Technology Development - GEO600

Aim: to develop technology relevant to upgrade of current detectors and building of new detectors such as EGO

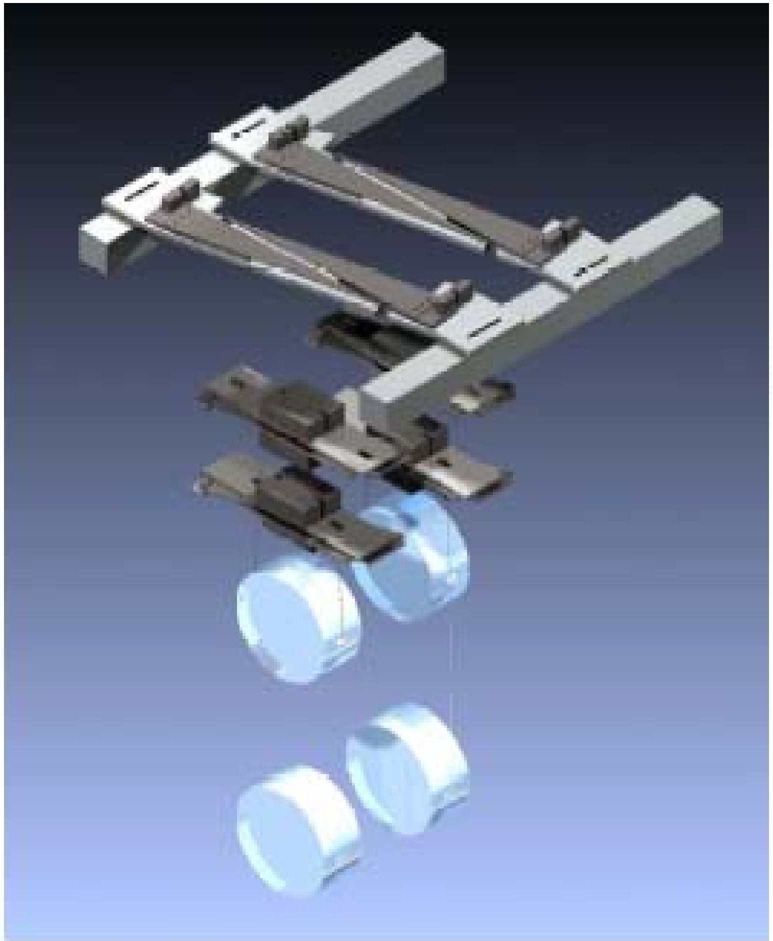
Jim Hough
for the GEO600 team

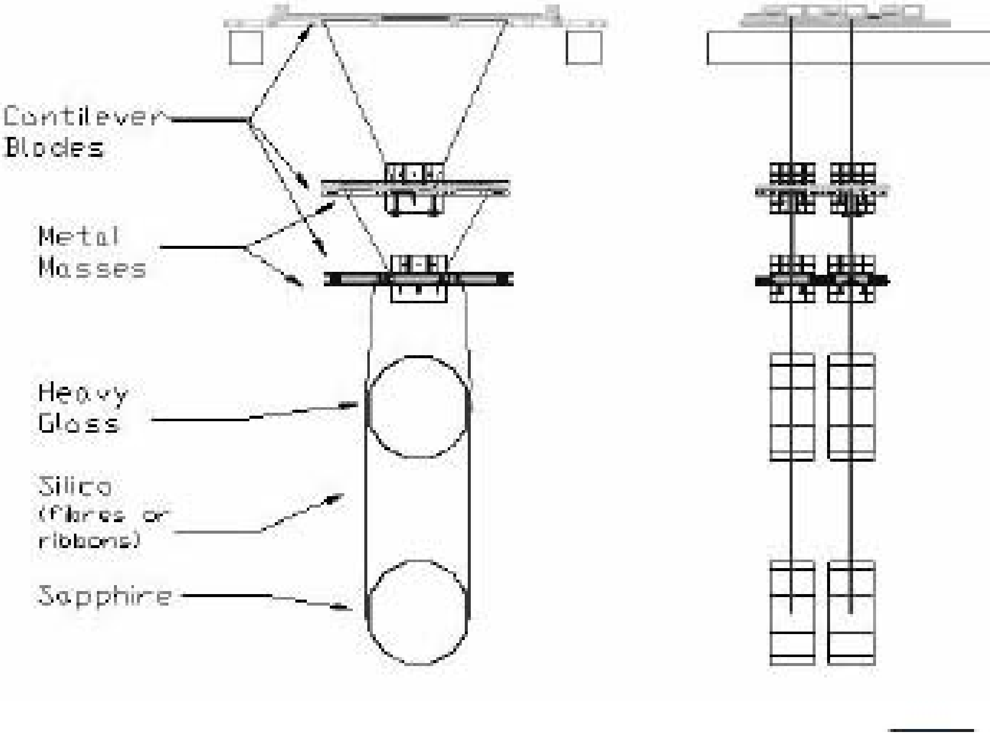
Perth Meeting
Western Australia, April 2004

