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# 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 summarise 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.

Short title: Charging effects on a silica test mass suspension

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## 1. Introduction

Each of the several ground based long baseline gravitational wave detectors currently under construction [1, 2, 3] is designed to use laser interferometry to sense the relative displacements of mirrors suspended as pendulums. These displacements result directly from the passage of gravitational waves. Of the many noise sources which may degrade the sensitivity of these detectors, it seems likely that in the frequency range of interest for gravitational wave detection, thermal noise from the various modes of the test masses and their suspensions will be dominant. It is thus important that the design of the test mass suspensions is chosen such that the associated thermal noise is acceptably low. Measurements of the losses of the internal modes of fused silica suggest that it is currently the most suitable material for interferometer test masses, with loss factors of approximately $2 \times 10^{-7}$ being reported [4, 5].

For the GEO 600 detector, the design sensitivity of the detector is based on the premise that above 50 Hz, the detector thermal noise will be dominated by the losses in the internal modes of the test masses. This requires that the thermally induced motion at 50 Hz from the pendulum mode of each test mass is less than that from the internal modes and a level of approximately $2 \times 10^{-20} m/\sqrt{Hz}$, a tenth in power terms, of the internal mode contribution, is a reasonable design target.

The motion of each test mass, $\tilde{x}(\omega)$, is related to the total loss tangent† of the suspension $\phi(\omega)$ by [6]

$$\tilde{x}^2(\omega) = \frac{4k_BTw_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]} \tag{1}$$

Where $k_B$ is Boltzmann's constant, $T$ is the temperature and $m$ is the mass of the bob, (16 kg). Thus a loss tangent for the pendulum mode (of frequency 1 Hz) of each suspension of less than $4 \times 10^{-8}$ is required. Experiments [7] suggest fused silica may be a promising choice of fibre suspension material. For a mass suspended on four fibres or two fibre loops the loss tangent of the pendulum mode of the suspension $\phi_{pend}(\omega)$ and

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† note that the Quality Factor, Q, of a system resonant at angular frequency $\omega_0$ is related to the loss tangent $\phi(\omega)$ by Q = $1/\phi(\omega_0)$

the loss tangent of the suspension fibre material $\phi_{mat}(\omega)$ are related by [6]

$$\frac{1}{\phi_{pend}(\omega)} = \frac{1}{\phi_{mat}(\omega)} \frac{mgl}{4\sqrt{TEI}} \qquad (2)$$

where $m$ is the mass of the pendulum, $l$ is the length of pendulum, $T$ is the tension in each wire, $E$ is the Young's modulus and $I$ is the moment of each fibre. The 16 kg test masses of GEO 600 thus require suspension fibres with a material loss factor of less than approximately $6 \times 10^{-6}$. Braginskii et al [7] have demonstrated lower loss factors in very carefully prepared fused silica samples. We have demonstrated that with normal grade fused quartz ribbon fibres suitable loss factors may be achieved. We have also measured the $Q$ factor of the pendulum mode of a mass suspended by cylindrical fibres of fused quartz and have found that electrostatic charging of the mass may significantly decrease the pendulum $Q$ factor through viscous damping. Such an increase in loss, resulting in a $\phi_{pend}(\omega) \propto \omega$ will significantly increase the thermal noise associated with the suspension.

## 2. Measurements of material $Q$ of fused quartz ribbon fibres

A fused quartz ribbon fibre was obtained by drawing a ribbon from a fused quartz slide in a radio frequency (r.f.) induction furnace. The fibre, of length 12.5 cm, width 3 mm and thickness 54 $\mu$m, was rigidly clamped in a horizontal position under high vacuum. The material $Q$ factors of the first four modes of the fibre were measured by using a shadow sensor to monitor the ringdown of each of the resonances at 6.06 Hz, 22.8 Hz, 59.6 Hz and 106 Hz respectively.

