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Lessons Learned from GEO 600

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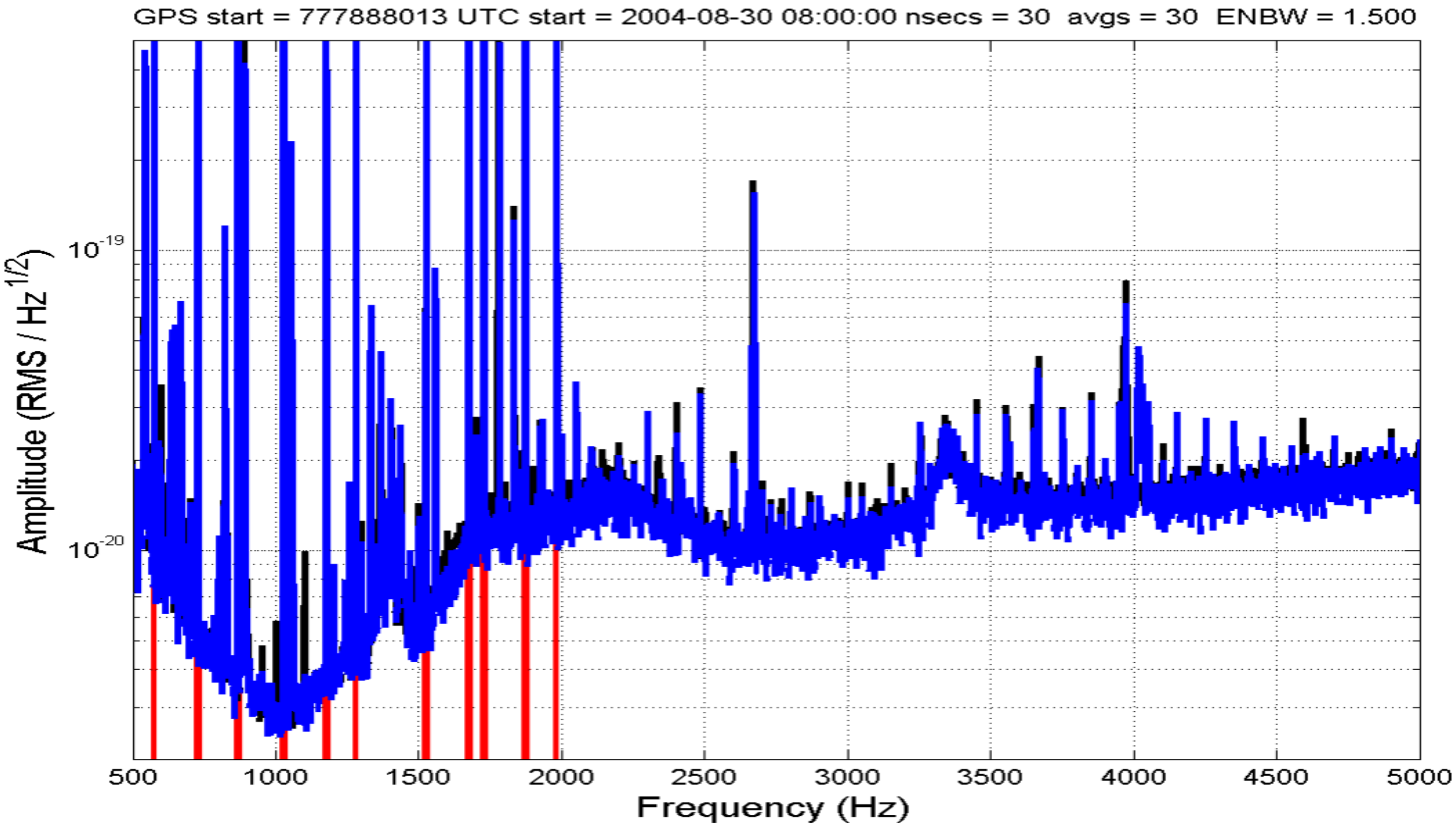
Introduction / Context

- What are *'the lessons'* learned from GEO600 ?
- Obviously there are many lessons on several levels to be learnt.
- I will try to give this talk a slightly different flavor than Hartmut's talk at last years GWADW.
  gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Grote.pdf
- The rest of the talk will be my personal TOP10 lessons, i.e. my subjective choice (other people might have a different selection of lessons in their TOP10).
- Be warned: the lessons I will present are of quite different 'quality'. Also the order is random.
- Fortunately, many of these lessons have already been learnt and have been taken into account in designing the advanced detectors.

LESSON 1:
Understanding your detector is essential!

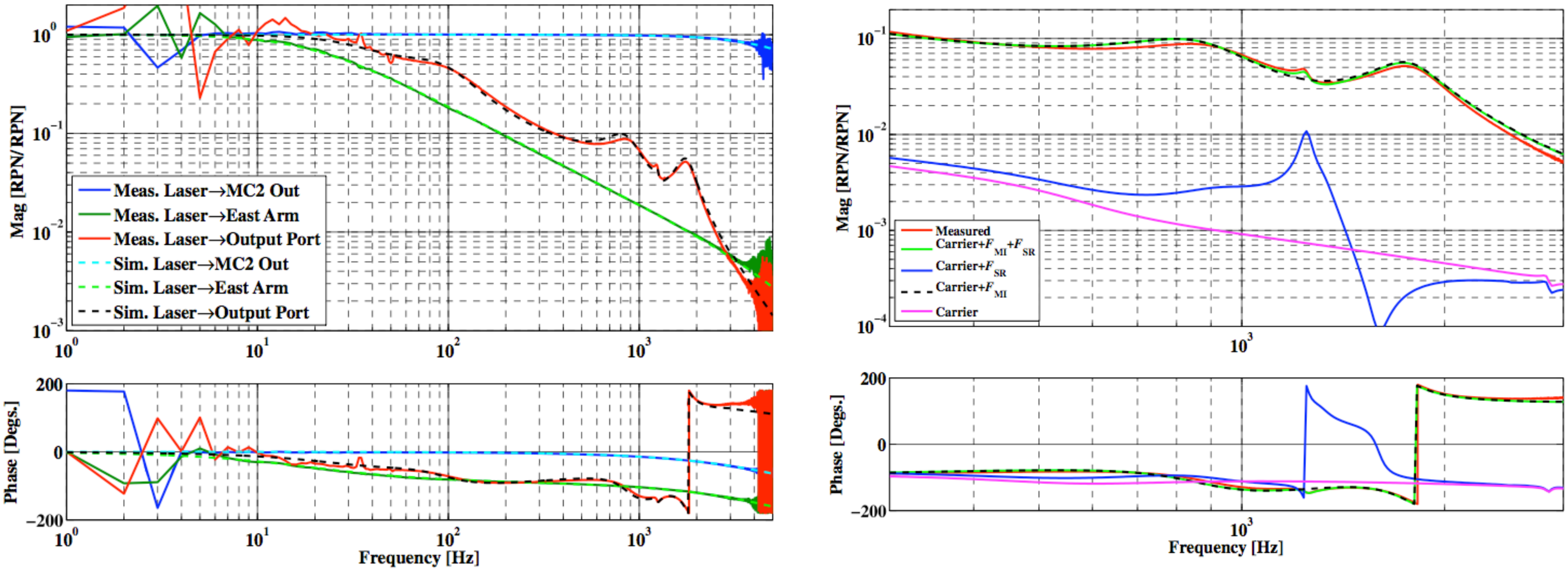
- Time lapse video: changing only one IFO parameter



LESSON 1b: Understanding your detector is essential! Simulations can help.

- Example: Laser power noise coupling in GEO. Excellent match of measurement and simulations even for complex details.

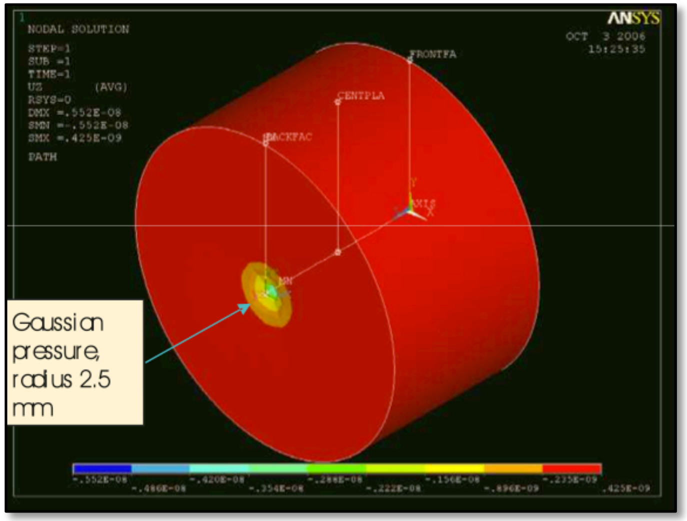
Measurement and simulation of laser power noise in GEO 600, *CQG,* **2008**, *25*, 035003



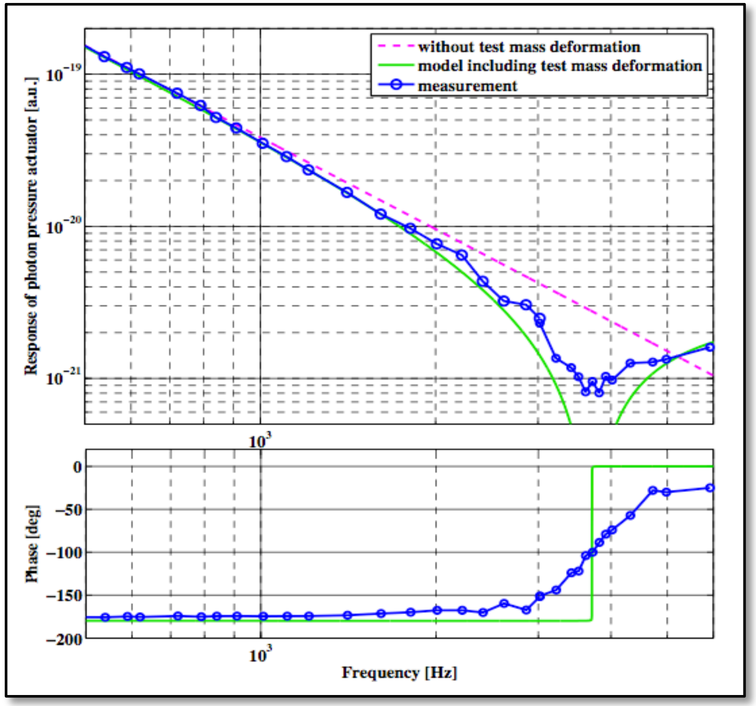
- However simulations are only as good as their input parameters.
- Need time and lots of measurements to build up a good model**. Make sure you get this time!**

LESSON 2: Most things are more complicated than you think

- Advise from Walter Winkler: “If you only look close enough you will find that you even do not understand the most simple things.”
- Unfortunately, in our business we tend to look quite close …
- One example from GEO was the test mass deformations induced by the photon pressure calibrators.



