Optical Spring Measurements with the Glasgow 10m Prototype

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GEO simulation meeting - 14th December 2010

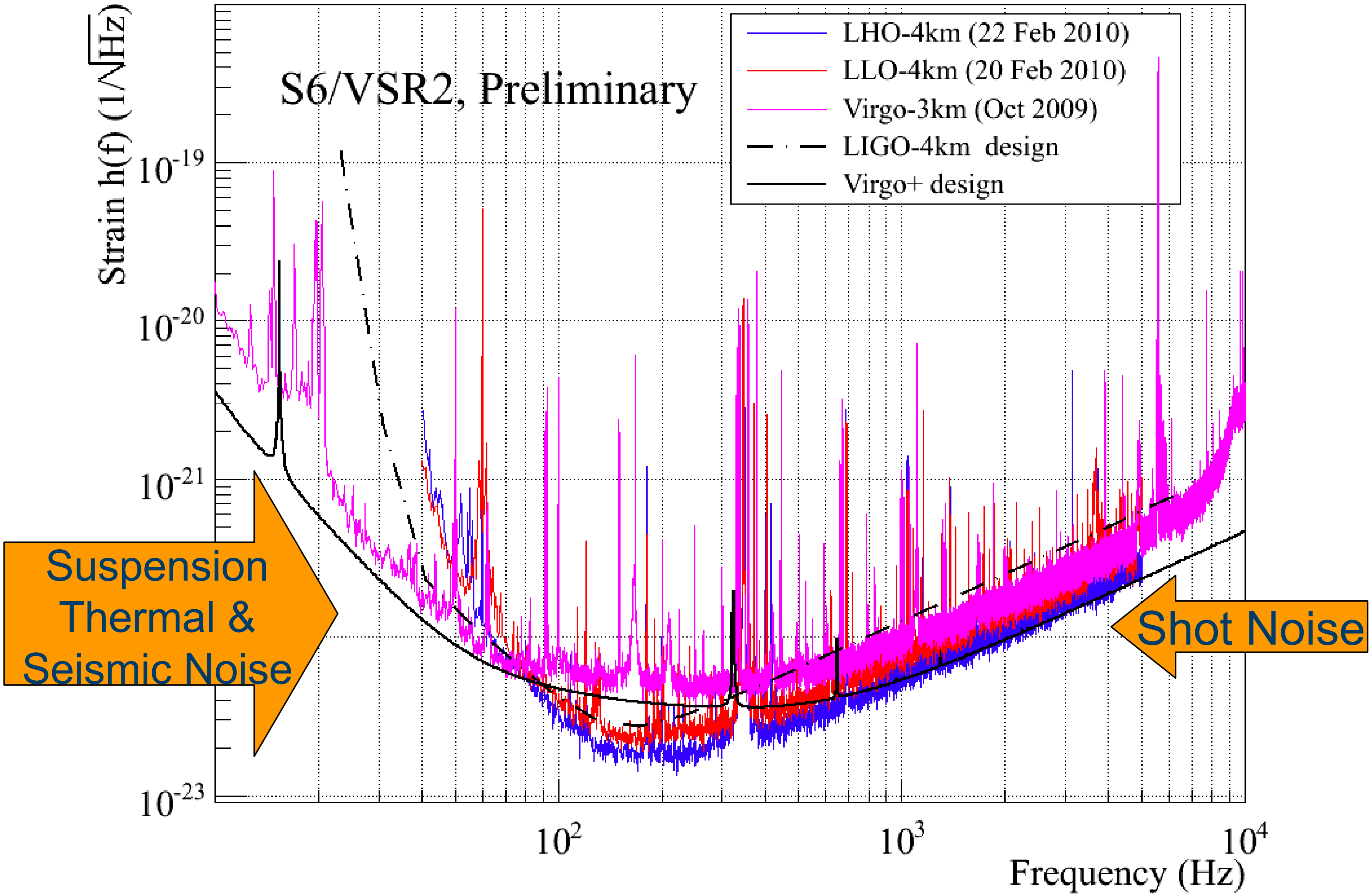
Talk Outline

- **An introduction to optical springs**
- **The Glasgow 10m prototype interferometer**
- **The optical spring experiment**
  - Experimental aims
  - Experimental design
- **Experimental method**
  - Coupled cavity control scheme
  - Characterising the coupled cavity
  - Generating optical springs
- **Experimental results**
- **Conclusions and future work**

An introduction to optical springs

- Current ground based detectors are already running close to fundamental limits imposed by HUP.
- Utilise coupled cavities to maximise the stored light level.
- Maximal strain sensitivity between 50Hz and 5kHz.
- Limited by suspension thermal noise/seismic vibrations at low frequency and shot noise at high frequencies.
- Improvements in future detectors
  - More effective seismic isolation
  - More powerful lasers
  - New optical topologies
  - Higher quality mechanical components

An introduction to optical springs



An introduction to optical springs

Future detectors will be limited by quantum noise.

Quantum noise

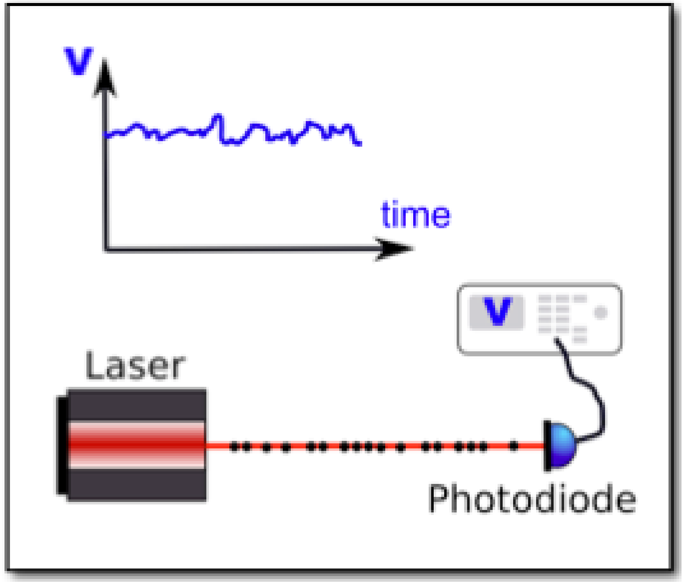
- Photon shot noise (Poissonian noise in in the number of photons detected) at high frequencies.
- Radiation pressure noise.

Radiation pressure effects

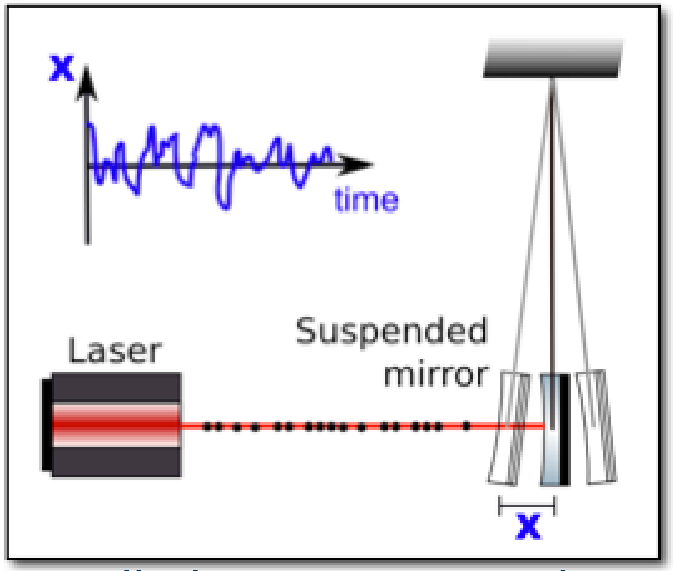
- Quantum scale force noise.

