Multiple Optical Springs in Coupled Resonators

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Outline

Surpassing the free-mass Standard Quantum Limit

- Single optical springs
- Multiple optical springs

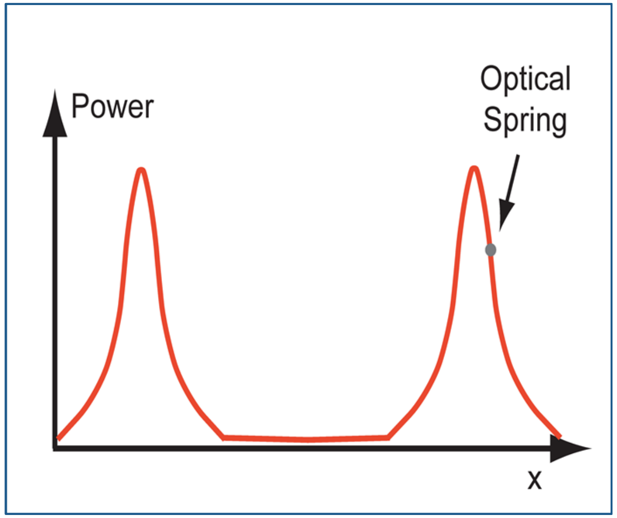
Coupled-cavity test system for Multiple Optical Springs

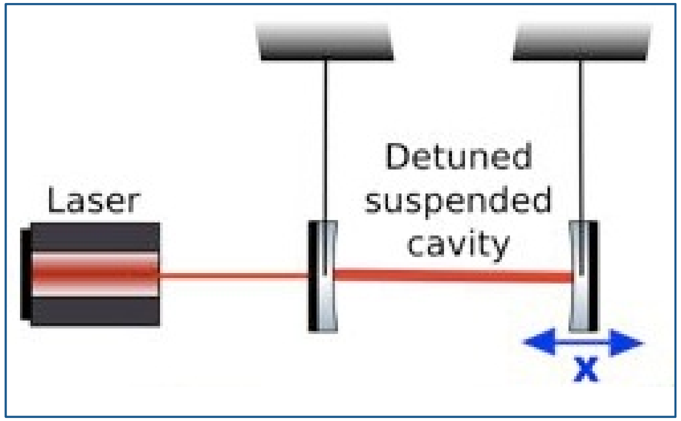
- Experimental design
- Simulations
- New optic suspensions at the Glasgow 10m Prototype

On-going Work

Optical Springs

- Suspended optical cavity, detuned from resonance
- Can create linear dependence of intra-cavity power, and hence radiation pressure force, on mirror position – i.e. a **spring**:
  - Radiation pressure force
    - ⇒Mirror movement
    - ⇒Change in stored power
    - ⇒Change in radiation pressure force…
- **Opto-mechanical coupling** of cavity optics
- Various applications in GW field:
  - Transducer for GW signals to mirror movement in the local frame
  - Narrowband sensitivity improvements in the detection band