Development Overview

- Suspensions for Advanced LIGO (Glasgow)
- Lasers for Advanced LIGO (Hannover LZH)
- Coatings (Glasgow and other groups in the LSC)
- Materials for future detectors eg Si at low temperature for test masses and suspension elements (Glasgow)
- Interferometry and Direct Thermal Noise measurement (Glasgow and Hannover)
- Diffractive optics (Hannover and Glasgow)
- Non-classical light (Hannover)
- White Light Cavities (Hannover)
- New Interferometer Prototype in Hannover planned (cryogenic?)

Suspension for Advanced LIGO





Prototype Quad suspension

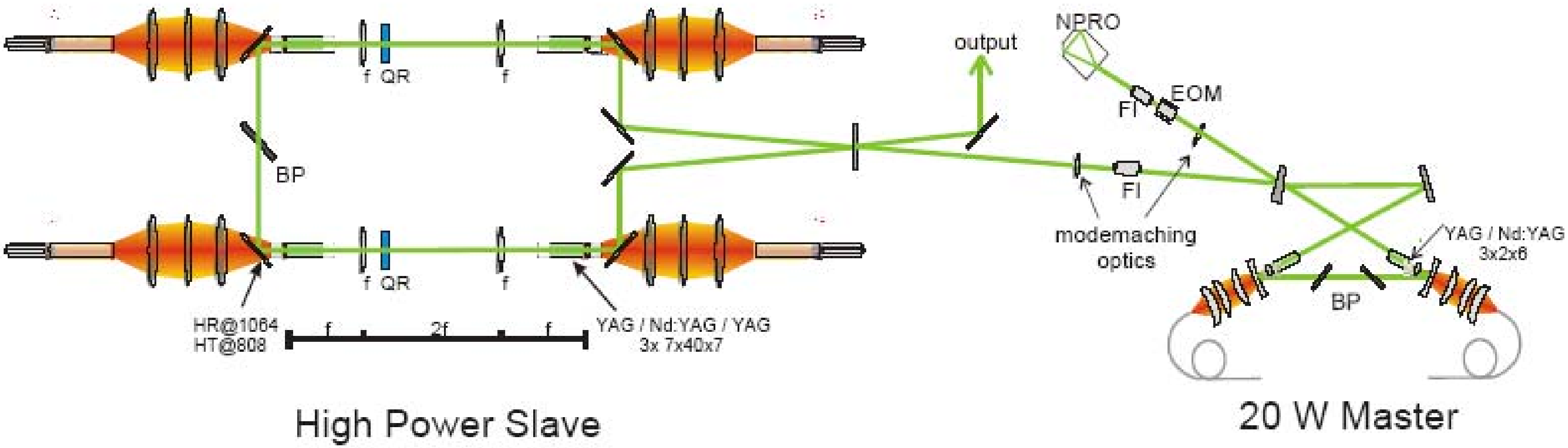
Prototype all-metal quadruple suspension designed in Glasgow, tested at LIGO MIT.

PPARC (UK) have awarded ~£8M grant to Glasgow, Rutherford Lab and Birmingham to develop and fabricate the quadruple suspensions + analog control electronics for Advanced LIGO

Suspension Team

- **LIGO LAB**: CIT: H. Armandula, M. Barton, J. Heefner, J. Romie, C. Torrie, P. Willems. MIT:P. Fritschel, R. Mittleman, D.Shoemaker LHO: B. Bland, D. Cook LLO: J. Hanson, J. Kern, H. Overmier, G. Traylor
- **GEO600**: GLASGOW: G. Cagnoli, C. Cantley, D. Crooks, E. Elliffe, A Grant, A. Heptonstall, J. Hough, R. Jones, M. Perreur-Lloyd, M. Plissi, D. Robertson, S. Rowan, K. Strain, P. Sneddon, H. Ward UNIVERSITAT HANNOVER: S. Gossler, H. Lueck
- **STANFORD UNIVERSITY**: N. Robertson (also GEO/Glasgow)
- **RUTHERFORD APPLETON LABORATORY**: J. Greenhalgh, I. Wilmut
- **THE UNIVERSITY OF BIRMINGHAM**: S. Aston, C. Castelli, D. Hoyland, C. Speake
- **STRATHCLYDE UNIVERSITY**: N. Lockerbie