Amplitude fluctuations → mirror position fluctuations

- Parametric instability.
- Opto-mechanical rigidity / optical springs!



photon shot noise

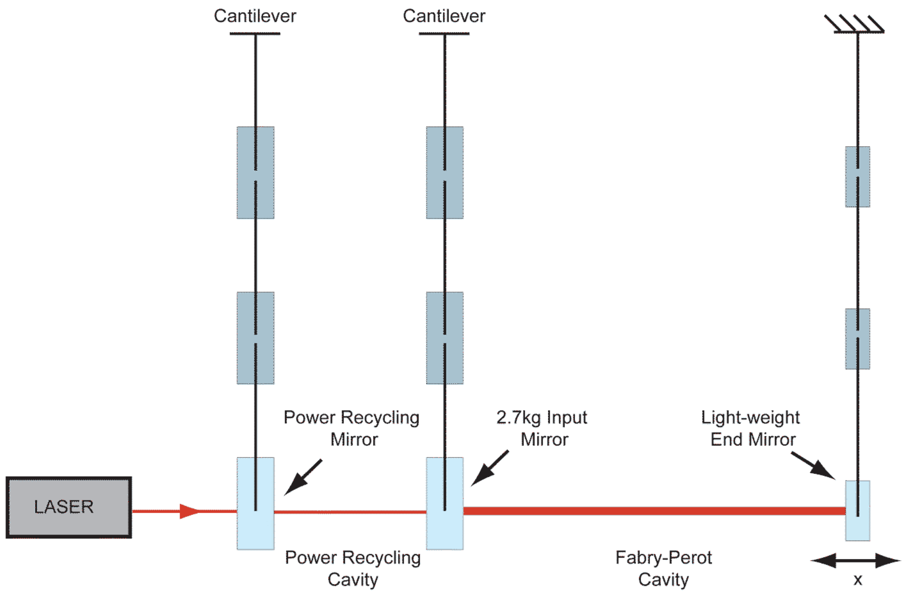


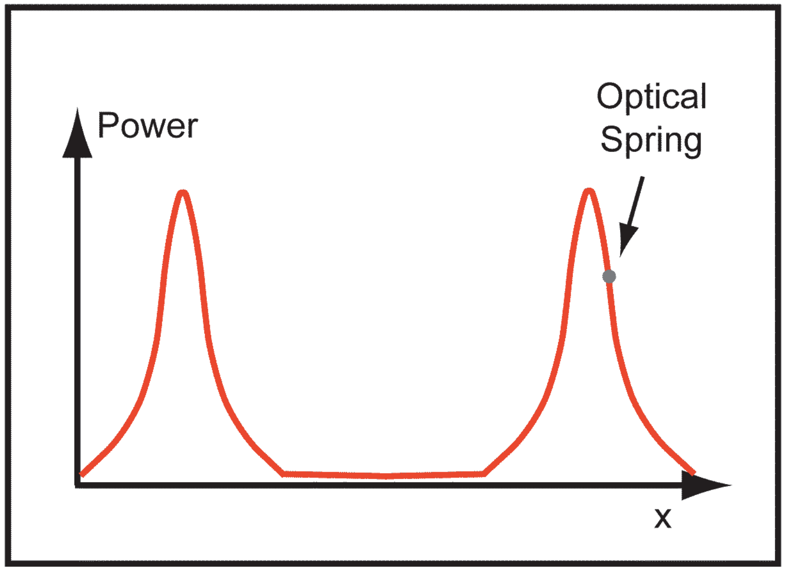
radiation pressure noise

illustrations courtesy of Stefan Hild

Optical springs

- Occurs in detuned optical cavities.
- Optical restoring force comparable to or greater than the mechanical restoring force.
- Phase fluctuations induced by mechanical motion of the mirrors are linearly coupled to intensity fluctuations of the intra-cavity field.
- Mirrors coupled with spring constant that can be as stiff as diamond!

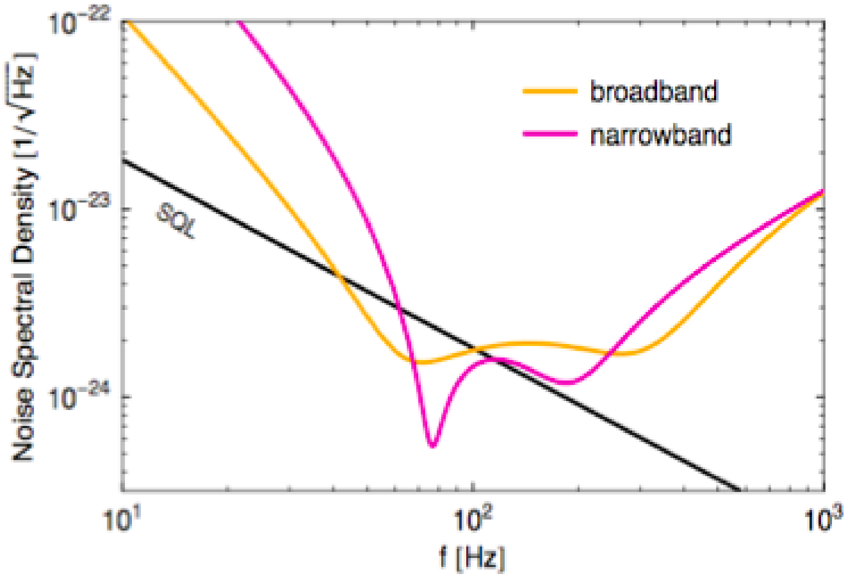




An introduction to optical springs

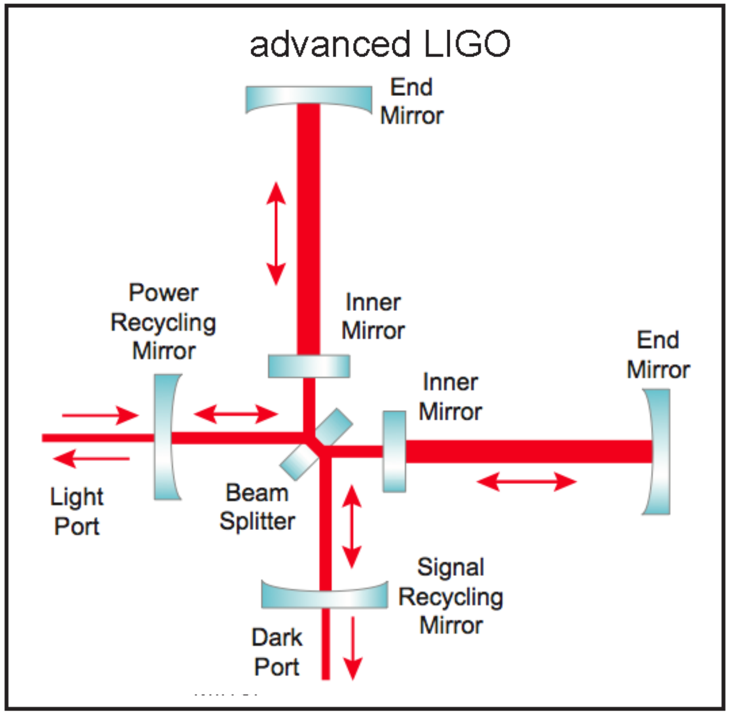
Future detectors will make use of significant strength optical springs

- Advanced LIGO - utilising detuned signal recycling.
- Optical Bar / Optical Lever - achieve optical rigidity.



