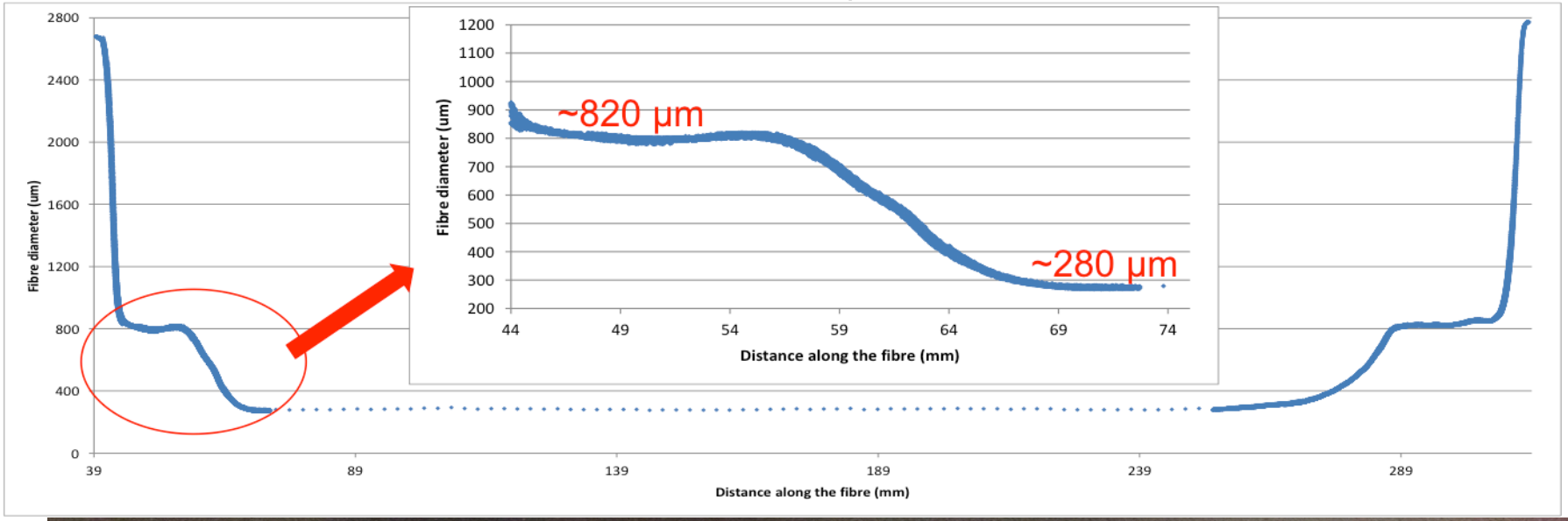


- Gravity gradient noise is not included in this plot.

(Only considering seismic, suspension thermal, coating Brownian noise)

Research Development in Glasgow

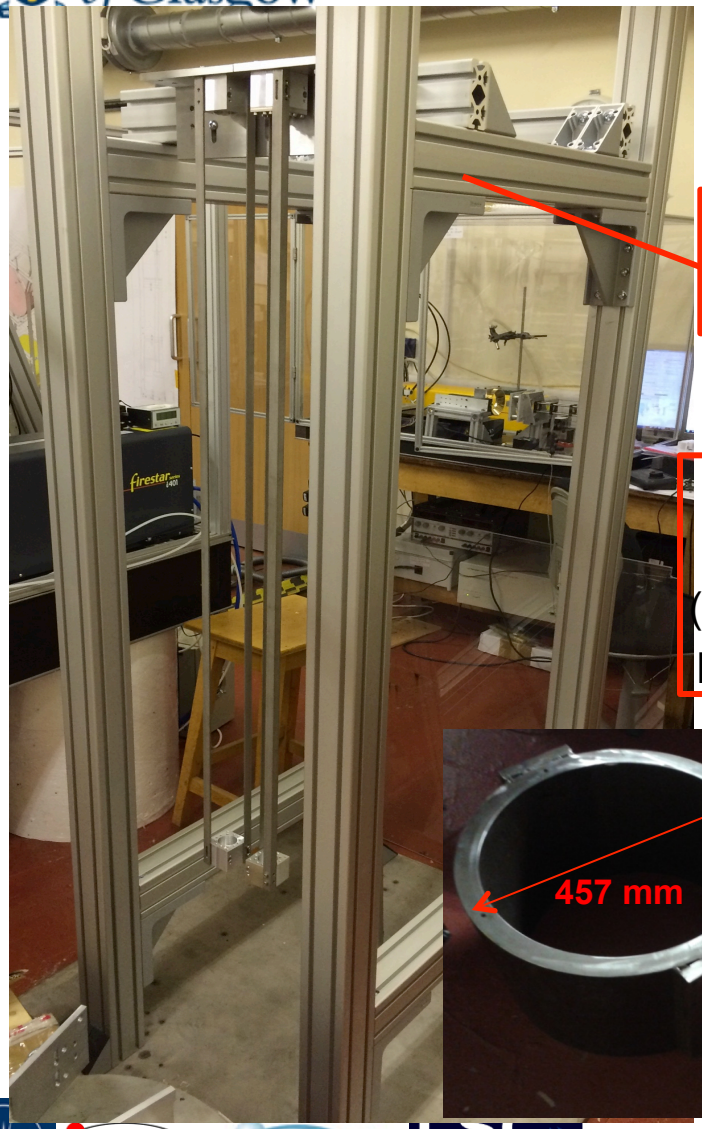
- Pulling fibres with new geometry for higher stress & longer suspension:
  - For 40 kg test mass
    - Thermoelastic nulling section = 822 μm
    - 1.54 GPa stress for thin section = 284 μm



