Mirror Suspensions for the Glasgow Sagnac Speed Meter

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1. Motivation

- Current gravitational wave detectors operate as position meters
- Continuous measurement of position is limited by back action noise
- Measurement of velocity or speed of a test mass is not limited
- Velocity sensing in Sagnac interferometer without any additions
- Proof of concept experiment: “Glasgow Sagnac Speed Meter” [1]
- Main goals:
  - Demonstrate reduction of back action noise in speed meter topology
  - Explore speed meters for use in future gravitational wave detectors
- Limited space requires compact suspension design with excellent performance

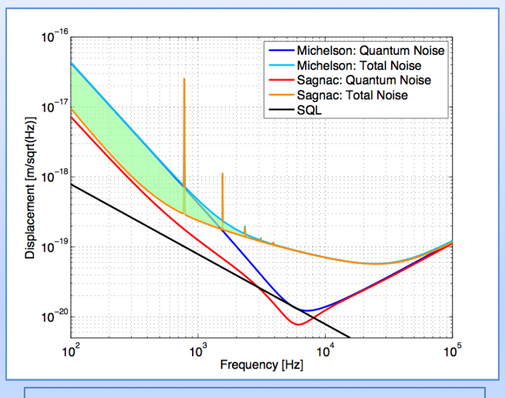


Figure 1: *Comparison of Sagnac and Michelson interferometer with equivalent parameters [1].*

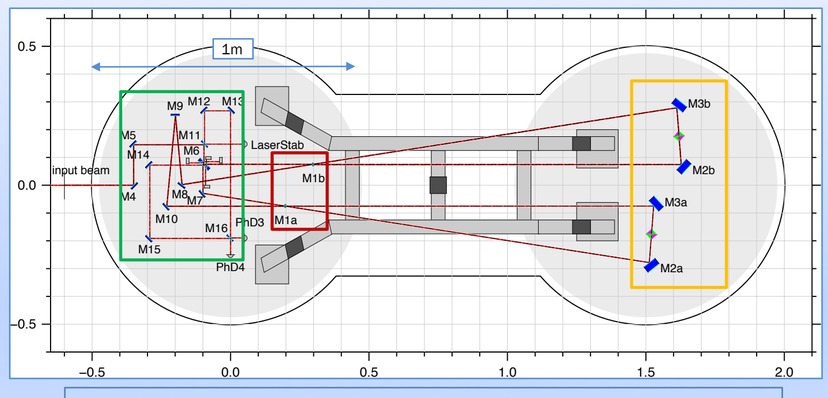


Figure 2: *Optical layout of the Glasgow Sagnac Speed Meter [1]. Highlighted are the different types of suspensions used in the experiment.*

2. Auxiliary Suspensions

- Constraint space in vacuum system (1m diameter) and high number of suspensions inside are challenge for design and performance of auxiliary suspensions.

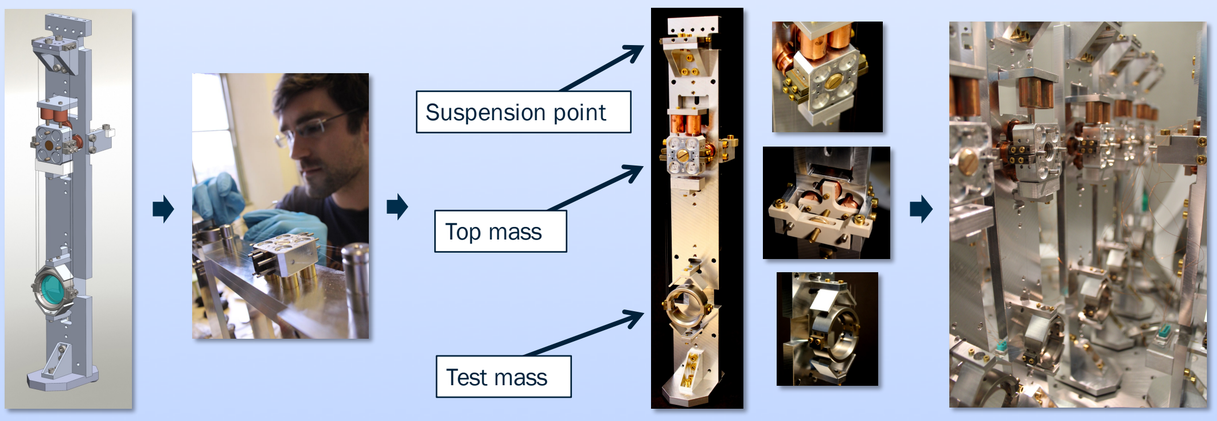


Figure 3: *Development stages of auxiliary suspensions. From the initial design on the left via cleaning and assembly to the final suspension on the right hand side.*