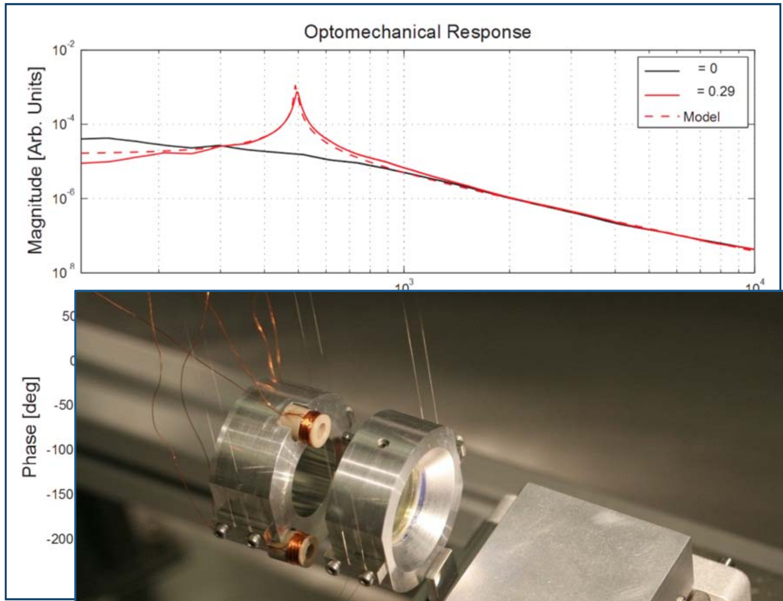


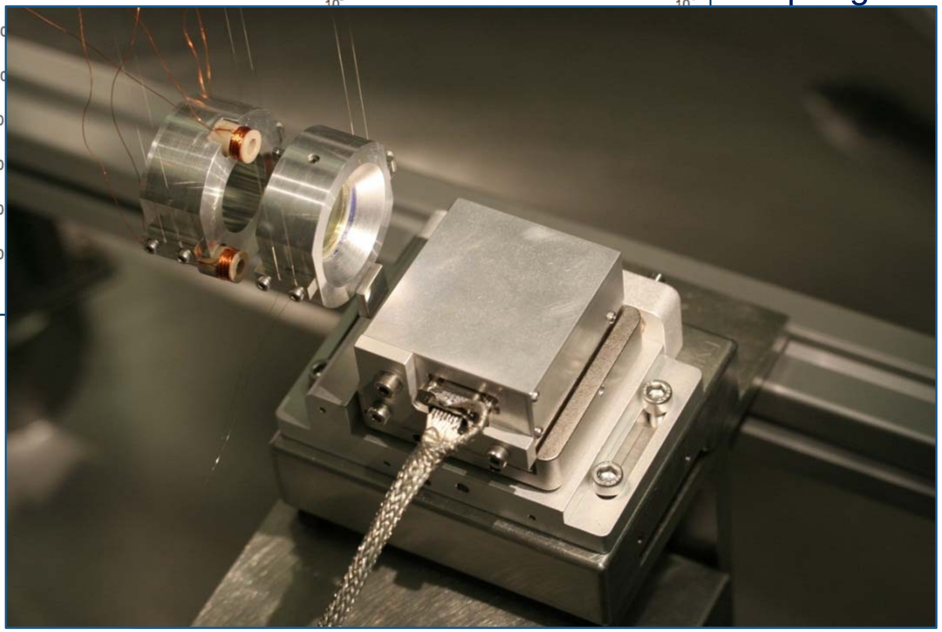
Optical Springs

- **Narrowband sensitivity improvements in the detection band**
  - Transformation of test-mass into a more responsive object.
    - » **Free-mass** force susceptibility: $$\chi_{\mathrm{FM}} = \frac{1}{\mu\Omega^2}$$
    - » **Harmonic oscillator**: $$\chi_{\mathrm{HO}} = \frac{1}{\mu\left(\Omega^2 - \Omega_0^2\right)}$$
  - Resonant enhancement of signal **before** read-out
  - Essentially **noise-free amplification** within the resonant bandwidth – the optical spring adds no “classical” noise

Optical Springs

Optical Springs at the Glasgow 10m prototype





2011
Optical spring in high-finesse cavity. [1]
Spring read out from in-loop transfer functions.

Maximum spring observed at **496Hz**, corresponding to spring constant of **9.4e5 N/m**.

2012 – present
"Local Readout" experiment:
Optics rigidly coupled beneath spring resonant frequency.

Local readout allows monitoring of light mirror position without disturbing quantum state of system. [2]

Can be applied to e.g. "Optical Bar" system – GW signal extracted from local readout of light coupled mirror below spring resonance

[1] M. Edgar, Ph.D. thesis, University of Glasgow (2011)
[2] J. Macarthur, Second Year Research Report, University of Glasgow (2012)

Optical Springs

But, not ideal:

- A single optical spring is inherently **unstable**

- The enhancement available to a single optical spring is **narrow**

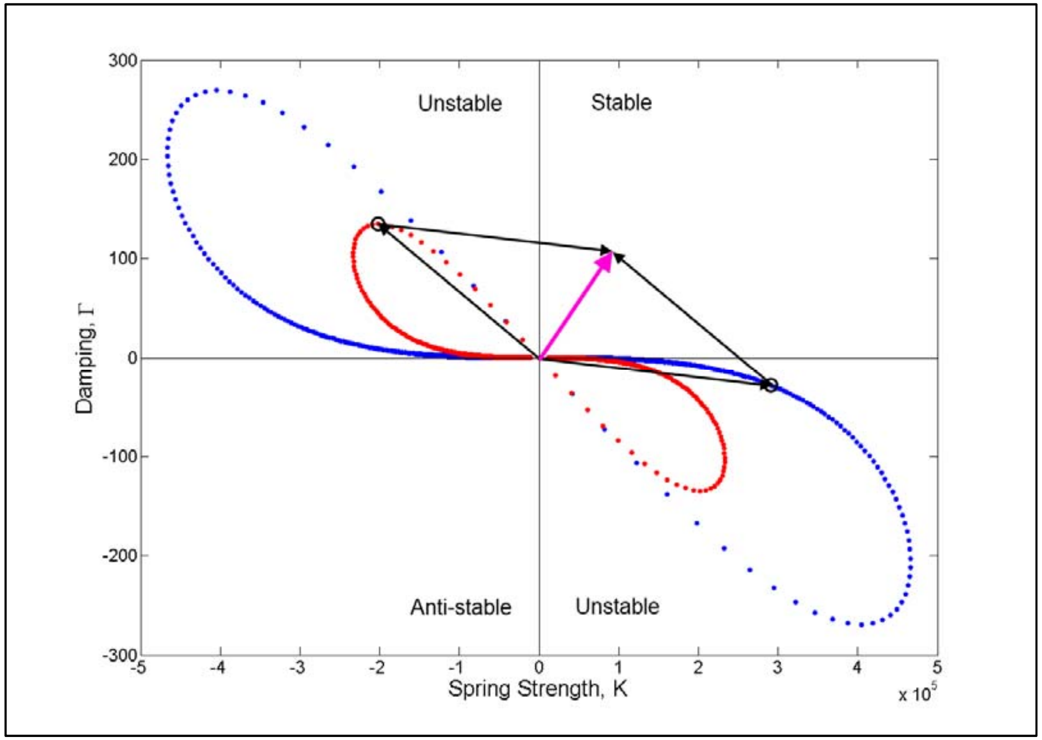
- Using **multiple** detuned optical fields, we can address some of these issues:
  - A **stable** configuration may be achieved by the inclusion of a second carrier, with each detuned appropriately such that the combined effect is stable
  - Multiple springs can be used to beneficially re-shape the noise spectral density of a detector for **wider-band enhancement**

  - Has been previously demonstrated:
    - Rehbein et al., *Double optical spring enhancement for gravitational wave detectors,* Phys. Rev. D 78, 062003 (2008)

Multiple Optical Springs

1. Stability

- The spring system may be made **stable** with the combined effect of two or more springs



e.g.
"weak stabilisation":

$$\frac{|K_+|}{|\Gamma_-|} \gg \frac{|K_-|}{|\Gamma_+|}$$

$$|\Gamma_-| \sim |\Gamma_+|$$

$$\Rightarrow |K_+| \gg |K_-|$$

- In general, we can add a **strong** spring with **weak** anti-damping to a **weak** anti-spring with **strong** damping to achieve stability
  - one spring gives mostly restoring force, one gives mostly damping

