Modern Optical Techniques For Gravitational Wave Detectors

Matt Edgar

Talk Outline

- **Interferometry for gravitational wave detection**
- **Limitations of current and future detectors**
- **Diffractive cavity input couplers**
  - The Glasgow JIF laboratory and 10m prototype
  - Full characterisation of signals from suspended diffractively coupled cavities
  - Dynamic effects associated to diffractive couplers
- **Opto-mechanical techniques**
  - Quantum noise and optomechanical behaviour
  - Inducing opto-mechanical rigidity
  - Characterisation of optical spring behaviour

Interferometry for gravitational wave detection

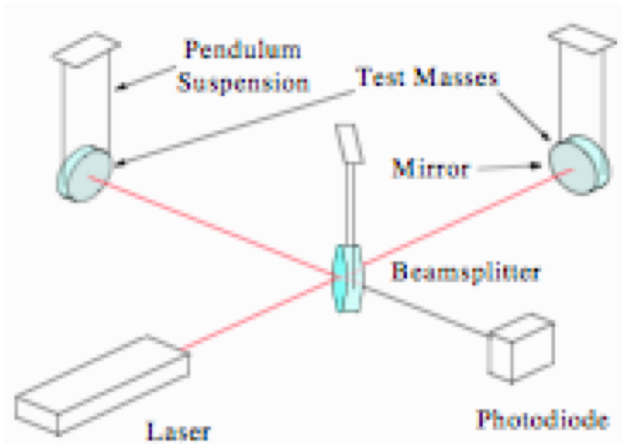
Gravitational waves (GW) are one of the more exotic predictions of Einstein's General Theory of Relativity.

LIGO, Livingstone, USA

Possible sources and good candidates for detection: *interacting **black holes***, coalescing ***compact binary systems***, ***stellar collapses***, ***pulsars***, and ***supernovae***.

Observing GW signals will significantly boost our understanding of the Universe.

Laser interferometry provides a means of sensing the motion of masses as they interact with a gravitational wave.



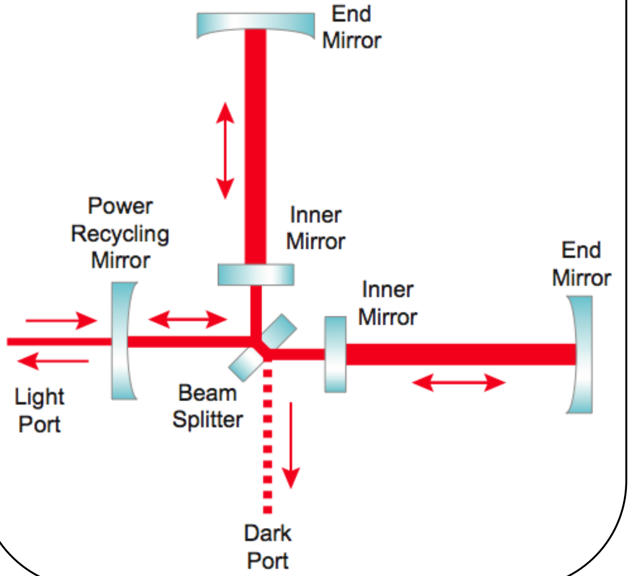
A huge effort has been spent testing new technology, materials and optical techniques in order to improve the detector sensitivity and ensure a result!

Interferometry for gravitational wave detection

Current Detectors

LIGO

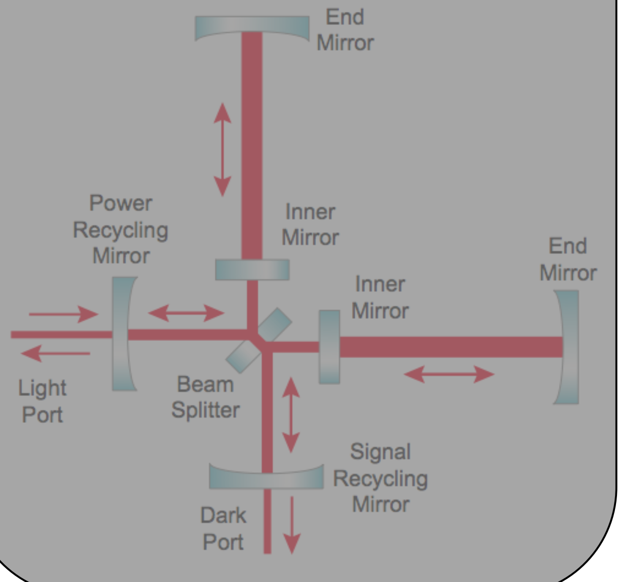
- Enhanced Michelson
- Power recycling
- Fabry-Perot cavities
- 30W input power
- ~kW's of laser light incident upon some of the optical components



Future Detectors

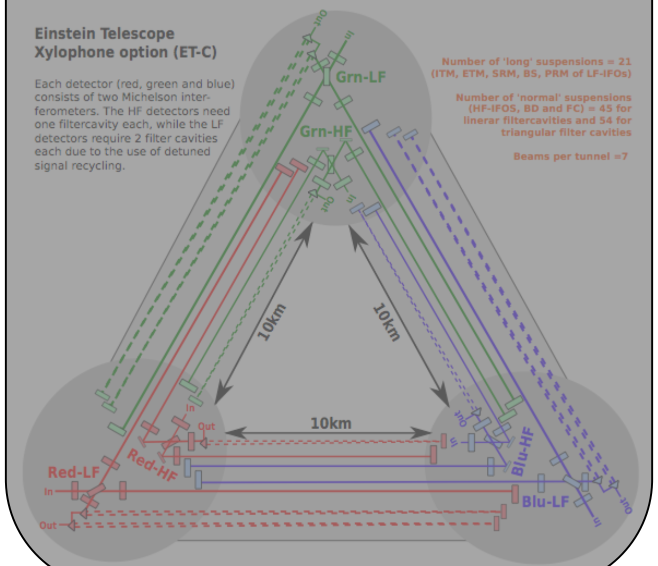
Advanced LIGO

- Better isolation system
- Dual recycling
- Fused silica suspension
- Increased input power
- ~MW's of laser light incident upon some of the optical components