Photon-pressure-induced test mass deformation in gravitational-wave detectors, *CQG*, **2007**, *24*, 5681-5688

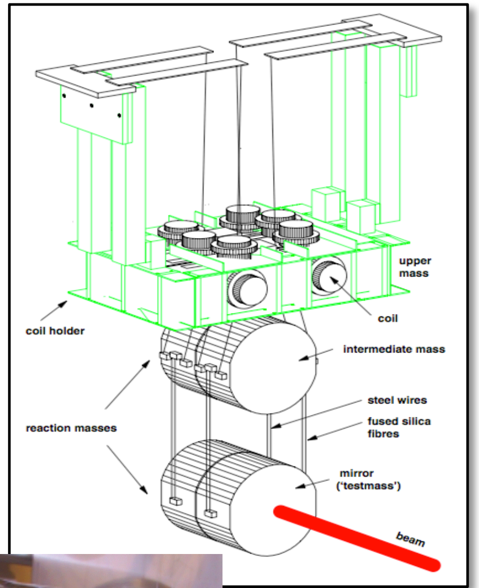


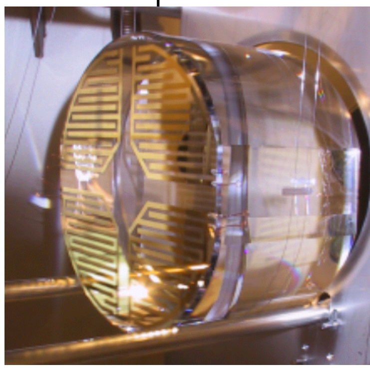
LESSON 3: Electrostatic actuators (ESD)

- Alternative to coil-magnet actuators:
  - Do not need to glue anything onto test mass.
  - No noise coupling from ambient magnetic fields.
  - Force spread over larger area (i.e. less deformation)
- Used as fast longitudinal actuator (UGF about 100 Hz) giving 350μN, i.e. 3.5 μm @ DC.
- As ESD pattern is arranged in quadrants we can also use it as alignment actuator (UGF about 10 Hz).
  - Increased phase margin, i.e. increased servo stability.
  - Less differentiation in intermediate mass path needed, i.e. less feedback noise.

$$x(\omega) = \frac{A'}{\omega_0^2}(V_{\mathrm{bias}} + V_0 \cos\omega_0)^2,$$

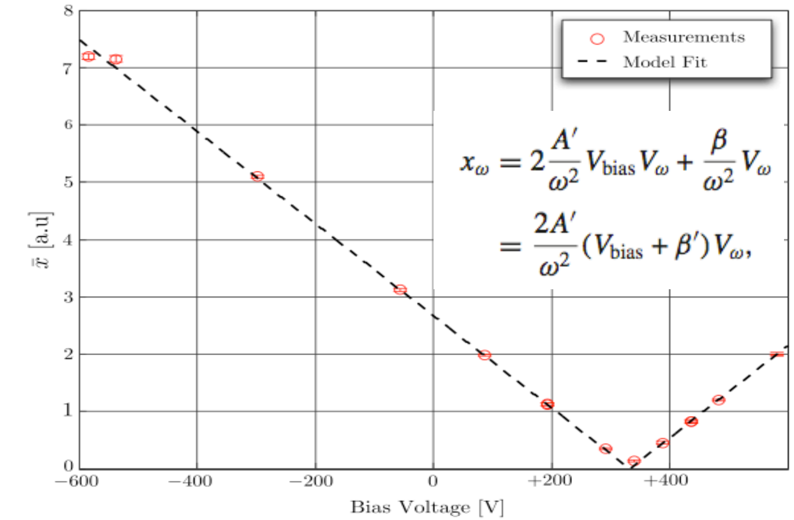
$$= \frac{A'}{\omega_0^2}\left(V_{\mathrm{bias}}^2 + 2V_{\mathrm{bias}}V_0\cos\omega_0 + \frac{V_0^2}{2}(1+\cos 2\omega_0)\right),$$

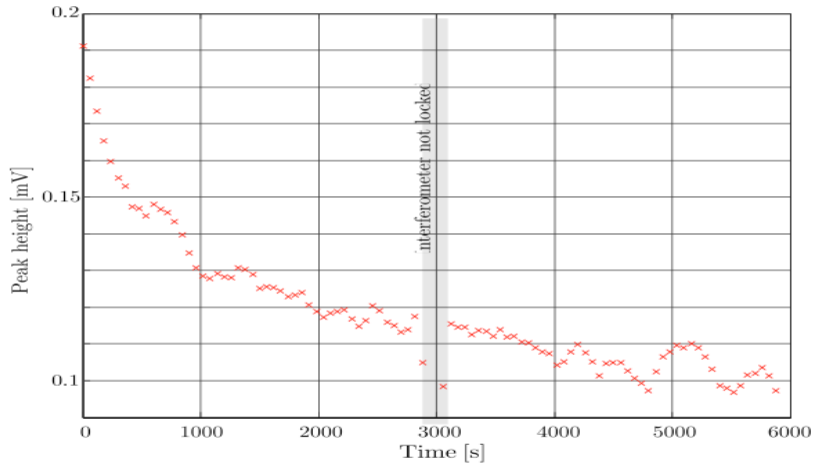




LESSON 3b: Electrostatic actuators (ESD)

- Be careful: ESD-strength strongly influenced by any potential charges on test mass.
  - Need to continuously track the ESD strength (e.g. photon pressure calibrators)
- Make sure the ESD never touches the test mass.
  - Dec 2006 accident: power cut left pendulums undamped and charged ESD touched test mass.
- Learnt how to measure the effective charge on the mirror using the ESDs.
- Showed discharging by means of UV light.





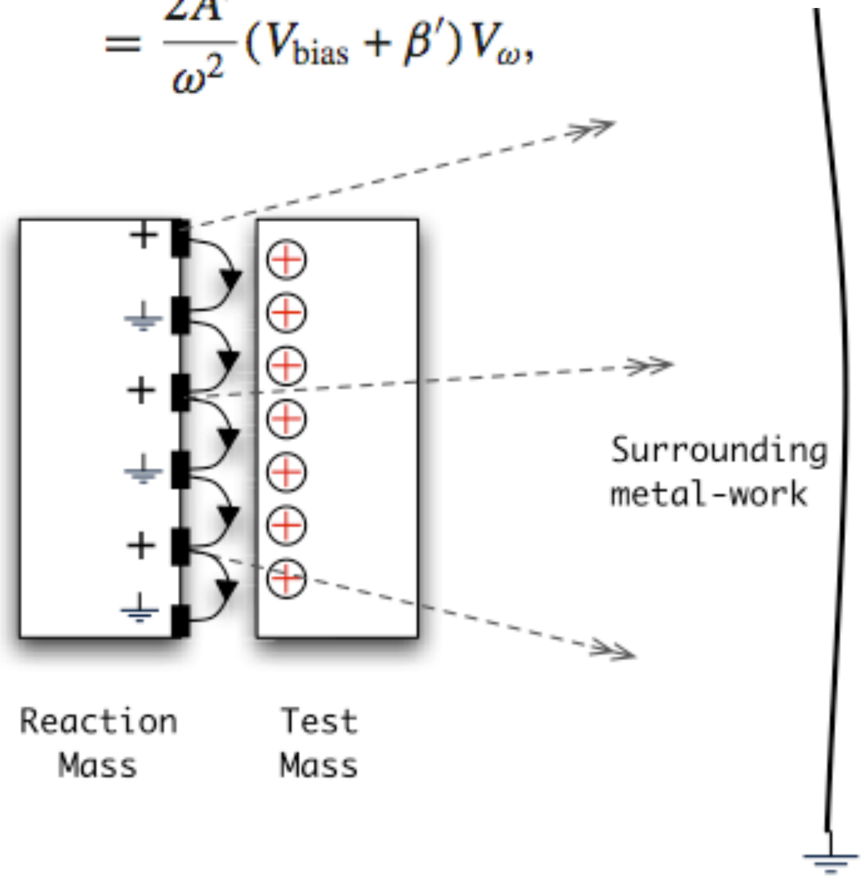
Charge measurement and mitigation for the main test masses of the GEO 600 gravitational wave observatory, CQG. **24 (2007) 6379–6391**

LESSON 3c: Discharging and recharging of the test masses using UV light

- UV light of suitable wavelength has been shown experimentally to remove electrons from the surface of dielectric components.

