To professors R. Vogt and S. Whitcomb
from V. Braginsky

January 17th, 1994

Dears Robbie and Stan,

I had no direct contacts with the LIGO team since February 6th 1993, and probably it will be interesting for you to know my opinion about the results achieved by the team during these 11 months in the area, which briefly may be called „suspension". I have conver-sation with Fred Raab and Aaron Gillespie, I saw the installa-tion in the basement, which permits to test the quality factors of the pendulum modes, violin modes and internal modes. And I may say absolutely sincerely that I am impressed and satisfied with the obtained numbers for Q_{pend}, Q_{viol} and Q_{intern}. I may say, that these numbers looks good for „the first approximation" of the suspension system despite the fact, that the numbers were obtained in different version of suspension which were favorable separately for pendulum, violin and internal modes.

I take the liberty to present below several simple estimates and sujestions (logically derived from the estimates), which, I hope, will not be ignored for the „second approximation" of the suspension.

Let me start with some kind of lirical description of the mentality of radioantennae designers: these people use to speak to each other in following manner: „In this plug we likely lose 0.7 db, in this cable we shall lose 2.3 db etc."*

and tottaly in the signal-to-noise ration we shall lose 12db, thus we have to have a <u>reserve</u> at least 15 db." Certainly this is not the case of Penzias and Wilson, these gentlemen had an opposite task. But the type of the approach of radioengeneers is typical and not stupid. The key word is <u>the reserve</u>. I do think, that the mood „to have a reserve" has to be „cultivated" for the final version of the full scale LIGO antenna.

For myself I rechecked the numbers for the first step of the LIGO project ($L = 4\times10^{+5}$ cm, $m = 10^{+4}$ gram, $\tau_{gr} \simeq 1\cdot10^{-2}$ sec, $h \simeq 2\times10^{-21}$ and the rate of random coincidences due to the heat bath : one per year). These numbers correspond to the condition $Q_{pendulum} \gtrsim 1\times10^{7}$ (or the relaxation time $\tau^{*}_{\mu} \simeq 3\times10^{+6}$ sec for 30 cm long suspension fiber). This condition is based on the „pessimistic" assumption, that the Nyquist model is a correct one. The <u>reserve</u> will appear only, if some part of the friction „obeys" to the P. Saulson model. I shown to Kip my estimates and we both agreed, that there is no disagreement between my numbers and the results of calculations presented in the article in „Scince". Thus, I want to repeat, that the crutial condition for to achieve the first promissed level of sensitivity is

$$Q_{pend} \gtrsim 1\times10^{+7},$$

with a hope, that some reserve may appear with the „contribution of the P. Saulson model".

All accumulated experience in my lab in Moscow about the losses permit me strongly recommend not to hesitate and to substitute the metal wires by fused silica fibers. I do think, that there are no hope to get $Q_{pend} \geq 1 \times 10^{+7}$ using metal wires. There is one important additional advantage in the fused silica fibers: it is possible to weld them and thus to evade clamps, which inevitably produce additional friction and which very likely may be a source of the excess noise.

To implement the fused silica suspension it is possible to use the following procedures:

1. To ask the manufacturer to cut out some fraction of the test masses to have two small, cylindrical shape „hills", as it is shown in the FIG 1. I may add that in Moscow our technitias are doeing this type of „body shaping" whithout assistance: the use only a diamond drill.

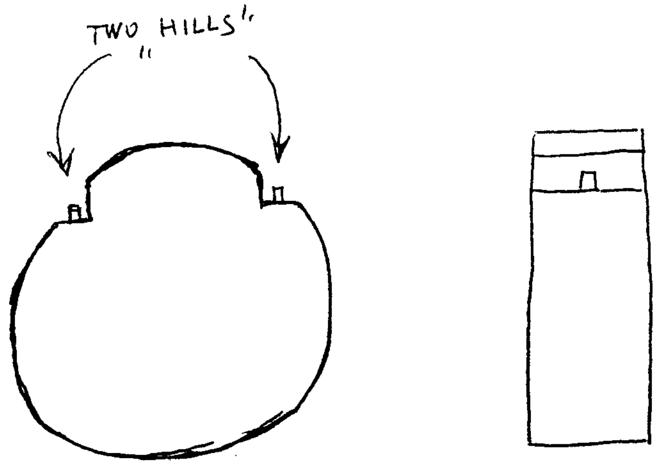


FIG 1.

The „hills" have to be 0,2 - 0,25 cm in diameter and higher than 0,3 cm.

