Charging experiences in the GEO project and investigations of mitigation techniques

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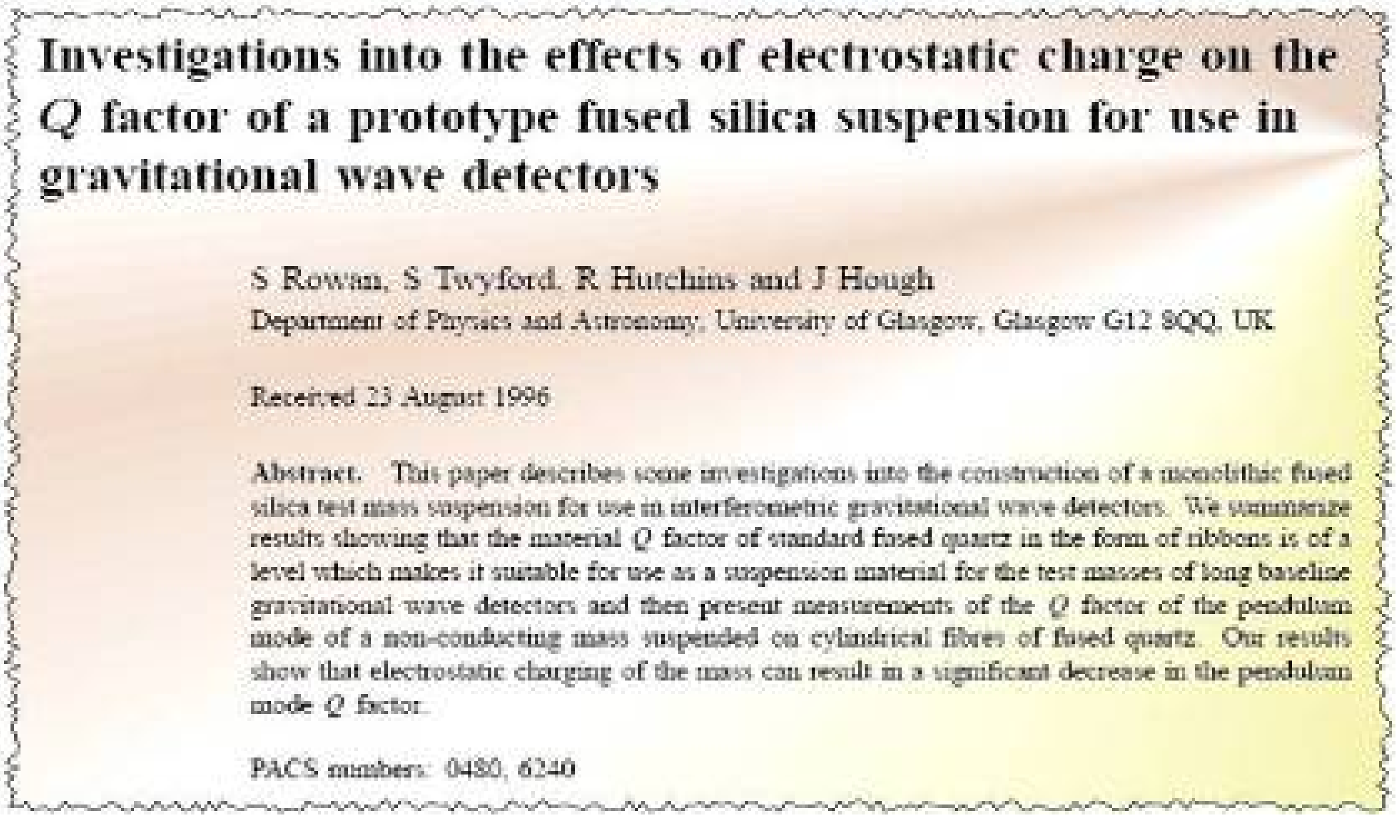
Overview – the effect of charging

- Electrostatic charging of the mirrors and suspensions in GW detectors can lead to several potential problems:
  - Electrostatic damping resulting from induced currents – this may lead to excess thermal noise
  - Control issues due to forces between mirrors and nearby surrounding objects (electrostatic actuators, earthquake stops etc)
  - Calibration issues – charging of the test masses can change parameters during calibration
  - Charge fluctuation noise (hopping/migration?)

- Experiments have suggested that potential excess thermal noise may result from charging, e.g.
  - S. Rowan, S. Twyford, R. Hutchins and J. Hough, CQG **14** (1997) 1537–1541.
  - M.J. Mortonson, C.C. Vassiliou, D.J. Ottaway, D.H. Shoemaker, G.M. Harry, RSI, **74** (2003) 4840-4845.
  - V. Mitrofanov, L. Prokhorov, K. Tokmakov and P. Willems, CQG **21** (2004) S1083–S1089.
  - D. Ugolini, R. Amin, G. Harry, J. Hough, I. Martin, V. Mitrofanov, S. Reid, S. Rowan, K-X. Sun, LIGO DCC P070068-00-Z, 2007.

Example 1 – effect of charge on a pendulum suspended on fused silica fibres

- Experiments in Glasgow observed evidence of a Macor pendulum under vacuum being charged



Investigations into the effects of electrostatic charge on the *Q* factor of a prototype fused silica suspension for use in gravitational wave detectors

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Abstract. This paper describes some investigations into the construction of a monolithic fused silica test mass suspension for use in interferometric gravitational wave detectors. We summarize results showing that the material *Q* factor of standard fused quartz in the form of ribbons is of a level which makes it suitable for use as a suspension material for the test masses of long baseline gravitational wave detectors and then present measurements of the *Q* factor of the pendulum mode of a non-conducting mass suspended on cylindrical fibres of fused quartz. Our results show that electrostatic charging of the mass can result in a significant decrease in the pendulum mode *Q* factor.

PACS numbers: 0480, 6240

S. Rowan et al., CQG, **14**, 1537–1541, (1997).

Reminder - effect of charge on a pendulum suspended on fused silica fibres

- Initial experiments showed the amplitude of the pendulum motion did not decay exponentially. Instead the rate of decay of the amplitude increased with time,

  i.e. the *Q* of the pendulum appeared to get worse with time, changing from a few times 10^6 to a few times 10^4.

- It was then noted that a bare wire inside the vacuum tank connected to a vacuum feedthrough was acting as an aerial and was picking up a signal at the pendulum frequency.

- This suggested that the pendulum was being charged during the expt and that this moving charge was inducing currents in the surroundings and resulting in excess dissipation