- Alternatively the light can be shone on to a metal target near the mass and any positive charge on the mass can be neutralized by photoelectrons released from the metal.

$$x_\omega = 2\frac{A'}{\omega^2}V_{\text{bias}}V_\omega + \frac{\beta}{\omega^2}V_\omega$$
$$= \frac{2A'}{\omega^2}(V_{\text{bias}} + \beta')V_\omega,$$

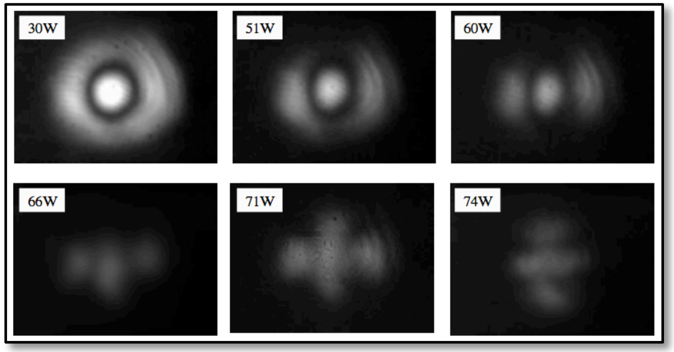


LESSON 4 : Sometimes quick & dirty is good enough

- Fixing problems does not always require rocket science.
- Example: ROC mismatch of the end mirrors (666m vs 687m).
- Build a UHV-compatible ring heater using scissors by non-experts within one afternoon.

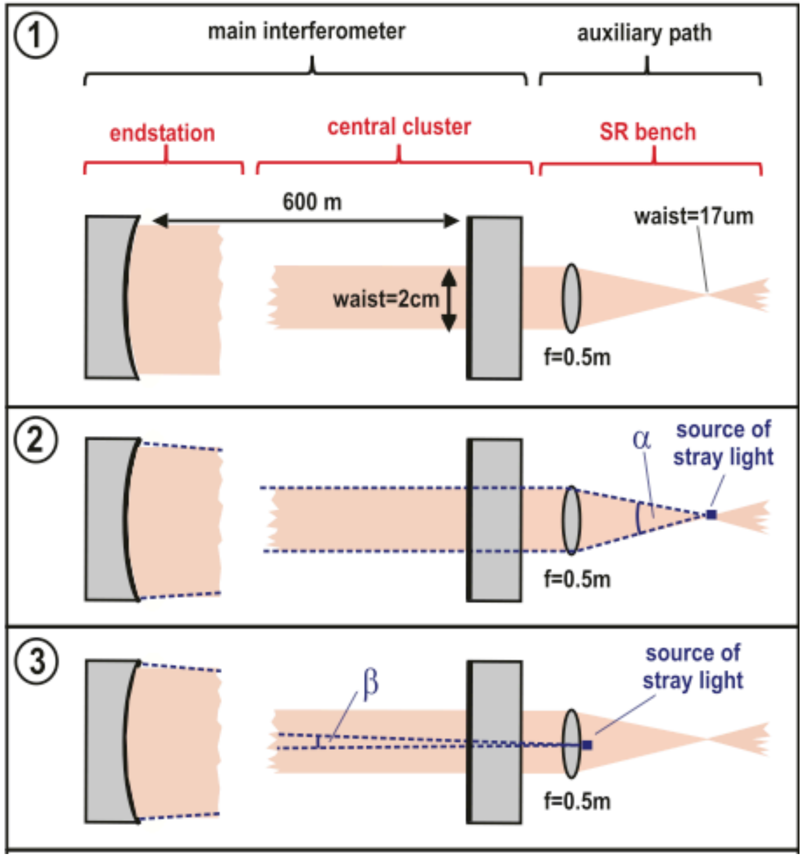
Thermal correction of the radii of curvature of mirrors for GEO 600, *CQG,* **2004**, *21*, S985-S989

- Originally only planned as a preliminary solution, this ring heater is now in continuous operation for more than 8 years.
- Now the ring heater is also used to partly compensate the thermal lensing.



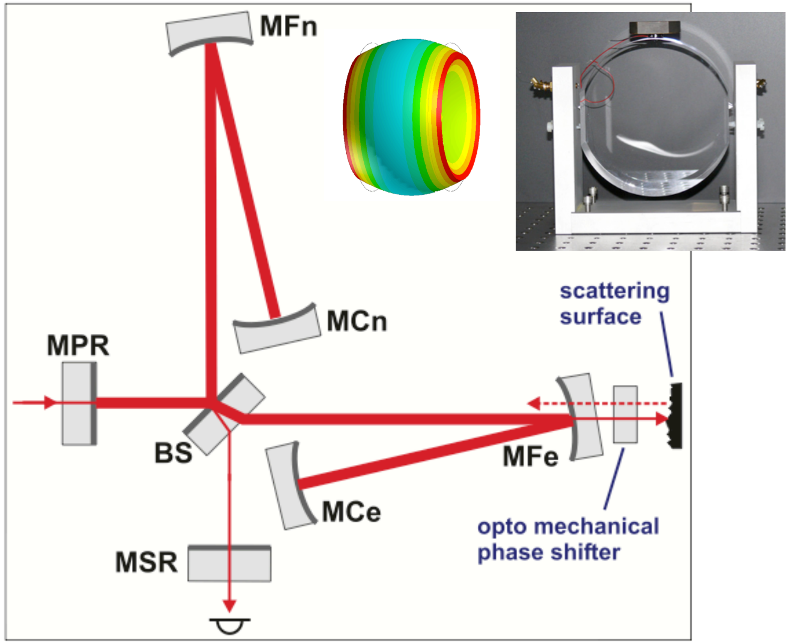
LESSON 5: Scattered light – Be aware of the cat's eye effect !

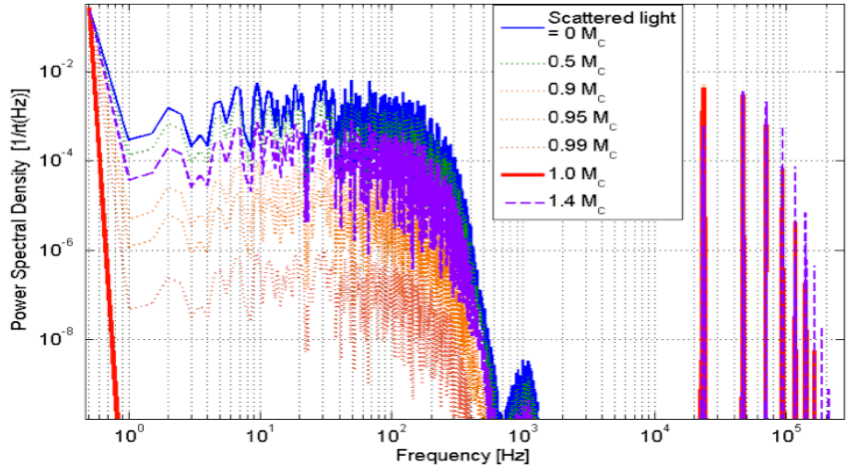
- The noise source we probably spend most time on is scattered light.
- Most problems from components outside the vacuum, e.g. photodiodes, mirrors and lenses.
- Cat's eye effect: Scattering from close to a waist is extremely harmful (high intensity + large acceptance angle).
- Basic rules:
  - Avoid any components close to a waist.
  - Replace PD windows by properly AR coated ones.
  - Curved mirrors are better than lenses.

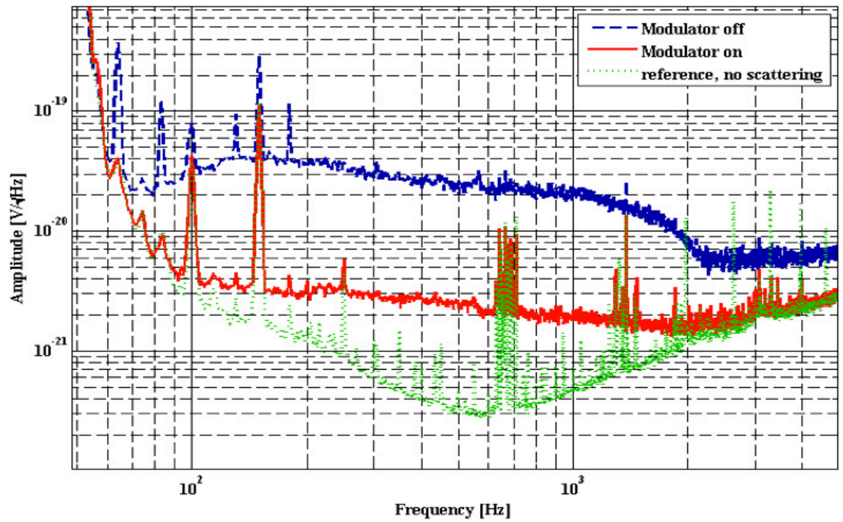


LESSON 5b: Fighting scattered light by 'phase scrambling'

- Use an opto-mechanical phase shifter (critical mod-index) between scattering component and the IFO to shift scattering components to higher frequencies.