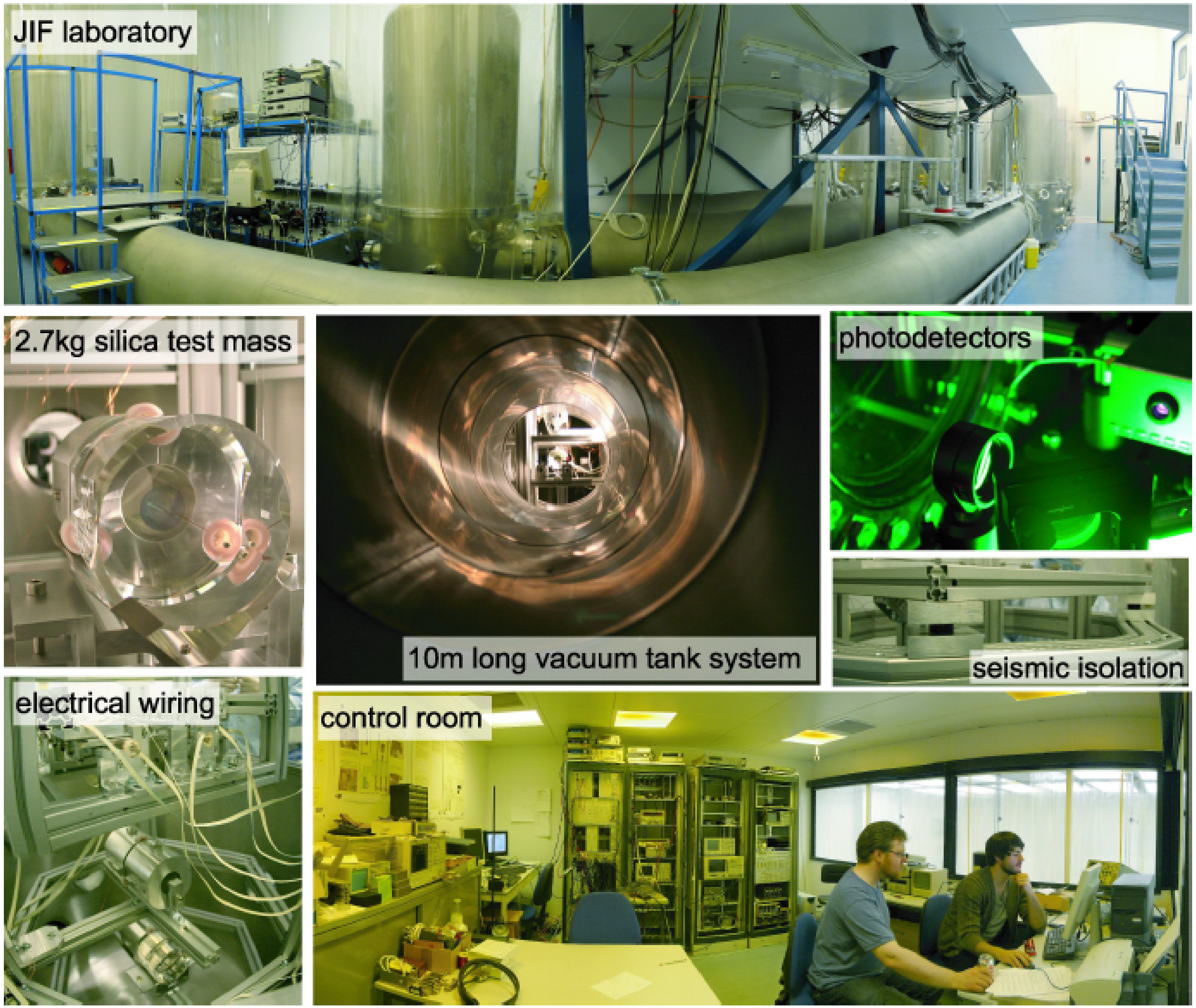
These techniques are possible approaches towards sub-SQL performance over at least some of the detection band.

At frequencies below opto-mechanical resonance, the response of the system to external disturbances (seismic or thermal) is suppressed by the optical rigidity.



The Glasgow 10m prototype interferometer

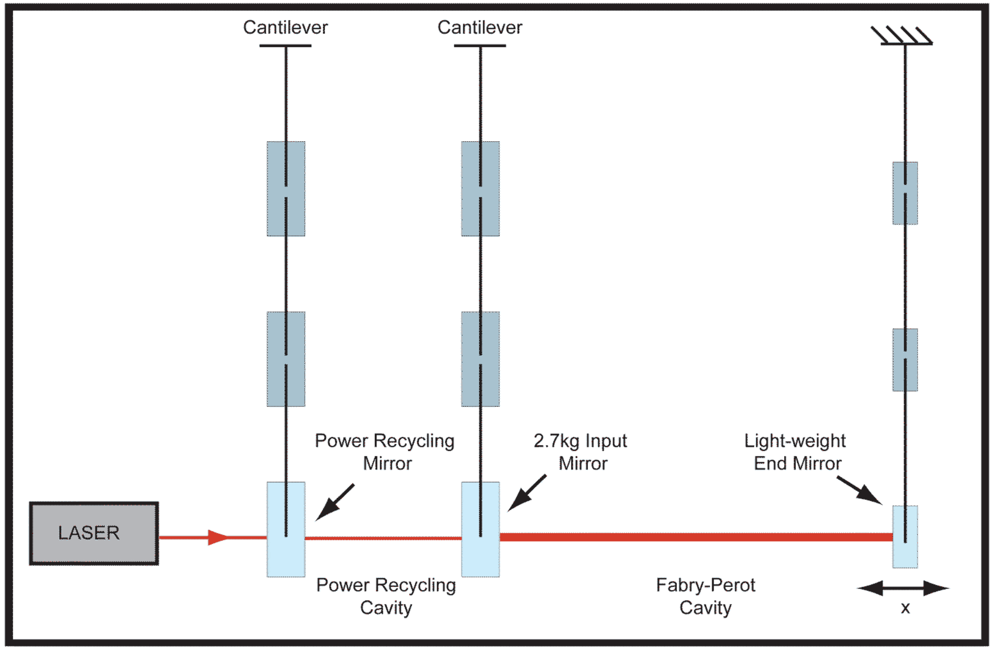
- 10m vacuum tank system
- Triple-stage suspensions
- Passive seismic isolation system
- Fused-silica mirrors
- 2W Nd:YAG 1064nm Laser light
- Sophisticated digital controller