The material $Q$ factors of the resonances were found to be all of the order of $5 \times 10^5$ to $10^6$ or equivalently loss factors of $2 \times 10^{-6}$ to $10^{-6}$ [8] which are more than adequate for this material to be used as the suspension material for the test masses in an interferometric gravitational wave detector.

The first four resonances of a second fibre, at frequencies 5.04 Hz, 31 Hz, 84.4 Hz, and 160 Hz, tested for reproducibility also had $Q$ factors of this order.

## 3. Measurements of the $Q$ of the pendulum mode of a mass suspended by cylindrical fused quartz fibres

### *3.1. Experimental setup*

For experimental simplicity tests were carried out on a pendulum bob suspended by two rather than four fibres. Two cylindrical fused quartz fibres were drawn from fused quartz rods using the r.f. oven mentioned above. A quartz rod diameter of 3 mm allowed fibres with a diameter of approximately 290 $\mu$m at the point of bending to be produced, with the ends of the fibres still having thicker portions of rod attached. The rod ends of each fibre were attached to a ceramic bob of mass 200 g, and an aluminium top clamp respectively, by a mixture of clamping and glueing. Clamping to the rod ends of the fibre rather than to the thin fibres themselves reduces the tendency for stick-slip damping to occur at the clamps [9].

The resulting pendulum, of length of approximately 25 cm, was rigidly clamped inside a vacuum tank which was then evacuated to a pressure of approximately $5 \times 10^{-7}$ mbar. The pendulum mode of this suspension was excited using a mechanical pusher operated using a coil and magnet drive as seen in figure 1. The $Q$ factor of the pendulum mode of this suspension was measured by monitoring the decay of the amplitude of the pendulum motion using a shadow sensor system.

### *3.2. Results*

Initial experiments showed that the amplitude of the pendulum motion did not decay exponentially as expected. 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 pendulum tank connected to a vacuum feedthrough was acting as an aerial and was picking up a signal at the pendulum frequency. This suggested the pendulum was charged and that this moving charge was inducing currents in the surroundings. 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.

This conclusion is supported by investigations which showed that a mesh placed in the mouth of the ion pump had no effect on the apparent charging of the pendulum suggesting that the effects seen were not a result of movement of the dielectric pendulum bob in the electric field of the ion pump. It was however possible to inhibit the charging of the pendulum by placing a solid earthed metal plate between the ion pump and the pendulum.

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 the light from a UV lamp placed inside the vacuum system.

The currents induced in the tank and structures surrounding the pendulum represent a possible source of the energy dissipation responsible for the degradation of the pendulum mode $Q$ factor and a model for this energy dissipation consistent with the magnitude of $Q$ factor obtained is shown in figure 1. The change in capacitance $C_1$, resulting from the movement of the charged pendulum, induced a fluctuating charge at the sensing capacitance $C_3$, and the associated change in voltage was measured at A. By measuring and estimating the capacitances involved, measuring the size of the voltage signal at A and using the model shown in figure 1 the magnitude of the charge on the pendulum was calculated. A measured root mean square (r.m.s.) voltage signal of 400 mV at point A corresponded to a charge on the pendulum of the order of $3 \times 10^{11}$ electrons and a measured $Q$ factor of approximately $2.5 \times 10^4$. This pendulum $Q$ may thus be accounted for by the model shown if approximately 0.3% of the change in stored electrical energy per cycle of pendulum motion is dissipated by the effect of the induced currents in the surrounding material.

The change in $Q$ of the pendulum mode, and the build up of charge on the pendulum were monitored simultaneously. A plot of $1/Q$ as a function of the square of the charge on the pendulum is shown in figure 2. By extrapolating the fit of this graph back to the y-axis it is possible to estimate the $Q$ factor of the pendulum with the charging effect removed. This is found to be of the order of approximately $3 \times 10^6$. For this type of pendulum it should be possible to achieve $Q$ factors for the pendulum mode of greater than $10^7$ and experiments to this end are continuing.