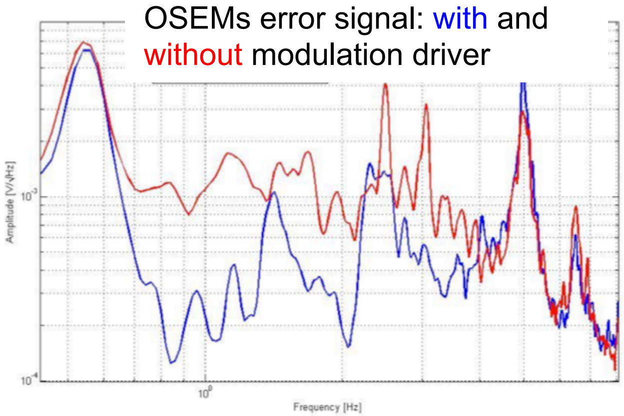


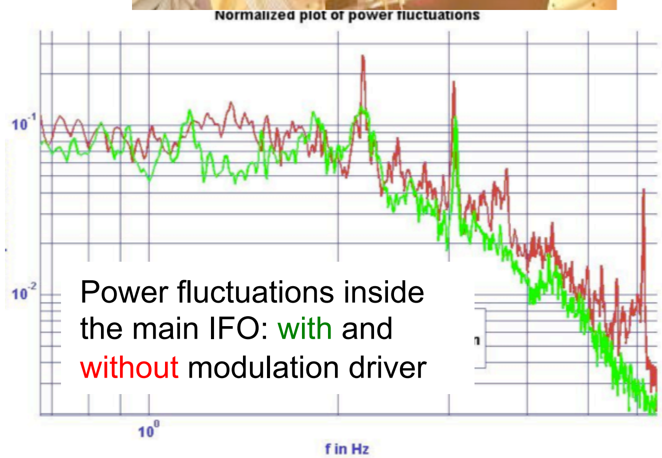


Opto-mechanical frequency shifting of scattered light, *Journal of Optics A: Pure and Applied Optics*, **2008**, *10*, 085004

LESSON 5c:
Scattered light coupling into OSEMs.

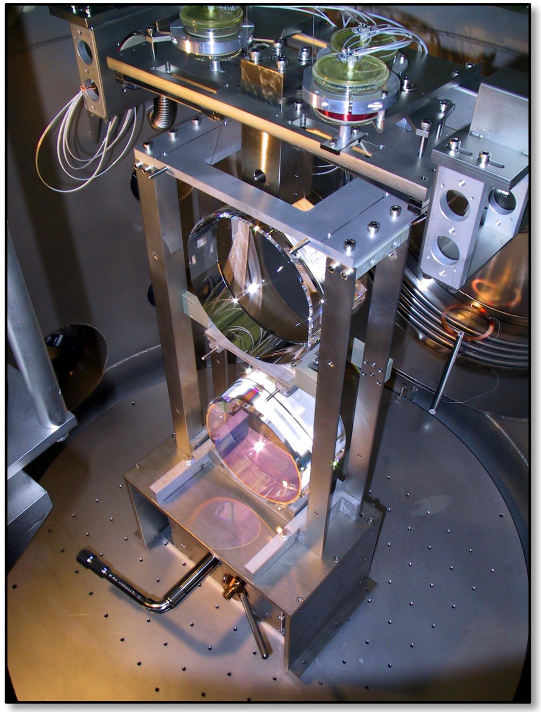
- GEO experienced lock-instabilities in high power operation.
- Scattered light from IFO coupled into OSEMs and led to contamination of the local control error signal and subsequently to instabilities.
- Solution: modulation of OSEM LED + demodulation of OSEM PD signal yields clean error signals. With this system GEO can be stable operated at full laser power.
- ALIGO: local control PDs are much better shielded from light at 1064nm.

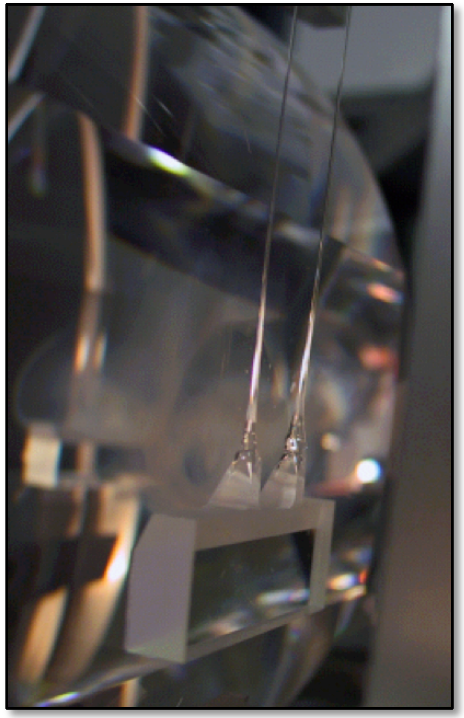




LESSON 6:
Do not be afraid of fused Silica fibers

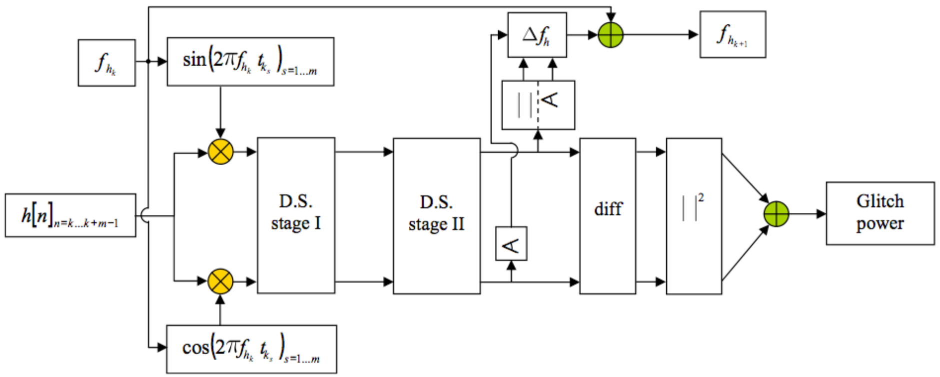
- GEO's main optics are suspended since 2002 with fused silica fibers.
- 20 fibres in the systems, i.e. close to 200 fiber-years without any faults, even though the vacuum system was vented several times during this period.



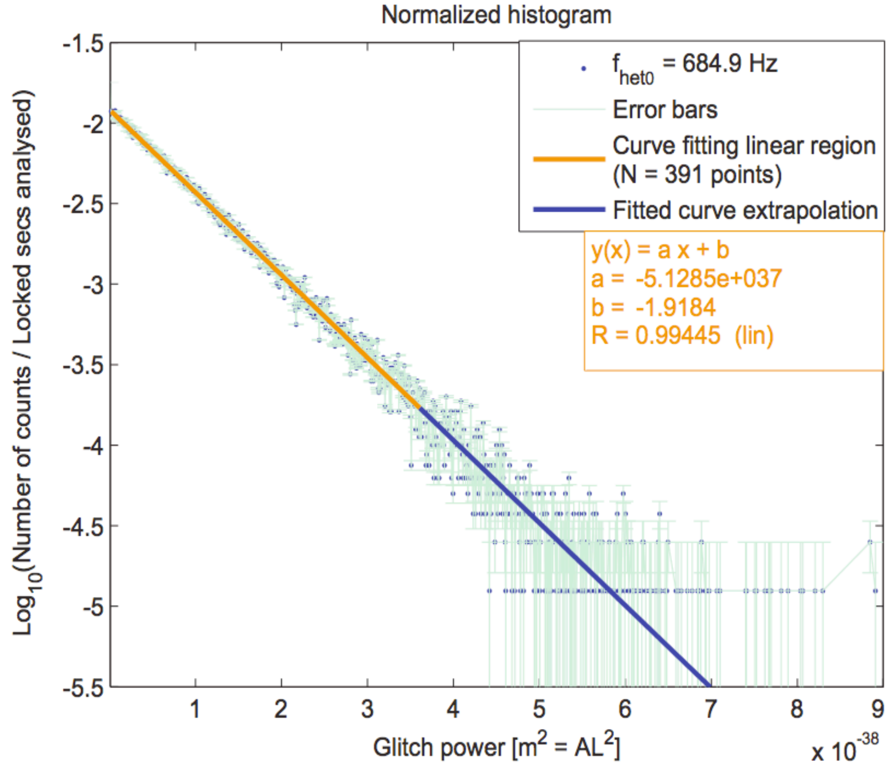


- Perhaps in the past we have been too hesitant (afraid of potentially breaking the fused silica suspensions) to open the vacuum system for fixing any commissioning problems.