- Double pendulum with compact footprint 8cm x 5cm
- Large actuation range and sufficient seismic isolation
- Testing of dynamics and damping with optical lever for rotational degrees of freedom and vibrometer for longitudinal degree of freedom show excellent overlap of simulation and measurement.

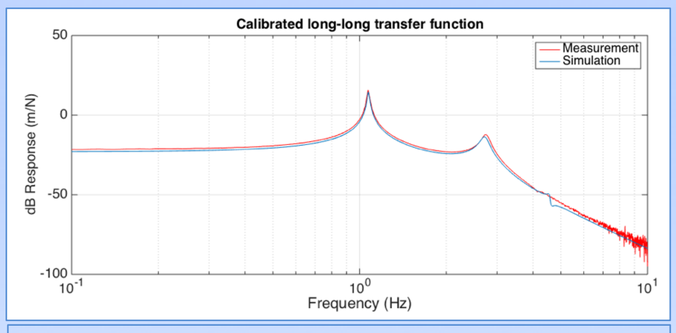


Figure 4*: Measurement of longitudinal force transfer function from top mass to test mass*

3. Suspension Thermal Noise

- Modelling of suspension thermal noise to find suitable parameters for fused silica fibres for 1g ITM mirror
- Calculations following [2]:

$$x^2(f) = \frac{k_B T}{2\pi^3 m f}\left(\frac{f_0^2\phi(f)}{f_0^4\phi^2(f)+(f_0^2-f^2)^2}\right)$$

$$\phi_{te} = \frac{YT}{\rho C}\left(\alpha-\sigma_0\frac{\beta}{Y}\right)^2\left(\frac{2\pi f\tau}{1+(2\pi f\tau)^2}\right)$$

$$\phi_s \approx \frac{8\rho\alpha_s}{d}$$

$$\phi_w \approx 5.8\times10^{-7}$$

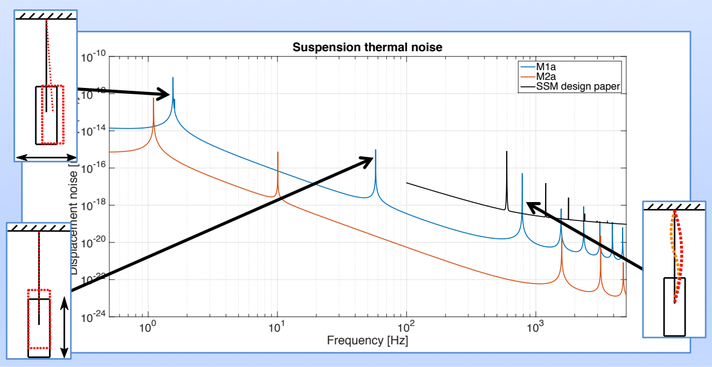
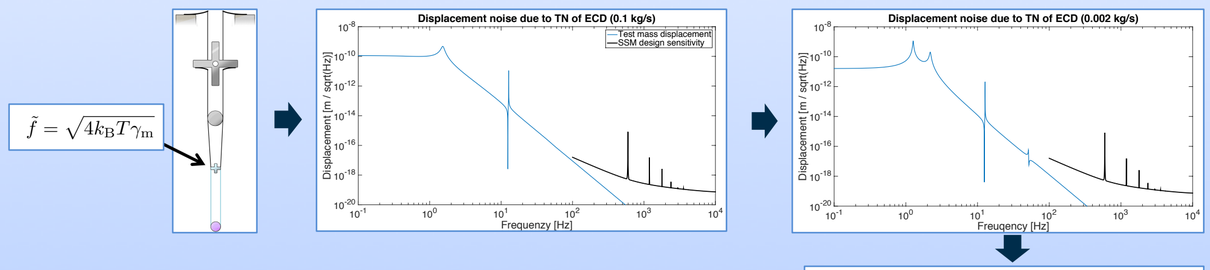
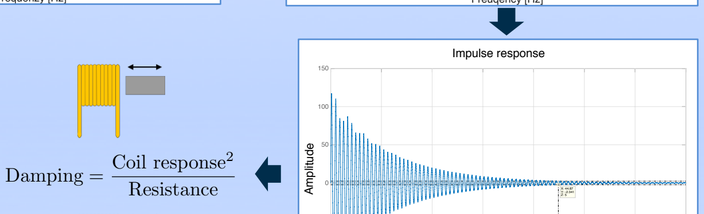