LZH High Power Laser



Coating Research (LSC) - Introduction

- Future GW detectors require coated test masses of low thermal noise and hence low mechanical loss
- For Advanced LIGO the most promising candidate materials for the substrates are silica and sapphire
- Addition of dielectric coatings could increases level of thermal noise [Levin, Nakagawa, Yamamoto] and measurements of loss suggest that this will be the case [Crooks, Harry et al]
- A set of experiments is being carried out to
  - determine level of mechanical loss associated with typical coatings (which allows the effect on thermal noise to be investigated)
  - investigate the source of the mechanical loss in coatings
  - study different types of dielectric coating
- Experiments carried out by LSC collaboration
  - Glasgow, Stanford, MIT, Caltech, Syracuse, Hobart and William Smith

Coating Research (LSC) - status 1

- All current GW detectors use coatings consisting of alternating quarter wave layers of SiO_2 and Ta_2O_5

- Mechanical loss ϕ_c of such a coating determined to be $\sim 2.8 \times 10^{-4}$. An estimate of the thermal noise level calculated from this value suggests that this could pose a problem for advanced detectors

- However, the frequency dependence of ϕ_c requires careful investigation as our measurements are typically made well above the detector frequency band

- Also, recent work on thermoelastic damping needs to be considered, both in terms of the interpretation of measurements and also the calculation of thermal noise

Coating Research (LSC) - status 2

- Potential sources of loss (from expt and calculation):
  - **Thermoelastic damping** (see Fejer et al, submitted Phys Rev D gr-qc/0402034v1)
    - resulting from the different thermal and elastic properties of the coating and the substrates
  - **Dissipation intrinsic** to the coating materials (defects, vacancies etc?)
- Investigations suggest:
  - Intrinsic loss of tantalum pentoxide dominates that of silica or alumina but seems to be reduced by doping with titania
  - Thermoelastic noise reduction requires careful matching of coating to substrate

Total coating thermal noise

Top level noise spec for Adv. LIGO at 100Hz →		Fused silica substrate 8×10^{-21} m/√Hz			Sapphire substrate 6×10^{-21} m/√Hz		
Coating type	Thickness (μm)	Residual thermal noise (m/√Hz)	Thermoelastic thermal noise (m/√Hz)	**Total coating thermal noise (m/√Hz)**	Residual thermal noise (m/√Hz)	Thermoelastic thermal noise (m/√Hz)	**Total coating thermal noise (m/√Hz)**
Silica Tantala	5.3	9.0×10^{-21}	2.1×10^{-21}	**9.2×10^{-21}**	5.0×10^{-21}	1.2×10^{-21}	**5.1×10^{-21}**
Alumina Tantala	7.9	1.4×10^{-20}	1.5×10^{-20}	**2.1×10^{-20}**	6.5×10^{-21}	5.5×10^{-22}	**6.5×10^{-21}**
Silica Alumina	14.8	1.2×10^{-20}	1.8×10^{-20}	**2.2×10^{-20}**	4.5×10^{-21}	2.3×10^{-21}	**5.1×10^{-21}**

(Individual noise values are added in quadrature)

Coating Plan (LSC)

- Both thermoelastic noise and noise resulting from residual dissipation are of significance for coating thermal noise.
- Results suggest that way forward is
  - To work on reducing residual mechanical loss of tantala

    Or
  - To find alternate high-index material with similar thermo-mechanical properties but lower residual mechanical loss
  - Nb: must in parallel consider optical loss/ absorption of coatings studied

Motivation for Upgrade to GEO

- Astrophysics motivation for a detector to look for ringing of neutron star modes is high
- Background:
  - Upgrade to LIGO planned over the period 2007-2010
  - To minimise the spell in which no interferometers are running, propose that GEO and VIRGO both take data until 2008.
  - At that time - VIRGO upgrade?
- At this point GEO design sensitivity will not be competitive

- **Propose:** *post 2008, GEO 600 be upgraded to a detector aimed at high frequency signals from neutron star oscillations to enable the study of neutron star seismology and fundamental physics - 'GEO-HF'*