S. Rowan et al., CQG, **14**, 1537-1541, (1997).

Reminder - effect of charge on a pendulum suspended on fused silica fibres

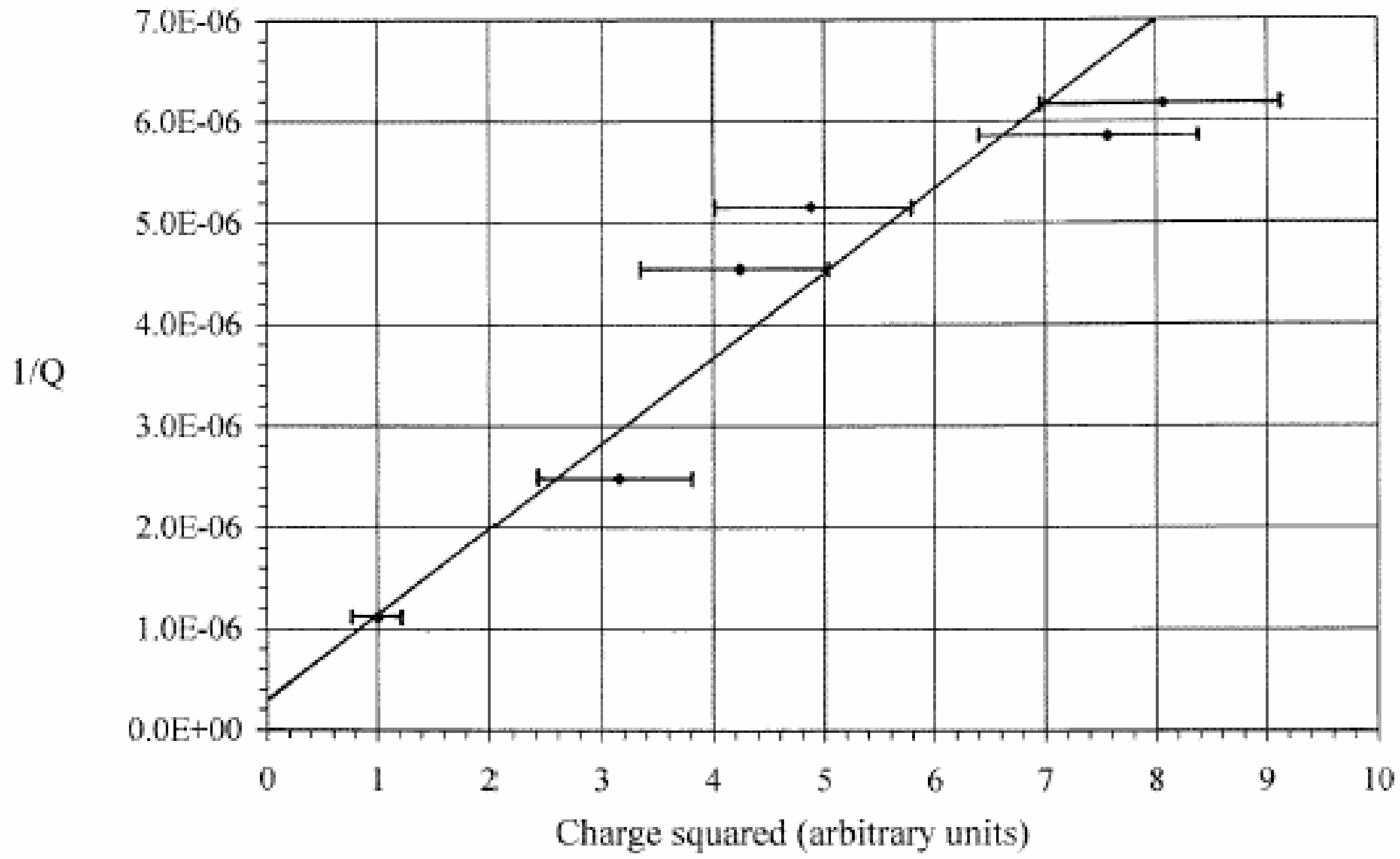


Figure 2. Variation of $1/Q$ for the pendulum mode of a 200 g mass suspended on fused quartz fibres as a function of the square of the electrostatic charge on the pendulum.

Reminder - effect of charge on a pendulum suspended on fused silica fibres

- Further investigations suggested that the pendulum was negatively charged and that an ion pump being used to evacuate the system was producing ultraviolet (UV) radiation which was liberating electrons from the walls of, and structure inside, the vacuum tank. These electrons then collected on the pendulum leaving it negatively charged.

- It was also found that the charge on the pendulum, as monitored by the size of the electrical pick-up signal on a piece of wire, could be decreased by directing onto the pendulum light from a UV lamp placed inside the vacuum system.

- (The charge could also be reduced by turning on the ion-gauge on the system which happened to be pointed directly at the pendulum)

S. Rowan et al., CQG, **14**, 1537–1541, (1997).

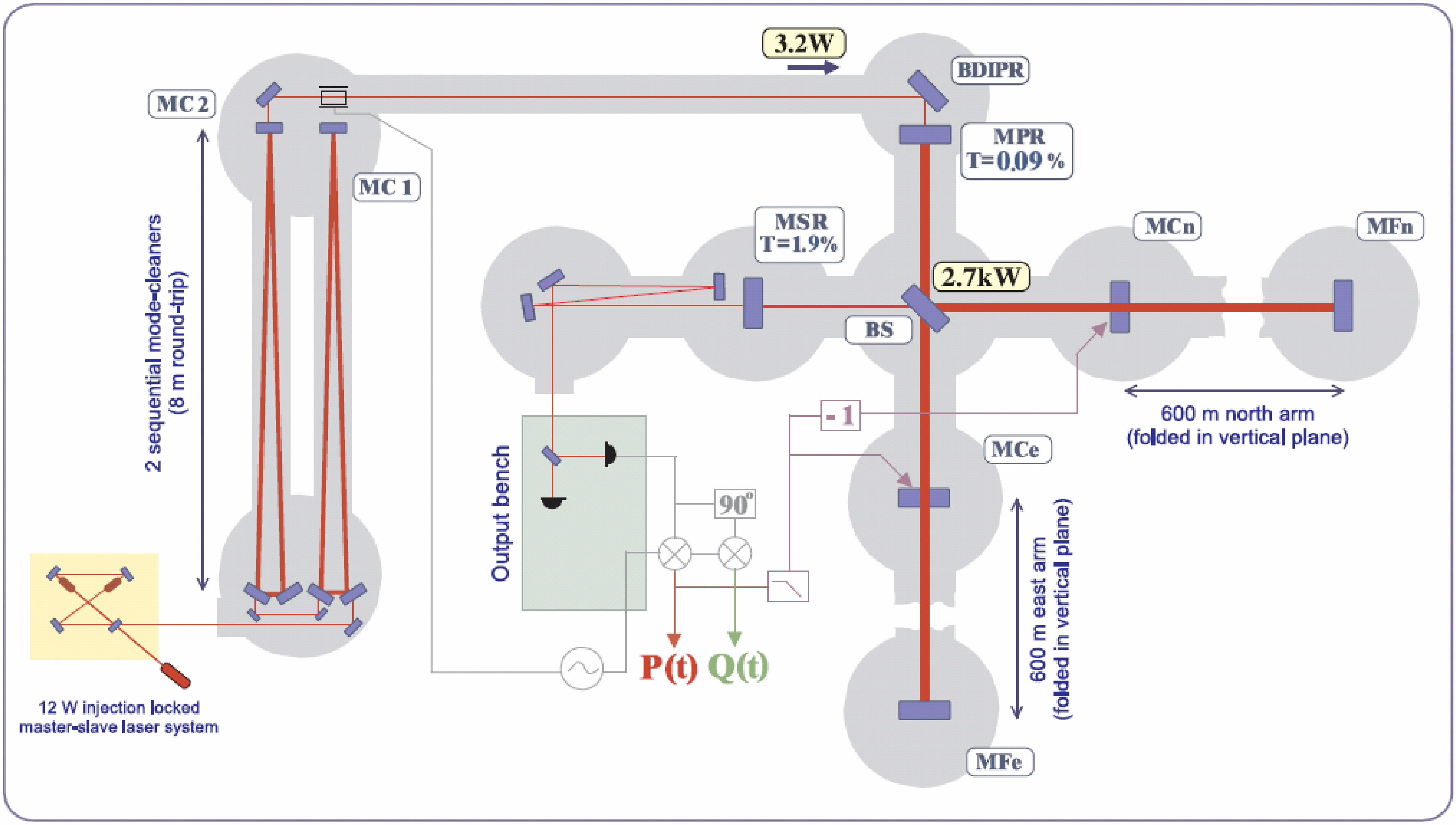
Example 2 -Recent effects of charging in GEO

“Charge measurement and mitigation for the main test-masses of the GEO 600 Gravitational Wave Observatory”