2. Wide-band enhancement

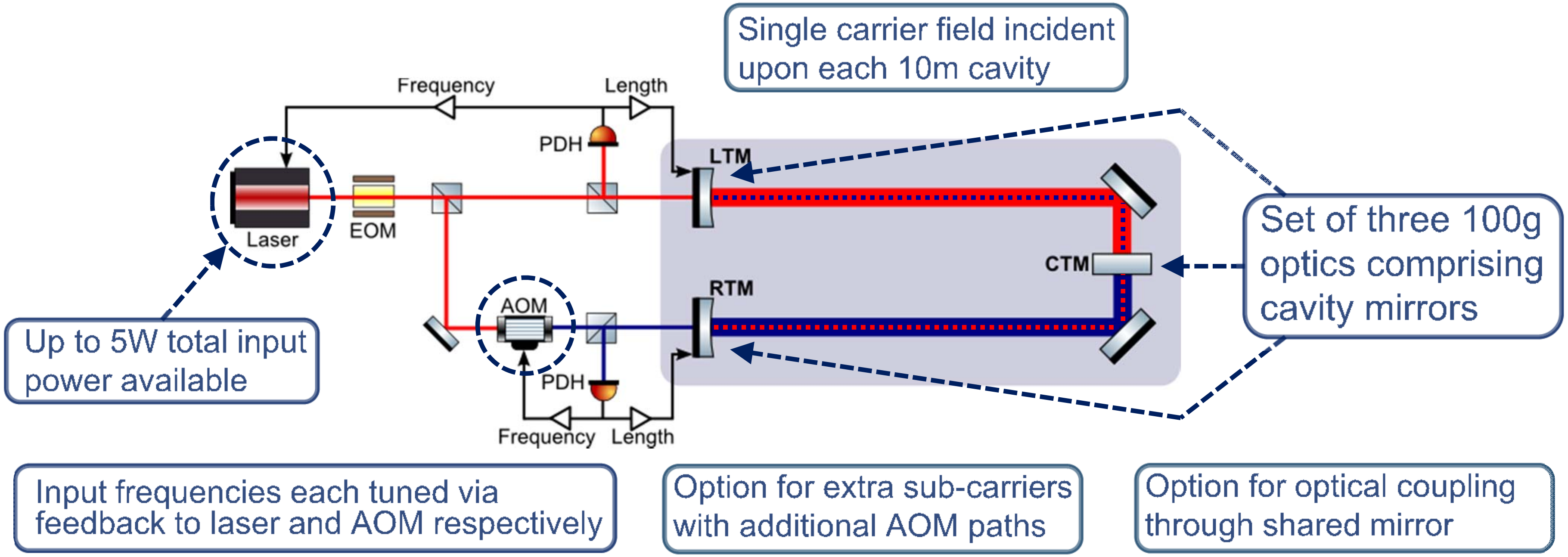
- Enhancement available to single springs is very **narrow**, and so only useful for highly-targeted GW searches
  - **Coupled** oscillators can produce enhancement over a wider band

- Each spring response can be modified via mutual interaction with shared optics

- Further, if we can somehow **combine** the response to each coupled spring, we can observe resonant structures spanning an octave in frequency
  - Electronic summing (at the expense of increased noise); subject to relative phase of each signal
  - Frequency-dependent homodyne read-out?

Experimental Setup

- **The experimental setup:**
  - We want a system flexible enough to investigate multiple springs, stable configurations and control strategies
  - Model system with two cavities coupled mechanically via a shared mirror (with optional optical coupling at a later stage)



  - **Flexible** model of equivalent system to GW detector, but easier to study on a prototype scale

Objectives

- This system is very flexible, allowing us to cover three main objectives of experimentation:

1. **Purely mechanical coupling between the two cavities**
   - Each cavity aligned slightly off-axis with respect to other, to ensure no optical coupling
   - Production and characterisation of broad resonant structures in the few hundred Hz to 1kHz range
   - Combination of coupled spring responses to give wide-band resonant response

2. **Optical and mechanical coupling between the two cavities**
   - Alignment of both cavities, modification of shared optic to **tuneable etalon**, allowing control of optical coupling
   - Further investigation of coupled spring responses, extending to dual-carrier spring stability
   - Further feedback paths required for control
   - Simulations ongoing