Requirements

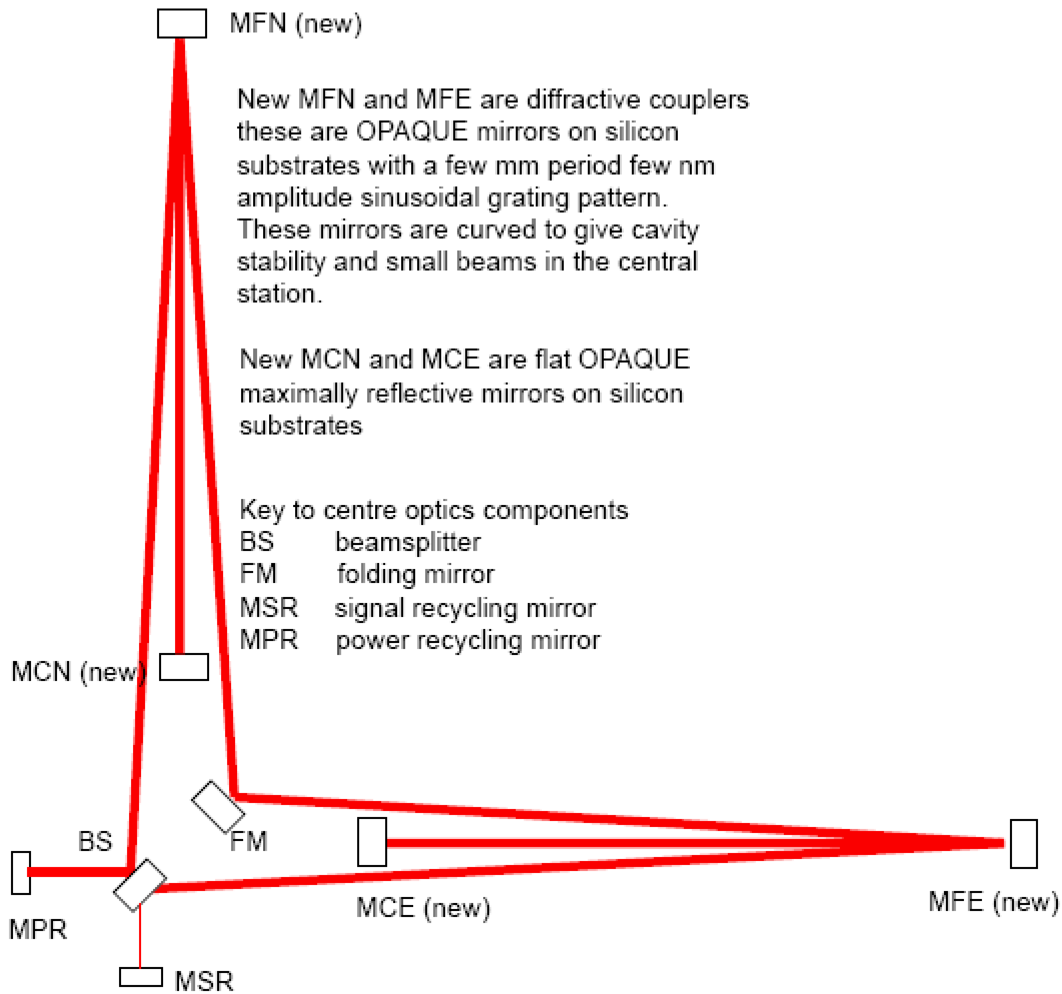
- An upgrade of the GEO 600 instrument tuned to the frequency band 2-4 kHz should observe these phenomena at the level of an effective dimensionless amplitude of h ~ 5×10^{-24}.
- Experimental limitations at these frequencies:

optical noise, ‘internal’ thermal noise

- Technology choices to deal with these noise types are related – consider optical issues first.

Proposed Optical Scheme GEO-HF

Diffractively coupled ring cavity Sagnac



New MFN and MFE are diffractive couplers these are OPAQUE mirrors on silicon substrates with a few mm period few nm amplitude sinusoidal grating pattern. These mirrors are curved to give cavity stability and small beams in the central station.