M. Hewitson et al

Submitted to the LSC for review

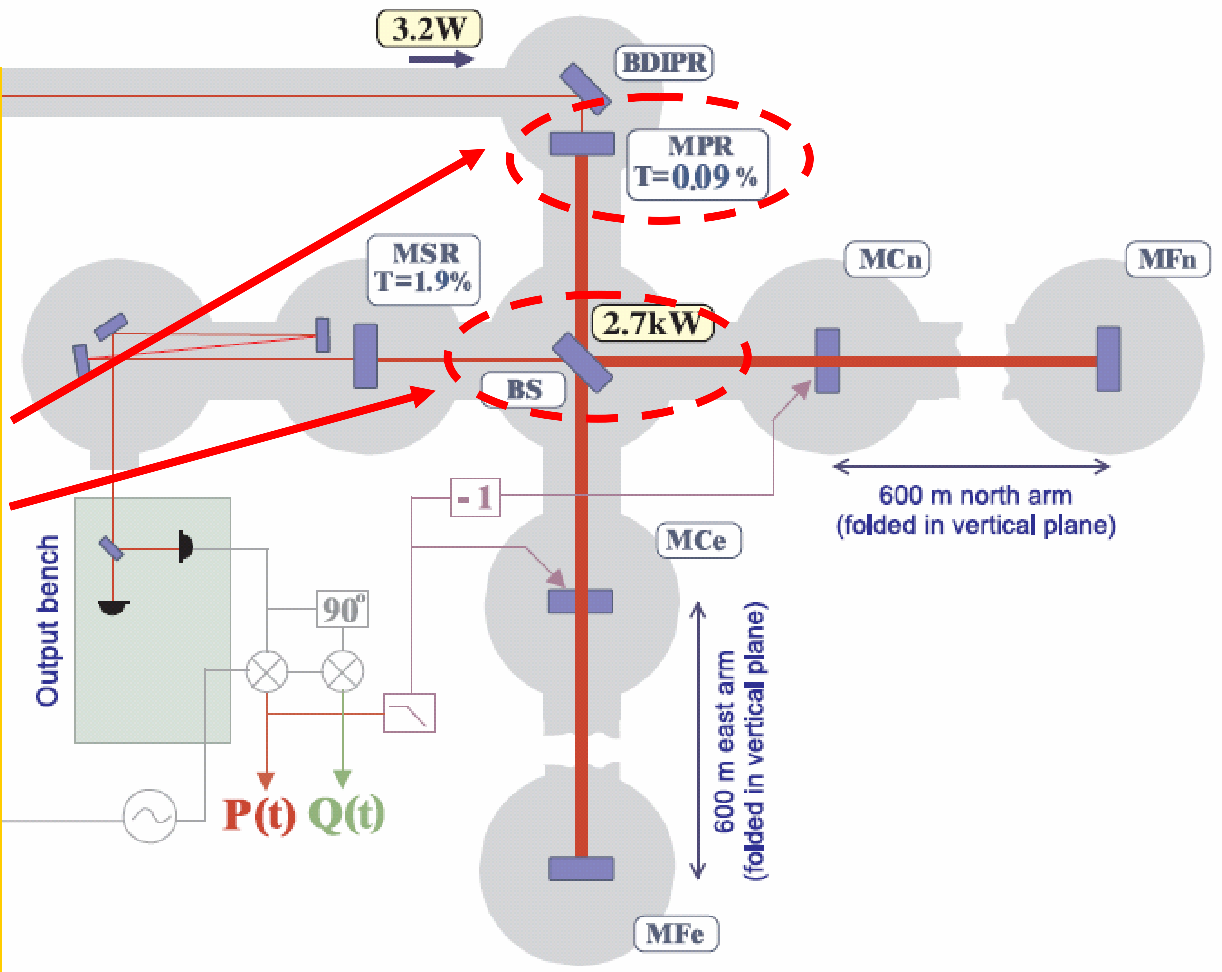
The GEO600 Interferometer



The GEO600 Interferometer

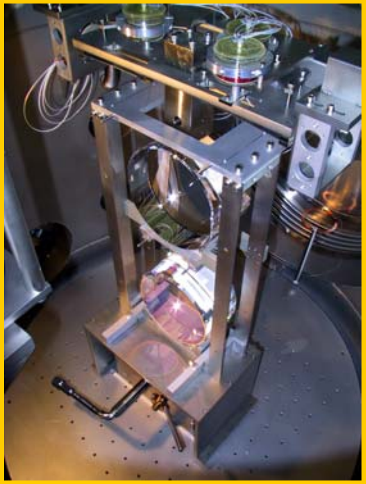
No arm cavities, but folded arms:

- **High PR factor (~1000)**
- **High power in BS substrate (~kW)**
- **Very low absorption of BS substrate (< 0.25 ppm/cm)**

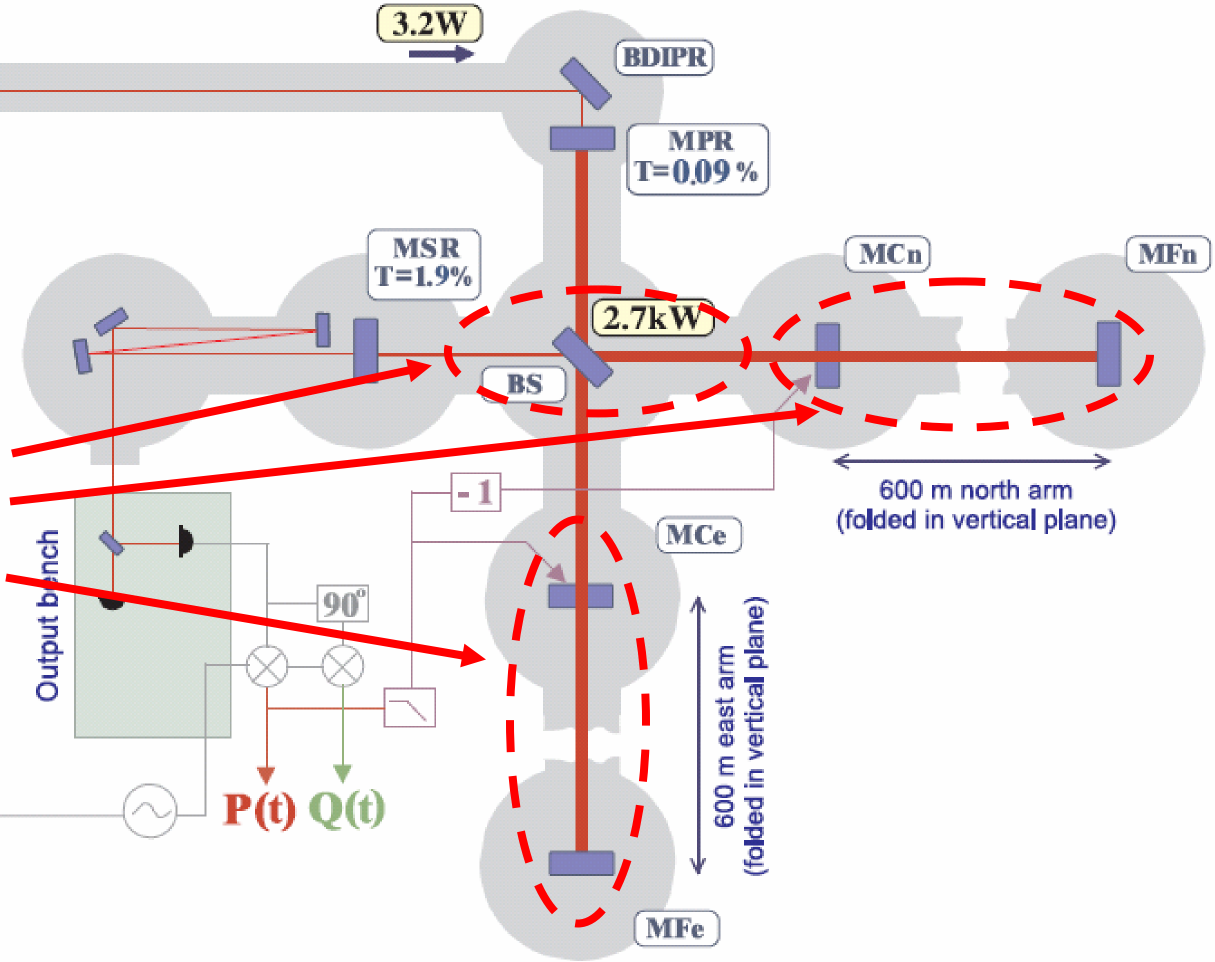


The GEO600 Interferometer

Triple suspensions:



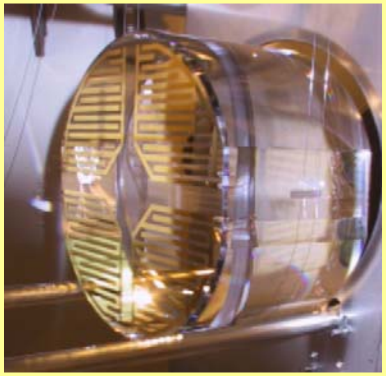
- **Monolithic stages**
- **Split-feedback (3 stage hierachical control)**

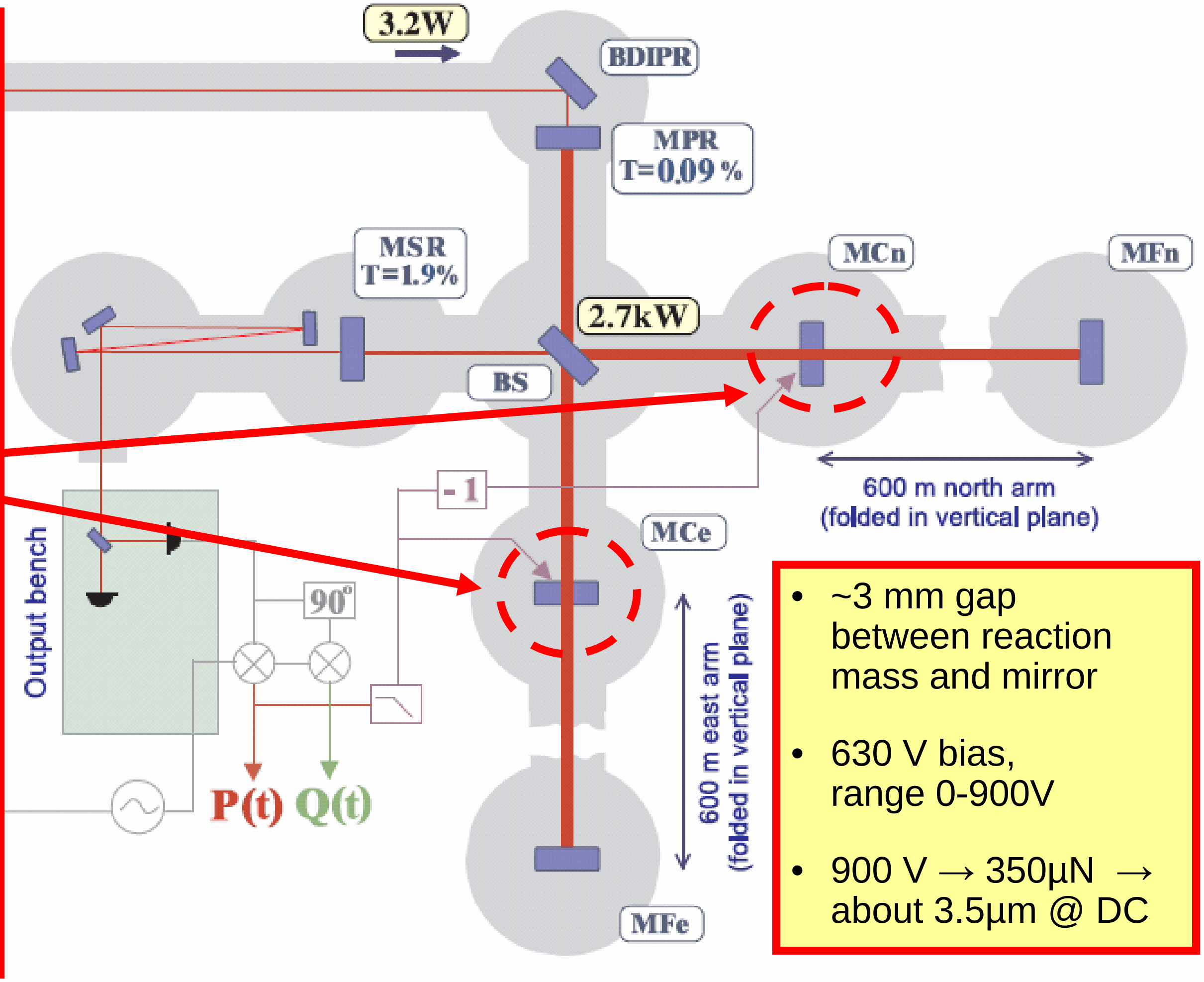


The GEO600 Interferometer

Electro-Static Drives:

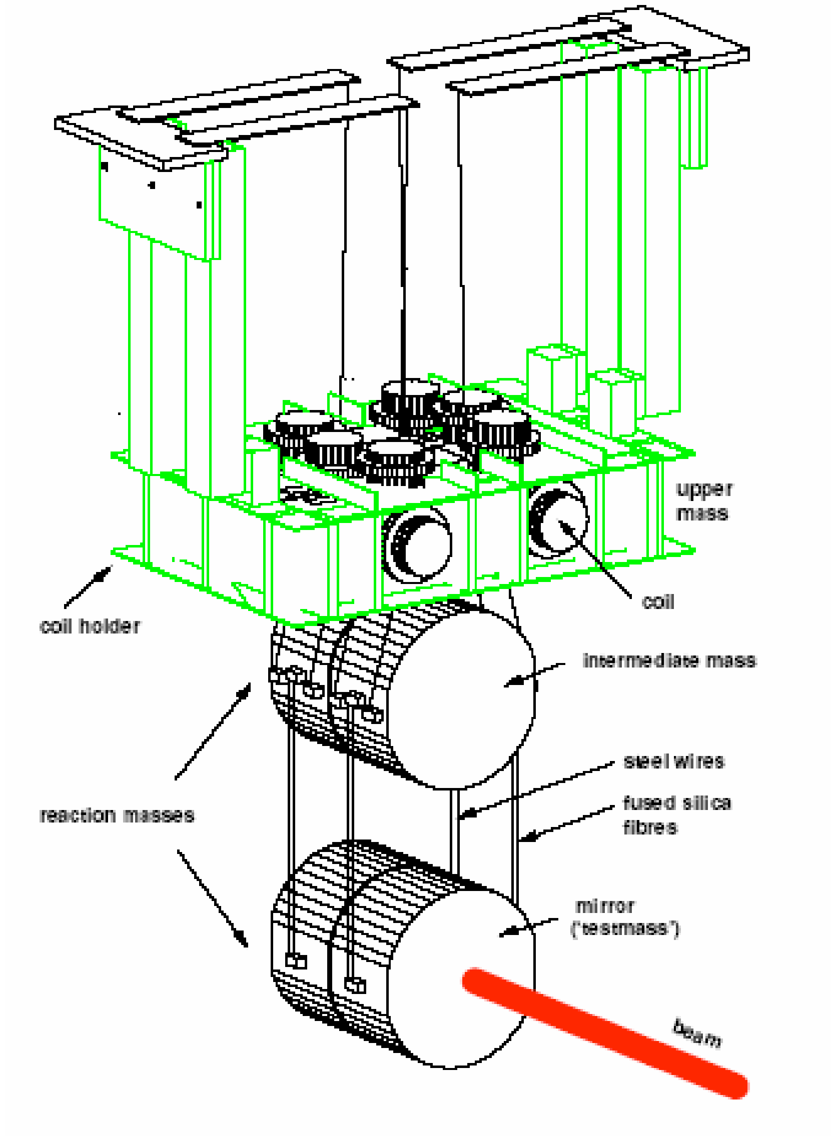
- **Used for fast control of differential armlength**