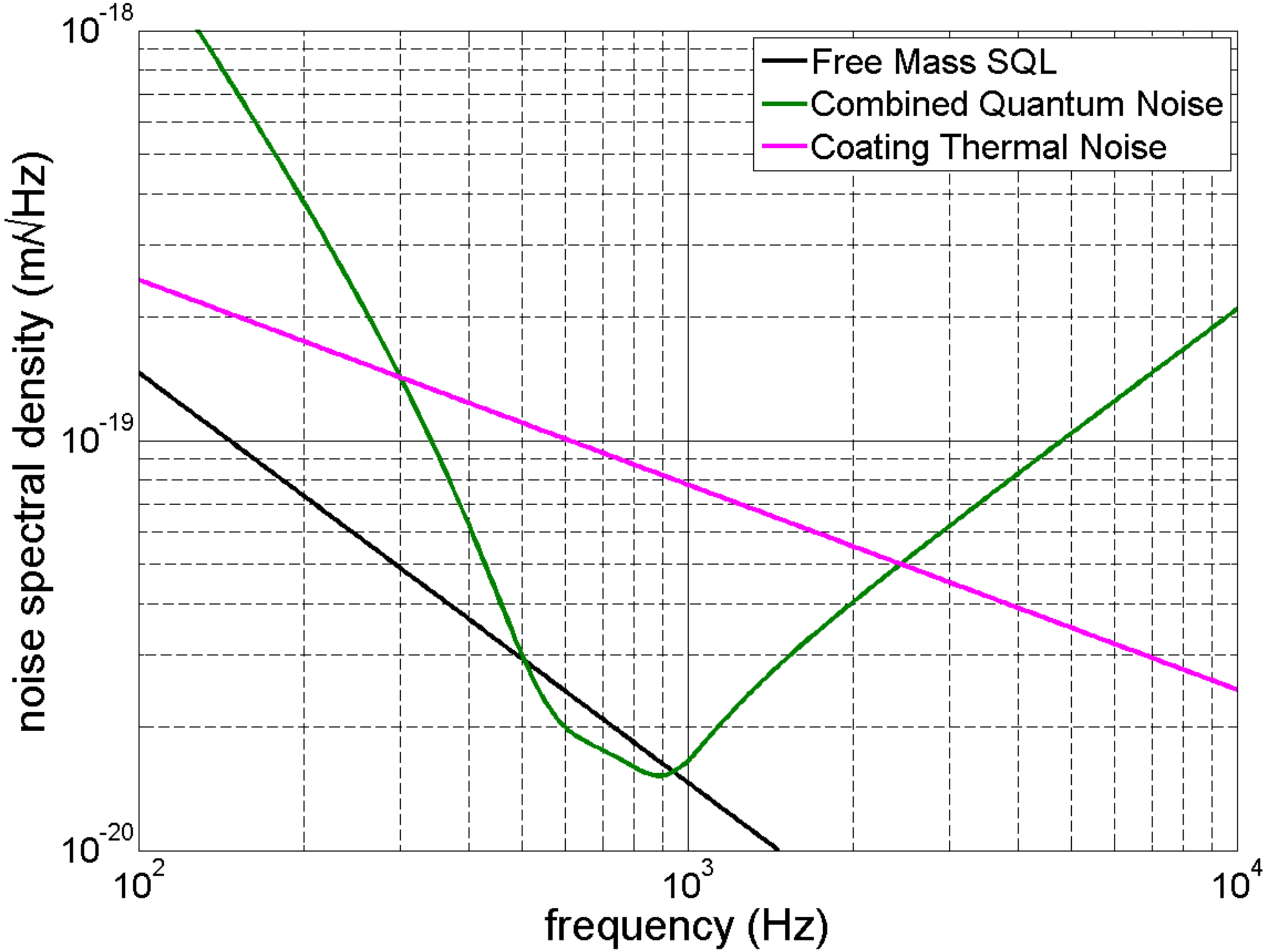
3. **Investigation of stability and control strategies**
   - Additional AOM paths allowing for injection of sub-carriers
   - Optical “trapping” of shared mass [3]?
   - Investigate control strategies for radiation-pressure-dominated systems

[3] T. Corbitt et al., *An All-Optical Trap for a Gram-Scale Mirror*, PRL 98,150802 (2007)

Simulations

- Simulate modifications to isolated spring transfer functions due to coupling of springs at the Central Test Mass (CTM)
- For **purely mechanical coupling** of cavities, we model the shared CTM as an opaque optic (achieved in practice by slight relative angular misalignment of each cavity)
- Summing the response of each cavity to each coupled spring, we can produce **wide-band resonant structures**, corresponding to **wide-band improvement in quantum-limited sensitivity**
- These simulations **include losses** in the optics, of realistic values comparable to the loss estimates for the real optics