LESSON 6b: no excess noise form fused Silica fibers



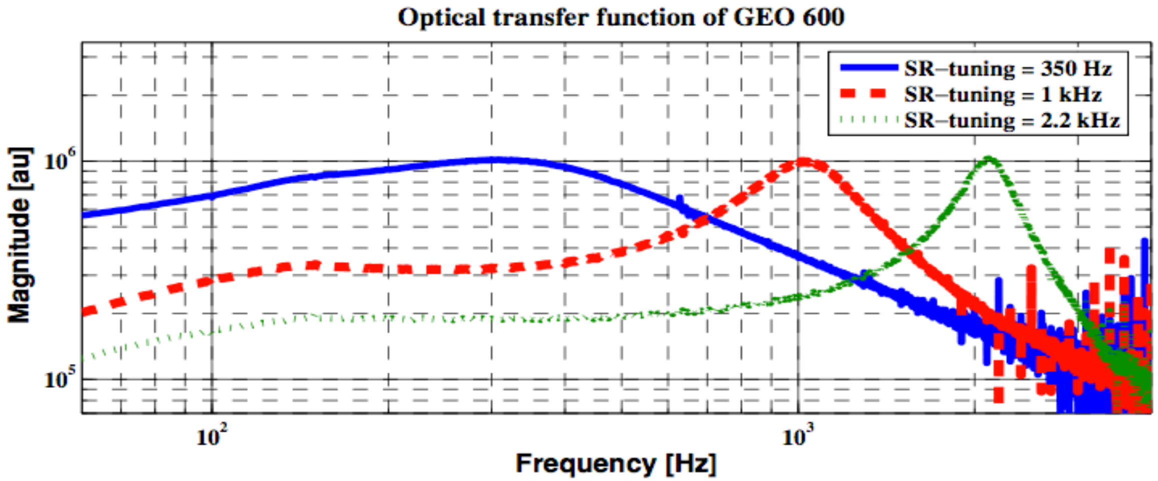
Violin mode amplitude glitch monitor for the presence of excess noise on the monolithic silica suspensions of GEO 600, *CQG*, **2010**, *27*, 155017

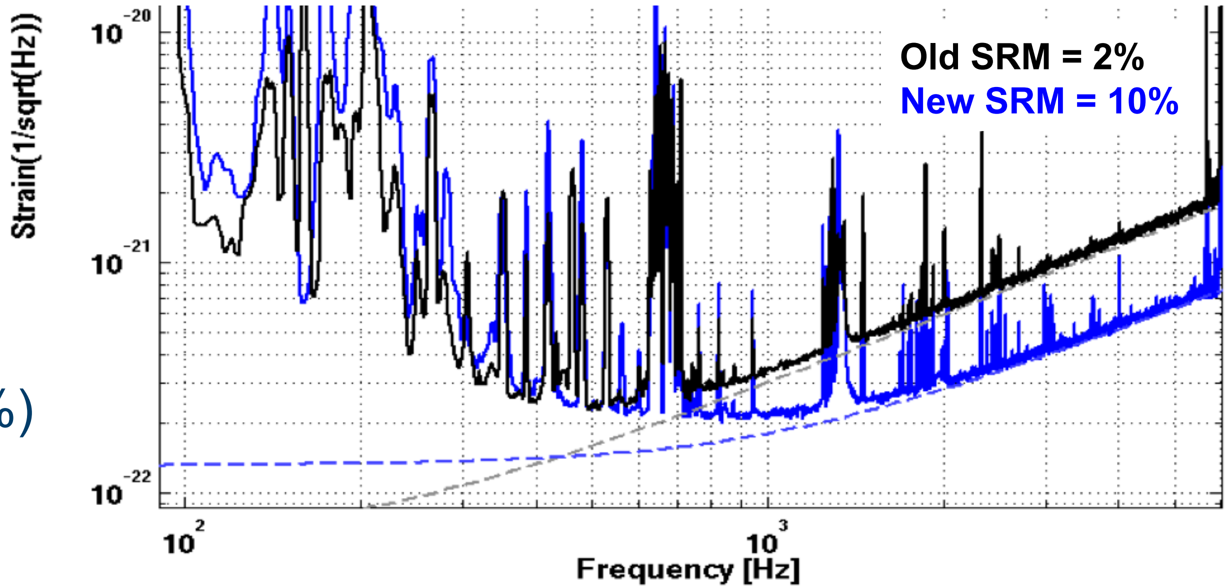


- Performed detailed analysis of glitch power at violin mode frequencies.
- No excess noise (above thermal noise level) was found.

LESSON 7: Signal Recycling works !

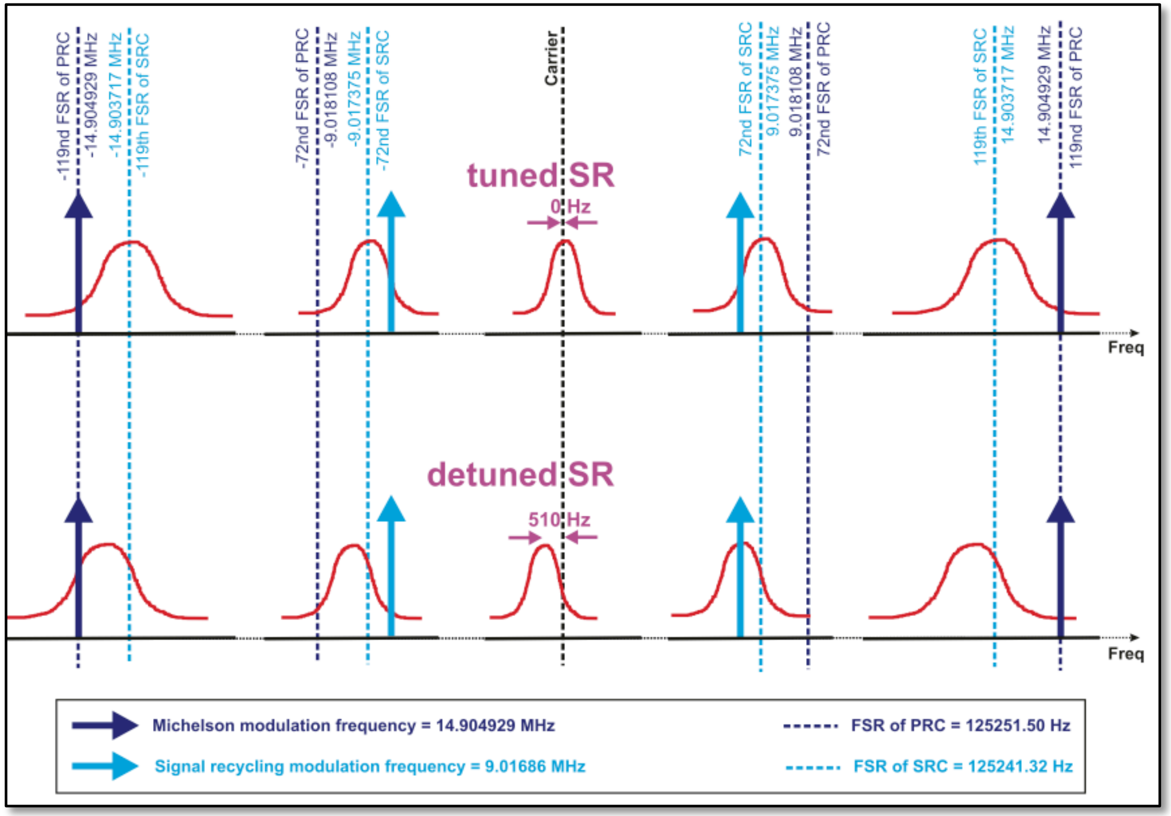
- Over the previous 8 years we collected plenty of experience with signal recycling.
- Shaping of shot noise by:
  - different detunings (SRM microscopic position)
  - different bandwidth (SRM reflectivity)
- Recently (Dec 2010), replaced the SRM with one of higher transmission (from 2% to 10%) to improve sensitivity at high frequencies.





LESSON 8: Tuned Signal recycling works better than detuned

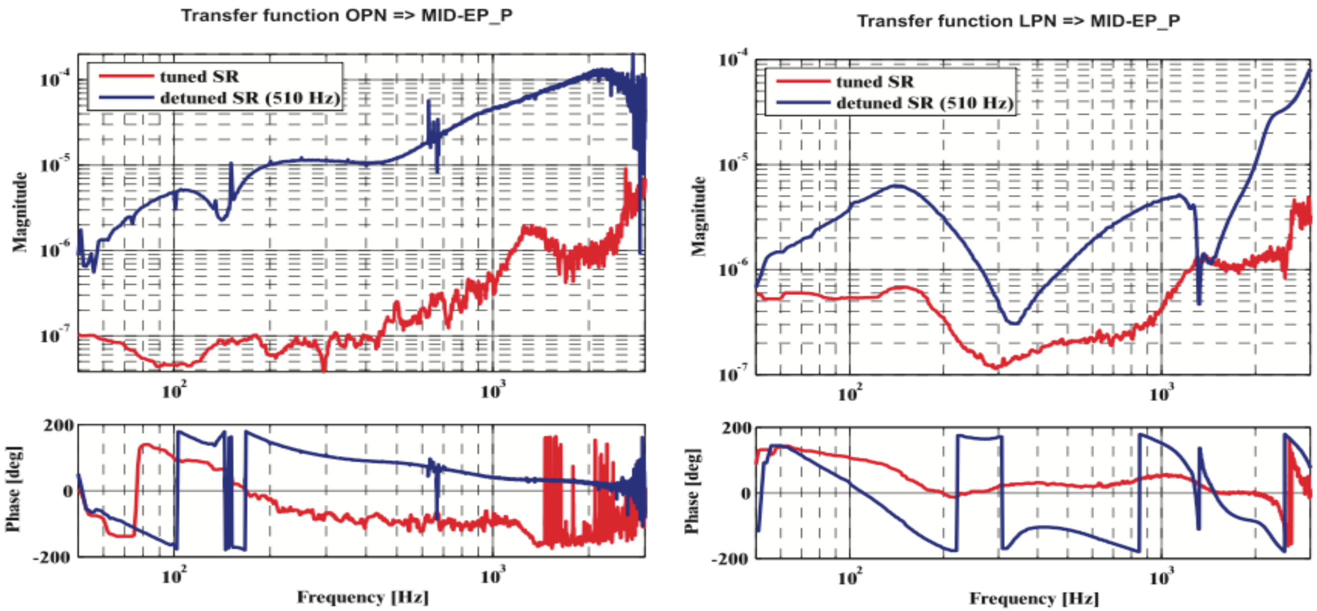
- Dispersion of signal recycling cavity cases sideband asymmetries in case of detuned signal recycling.



- Upper and lower RF/signal-sidebands have different magnitude and phase.

LESSON 8: Tuned Signal recycling works better than detuned

- Due to symmetric sidebands many noise couplings are much lower in tuned than in detuned signal recycling.