- ~3 mm gap between reaction mass and mirror
- 630 V bias, range 0-900V
- 900 V → 350µN → about 3.5µm @ DC

Charging effects in suspension systems



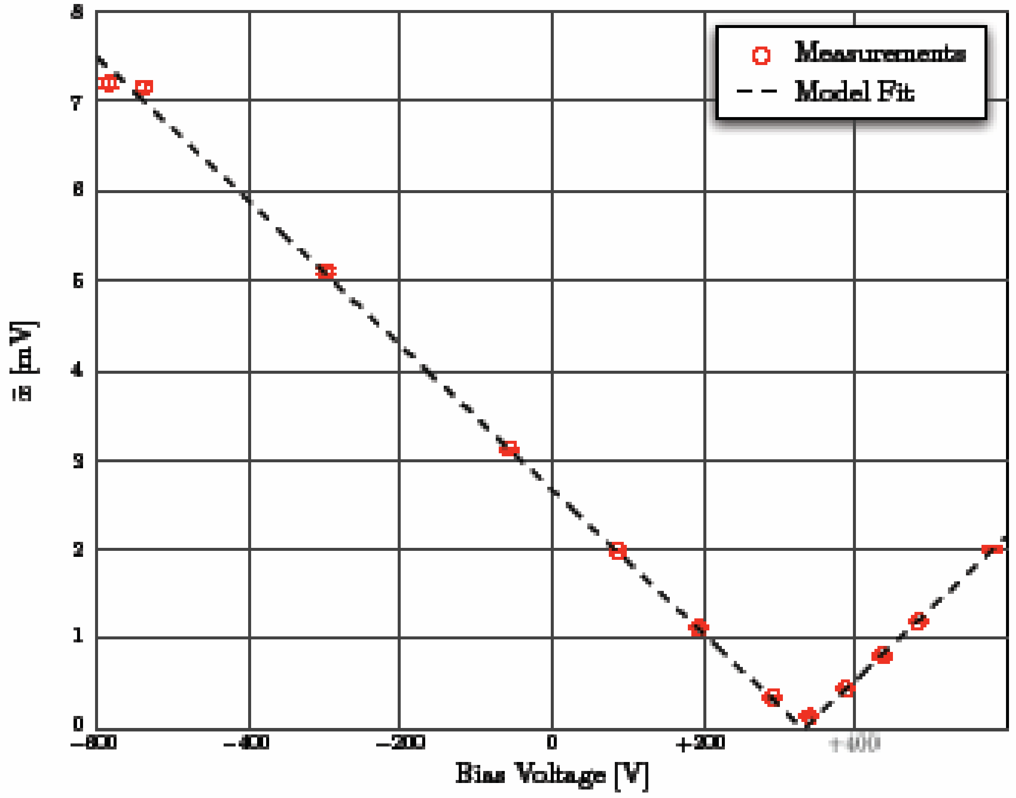
- There are various mechanisms by which the test-masses can become charged:
  - venting and evacuation of the vacuum chambers (friction)
  - the test-mass making electrical contact with the reaction-mass when the electrodes are held at their nominal bias voltage
  - accumulating charge from cosmic-ray interactions.
- Having charged-up test-masses can affect noise but also has a strong effect on the strength of electrostatic actuators eg
  - change in the gain of the Michelson longitudinal servo
  - change to the absolute calibration of the main GW output which assumes constancy of the ESD strength over periods of several months

GEO

- During early December of 2006, a power cut at GEO 600 left the pendulums supporting the main test masses un-damped, but with the bias voltage still supplied to the ESDs.
- After the power-cut, locking was not possible with normal parameters
- The strength of the ESDs was significantly reduced

Charging effect observed through ESD behaviour

- The effective bias, V_{eff} , due to charges on the test-mass is given by the bias voltage needed to produce zero displacement from the ESDs



Measurement of the East test-mass charge-state after the powercut.

This measurement was made on 12 December 2006.

Effective bias due to charges of around +333V.

Discharging methods

Venting: For a -vely charged component - venting with a gas of significant electron affinity, eg oxygen (in air).

For a +vely charged component - use a gas mixture, such as air, where there are already negatively charged ions present. Alternatively, a gas of negative electron affinity, eg Argon, may be tried.

UV illumination: UV light of suitable wavelength can be used to remove electrons from the surface of a dielectric component thus removing excess negative charge. Alternatively the light can be shone on to a metal target near the mass and any positive charge on the mass can be neutralised by photoelectrons released from the metal. This method is employed in many experiments.

Electrical contact: Electrical charge can be removed from a local area of a mass by contact with an earthed conductor. However this method is not very effective for large and delicately suspended or mounted optical components.

Venting with Argon

- Vacuum system was filled with about 1 mbar of Argon with the ESDs switched off
- Hope was that at pressures around 1 mbar the electrical field of the charges present would sustain a short-duration glow-discharge, removing the charges from the mirror surface.
- Evacuate and re-measure charge state – no difference

Venting and installation of fused silica viewport

- Central cluster opened for planned commissioning work (21 February 2007)
- Simultaneously fused silica viewports installed to allow illumination of test masses by an external UV source
- Charge state re-measured (7 March 2007)

- Find effective bias due to charges of around +148V

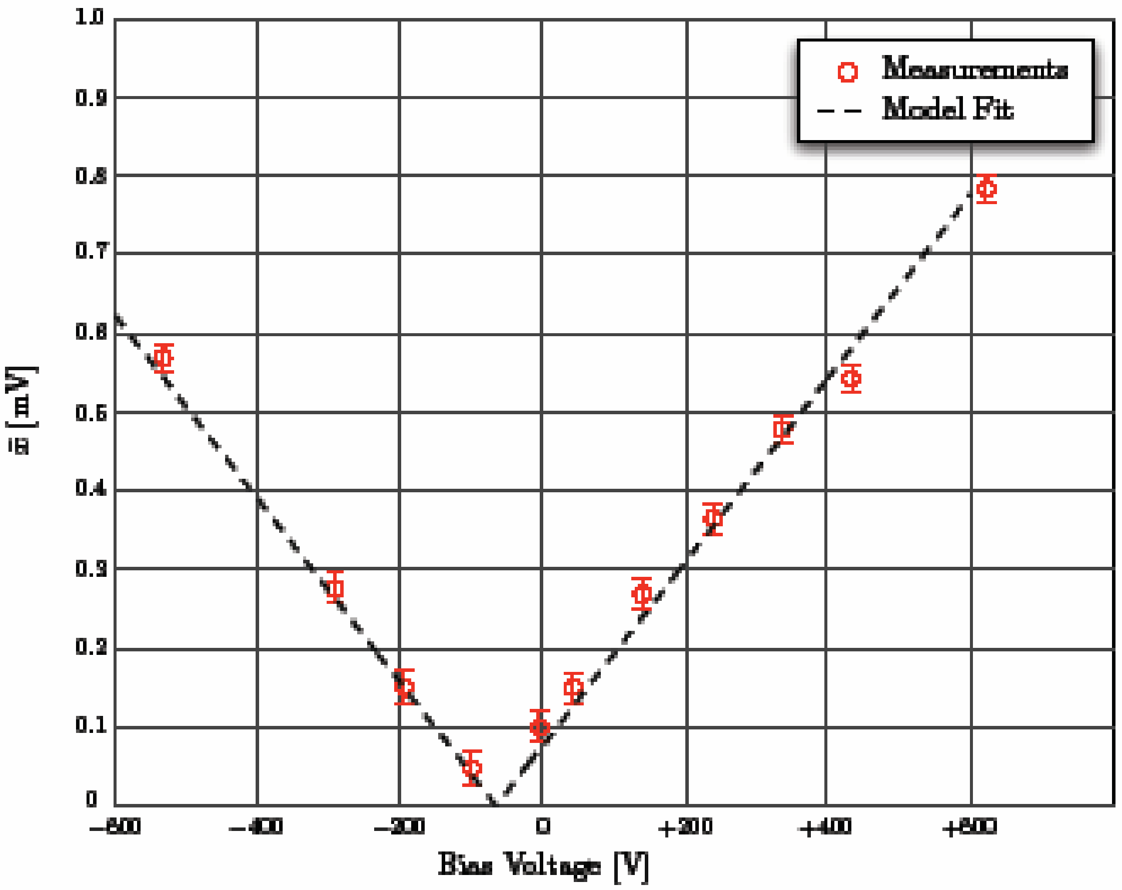
- Either the test-mass was not fully discharged while being in air (room temperature around 20 C, relative humidity of about 20%), or (more probably) the test-mass was charged again during the evacuation process.