2. To ask the manufacturer to make a deep anealing of the test mass <u>after</u> the cutting (the numbers we got in MSU were obtained whithout this procedure, but I guess, that deep anealing will help with the quality factor of the internal modes)
3. To polish the part of the surface, which was damaged by the diamond drill.
4. To cover the surface with the multilayer reflector (coating).
5. To weld to the „hills" the massive part of the prepared in advance fused silica fibers ends. In this last procedure it is necessary to add a shield to protect the mirror from open fire (see FIG 2)

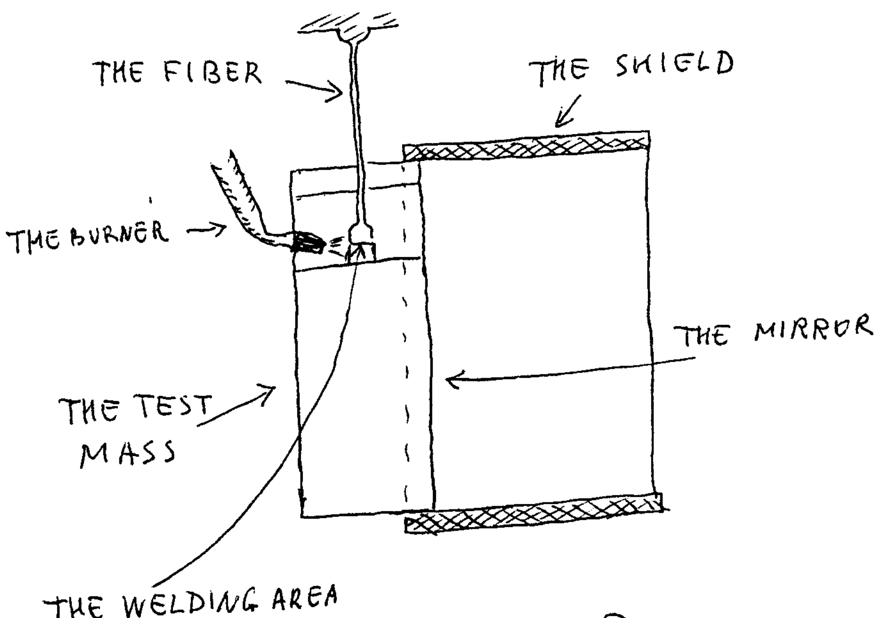


FIG 2

If the shield will be done properly (no slots between its ~~t~~ inner surface and the surface of the test mass), then I guess that the mirror will not be damaged by a small (1÷2 cm long) open fire.

I also strongly recommend to repeat our trick with the massive slab in the upper part of the suspension (also with two mini „hills") to reduce the leakage in the upward direction. The mass of the slab has to be larger than the test mass. Thus the final design of the suspension may look like FIG 3.