  - Currently using 3 mm stock with 120 W CO_2 laser

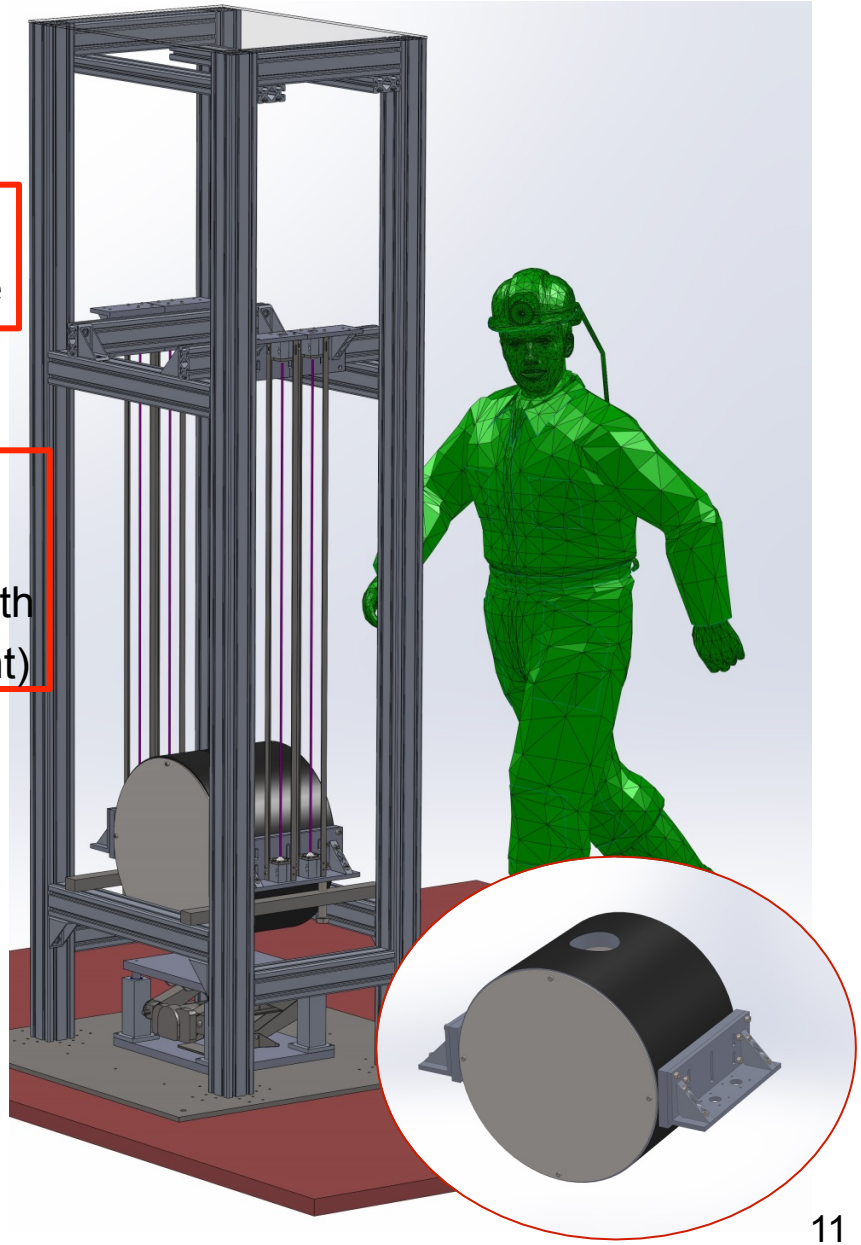
    ➔ will move on to 5 mm stock with 400 W CO_2 laser

Research Development in Glasgow

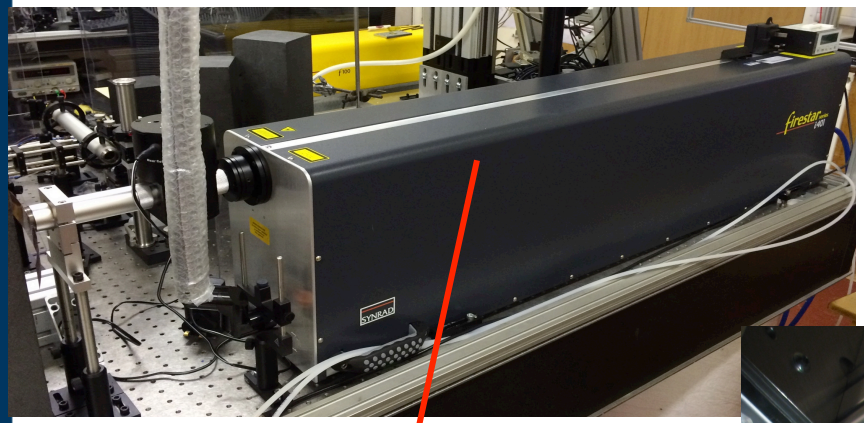


2.5 m
Structure

136 kg
Mass
(~200kg with
lead weight)