Effect of UV illumination

- UV source (Heraeus Noblelight: NK6-12, Mercury lamp with 800mW output at 253.7 nm) then used to illuminate the East test-mass.

- Charge-state was measured for the East test-mass after one night (around 15 hours) of UV illumination

- The effective bias has gone from +148V to -66V

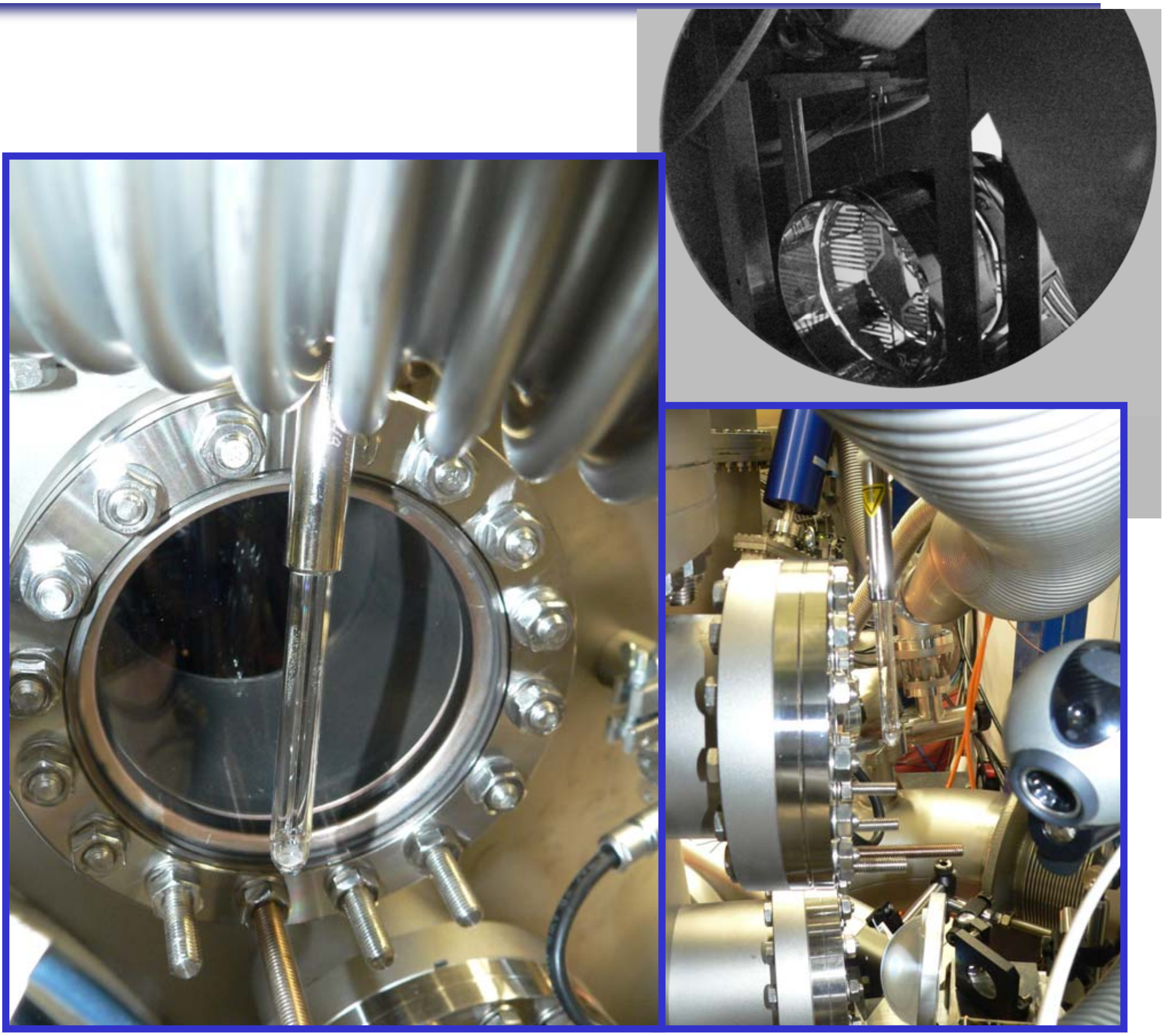


Discharging test mass in situ by UV light

Discharging by use of UV light to free electrons.

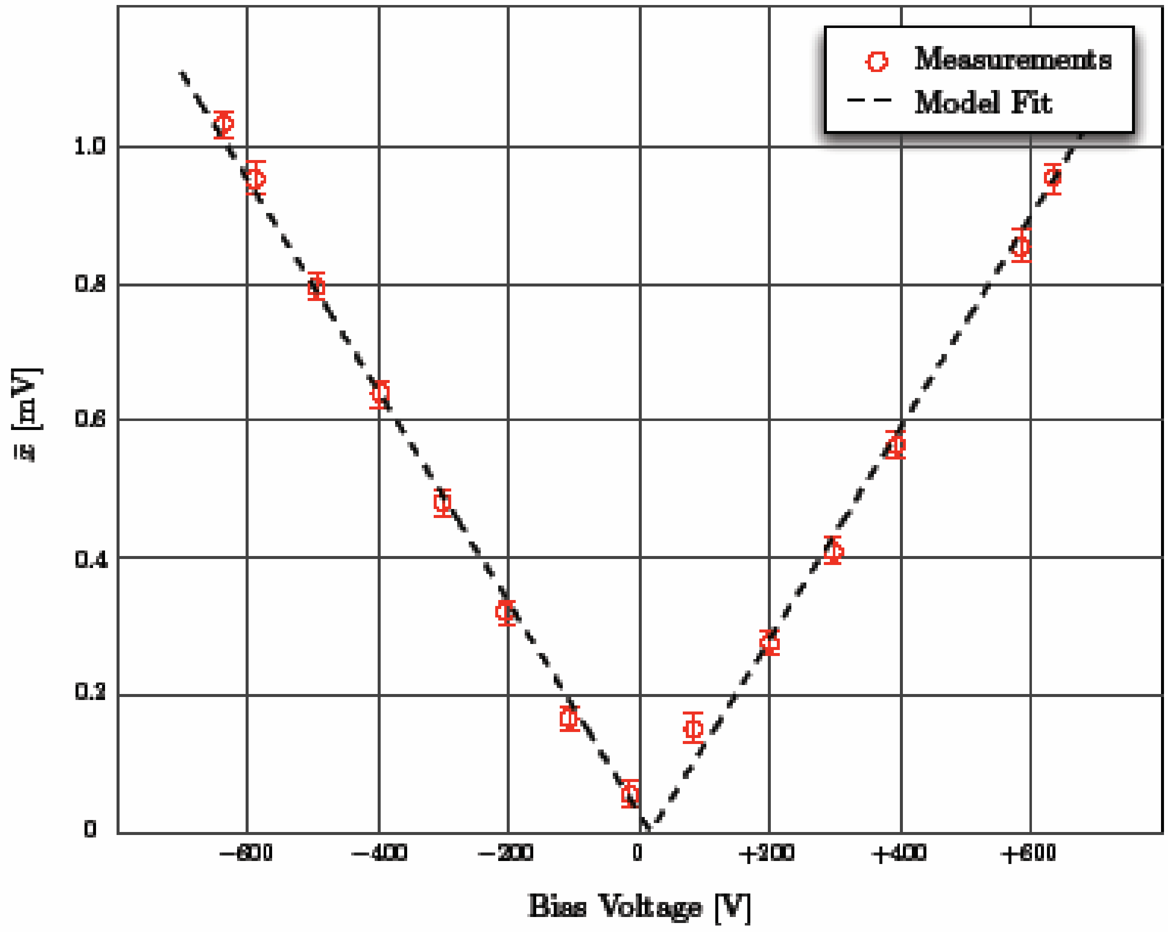
In our case:

- **UV transmitted through test mass**
- **deduce electrons are freed from the ESD electrodes**
- **electrons compensate positive charge on test mass**



UV illumination with bias voltage on

- Aim to get an effective bias voltage due to charging close to zero Volts.
- Bias voltage set to +200V whilst UV illumination on



Deduce that liberated electrons from the surface of the test mass and these have migrated to the appropriate electrode of the electrostatic drive under the applied electric field.

Other methods for charge mitigation under investigation in Glasgow

Doping of silica substrates:

- Initial tests have been carried out to lithiate silica surfaces by treatment with lithium hydroxide.
- Small increase currently observed in the surface conductivity, but with apparent surface damage, and we will investigate whether increased lithium ion activation is required to increase surface charge migration effects without damage and thus increase electrical conductivity.
- We plan to return to high temperature baking of silica in a lithium environment and investigate other doping materials.

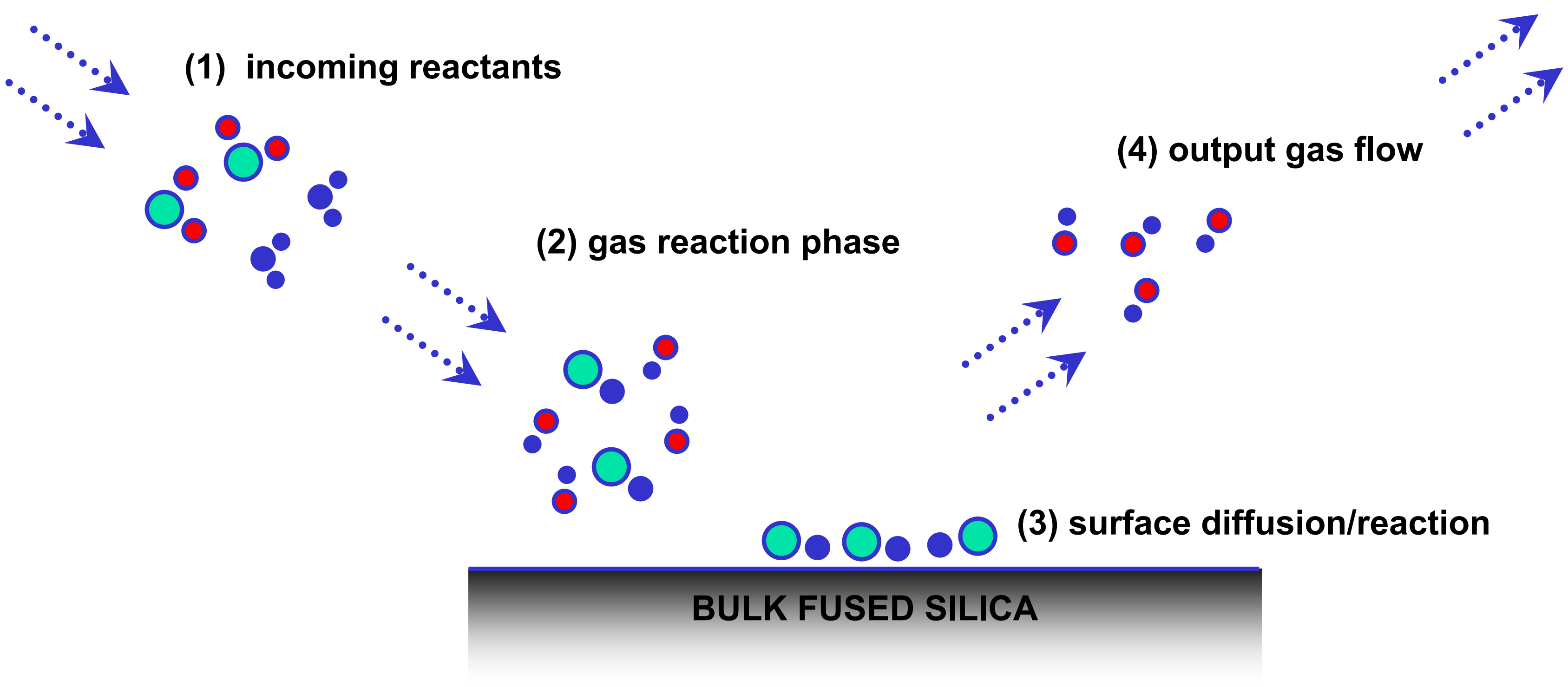
Conductive coatings of Tin Oxide deposited on silica substrates:

- Initial experiments carried out using the spray pyrolysis deposition method.
- Well known, successful method for conductive oxide coatings.

Deposition of conductive oxide coatings on silica substrates

- Deposited tin oxide coating formed through the reaction:

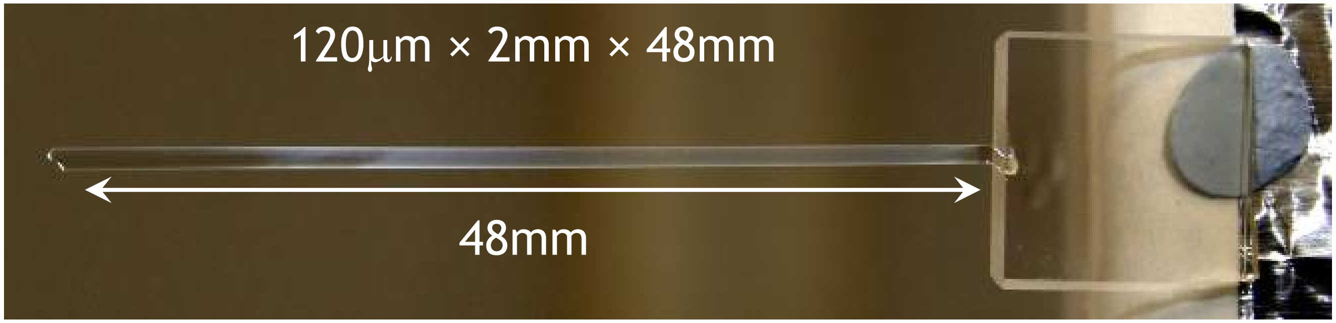
$$\mathrm{SnCl_2 + H_2O \rightarrow SnO + 2HCl}$$



Coating procedure

- Fused silica cantilevers were fabricated by flame pulling a Heraeus Suprasil 3 polished slide.
- CO_2 welded to 1mm thick fused silica clamping block.
- Coating deposited by pulsed spray pyrolysis using methanol solution of tin (II) chloride as precursor at 600°C