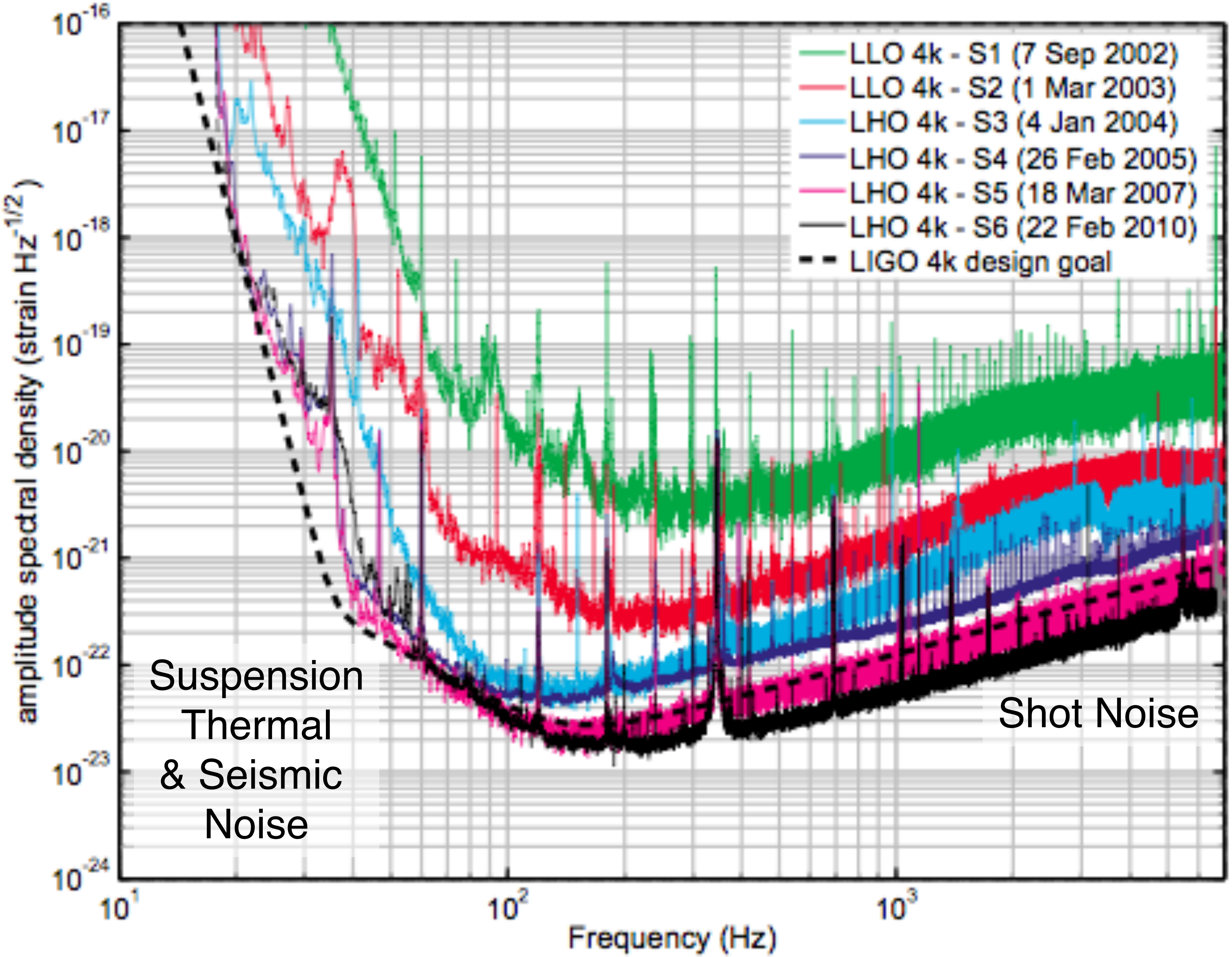


*Einstein Telescope**

- Xylophone topology
- Dual recycling
- Utilise optomechanical and optical resonance



Limitations of current detectors - LIGO



Interferometry for gravitational wave detection

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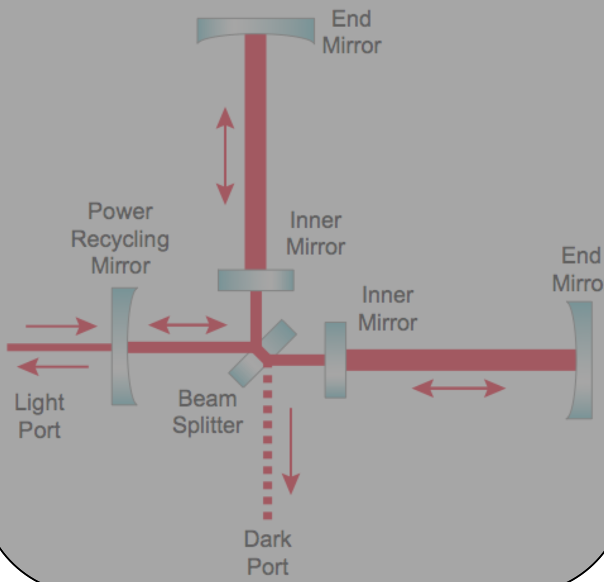

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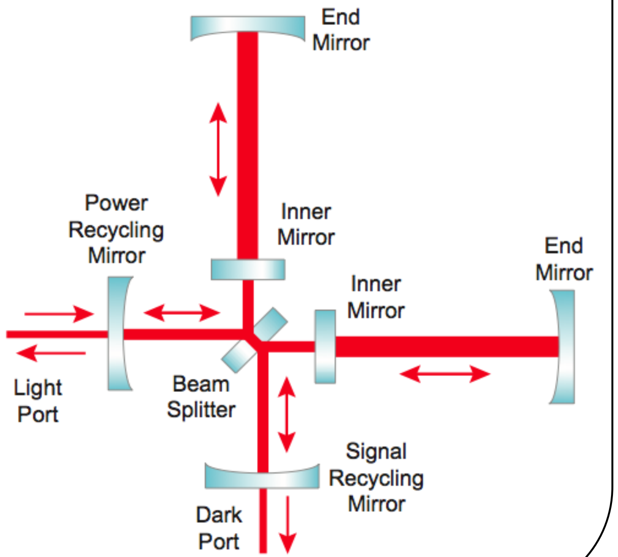
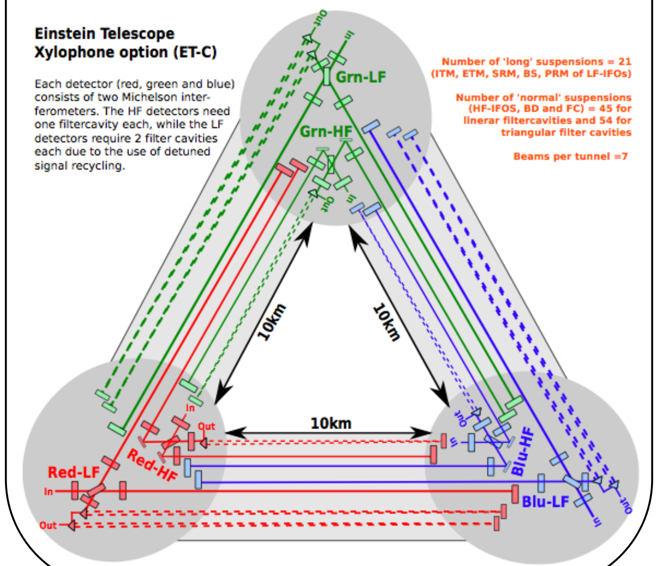
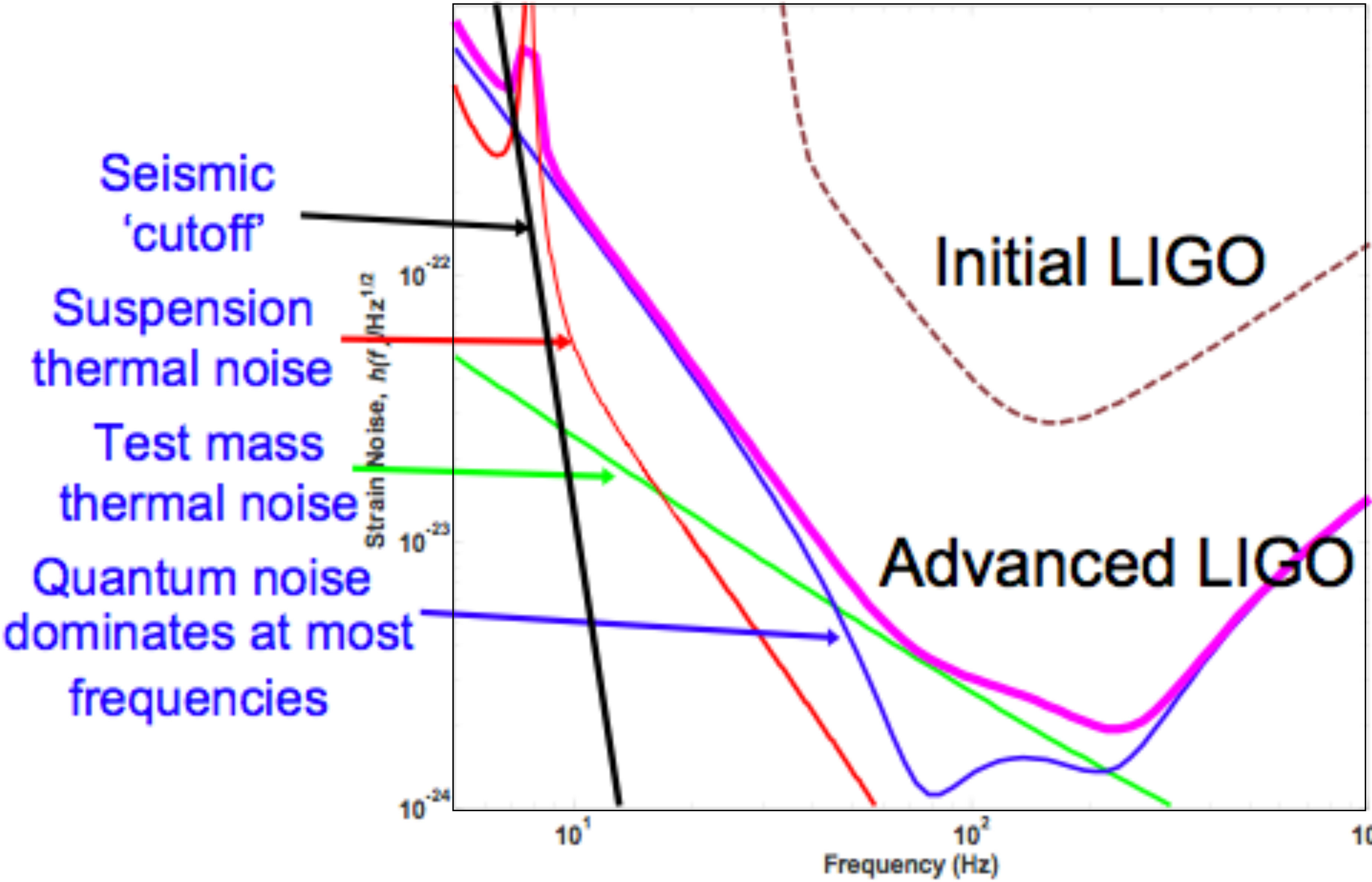