Figure 5: *Suspension thermal noise for the ITM and ETM suspension. This model was used to find suitable parameters for the 1g mirror fibre geometry.*

4. Switchable Eddy Current Damping

- Eddy current damping needed for control of 1g ITM suspension, but introduces displacement noise on test mass due to thermal noise.





- Damping (γ_m) of a coil magnet actuator dependent on force per current response and its residual resistance. Closing and opening the coil will allow switching of ECD.

$$\text{Damping} = \frac{\text{Coil response}^2}{\text{Resistance}}$$

Figure 6: *Illustration of the need to have switchable ECD. Thermal noise of ECD causes displacement noise. Reducing damping strength solves this, but makes ringdown times too long. Switchable ECD is solution to this issue.*

5. 1g ITM Suspension

- How to suspend a mirror as light as a one dollar note?
  - Quadruple pendulum design
  - 1g mirror on “cradle” ear
  - 10cm long, 10µm thick fused silica fibres
  - Switchable Eddy current damping

Figure 7: *One dollar note on a scale.*

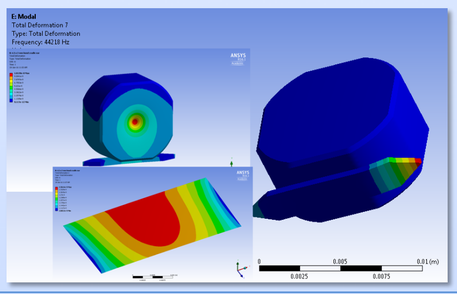


Figure 8: *FEM of cradle design to show feasibility. First mode at ~40kHz and sufficient bond loss.*

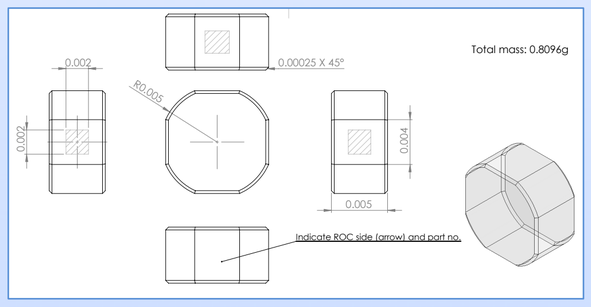


Figure 9: *CAD drawing of the 1g input test mass. The optic has small (2 mm x 2 mm) bonding areas on three flat sides.*