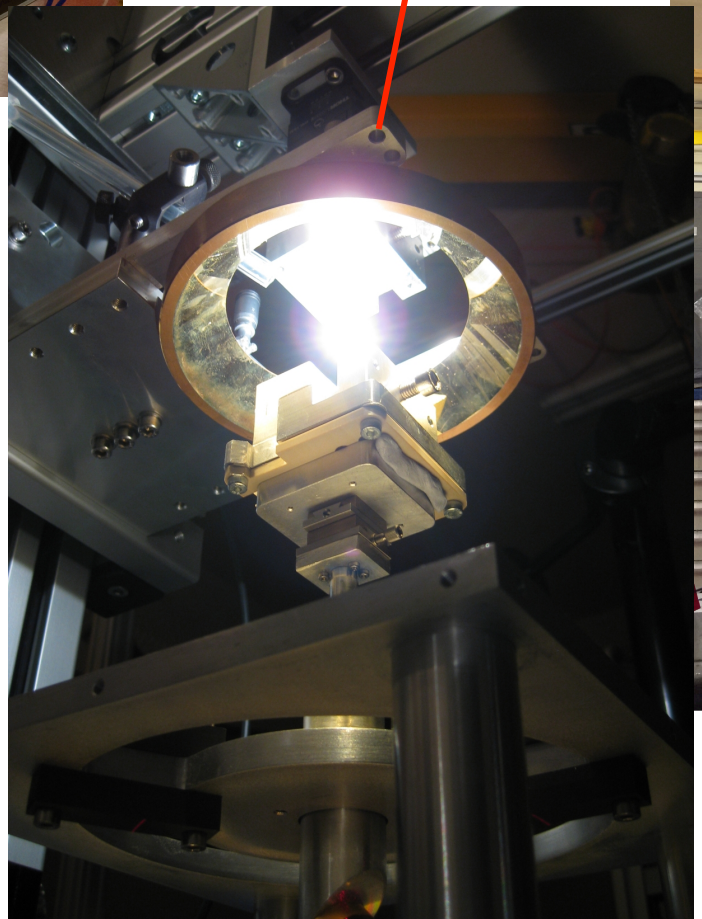


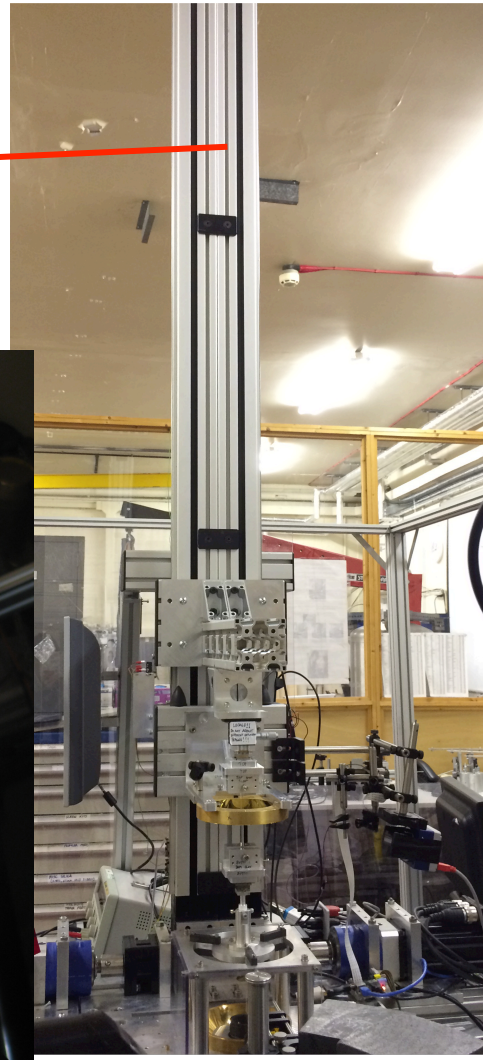
Research Development in Glasgow



400 W CO_2 Laser

Laser pulling machine





Summary

- There are a range of warm upgrade options which offer improvements of up to 5 in total noise performance at 10 Hz. (80kg, optimised mass, longer suspensions, higher stress)
- The most modest hardware upgrades utilise thicker fused silica stock (3 mm → 5 mm) and higher fibre stress (770 MPa → 1.54 GPa).
- An 80 kg suspension (80 kg/36.65 kg/53.44 kg/77.92 kg) with wire lengths 1.1 m/0.35 m/ 0.35 m/0.35 m offers good improvement around 10 Hz. (factor of 5 in total noise performance)
- We are currently developing the hardware necessary to prove upgrades in the mass range of 136 kg - 200 kg.

Thank you for your attention.