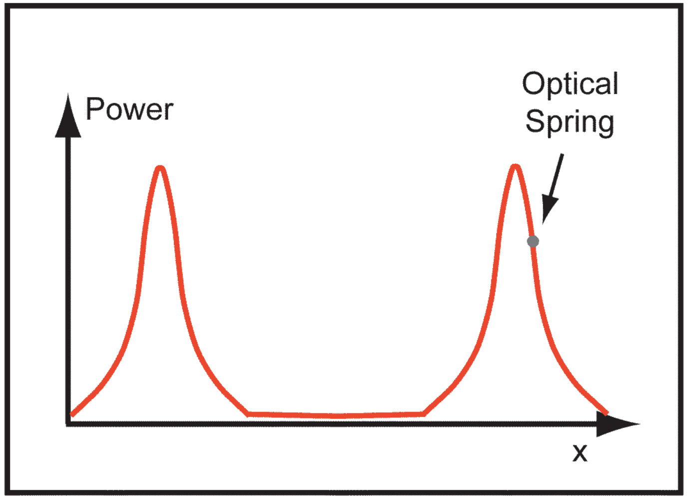


The optical spring experiment

Experimental aims:

- Examine properties of optical spring in a fully suspended environment.
- Create an optical spring in a coupled cavity configuration – analogous to recycling cavities.
- Characterise the optical spring effect and investigate the effect of detuning to spring strength.
- Explore the interactions with the control system. Take steps towards digital control.

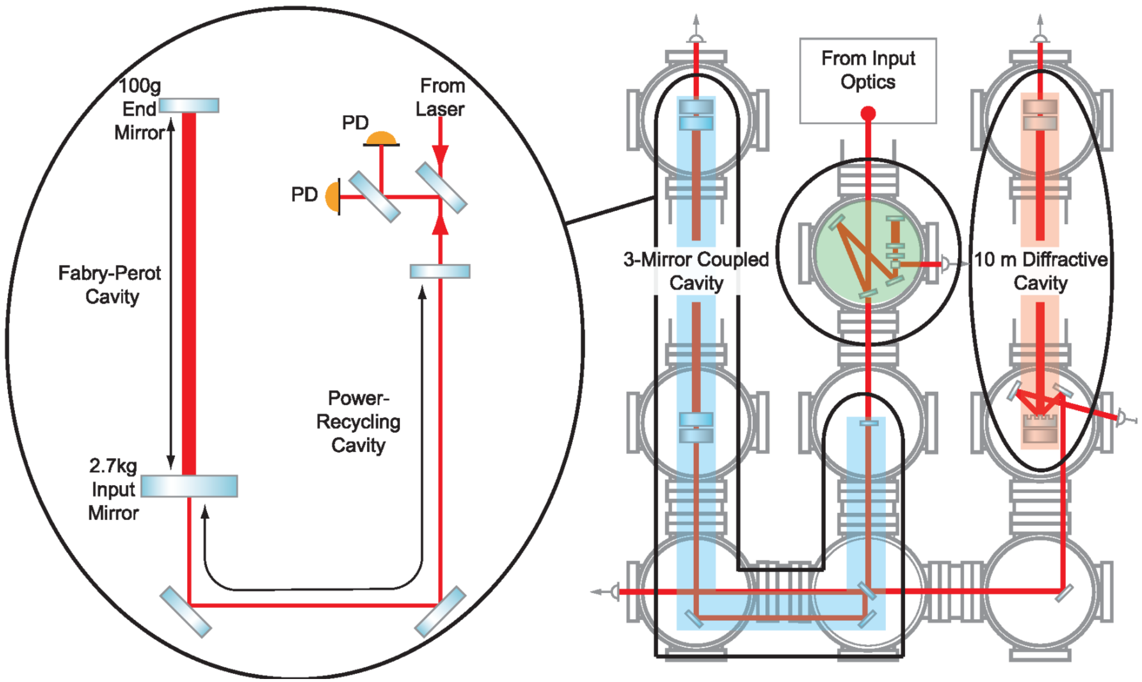




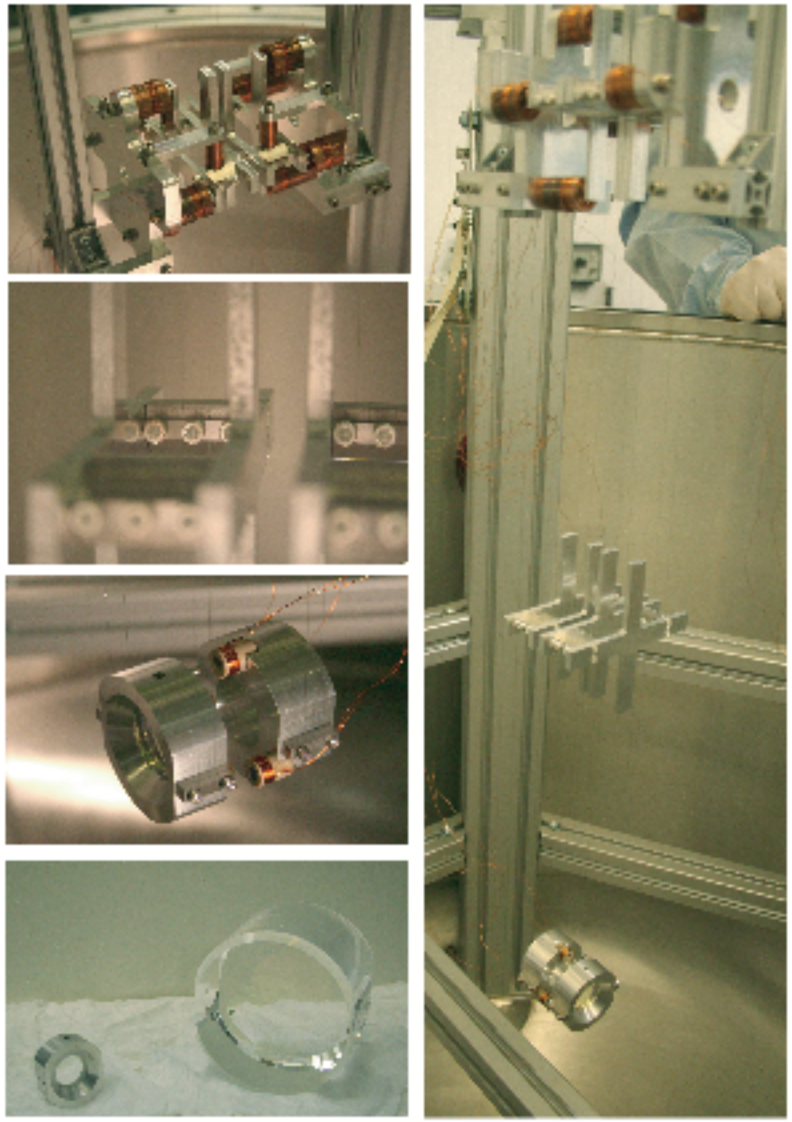
The optical spring experiment

Experimental design:

- Triple stage light-weight suspension design featuring passive eddy-current damping.
- 100g end test mass (with fused silica mirror).
- Detuned Fabry-Perot cavity.
- Three mirror coupled cavity configuration.