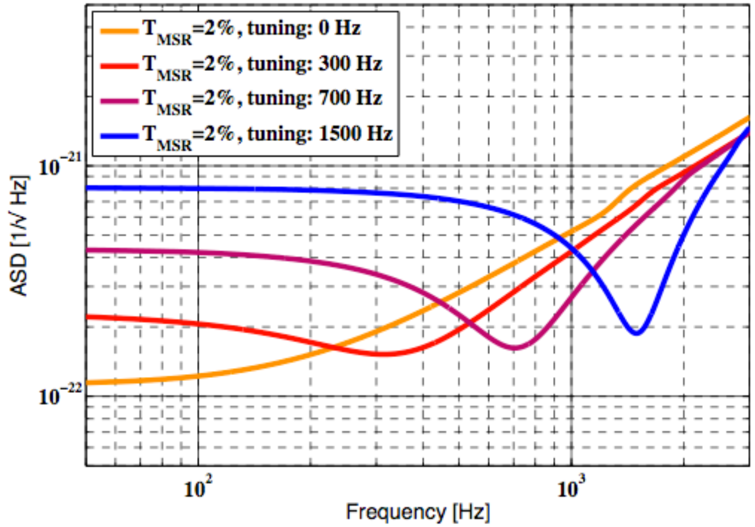
Demonstration and comparison of tuned and detuned signal recycling in a large-scale gravitational wave detector, *CQG*, **2007**, *24*, 1513-1523

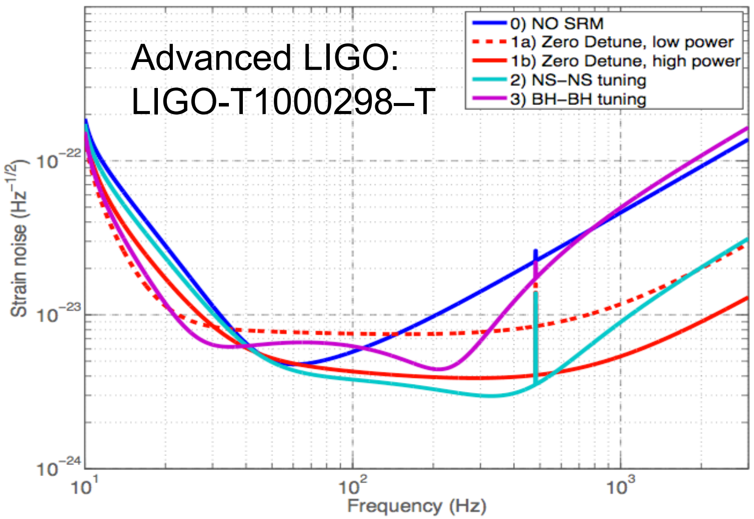
- Combination of heterodyne readout and detuned signal recycling turns out to be disadvantageous !!
- Tuned signal recycling + DC readout also better for squeezed light injection.

See Henning's talk for details on the experience with squeezing in GEO600

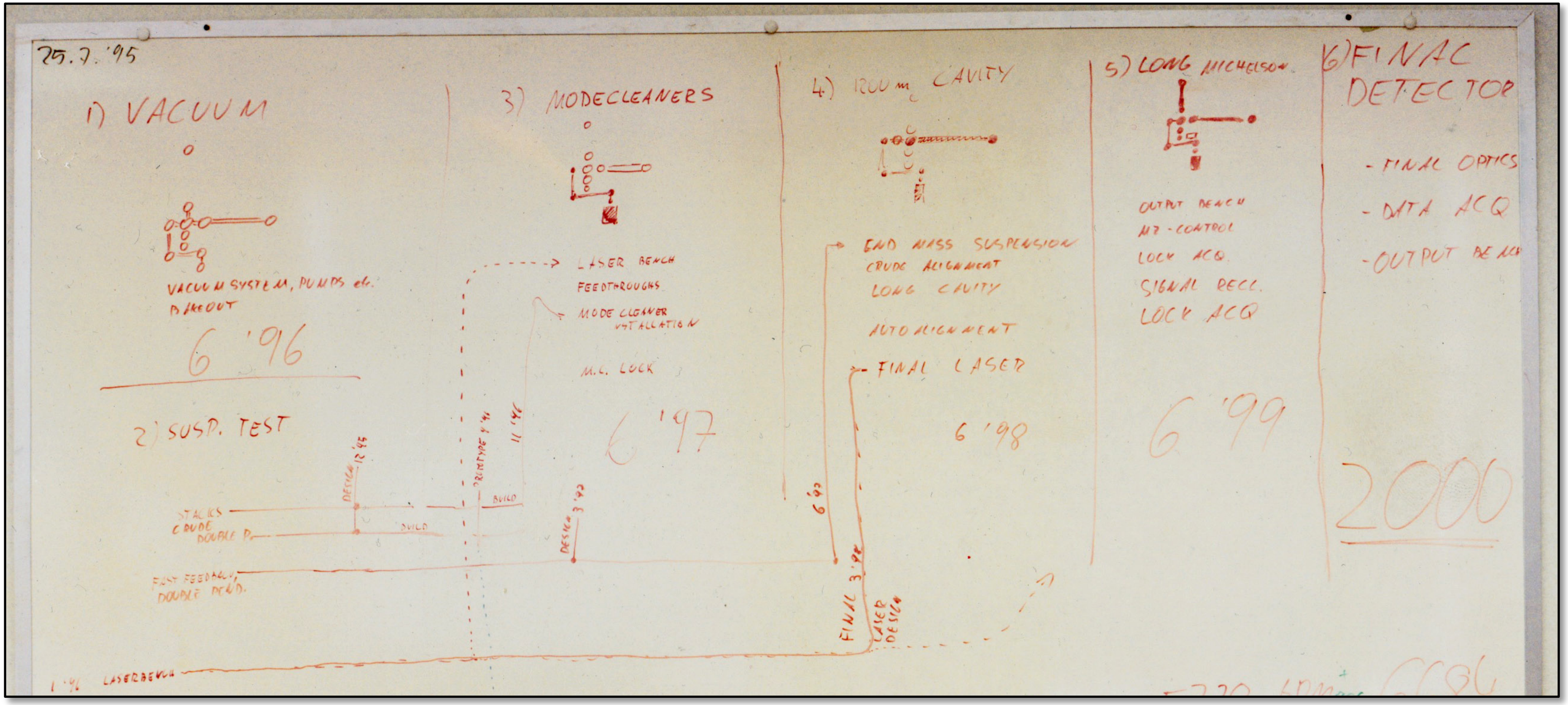
LESSON 9: For every SR tuning you have a different detector

- Signal-Recycling / Resonant Sideband Extraction offer amble possibilities for adjusting and shaping quantum noise.
- Every change of the Signal recycling configuration will mean that you have to deal with a new detector.
- It is easy to change the SR tuning within a few second. However, it might take weeks to months to understand the 'new' detector from the detector characterisation point of view.





LESSON 10: Thinks tend to take longer than you expect

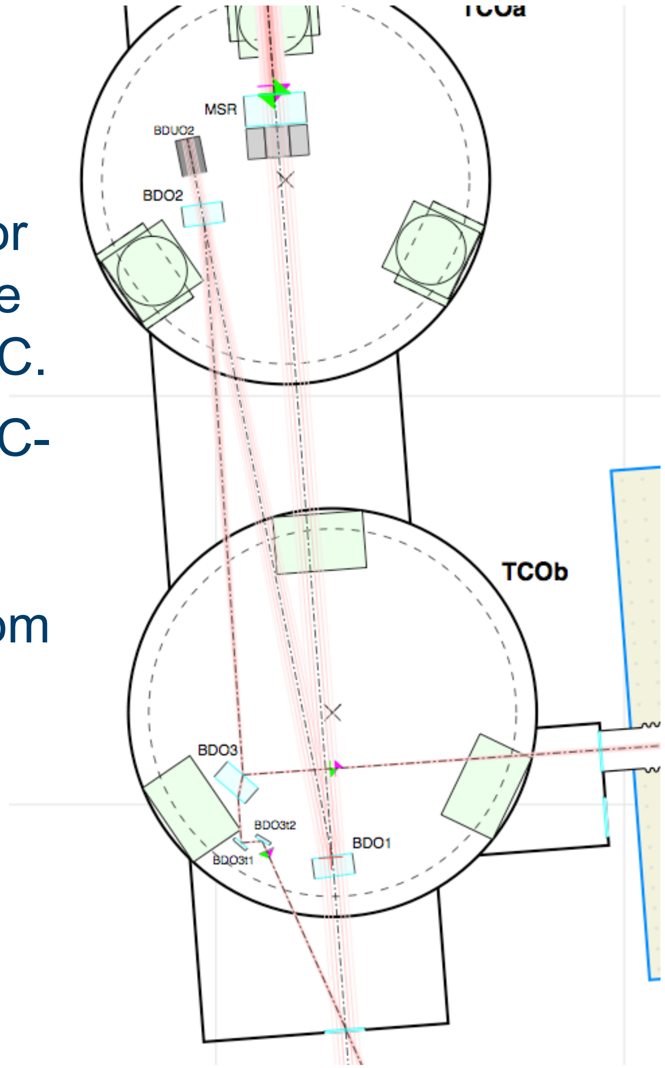


- Signal Recycling in 2003 (just before S3)
- Final power recycling mirror (T=0.0009) in spring 2005 (after S4).