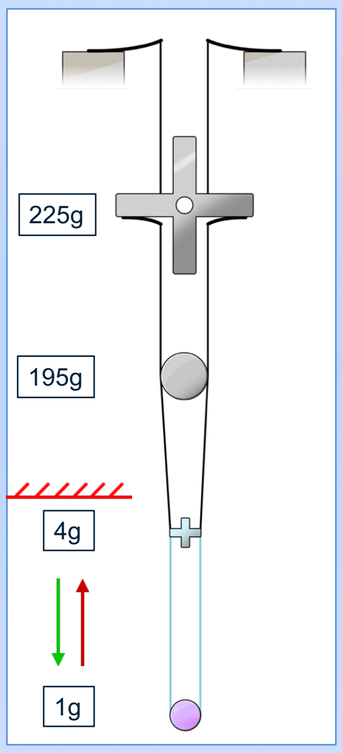


Figure 10: *Conceptual design of the 1g ITM quadruple suspension.*

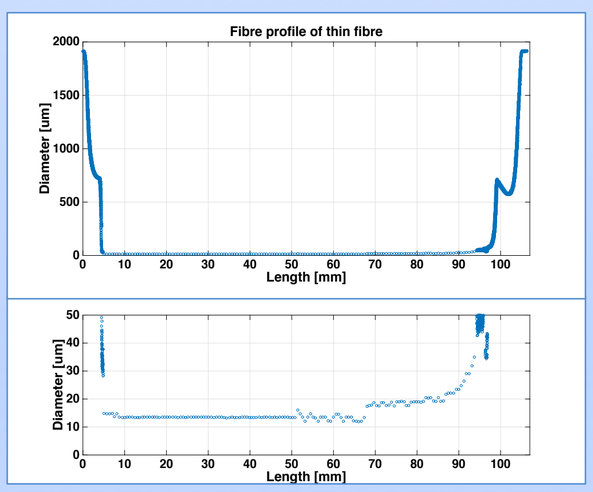


Figure 11: *Measured profile of a thin fibre pulled at the IGR in Glasgow. Work carried out by Karl Toland.*

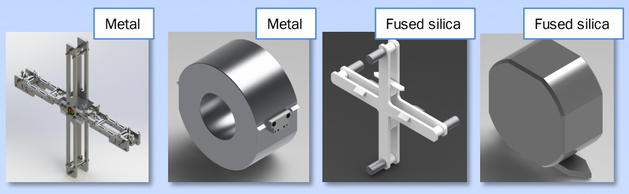


Figure 12: *Rendered images of masses for 1g ITM suspension. Left to right: Top, penultimate and test mass*

6. 100g ETM Suspension

- Triple pendulum design originally developed for AEI SQL experiment [3]
- Adaptation of suspended chain in modified support structure

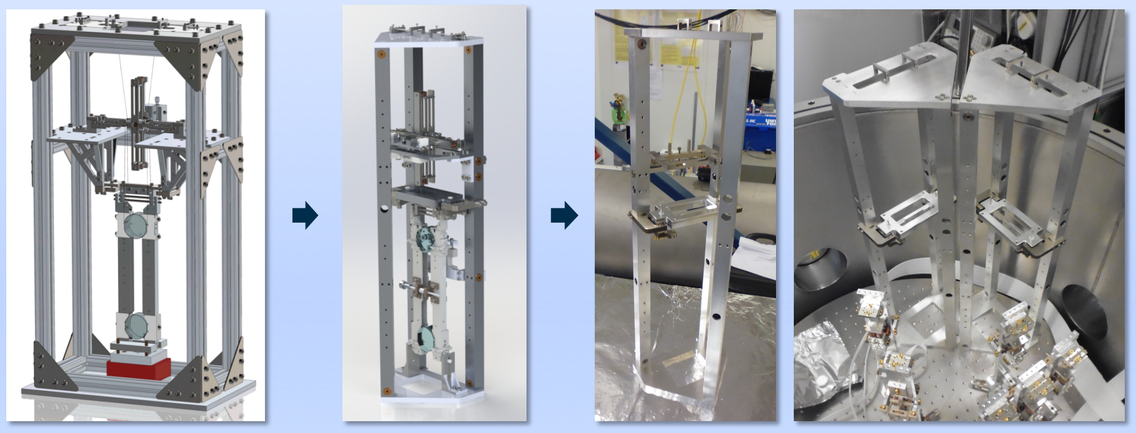


Figure 13: *Design changes made for the 100g ETM suspension. CAD model of the orginal design (left), modified support structure (center) and support structures in scaled tank model (right).*

7. Conclusion and Outlook

Done:
- Auxiliary suspension built and tested
- 100g ETM parts delivered
- 1g ITM design in final steps

To Do:
- Build prototype for testing switchable Eddy current damping
- Clean-build 100g ETM suspensions

References:
[1] C. Graef et al: *Design of a speed meter interferometer proof-of-principle experiment*, CQG, vol. 31, 215009, 2014
[2] G. Hammond et al: *Reducing the suspension thermal noise of advanced gravitational wave detectors*, CQG, vol. 29, 124009, 2012
[3] C. Graef: *Optical Design and Numerical Modelling of the AEI 10m Prototype sub-SQL Interferometer.*, PhD thesis, 2013, Leibnitz Universität Hannover

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