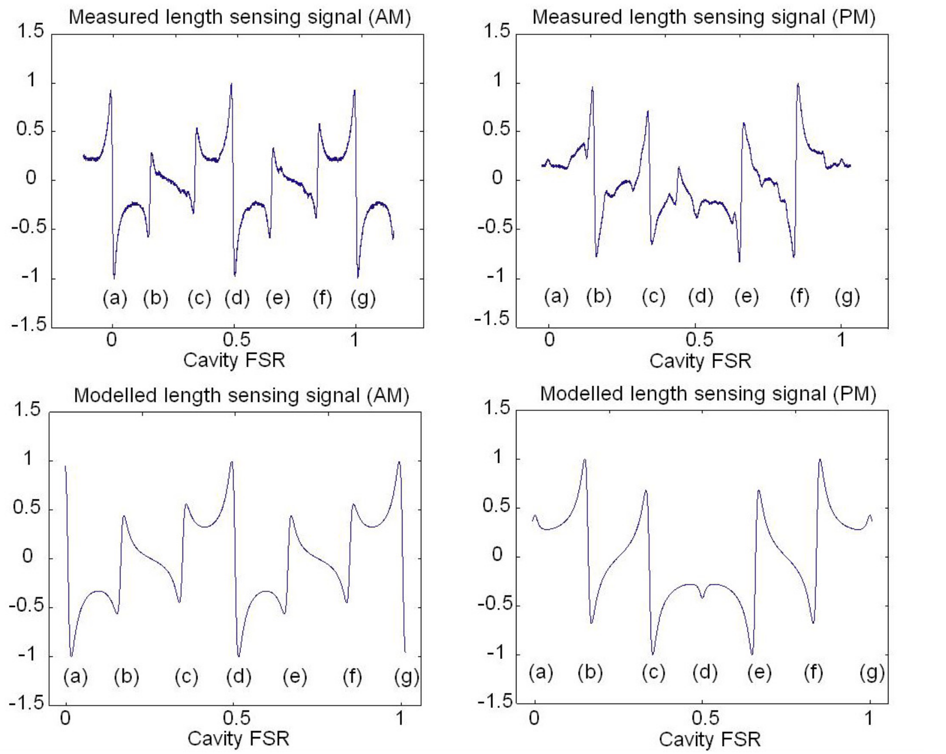


Optical spring experiment



Coupled cavity control scheme:

- Modified PDH technique.
- Amplitude and Phase Modulation.
- PM sidebands @ 18MHz used to derive arm cavity length-sensing signal.
- PM sidebands @ 10MHz, and AM sidebands @ 14.525MHz used to derive recycling cavity length-sensing signal.
- Flexible scheme to decouple the control signals of the two cavities.
- Already tested on cavity with 2.7kg test masses [1].
- Allows us to detune one cavity and maintain decoupling.



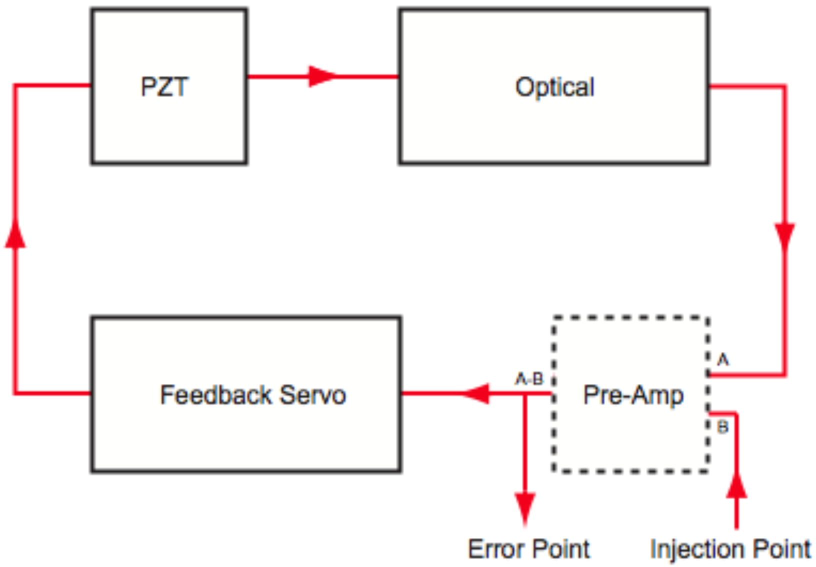
(a)Carrier, (b)4.525MHz, (c)10MHz, (d)14.525MHz, (e)10MHz, (f)4.525MHz, (g)Carrier

[1] **Techniques in the optimization of length sensing and control systems for a three-mirror coupled cavity 2008 Clas Quan. Grav., Huttner et al**

- Error signals are fed back to the PZT and temperature of laser to control AC and to recycling mirror EM actuators to control PRC.

Characterising the coupled cavity

- Obtain open loop transfer function, which contains the sum of all the elements in the loop.
- Inject into channel B and monitor error point.
- Subtract feedback servo shape and PZT response.



Generating optical springs

- Detune arm cavity by injecting an offset to the laser frequency.

Blueshifting the cavity = *redshifting* the laser frequency

- Inject characterisation signals into the same channel.

Initial observations

- **The transmitted power and therefore intra-cavity power changed depending on level of detuning.**

  Moving cavity away from optimum resonance condition.