*Einstein Telescope**

- Xylophone topology
- Dual recycling
- Ultra high sensitivity around the optical and optomechanical resonance.

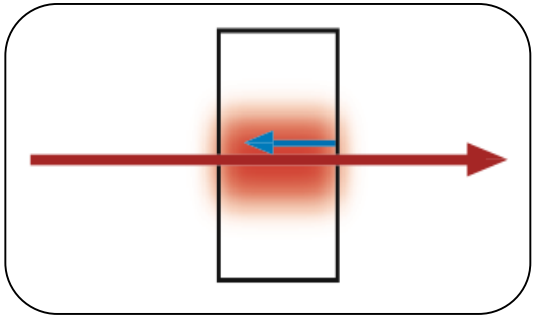


Limitations of future detectors - Advanced LIGO



Diffractive cavity input coupler

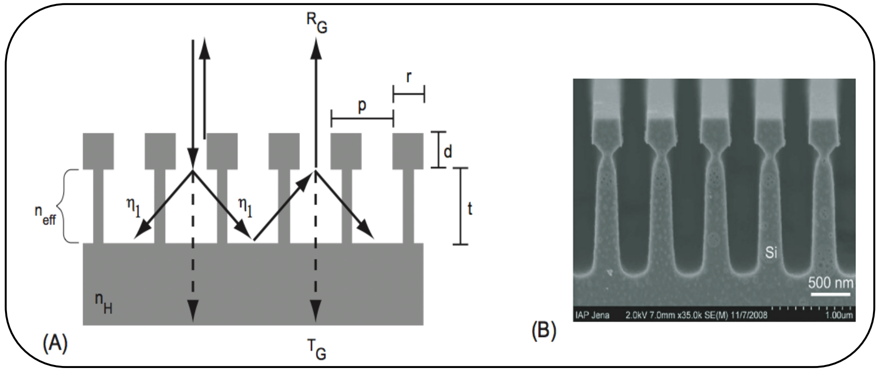
Concerns with increased laser power

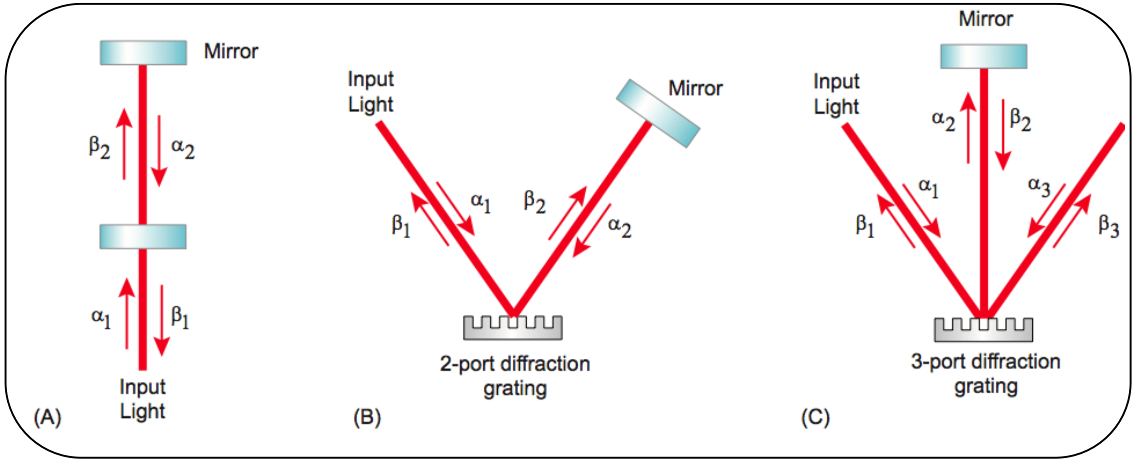


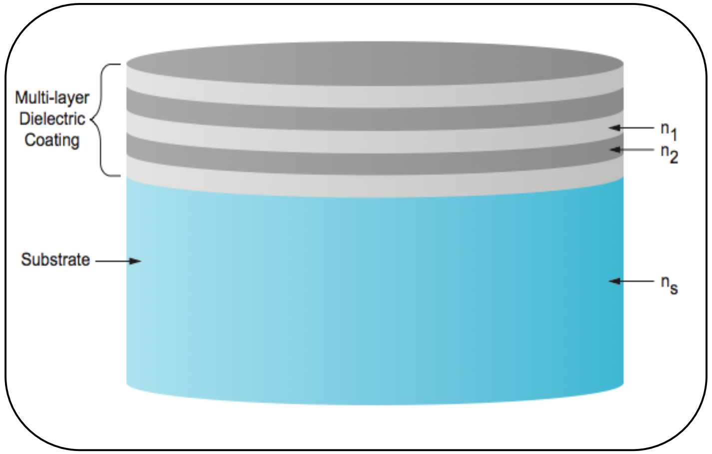
• Constant fraction light always absorbed causing ***localised heating*** leads to ***thermal lenses***!