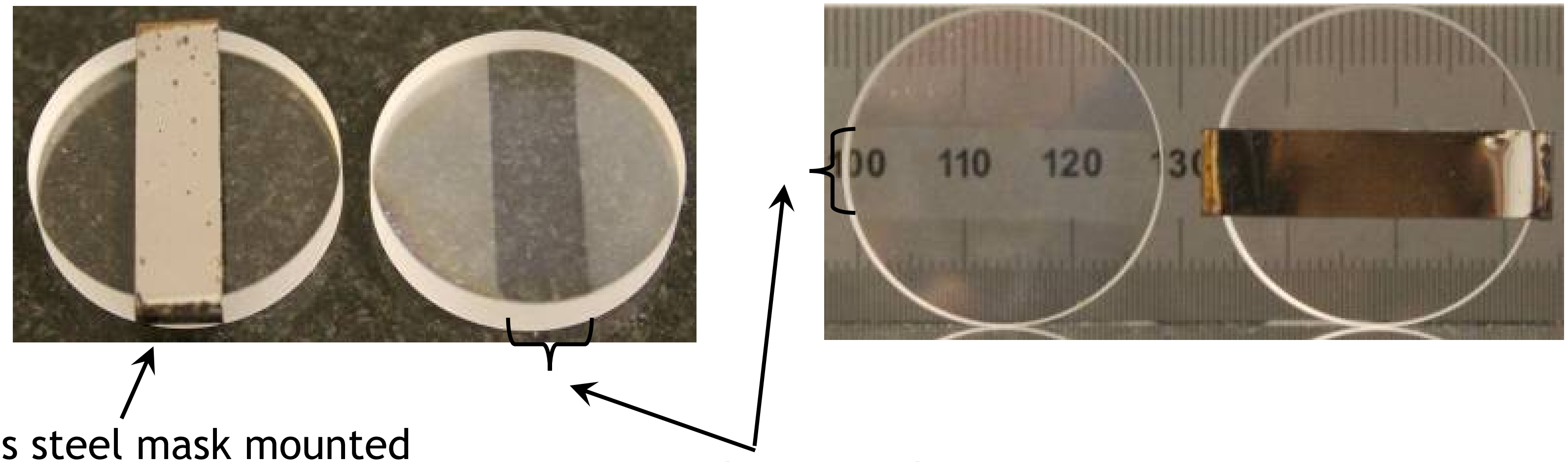
- Faint whitening was observed over approximately ¾ of the cantilever perhaps due to silica vapour deposition during welding. This effect only became apparent after SnO coating.



SnO coated SiO_2 cantilever
(illuminated to highlight whitening)

SnO coating characterisation - 1

- The coating thicknesses were directly measured from witness samples placed alongside the cantilever during coating. Measurements were taken using a Talysurf stylus profiler.
- Variations in coating thickness across the surface of these 1” samples was observed to be within the range of ±10%.



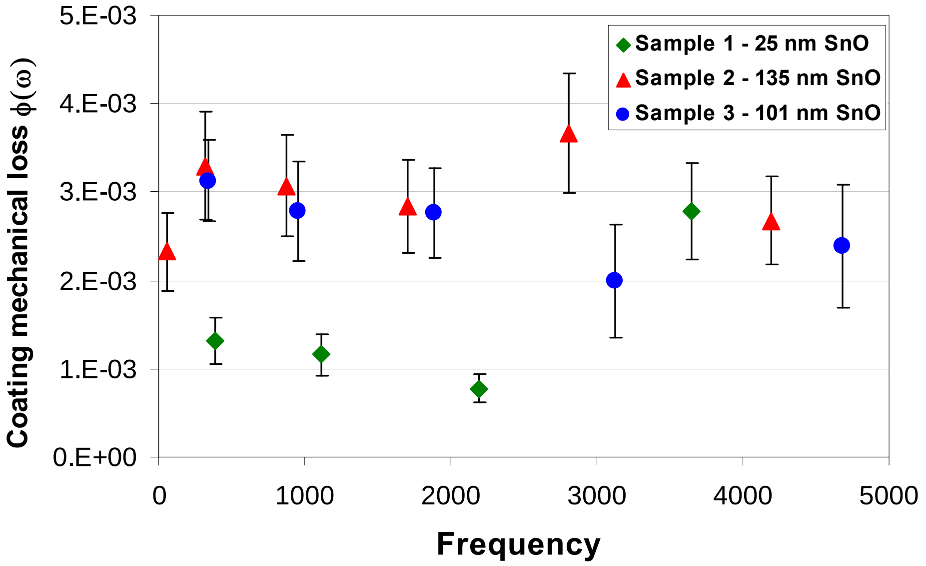
stainless steel mask mounted
prior to coating

central uncoated region

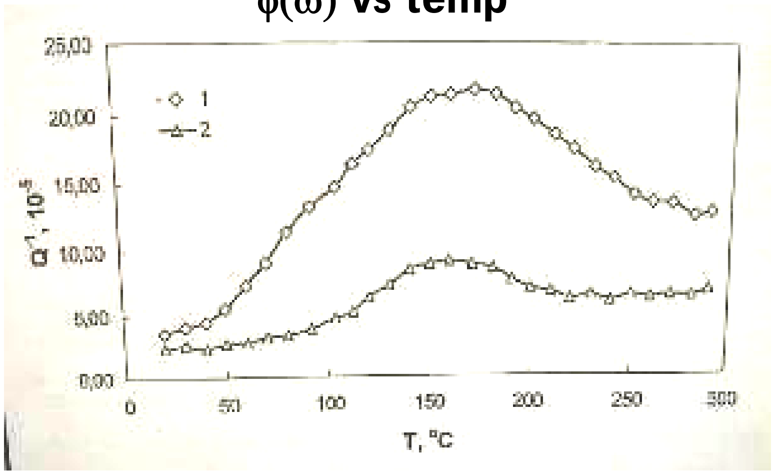
SnO coating characterisation - 2

- The mechanical loss was measured before and after coating for 4 resonant bending modes.

$\phi(\omega)$ **vs freq**



$\phi(\omega)$ **vs temp**



Mitrokhin et al., $\phi(\omega)_{\text{SnO-Hydrolysis}} = 2.5 \times 10^{-3}$,

$\phi(\omega)_{\text{SnO-Magnetron-Sput}} = 3.6 \times 10^{-3}$

over the frequency range 5-20kHz.

- Measuring the mechanical loss associated with conductive coatings will allow the tolerable thickness to be calculated from the thermal noise point of view.
- Measuring the optical loss will likewise allow the tolerable thickness to be calculated from an optical point of view (assuming that the SnO coating is deposited below the dielectric HR mirror coating)

SnO coating feasibility

- The loss of $\phi_{\text{coating material}}$ ~3×10^{-3} , when compared with a typical dielectric coating of loss ~2×10^{-4} and thickness of ~4.5um, would suggest a coating of ≤~300nm would appear to be acceptable from a thermal noise view point.

- Measured optical losses were in the range 17→290ppm.

- Therefore it is not *as* clear that SnO coatings will meet the optical requirements necessary (<1 ppm above HR coating, although <66 ppm permissible below the HR coating for the same power loss (heat deposition) in the Advanced LIGO design).

- This may rule out the use of such coatings on mirror faces – however barrel coatings remain an option.

Charge Mitigation - conclusions

- UV illumination is clearly a candidate technique for controlled charge mitigation for the test masses in current and future detectors using silica substrates
  - Successfully used in experiments in Glasgow (1997) and in GEO (2007).
  - UV lamps either mounted inside vacuum or line-of-sight illumination through fused silica windows.
- The use of gold coatings on the barrels of optics in Advanced LIGO, which have been proposed for thermal compensation reasons, may help charge mitigation (see LIGO DCC: G070146-00-Z).
  - $\phi(\omega)_{GOLD} \sim \sim 2\times10^{-3}$ (single crystal Au coating)

    B.S. Lunin *Physical and chemical bases for the development of hemispherical resonators for solid-state gyroscopes*.

  - Charge mitigation may also be required for fused silica suspension elements – and conductive elements will provide a direct path to for charge to be carried away.
  - Plans in Glasgow to investigate integrating conductive oxide deposition during CO_2 laser pulling.
  - We also plan to continue and extend the study into the effect of these coatings on mechanical loss, optical loss, mechanical strength and durability (many of these oxide coatings are known to be chemically resistant (“hard”) and may therefore protect the surface of silica suspension elements from contamination and micro-cracks that can otherwise be detrimental to strength.