E N D

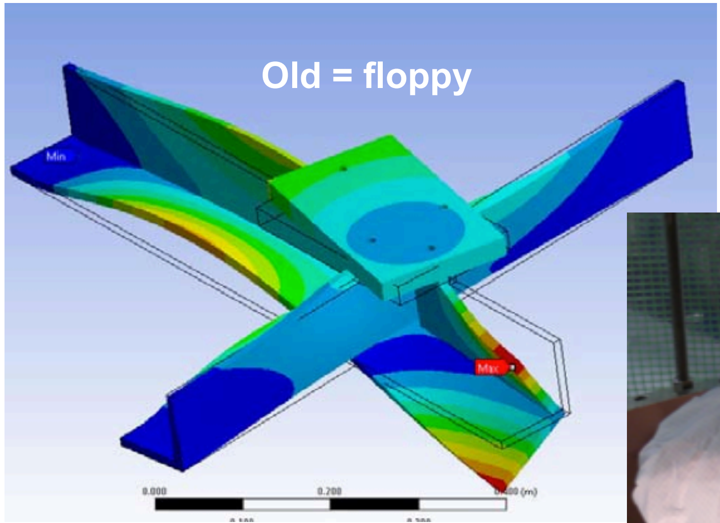
Beam jitter coupling into GW channel

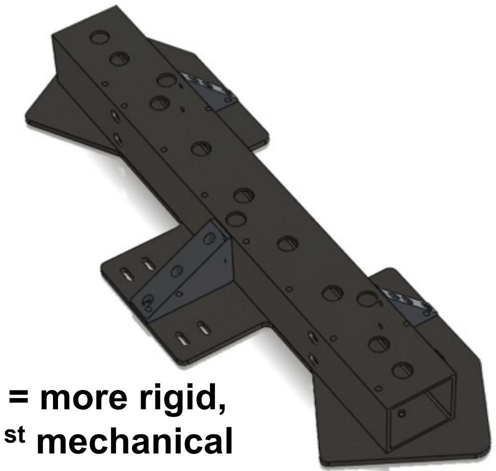
- 3 mirror output telescope.
- Only single pendu-lums as designed for needs of heterodyne readout and no OMC.
- After switching to DC-readout and install-ation of OMC, we saw lots of noise from beamjitter noise.
- Mirror motion dominated by seismically excited violin modes.



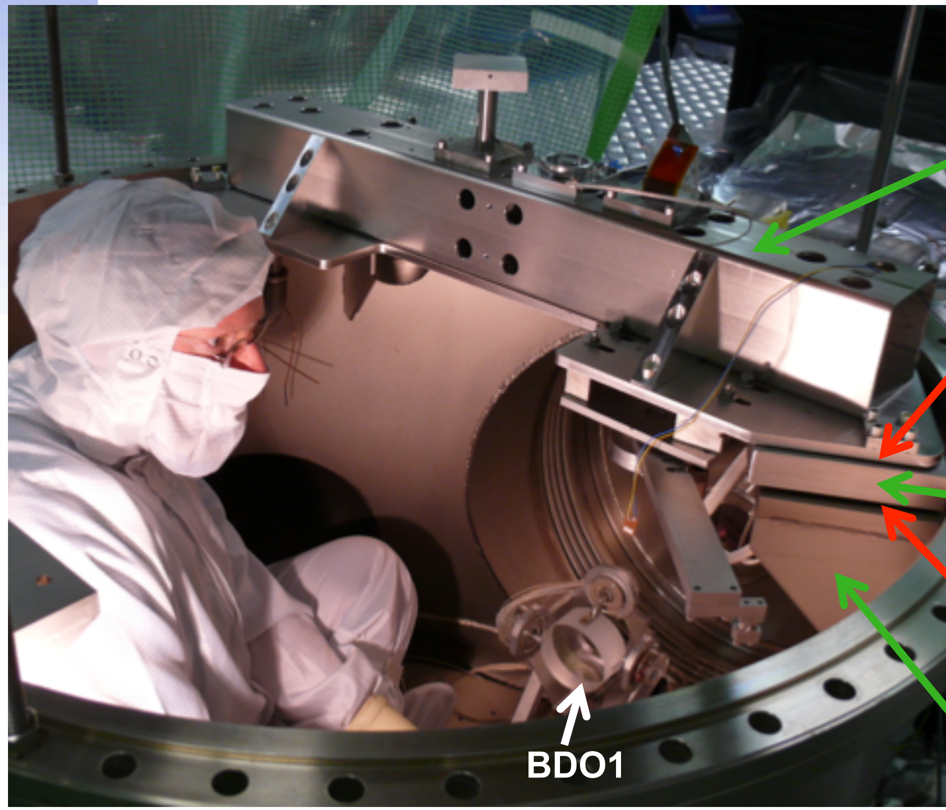
Improvement of seismic isolation of the output telescope

Old: Single pendulum + blade stage.
New: 2 additional Fluorel stages (vertical resonance 10-20Hz)