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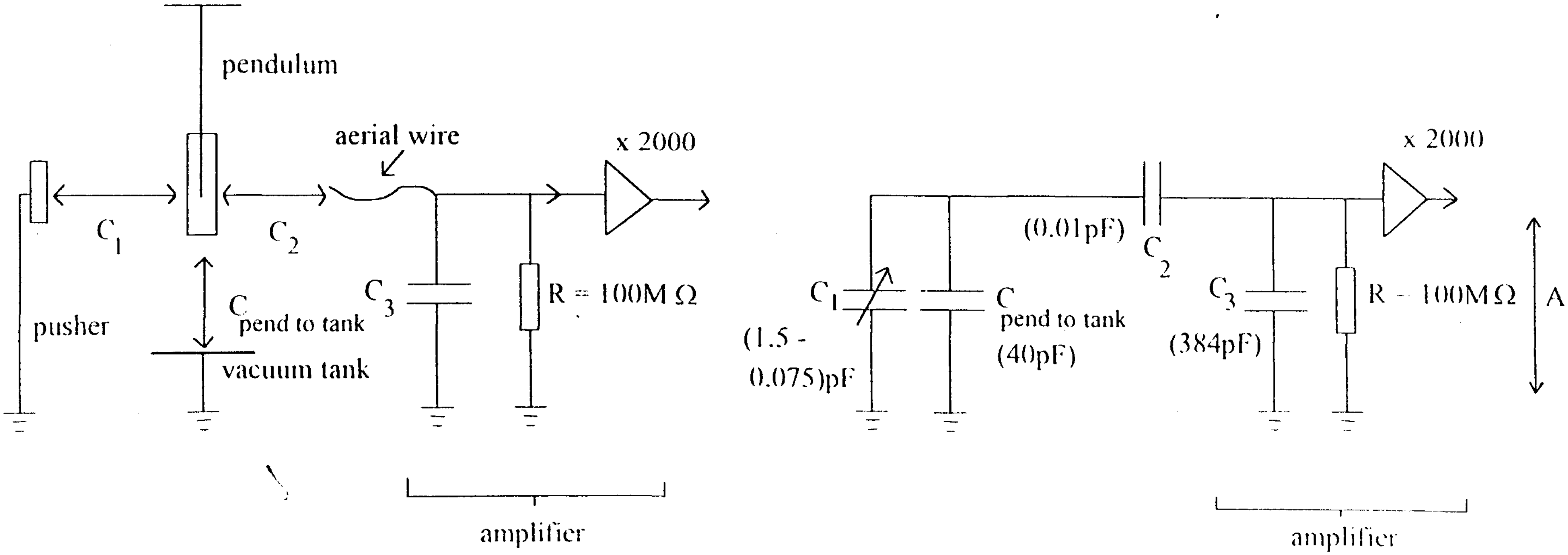
# Figure captions

**Figure 1.** (a) Schematic diagram of the effective experimental set-up when detecting induced currents from the movements of the charged pendulum. showing the pusher, pendulum and pick-up wire. (b) Diagram of the electrical circuit analogue to the experimental arrangement shown in part (a).