Non-transmissive mechanism should be found

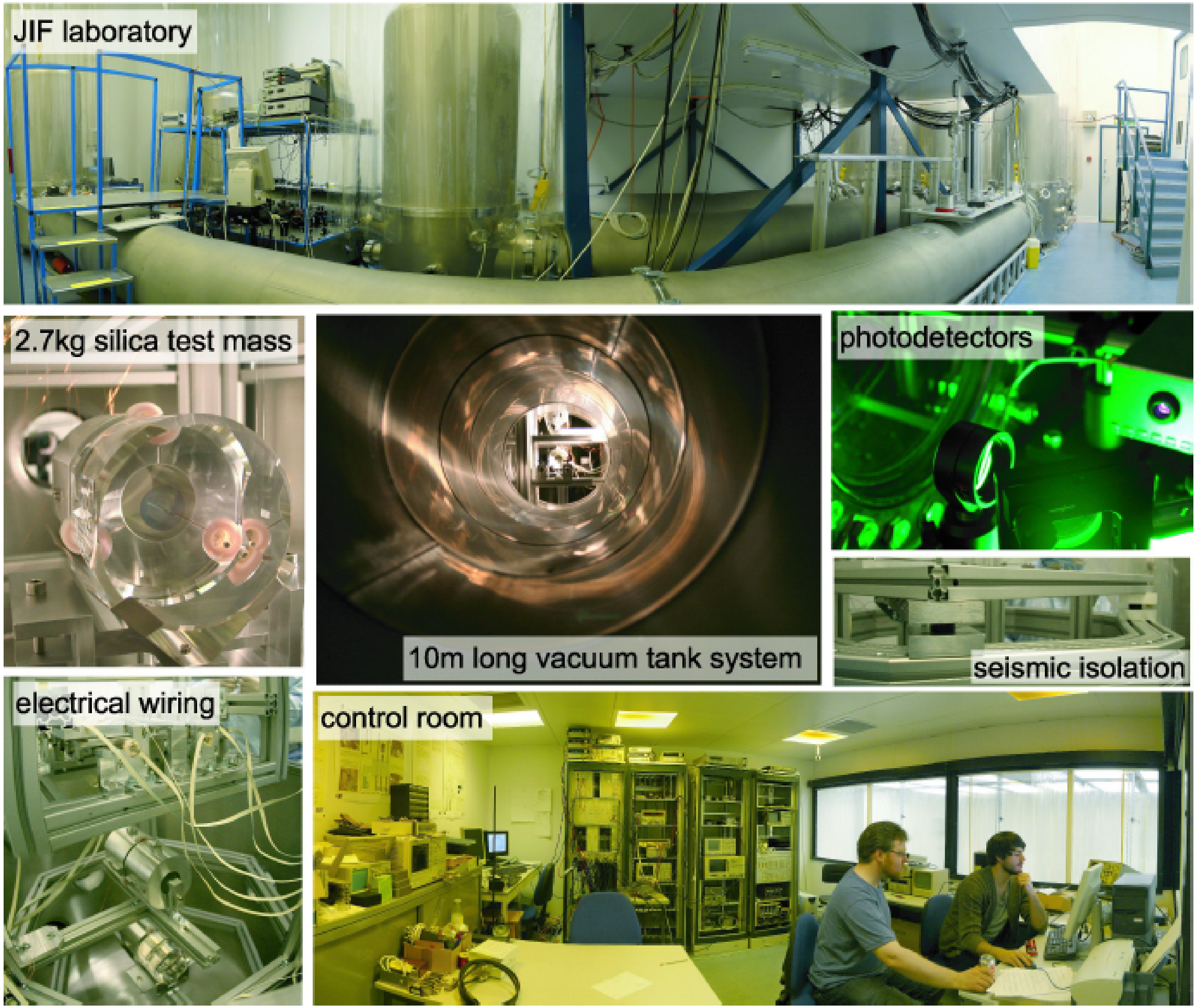
• Remove coating thermal noise issues.
• Consideration of alternative favourable substrate materials such as silicon.
• Use diffraction gratings as **beam splitters** or as **diffractive input couplers**.



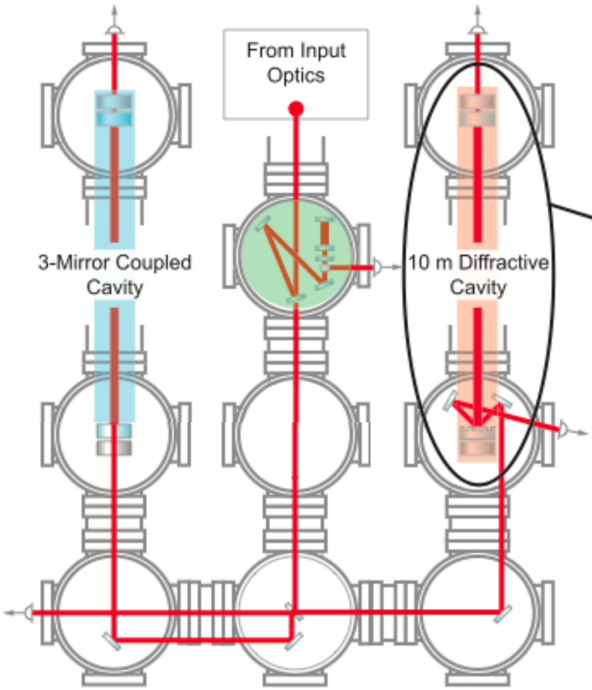


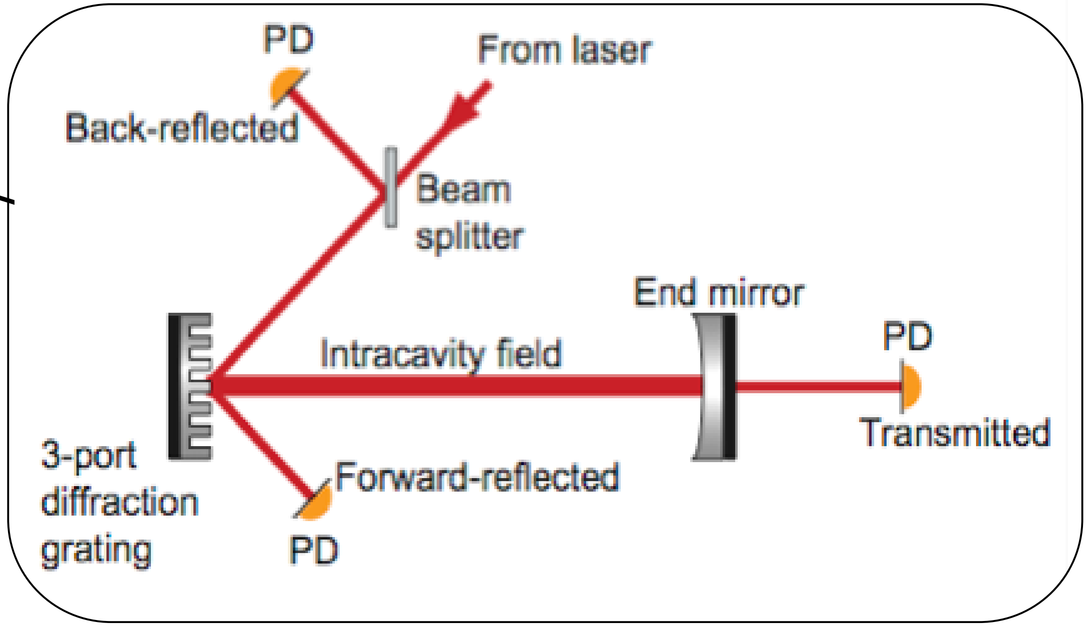


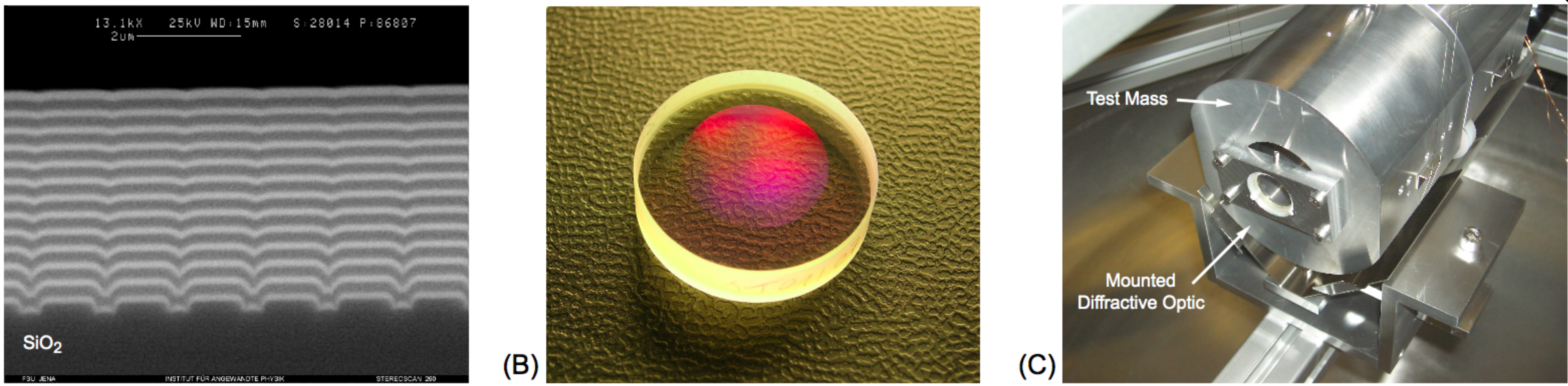
The Glasgow JIF laboratory and 10m prototype