Simulations



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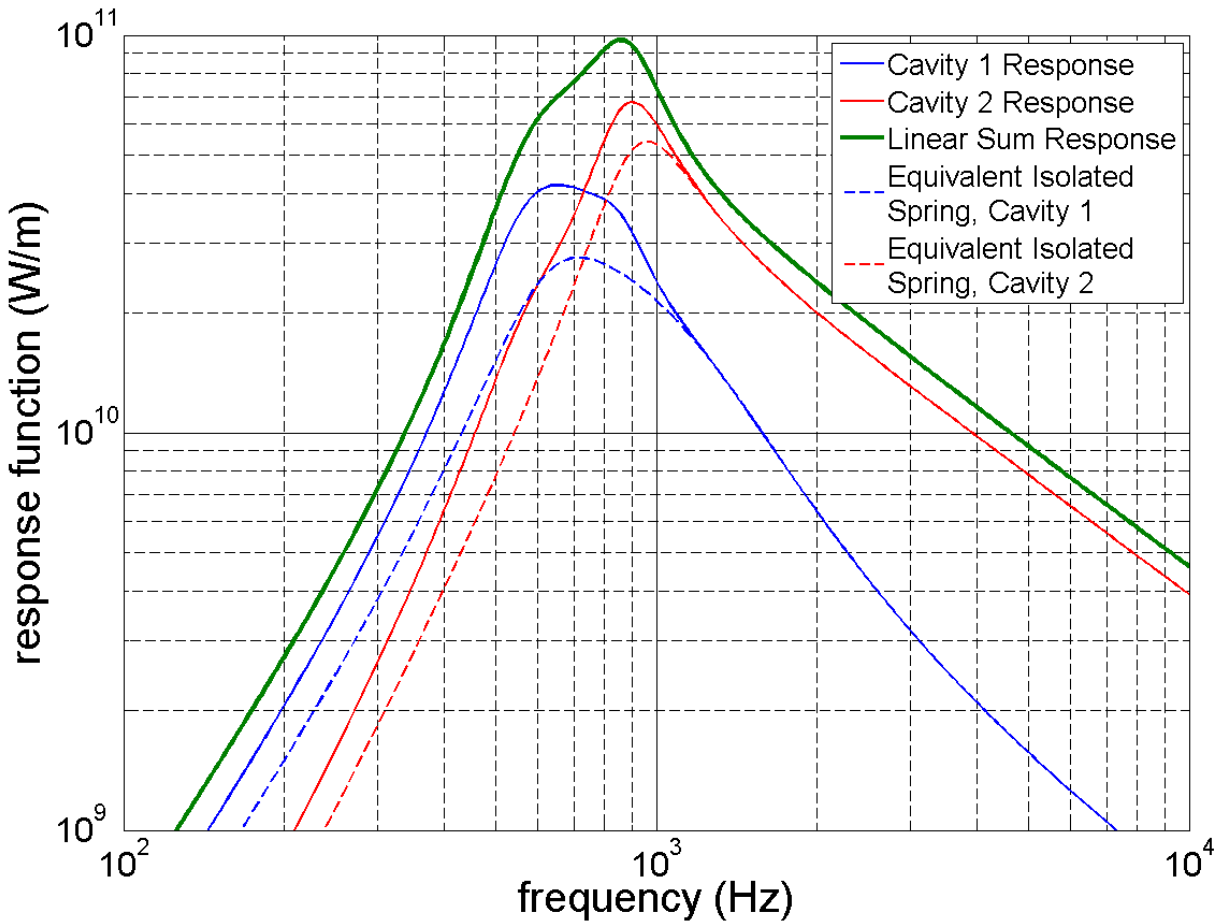
Here, input power to each cavity is 2W, each detuning is -2 and 0.5 respectively, expressed as fractions of the cavity linewidth.

- Will require widening of the detuning range

Simulations

- Coating thermal noise is a factor ~5 higher than quantum noise, so we must measure the modified spring structures via in-loop cavity transfer functions

  [Alternatively, local readout of the light central mass (c.f. optical bar)]



In practice, such signals will be read out from the photodiodes on the input bench used for PDH locking of each cavity.

Control and Stability

3. **Investigation of stability and control strategies**
   - Additional AOM paths allowing for injection of sub-carriers
   - Optical “trapping” of shared mass?
   - Investigate control strategies for radiation-pressure-dominated systems

- Further to achieving stable combined spring configurations, there are three key challenges to our control systems:

1. Systems must be able to cope with **evolving dynamics** as power builds up to operating level (up to tens of kW on-resonance)
2. **Strong control** to stabilise the multiple optical springs in the system
3. **Reduction of back-action noise** from position sensing – sensing and controls able to preserve the quantum state of the system

- … as well as other issues for stability:
  - » Auto-alignment systems (spot position detectors, feedback to control coils) to stabilise angular instabilities due to radiation-pressure effects