- **Only one polarity of detuning created 180 degree phase flips.**

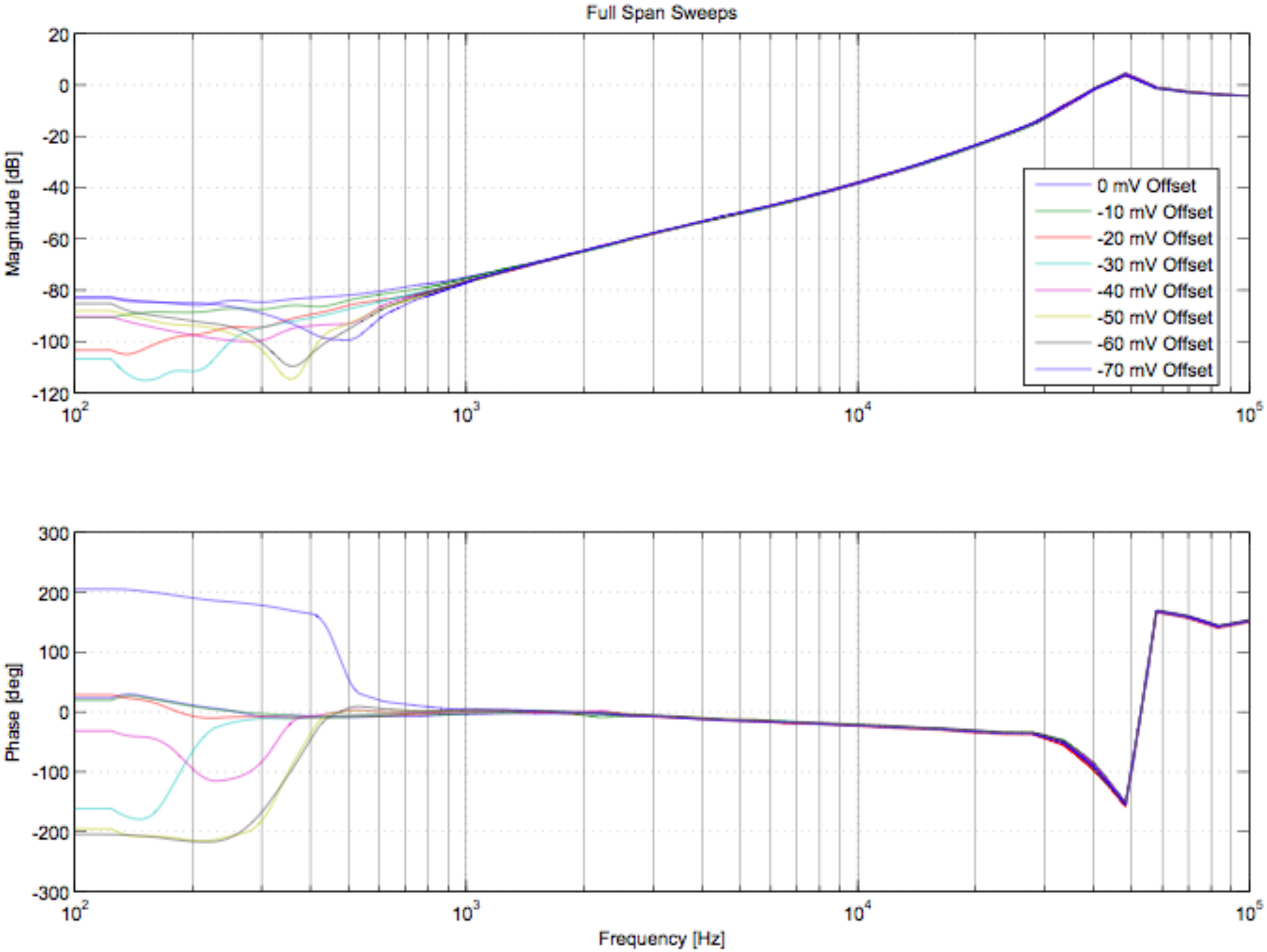
  Blueshifting cavity = optical spring

  Redshifting cavity = optical anti-spring

- **Error signal increasingly more difficult to observe at frequencies below opto-mechanical resonance.**

  Optical rigidity suppressing cavity response

Experimental results



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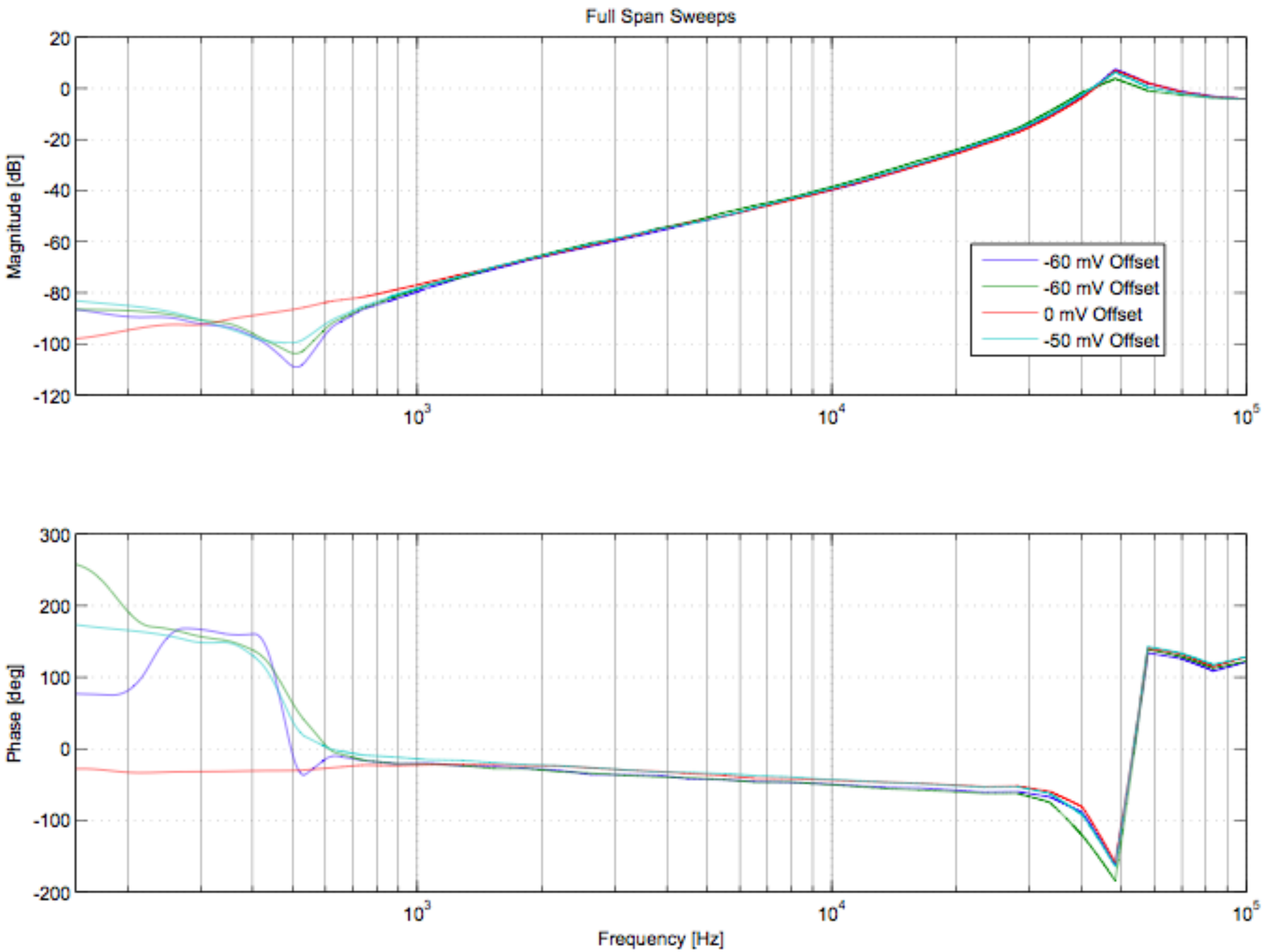