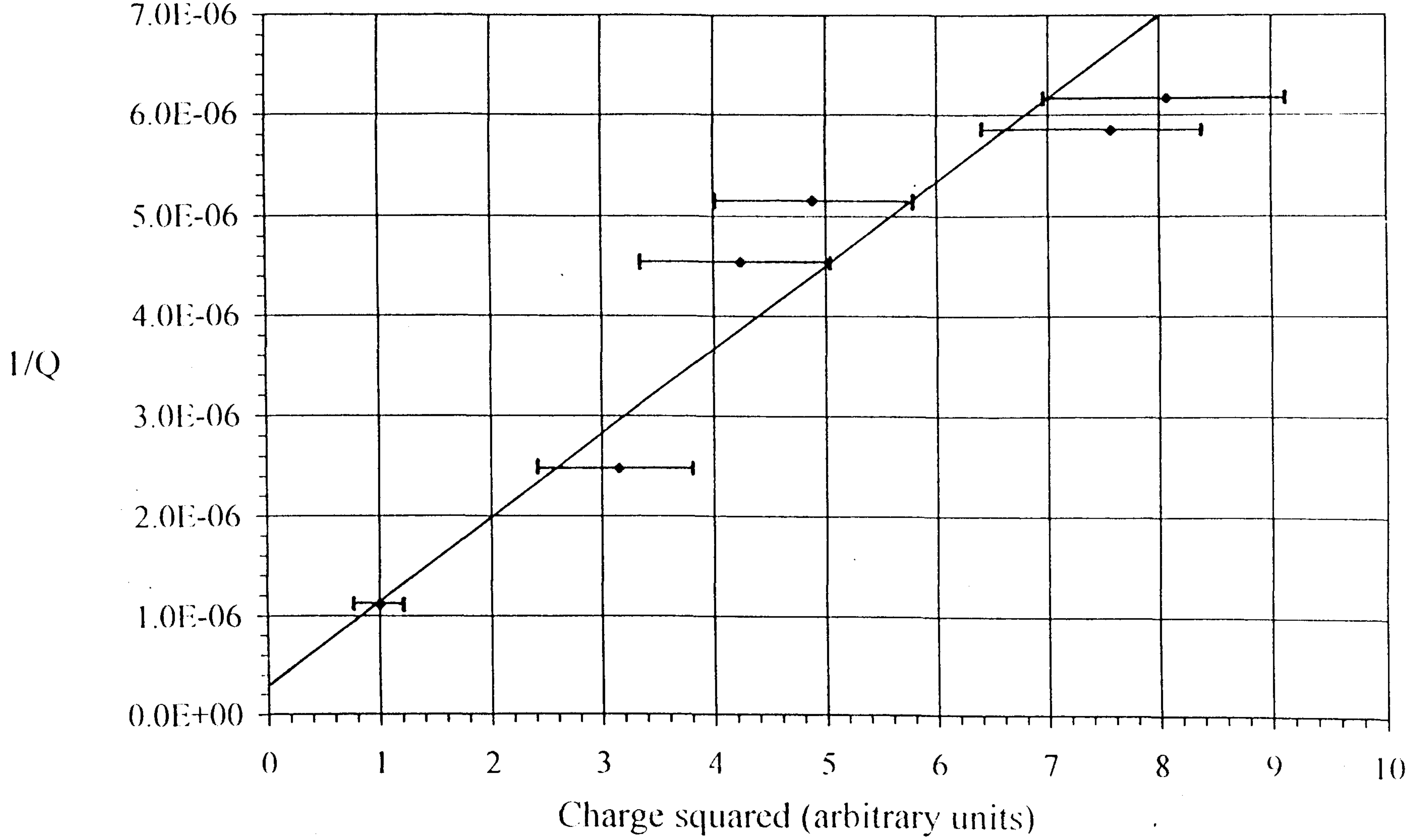
**Figure 2.** Variation of $1/Q$ for the pendulum mode of a 200 g mass suspended on fused quartz fibres as a function of the square of the electrostatic charge on the pendulum.


pendulum
aerial wire
x 2000
$C_1$
$C_2$
$C_3$
pusher
$C_{\text{pend to tank}}$
vacuum tank
R = 100M Ω
amplifier
x 2000
(0.01pF)
$C_2$
$C_1$
(1.5 - 0.075)pF
$C_{\text{pend to tank}}$
(40pF)
$C_3$
(384pF)
R = 100M Ω
A
amplifier

(a)

(b)

FIG 1



7.0E-06
6.0E-06
5.0E-06
4.0E-06
3.0E-06
2.0E-06
1.0E-06
0.0E+00
1/Q
0
1
2
3
4
5
6
7
8
9
10
Charge squared (arbitrary units)

FIG 2