The Glasgow 10m prototype interferometer







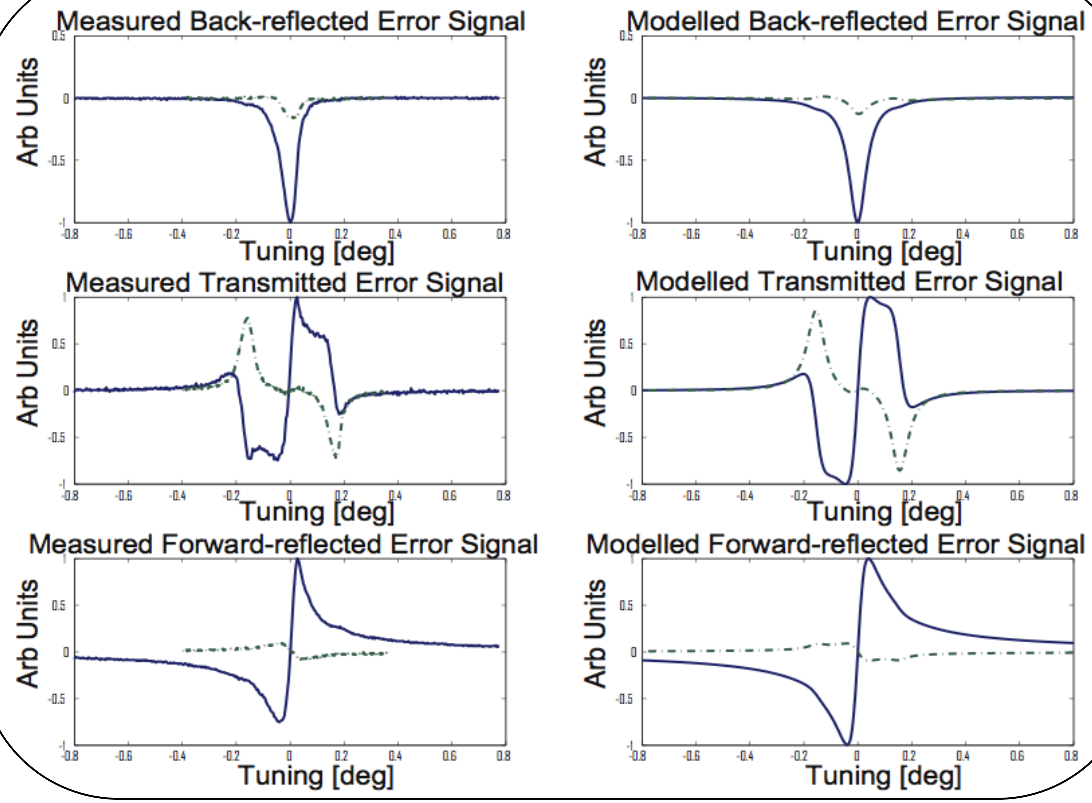
(A) (B) (C)

Characterisation of signals from diffractive cavity

As with any optical component, the three-port grating can be represented by a scattering matrix

The input/output relations for a three-port diffractive cavity yield amplitudes for the fields at each port described by equations [1].

A numerical model was built to allow comparison with the experimental results.



$$c_1 = \eta_2 e^{i\phi_2} + \eta_1^2 e^{2i(\phi_1+\phi)} d,$$

$$c_{2t} = i\tau_1 \eta_1 e^{i\phi_1} e^{\phi} d,$$

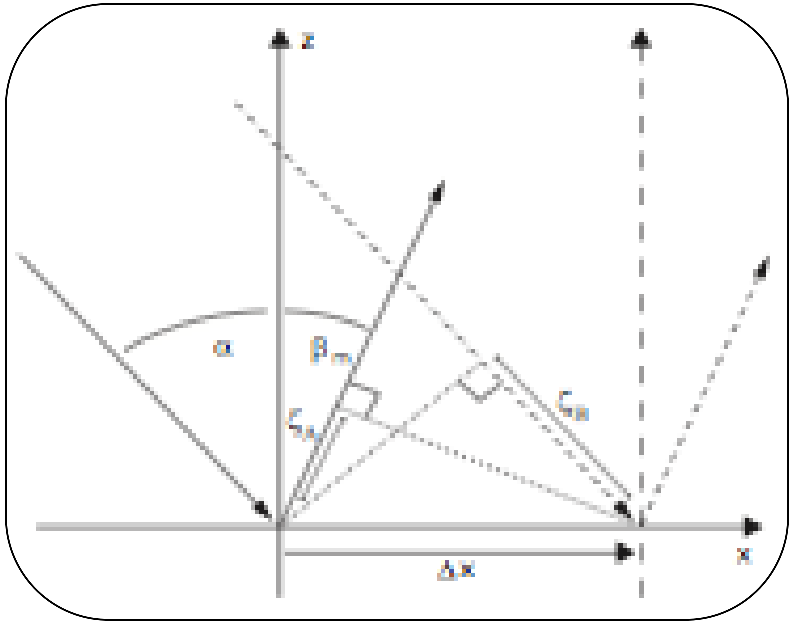
$$c_3 = \eta_0 + \eta_1^2 e^{2i(\phi_1+\phi)} d.$$

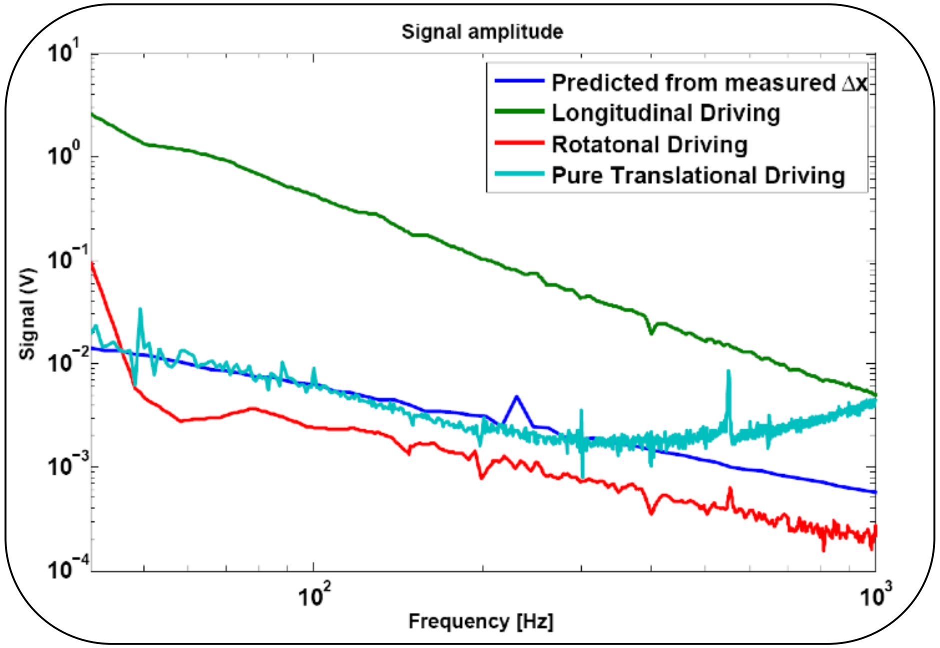
[1]

Parameter	Measured Value[dB]	Modelled Value[dB]
back-reflected/transmitted	−26.93	-26.99
transmitted/transmitted	0	0
forward-reflected/transmitted	43.07	44.74

Dynamic effects associated to diffractive couplers

A feature of gratings that has been viewed as a potential weakness is the fact that the phase of a diffracted light field is dependent on translation of the grating.