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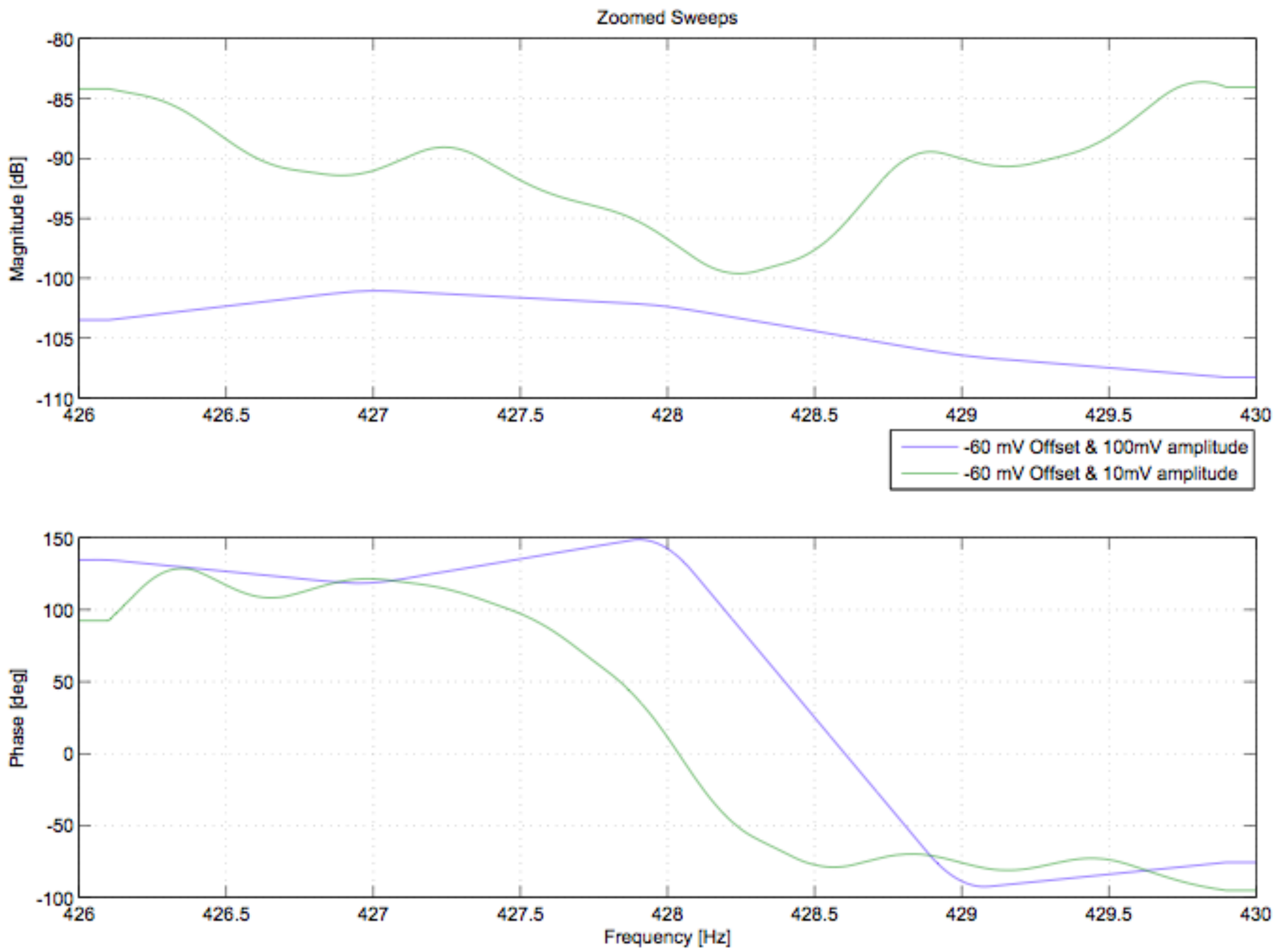
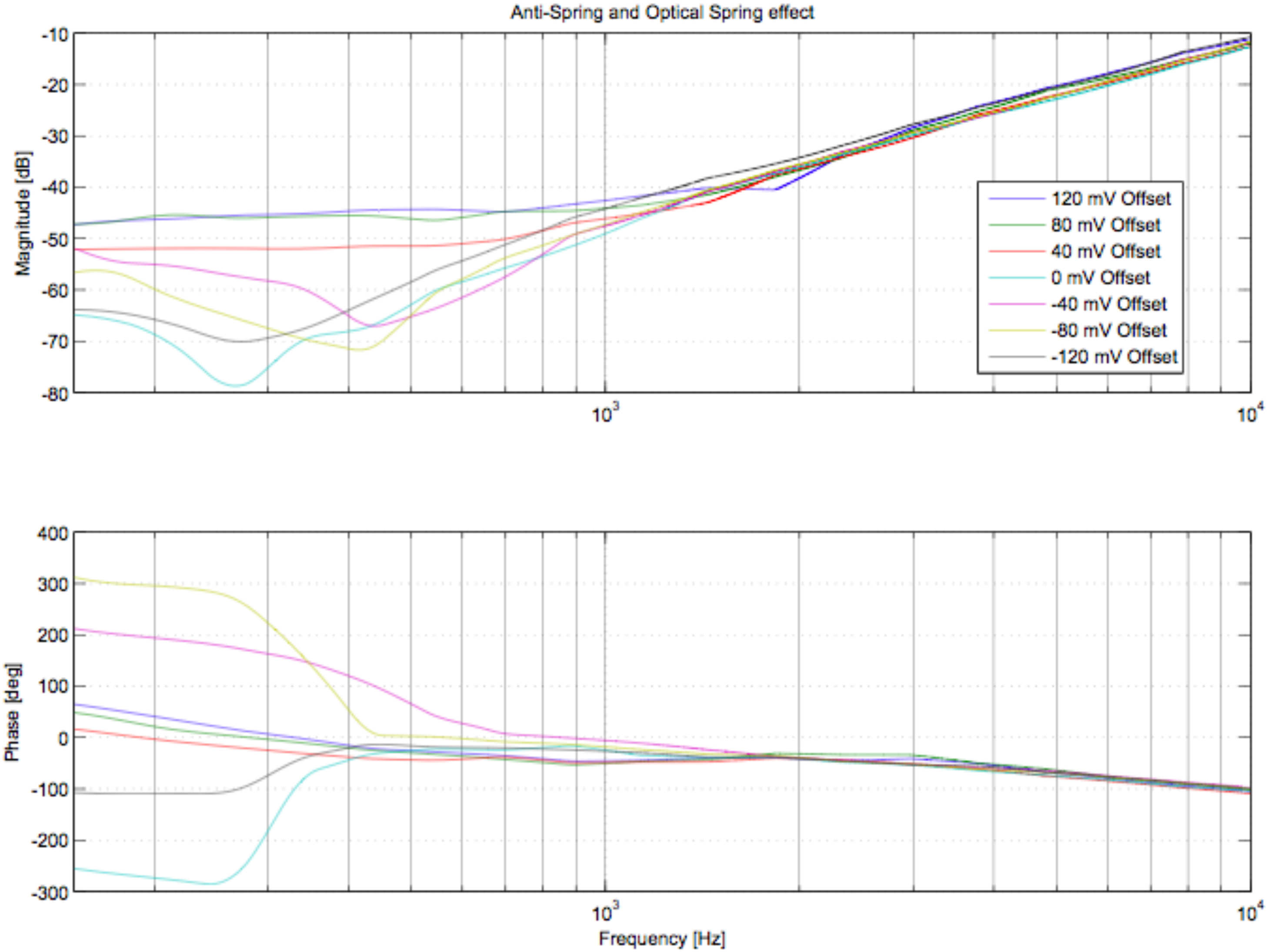


Experimental results



Challenges that we faced measuring optical spring effect:

- **Getting a feel for the level of detuning required.**

  Cavity alignment and mode matching can have an affect!