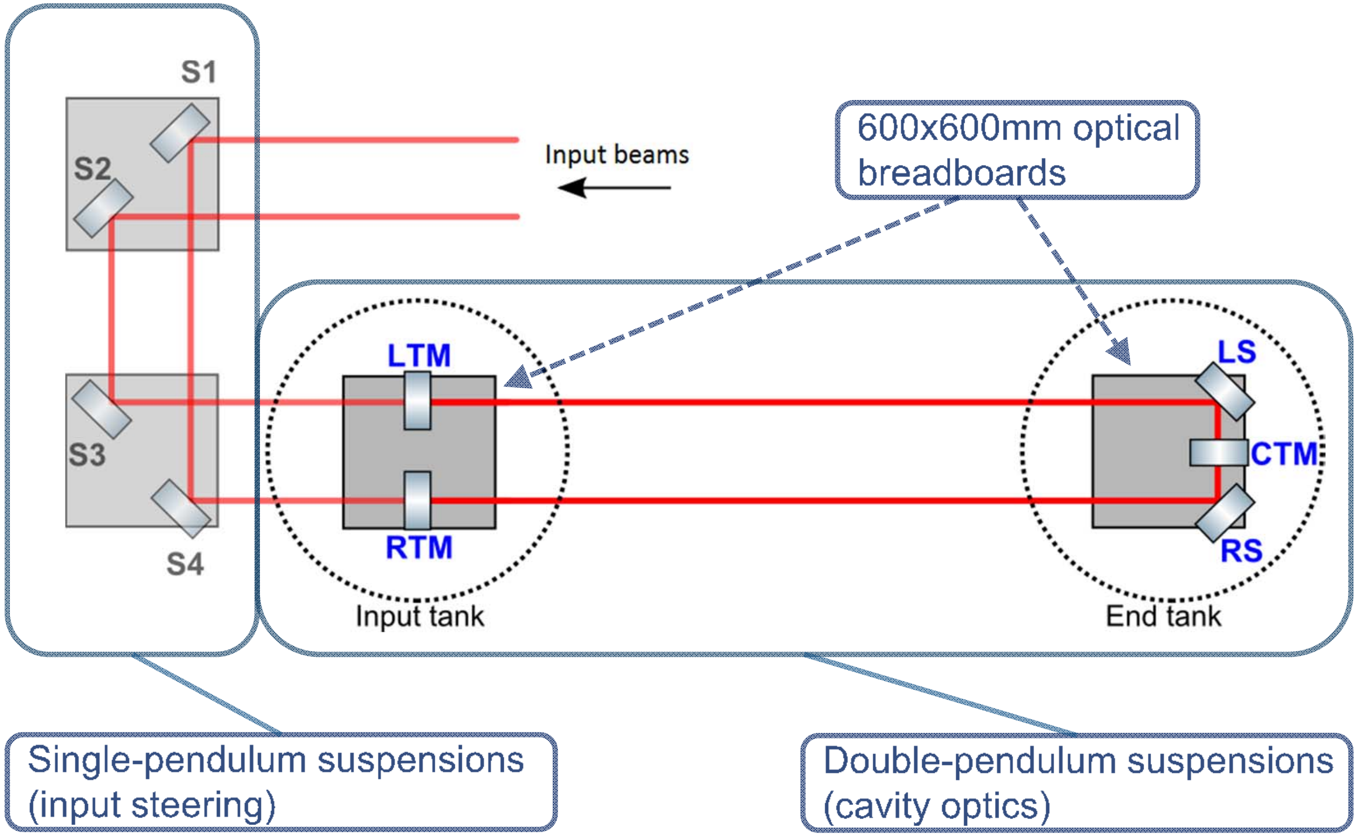
New Optic Suspensions

- This new work requires us to modify the current laboratory infrastructure
  - Currently single 10m end-pumped cavity in a single vacuum system
  - We will need to fold our two-cavity system to fit in the same infrastructure

  - So, we need **nine** new suspension systems, subject to the following requirements:
    - Simple in design and adaptable, for further application during and following this work
    - Provide displacement noise of $\leq 10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ in the experimental region (above ~300Hz)