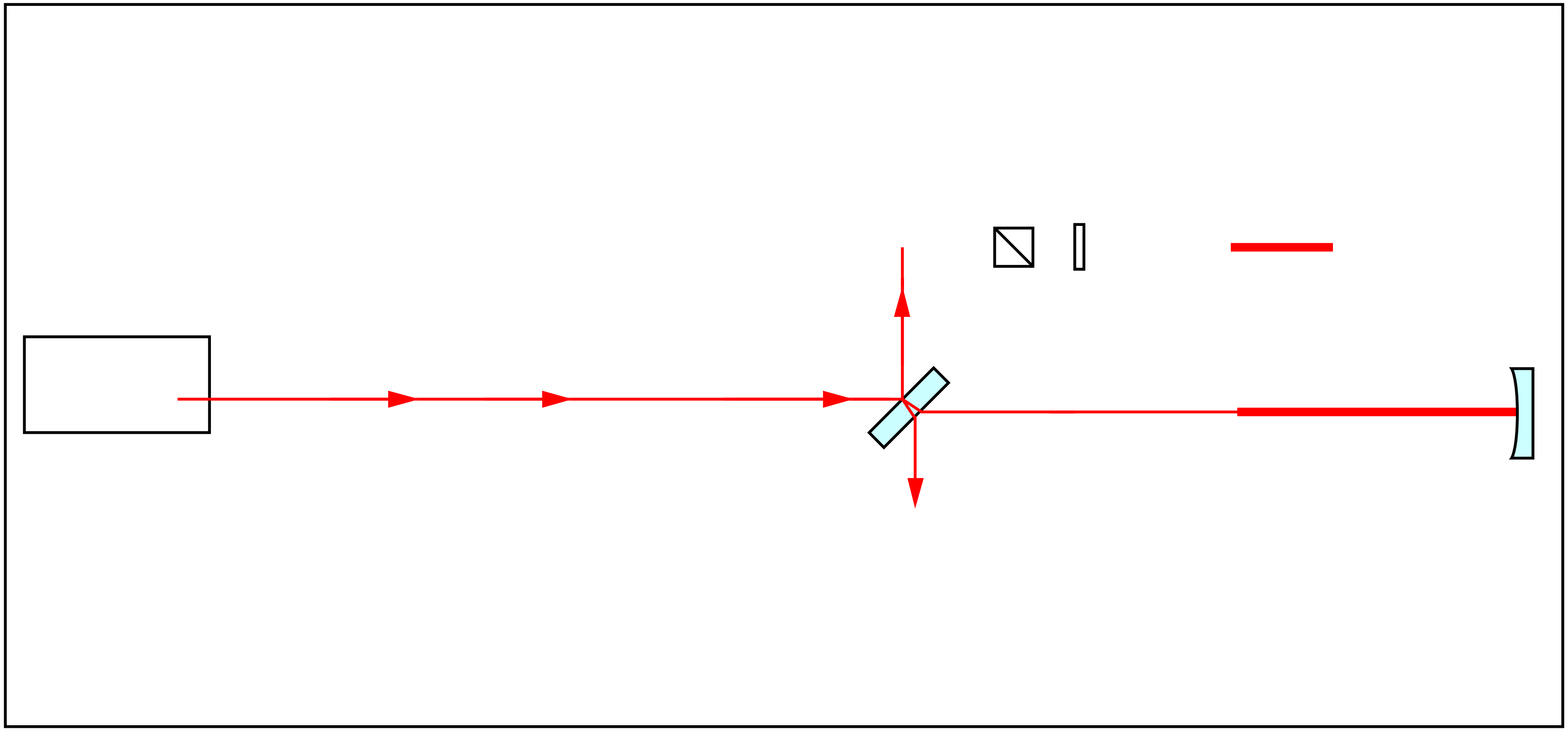
New MCN and MCE are flat OPAQUE maximally reflective mirrors on silicon substrates

Key to centre optics components

BS	beamsplitter
FM	folding mirror
MSR	signal recycling mirror
MPR	power recycling mirror