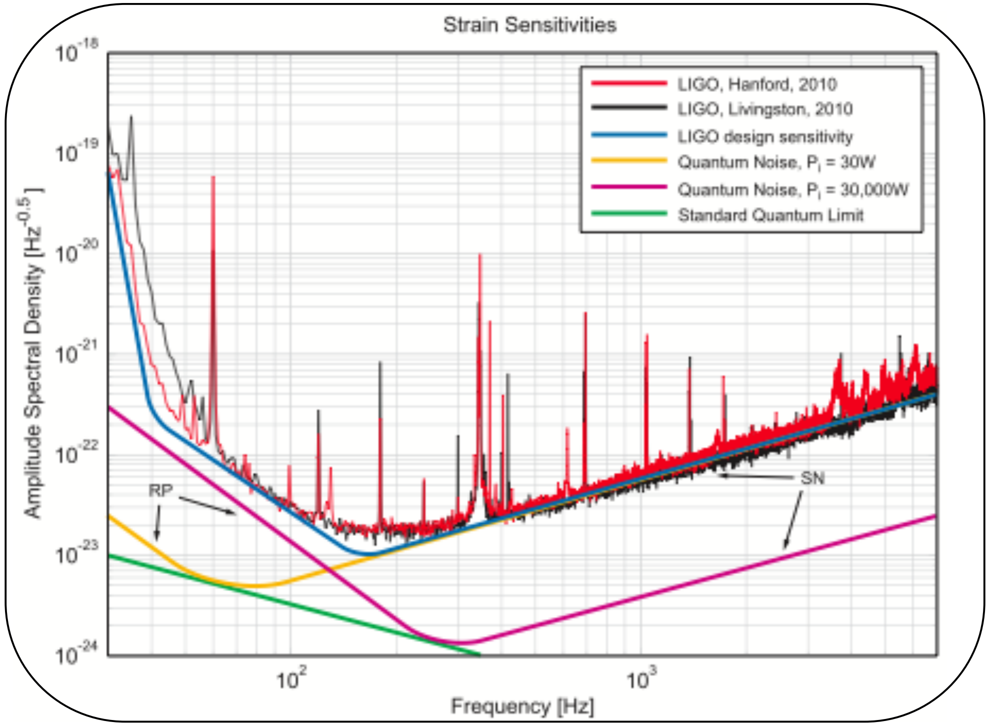


- Our results matched theoretical predictions.
- Observed the dependence on **rotational**, **vibrational** and **translational** grating motion on the output signals.
- Suspended diffractive systems now well understood.
- Stricter requirements on the isolation system employed.

Quantum noise and optomechanical behaviour

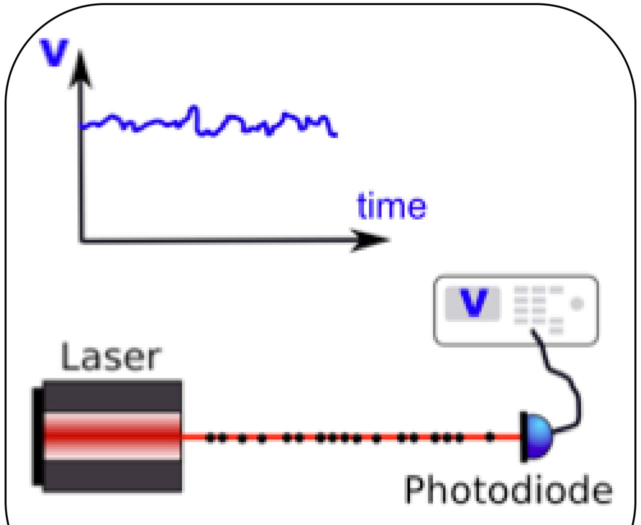
Future detectors limited by quantum noise

- Photon shot noise at high frequencies
- Radiation pressure noise at low frequencies

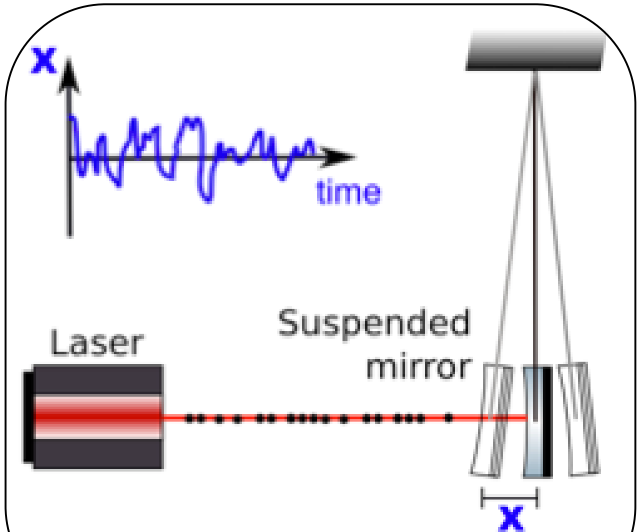


Radiation pressure effects

- Quantum scale force noise
- Amplitude fluctuations = mirror position changes
- Optomechanical behaviour - optical springs!