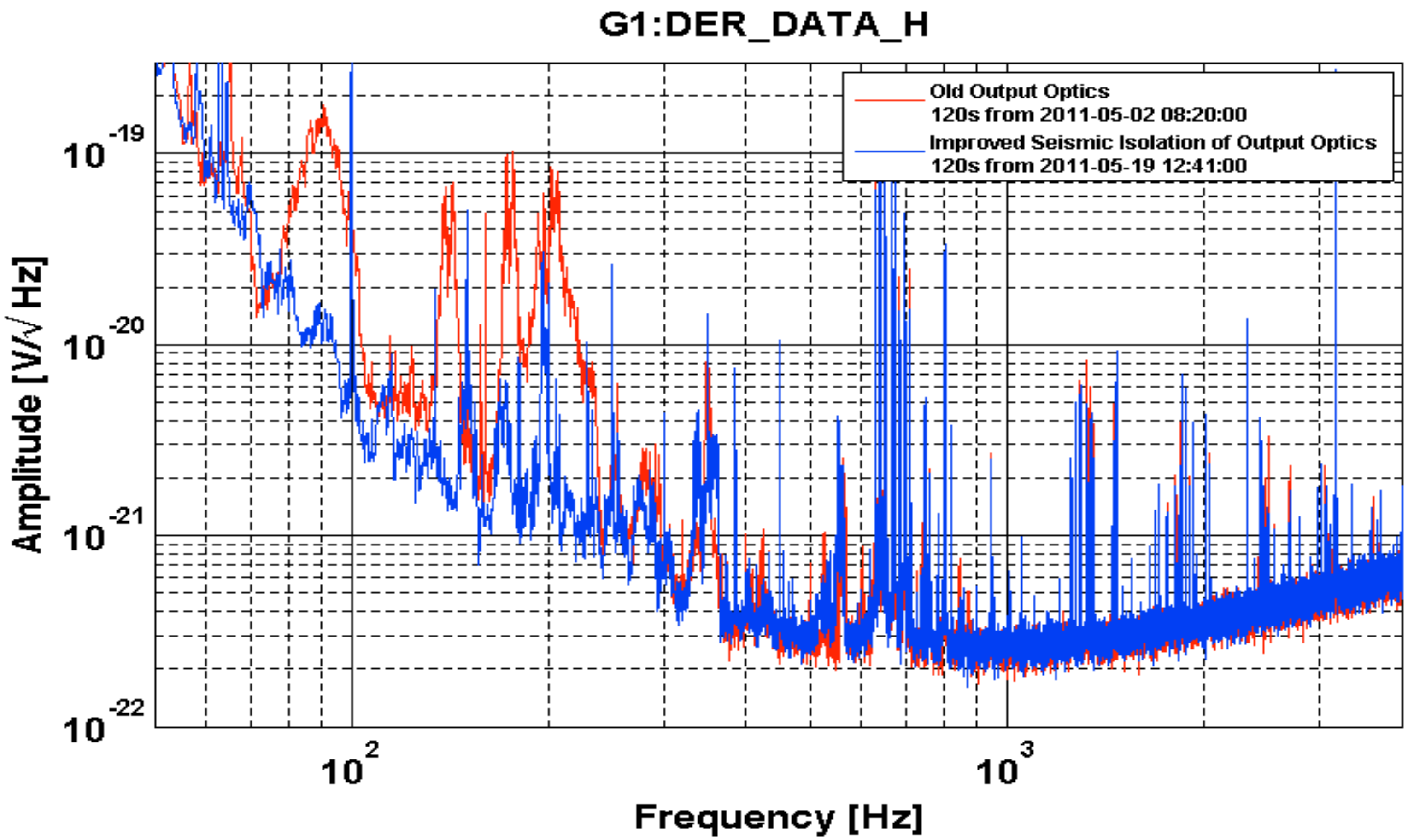




New = more rigid, i.e. 1^{st} mechanical resonance at 500Hz

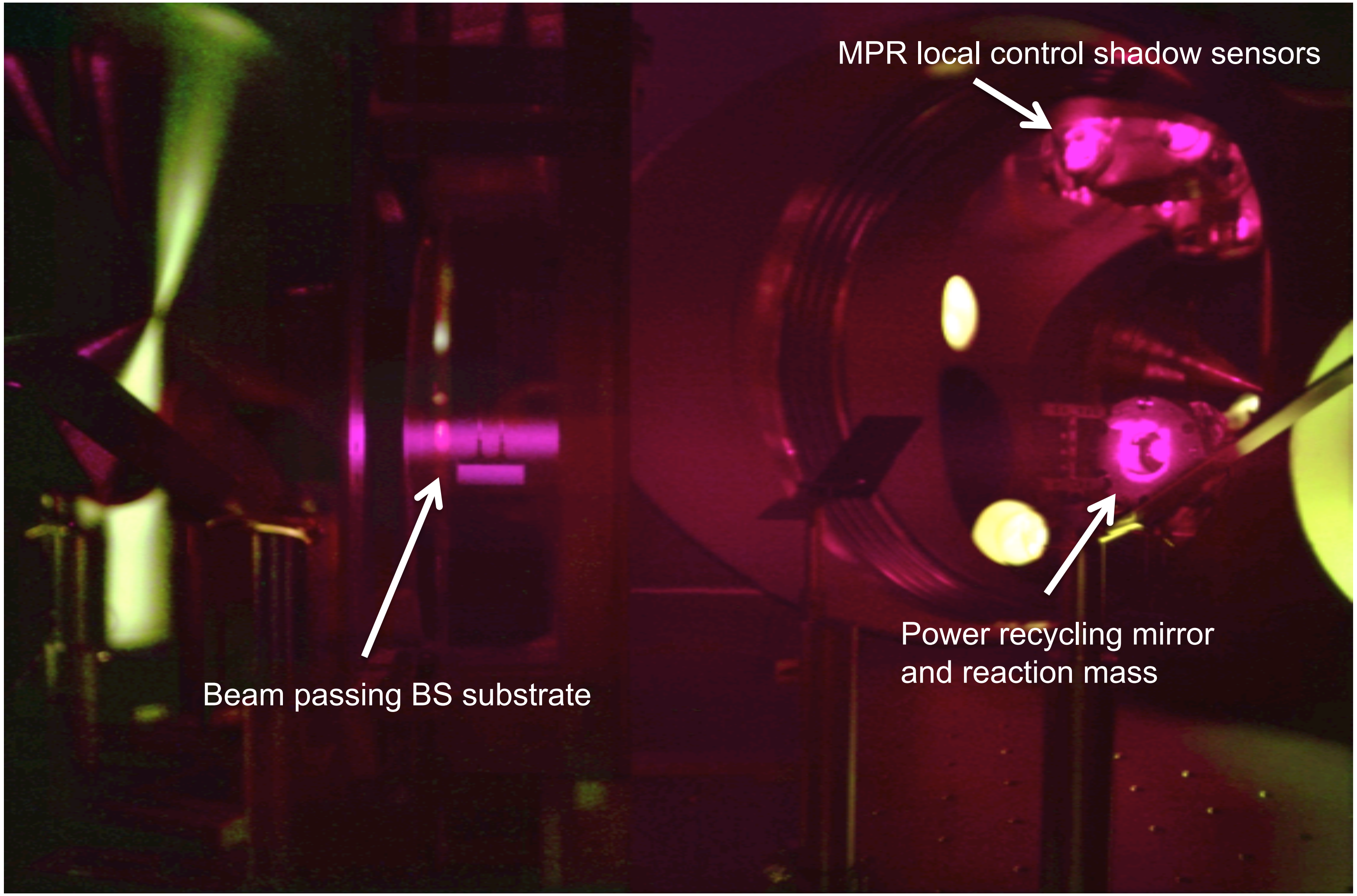


Recent sensitivity improvements from improved seismic isolation of the output telescope



- Please note: Both traces without squeezing and not at full power. Above 1kHz the S6e sensitivity will be about a factor sqrt(2) better

Scattered light inside the GEO central cluster

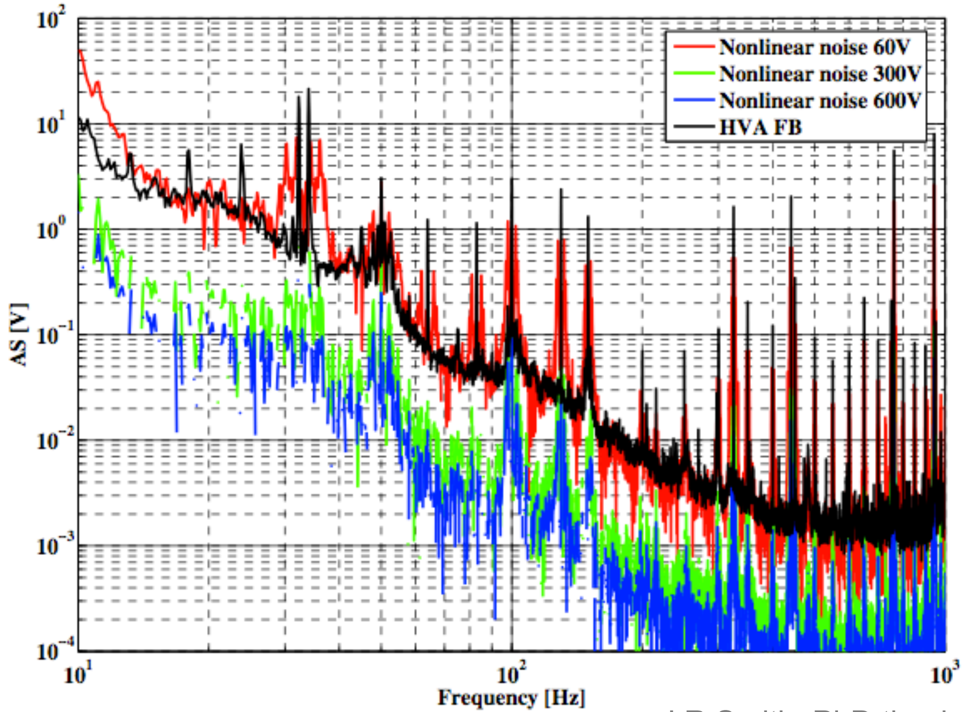
- 

ESD details 2: Non-linearity

- We use the ESDs with a large bias voltage to allow for a the creation of a bi-polar actuation:

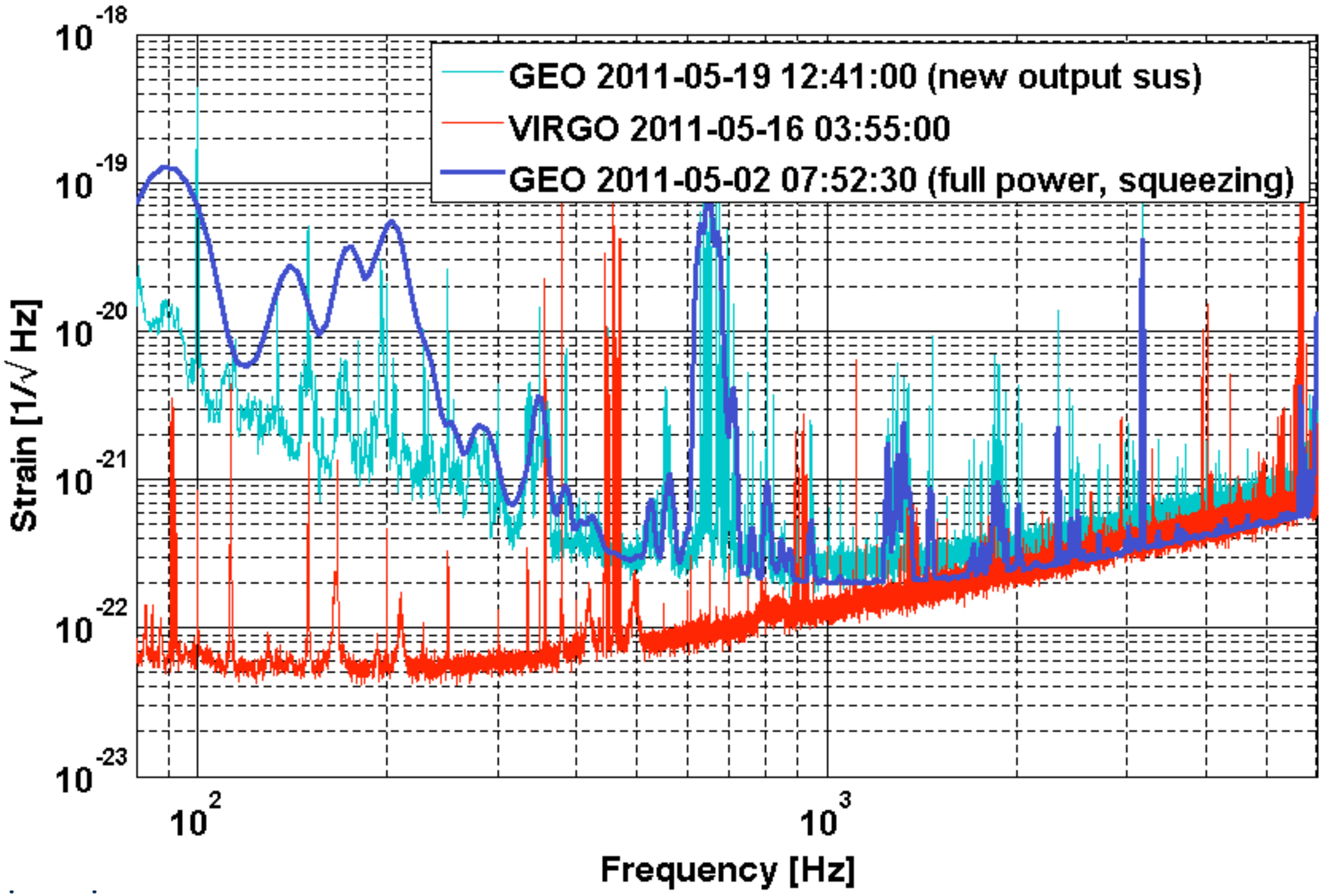
$$x(\omega) = \frac{A'}{\omega_0^2}(V_{\text{bias}} + V_0 \cos\omega_0)^2,$$

$$= \frac{A'}{\omega_0^2}\left(V_{\text{bias}}^2 + 2V_{\text{bias}}V_0\cos\omega_0 + \frac{V_0^2}{2}(1+\cos 2\omega_0)\right),$$



J.R.Smith: PhD thesis

VIRGO – GEO comparison



Preliminary Noise Projections