Glasgow Prototype

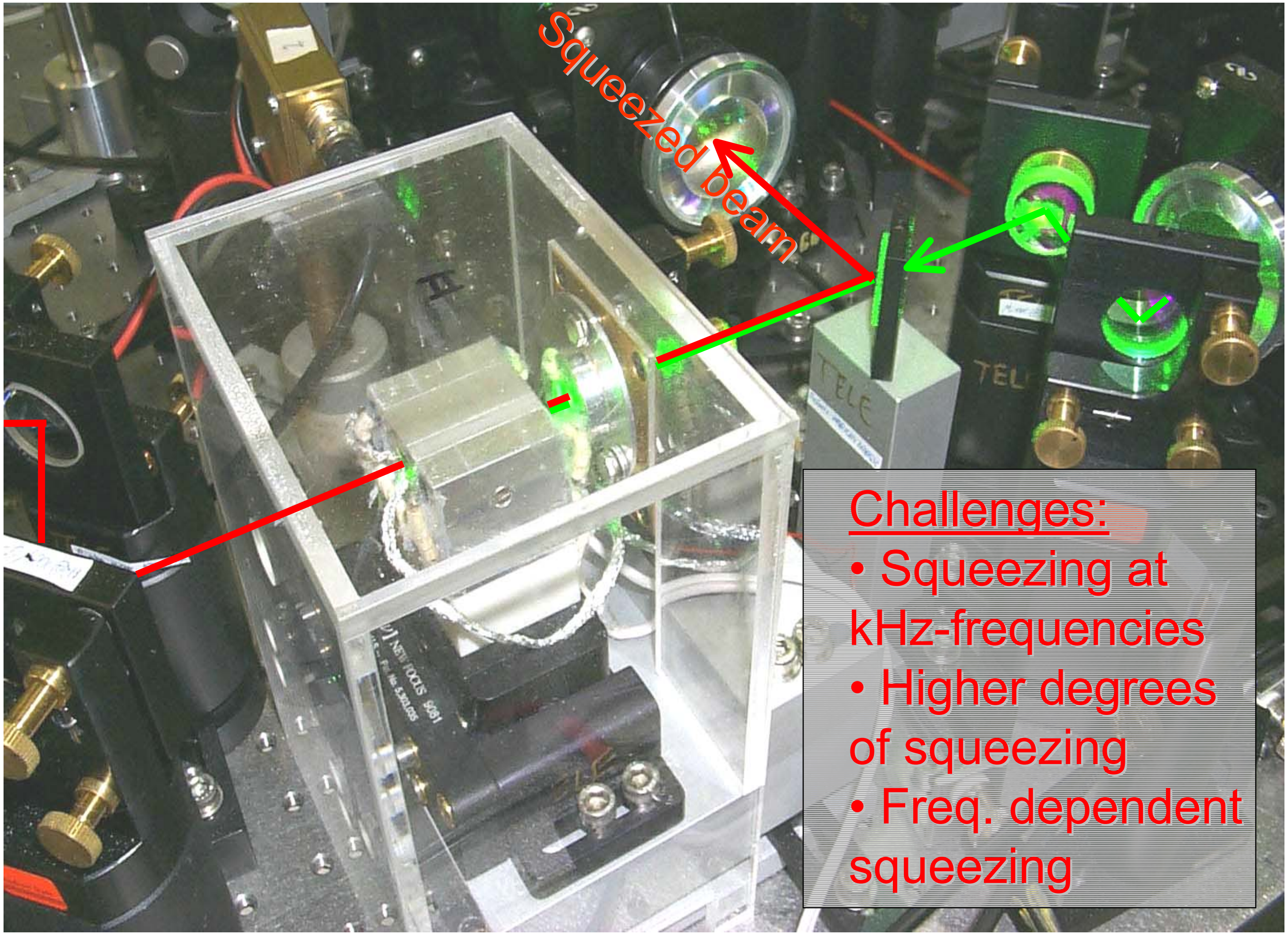
The performance of coupled cavities as present in all future gravitational wave detectors and direct detection of thermal noise in interferometer test masses and coatings will be investigated