- **Amplitude of characterisation signal must be carefully chosen.**

  Small enough yet large enough!

  Characterising modulates the strength and frequency of OS.

- **We don't have an independent frequency reference.**

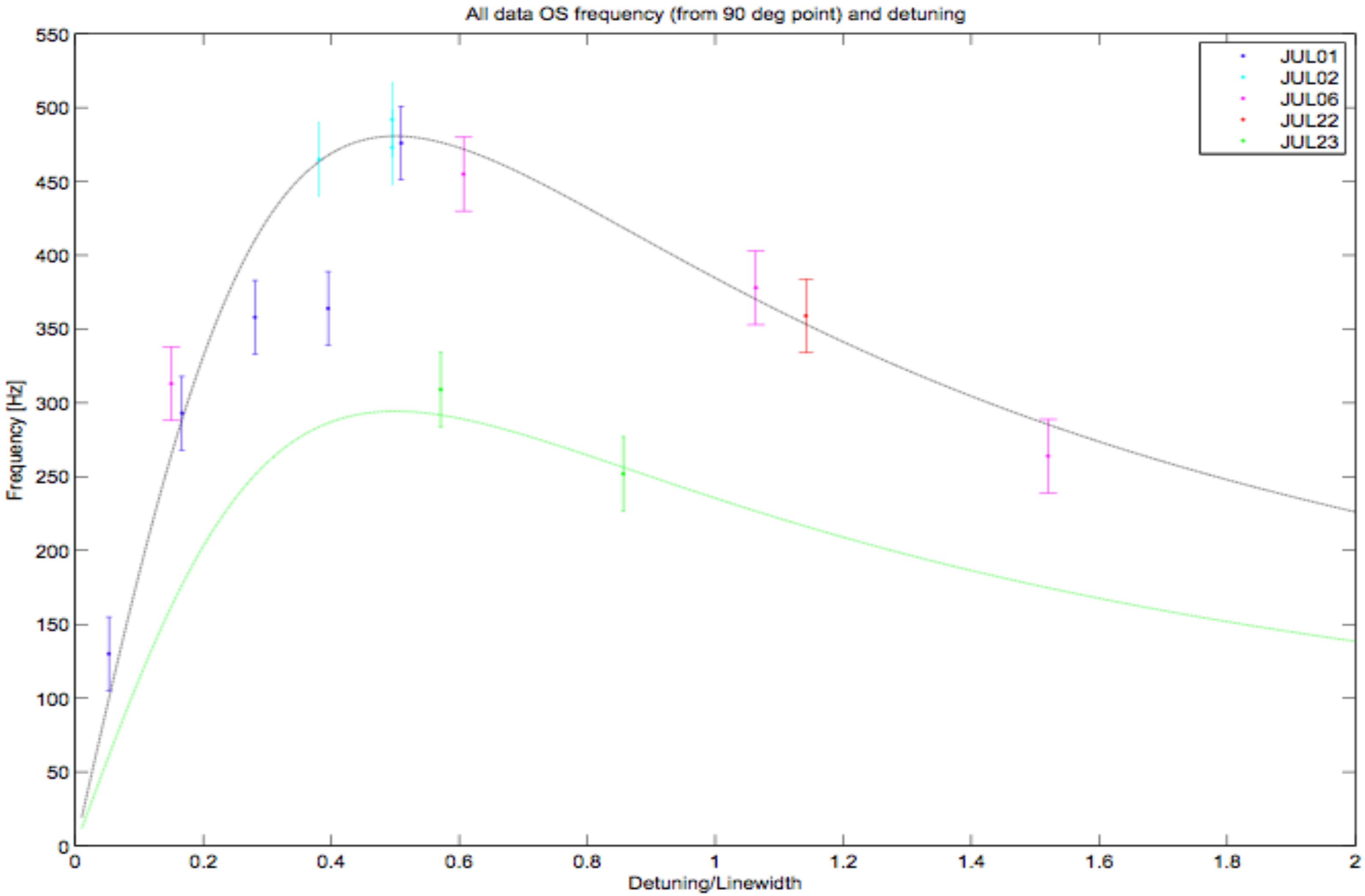
  We used the same cavity length as a reference.

  Mirror motions require high gain servo.

  Optical spring in bandwidth of servo!

Experimental results

All of the data that was collected has been analysed together.



Experimental results

- Maximum optical spring occurs @ **480Hz** when **detuning/linewidth = 0.5**.
- Optical spring strength of **K = 8.3 x 10^5 N/m**.
- Towards the end of the month when alignment had improved and intra-cavity power increased, a 100mV offset had a much bigger effect, resulting in **detuning/linewidth > 0.5**.
- If we consider replacing the optical mode with a rigid beam with a Youngs modulus **E**, and area **A** of the beam spot (**7μm^2**), and length **L = 9.87 m** of the cavity, gives

E = K L/A = 1.16 Tpa

<u>effectively stiffer than diamond!</u>

Conclusions and future work

- Successfully demonstrated use of lightweight cavity end mirror, as part of coupled Fabry-Perot cavity, sensitive to RP forces.
- By *blueshifting* optical cavity -> created, observed and characterised the OS effect and probed system dynamics.
- Produced OS with frequencies up to 480 Hz corresponding to an impressive optical spring strength of 8.3 x 10^5N/m.
- Results were not obtained easily.
- Fully implement GEO style digital controller soon.
- Take steps towards optical bar topology proof-of-principle experiment.
  - Swap input mass for lightweight suspension and mass.
  - Use separate local readout scheme to monitor position.

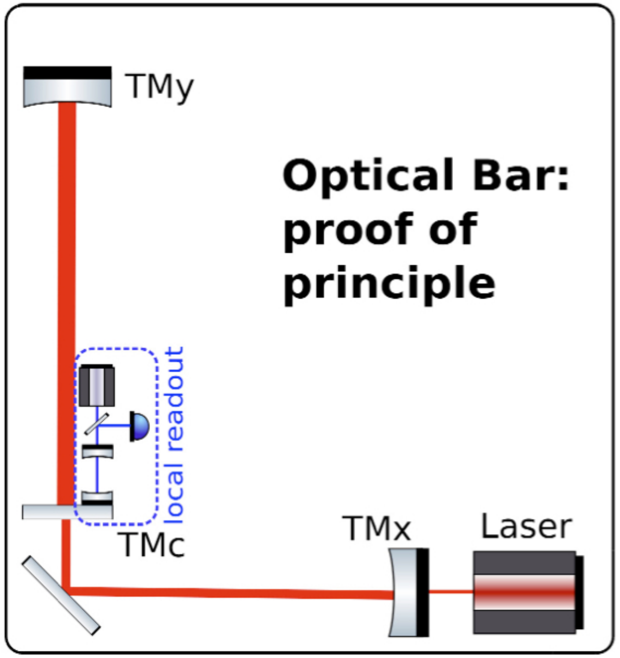


illustration courtesy of Stefan Hild

The end!

Thanks for your attention.