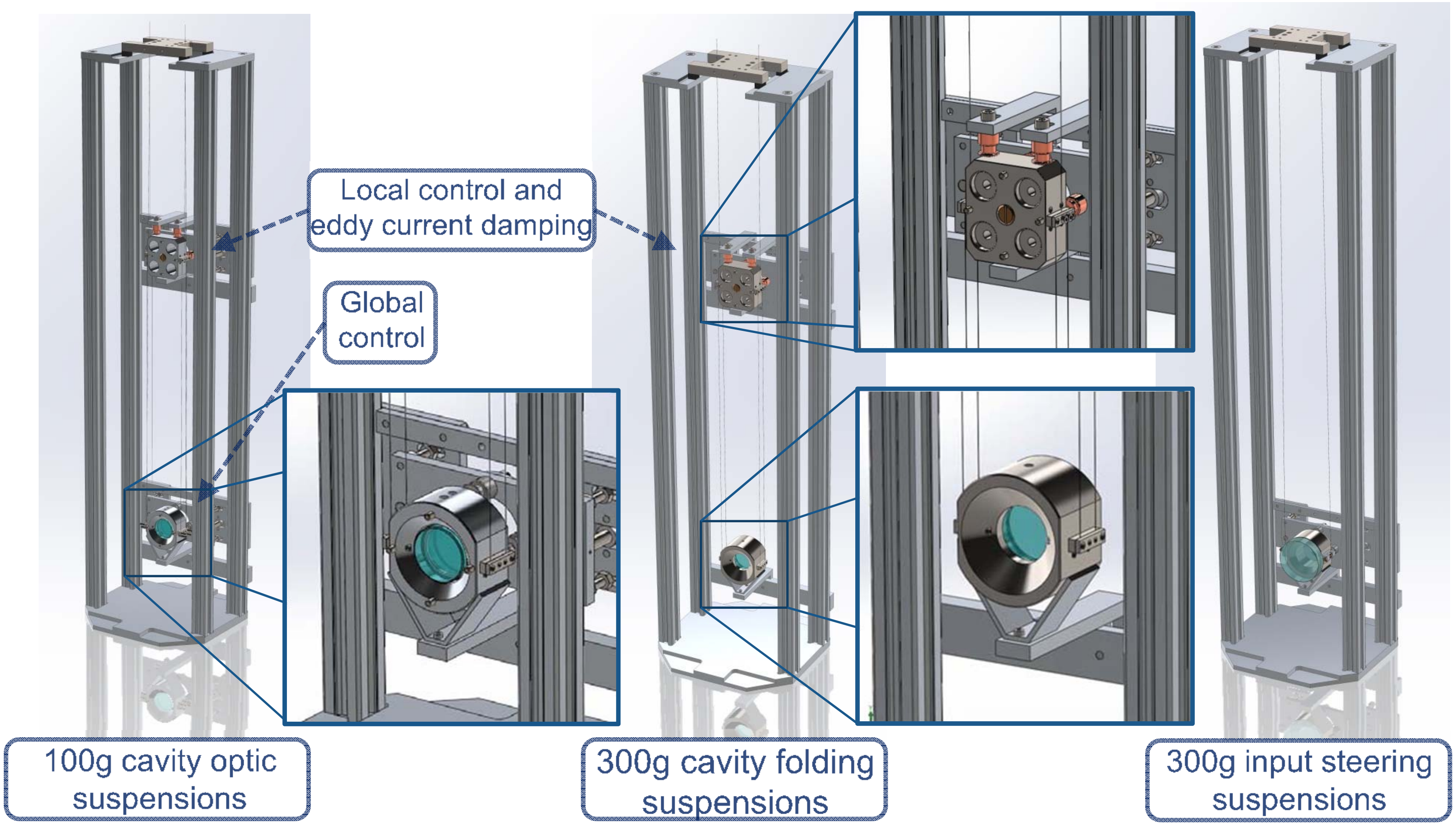
New Optic Suspensions

– Isolation: **double-pendulum suspensions** mounted upon optical breadboards with **three layers of rubber stack pre-isolation**



New Optic Suspensions

– All suspensions based on the same simple structure



On-going Work

- “To do” list:
  – Simulations for e.g. aLIGO or ET parameters
    - Full interferometer model incorporating multiple springs, novel cavity setup

  – Construction and installation of new suspension systems.
    - Beginning **now**
    - Mechanical parts being delivered
    - Coated optics arriving early next month

  – Setting up of new input optics, RF electronics and control systems.

  – Aiming to have the coupled-cavity system up and running by the end of the summer.

Summary

- Aim to construct a two-mode optical spring system in a 10m, high-finesse coupled-cavity experiment illuminated with up to 5W total input light at 1064nm, with the eventual goal being to produce and characterise a broad resonant structure in the few hundred Hz to 1kHz range.
- The flexible new laboratory layout also allows us to both optically and mechanically couple the cavities, with the coupling mass modified to be a tuneable etalon, to investigate more complex resonant responses.
- To facilitate this, a completely new suspension design will be adopted for the Glasgow 10m prototype – simple, effective and adaptable.
- We also aim to investigate the control challenges to radiation-pressure-dominated systems.
- Commissioning due to begin next month.