Also diffractive cavity mirrors will be investigated

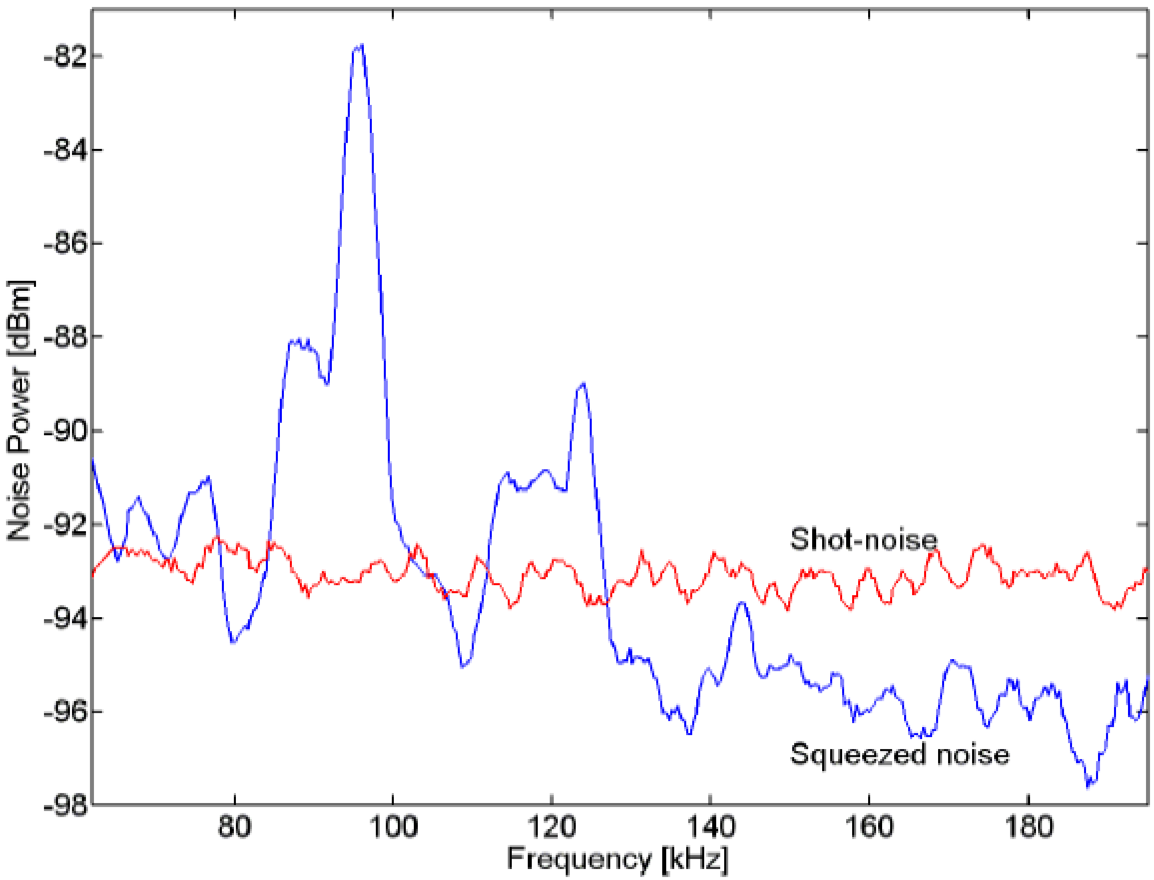
GEO 600

Squeezed Light for 3rd Generation Interferometers Schnabel et al (Hannover)



<u>Challenges:</u>
- Squeezing at kHz-frequencies
- Higher degrees of squeezing
- Freq. dependent squeezing

Squeezed Spectrum at mid-frequencies



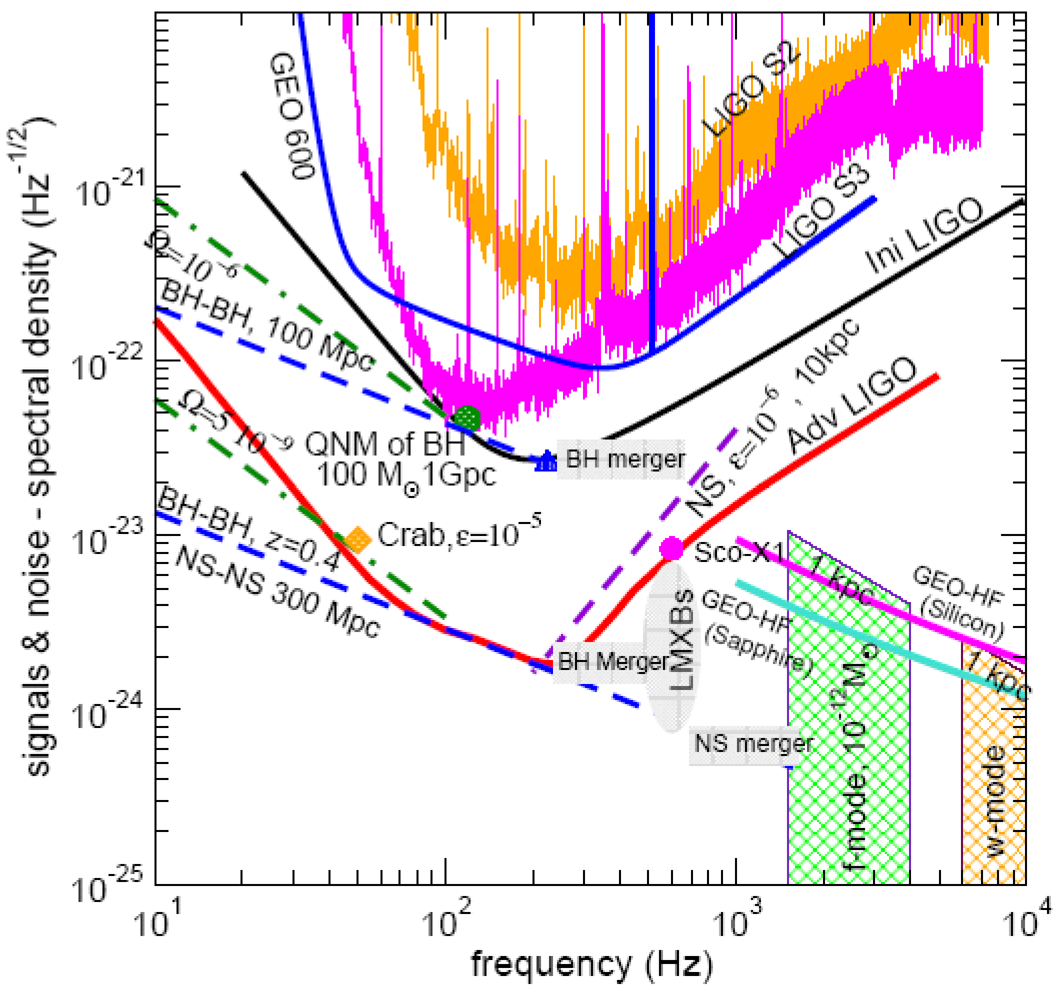
- We used a single OPA scheme employing 600 mW laser power in total.