photon shot noise

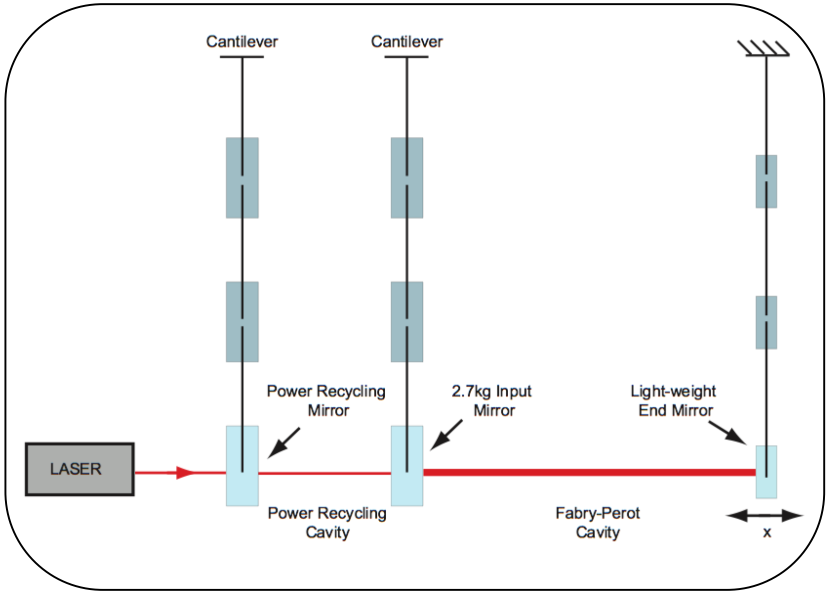


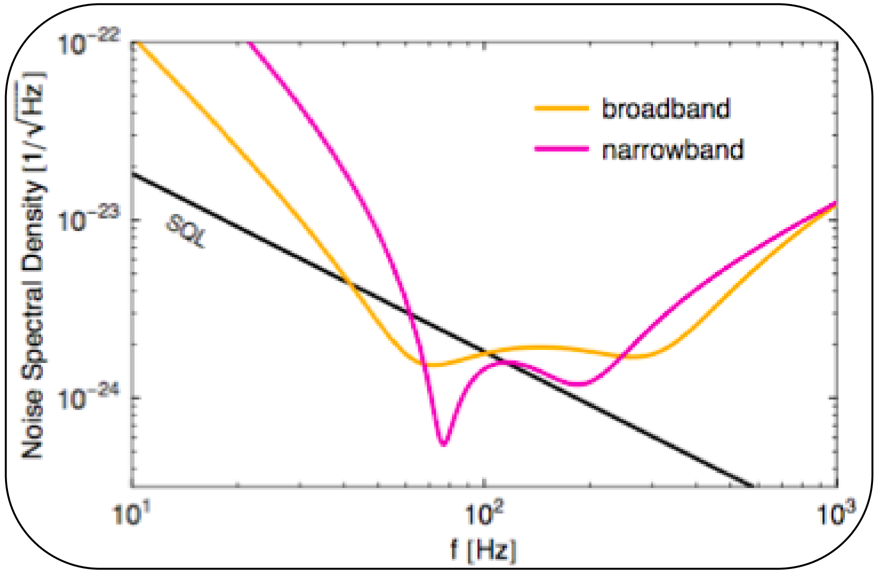
radiation pressure noise

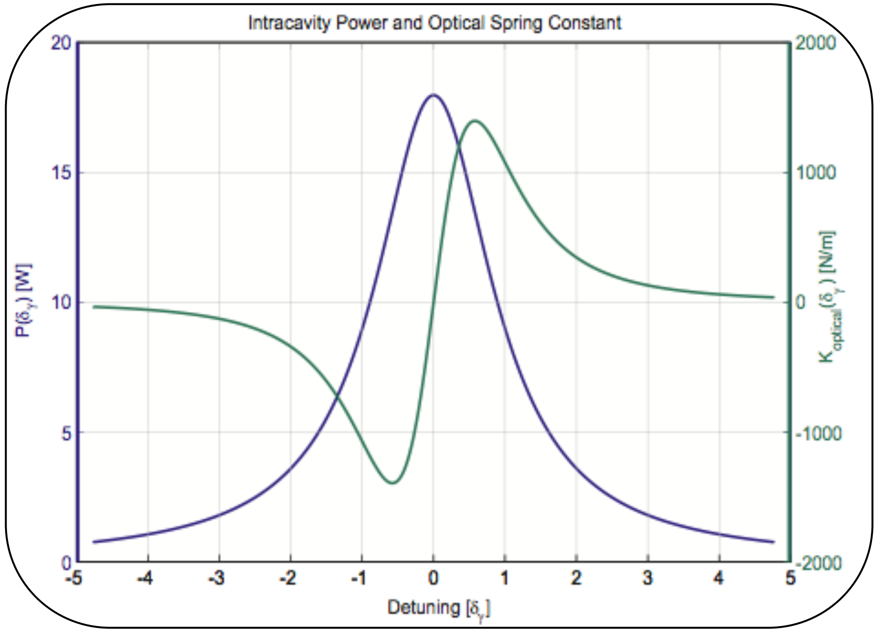
illustrations courtesy of Stefan Hild

Optical springs - tools to improve narrow band sensitivity

- Occur in *detuned* optical cavities.
- Optical restoring force comparable to or greater than mechanical restoring force.
- Phase fluctuations induced by mechanical motion of the mirrors are linearly coupled to intensity fluctuations of the intra-cavity field.
- Both cavity mirrors rigidly coupled.



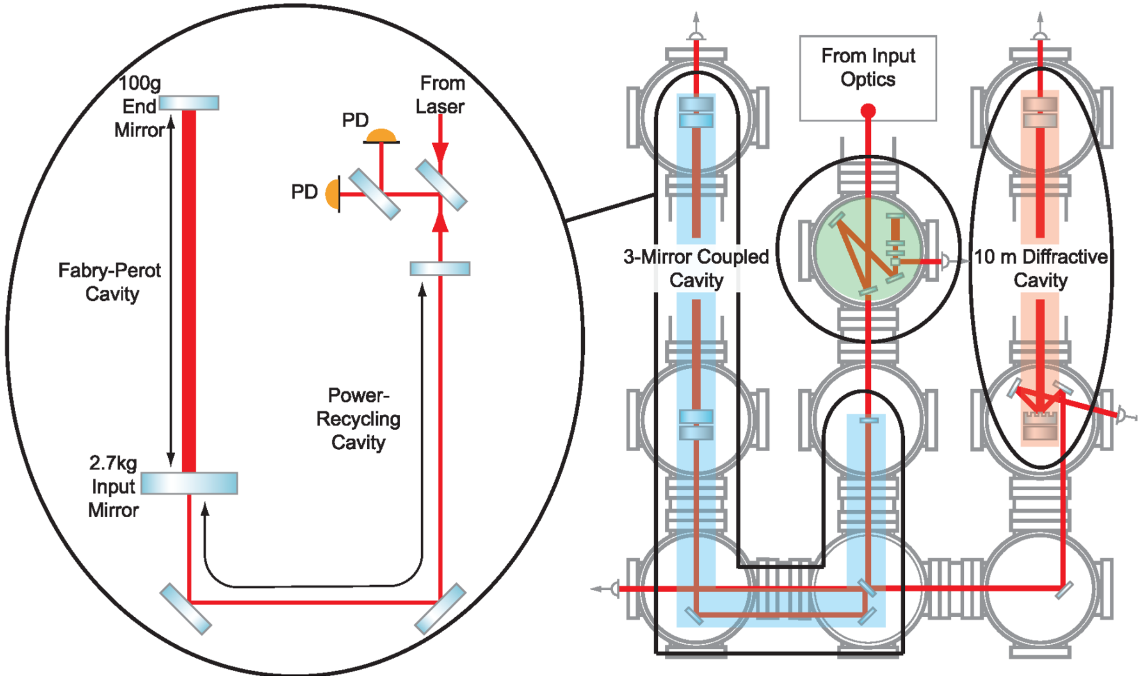




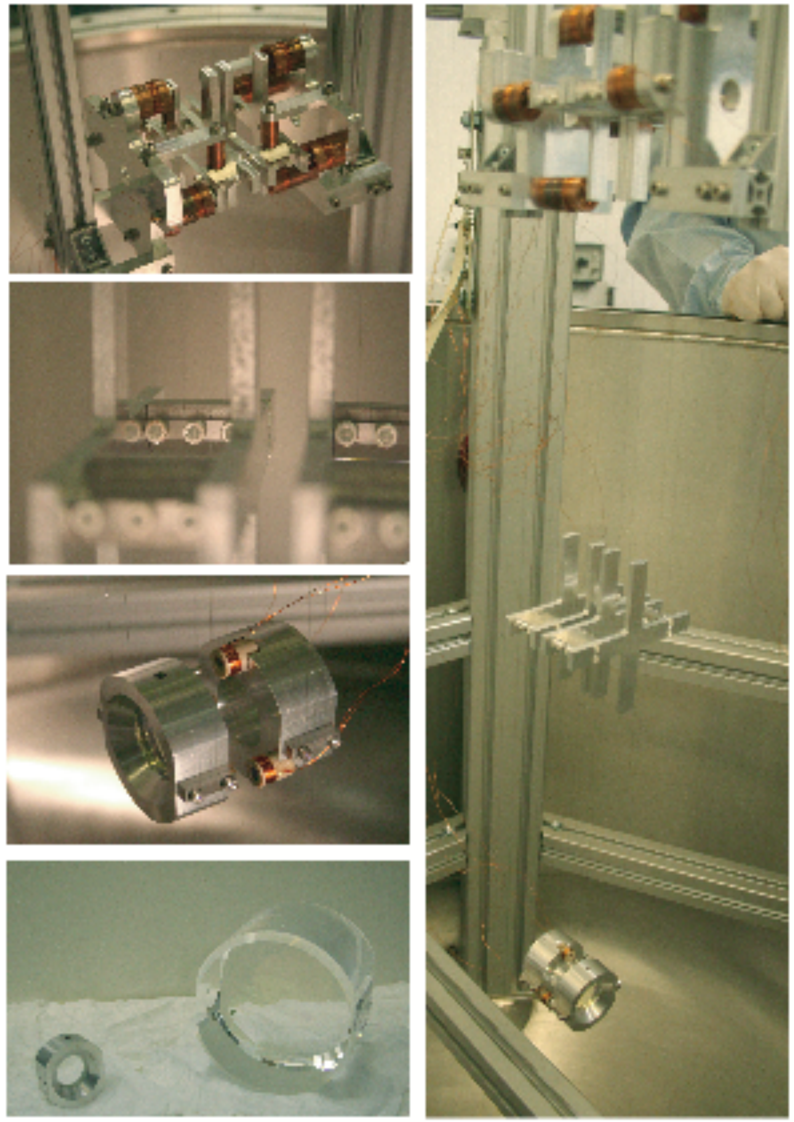
Characterising optomechanical behaviour

Experimental design:

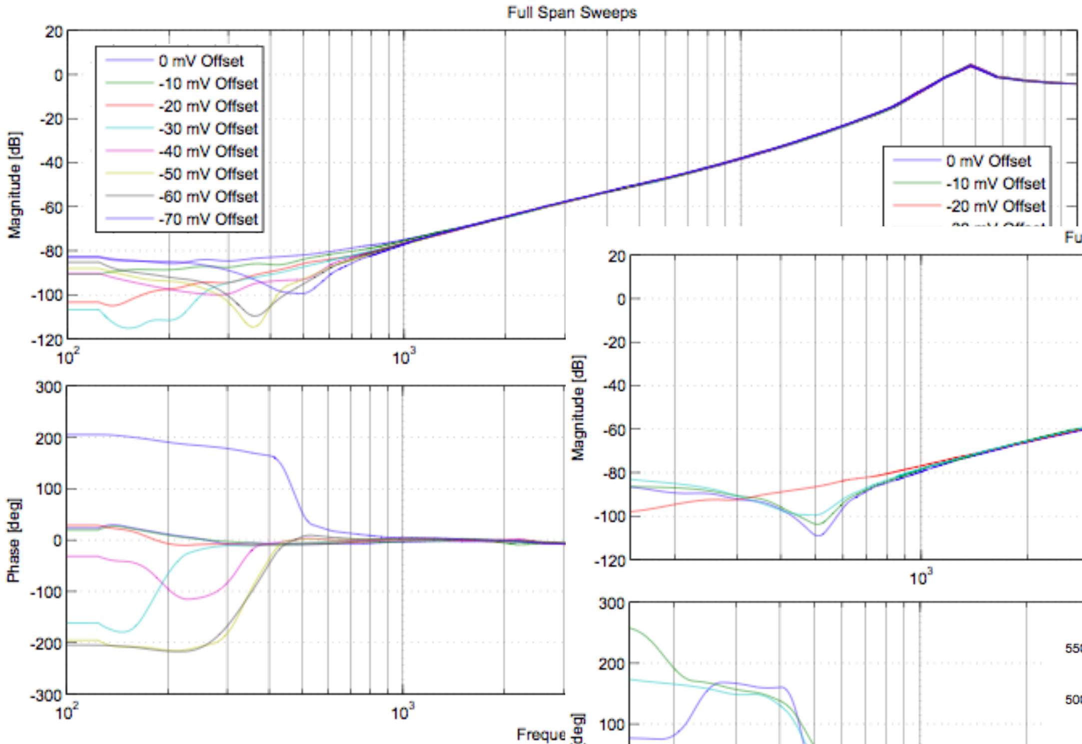
- Triple stage light-weight suspension design featuring passive eddy-current damping.
- 100g end test mass (with fused silica mirror).
- Detuned Fabry-Perot cavity.
- Three mirror coupled cavity configuration.



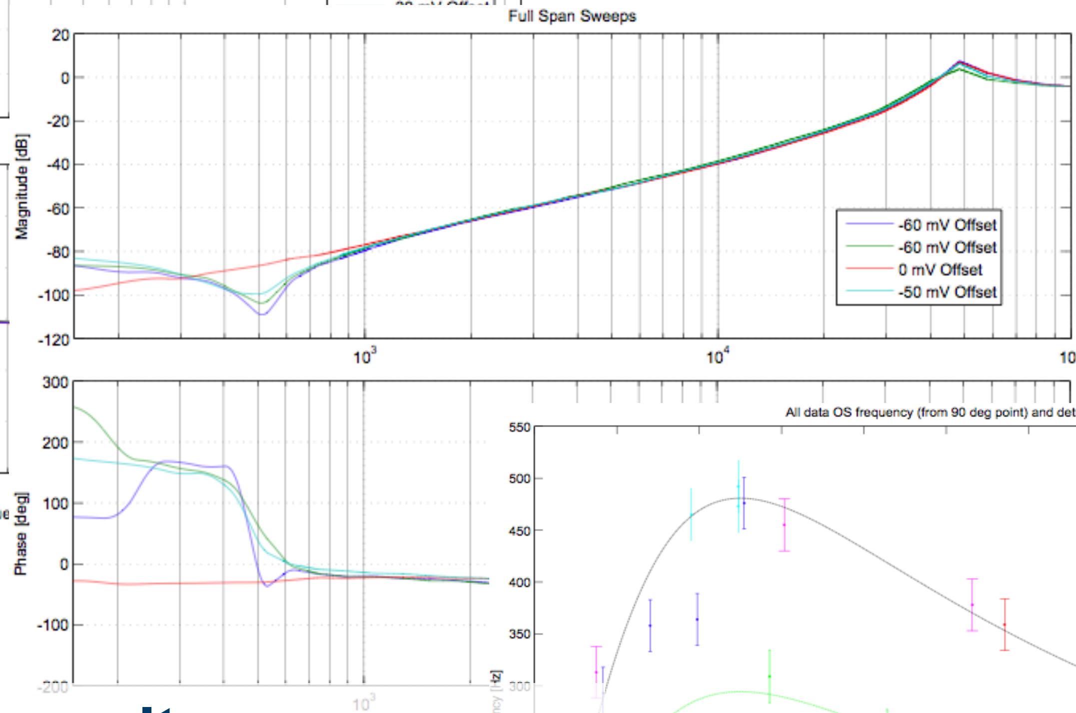
Optical spring experiment

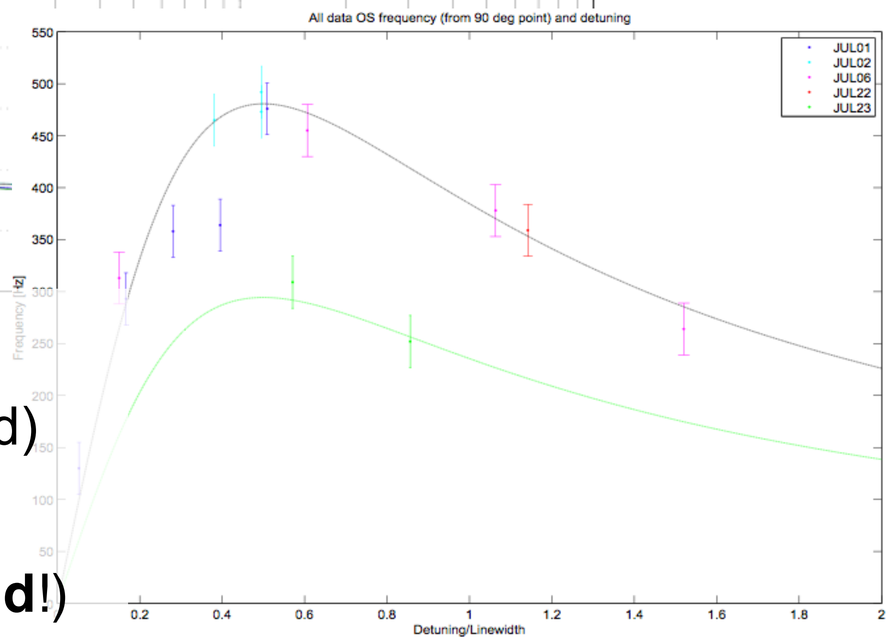


Characterisation of optomechanical behaviour



$$K_{opt} = \frac{8\pi T_0 P_{in}}{\lambda\gamma\left(1-\sqrt{1-\frac{2L\gamma}{c}-\frac{L\gamma}{c}}\right)} \frac{\delta_\gamma}{\left(1+\delta_\gamma^2\right)^2}.$$





Difficulty obtaining results

- Max OS frequency 480Hz (close to expected)
- K = 8.3 x 10^5 N/m
- E = K L / A = 1.16 Tpa (**stiffer than diamond**!)

Conclusions and future work

Important progress made towards advanced optical techniques for use in future gravitational wave detectors.

Diffractive cavity input couplers and associated dynamic effects are now well understood.

Gained valuable practical experience in controlling systems whose mirrors dynamics are controlled by optomechanical rigidity.

There are also many other interesting experiments being carried out by our colleagues around the world (<u>sub-SQL measurements</u>, <u>squeezing experiments</u>, etc).

The end!

Thanks for your attention.