Materials under thermal load

Material At 300K	Lensing Figure of merit (dn/dt)/K (nm/W)	Expansion Figure of merit (α/K) (nm/W)	Absorption (ppm/cm)	Power limit inside cavity (kW)
Transmissive				
Sapphire	250	125	20	630
Fused silica	7250	362	1	196
Reflective				
Sapphire	-	125	-	**1.7×10^4**
Fused silica	-	362	-	**5.87×10^3**
Silicon	-	17	-	**1.27×10^5**

- The very high thermal conductivity of silicon allows it to support almost 10 times more power than sapphire

Thermal noise limitations in the kHz range



Research and development of low mechanical dissipation test mass materials and suspensions

This includes

- Study of mechanical loss properties of materials such as silicon, at room and low temperature for both test masses and suspension elements
- Thermal noise associated with hydroxy-catalysis bonding/jointing techniques
- FE Modelling of spatially inhomogeneous dissipation
- Development of large test masses possibly of composite (bonded) materials

The ongoing lab developments in GEO in these areas will inform the design study process for the 3rd generation European interferometers and could be the basis of a hardware contribution to a 3rd generation observatory

Example: silicon as a test mass/suspension material

Silicon: unique combination of material properties on cooling:

(a) Intrinsic mechanical loss decreases

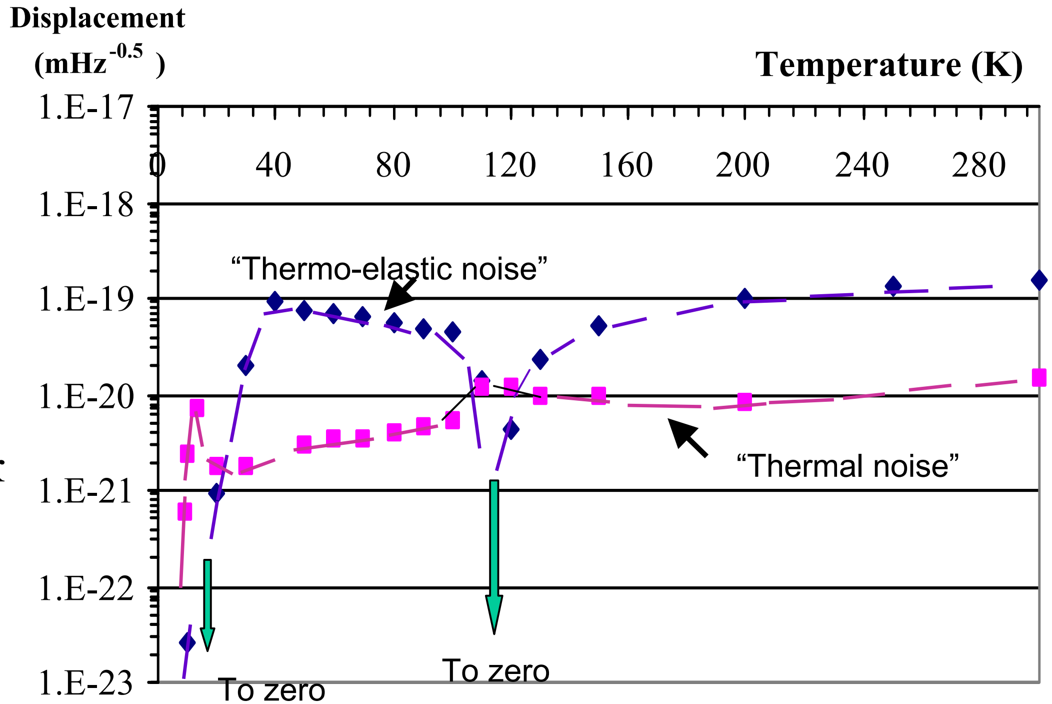
(b) Two zero's in coefficient thermal expansion, α, at ~130K and ~20K

Dual benefits:

Thermal deformation proportional to α/κ

Thermo-elastic noise proportional to α

both should vanish as α tends to zero



"Thermo-elastic" displacement noise and "thermal" noise in a silicon test mass as a function of temperature

Silicon substrates open avenues for significant thermal noise improvements at low temperatures but material properties need further study

Conclusion

- GEO research targeted at future detectors
  - – Advanced LIGO
  - – Potential GEO-HF
  - – Potential EGO