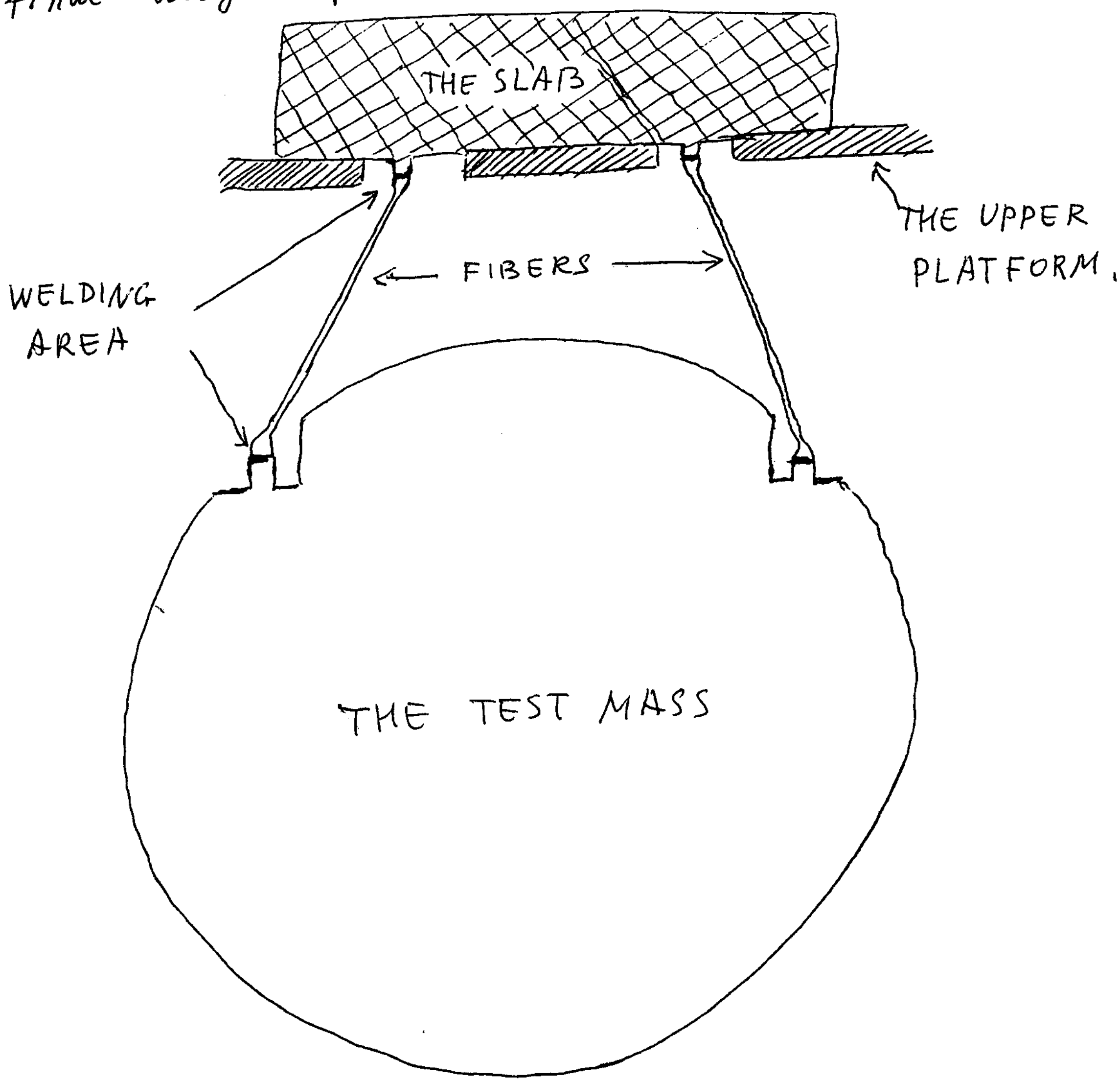


FIG 3.

I have had long and extensive conversation about this subject with Valery Mitrofanov. He agrees both with the estimates and with the recomendations for the design.

After all these steps will be done it desizable (but not necessary) to make soft anealing of the fibers (250 °c during 4–5 hours), to evaporate the last monolayers of the water from the surface. ~~But~~ To realize this it is necessary to surround the fiber with small „ovens" (heated by special coils). But V. Mitrofanov and I guess that this last procedure may not be obligatory necessary one, for $Q_{pend} \simeq 1 \times 10^{+7}$.

I also recommend to be very cautions with the fresh prepared fibers: when the fiber is prepared it is very desizable to start to weld it to the slab and to the test mass and never touch the fiber's surface (to handle it only with the thick ends).

The last recommendation is: not to try in the begining to suspend the test mass on the thinest fiber which will sustain the test mass weight. I guess that the desired Q_{pend} may be obtained with fibers with the strain $\simeq 10^{+8} \div 10^{+9}$ dyn/cm².

Our plans in Moscow for 1994:

1. to try to find Q_{pend} and Q_{viol} first with the test mass $\simeq 1{,}5 \times 10^{+3}$ gram and then with the test mass $\simeq 1 \times 10^{+4}$ gram.

2. to make the first attempts to observe the excess noise. My colleagues and I presume, that this noise has to appear not far from the breaking strain and due to this it may exist an optimal size for the fiber diameter.

cc. K.S. Thorne
F. Raab
A. Gillespie

V. B. Braginsky.

To professor S. Whitcomb
from V. Braginsky

January 24th, 1994

Dear Stan,

I guess, that the time to issue a decree (as Eltzin likes to do) has come. The decree may be formulated like this:

i) stop the use of ferroelectrical materials in the suspension.

ii) Stop the use of ferroelectrical materials in the feedback system (close to the test masses)

iii) stop the use of ferroelectrical materials in the last elements of the antiseismic filter.

The trivial estimates below, I guess, demonstrates the reasons for such a decree:

If the suspending wire is made from the steel it is very likely that it will have a d.c. magnetization $B_0 \simeq 10^{+1}-10^{+2}$ gauss. The, depending of the magnetization's orientation, the sudden change of the local magnetic field in the lab δH will provide a force

$$\delta F_{magn} \simeq \frac{B_0 V \delta H}{4\pi l},$$

where V is the volume of the wire, l -is the characteristic lengh for the wire (which depends on the orientation of the d.c. magnetization). For $B = 10^{+2}$ gauss, $V = 3\times10^{-3}\ cm^3$, $l \simeq 10^{1}$ cm, $\delta H \simeq 3\cdot10^{-4}$ gauss, we obtain $\delta F_{magn} \simeq 10^{-6}$ dyn.

This number is approximately equal to $F_{grav} = \frac{1}{2} h m L \omega_{grav}^2$, when $m = 10^{+4}$ g, $L = 4\cdot10^{+5}$ cm, $\omega_{grav} = 2\pi\times10^{+2}\ \frac{rad}{sec}$. For my best recollection in a typical lab the level of $\delta H \simeq 10^{-3}$ gauss mainly due to the a.c. power supply.

Yours
Vladimir.

To professor Stan Whitcomb
from V. Braginsky

October 17th, 1994.

Dear Stan,

According to your proposal I collected some estimates and prepared the drafts of designs cosidering the feed-back system for the full scale LIGO project. Please, regard the below estimates and arguments not as final ones and not as absolutely exact ones. But I guess that the key numbers and conclusions I am presenting here are not too far from the severe reality and probably will be useful.

The displacements which have to be compensated

„Low" frequency

There are two major sources (effects) which produce the slow („low" frequency) displacements between the test masses (between the „locations" where the test masses are suspended):

a) The tidal wave produces the displacements with the amplitude

$$\Delta L_{(a)} \simeq \Delta R \times \frac{L}{R_{♀}} \simeq 60\,cm\,\frac{4\times10^{+5}\,cm}{6{,}4\times10^{8}\,cm} \simeq 4\times10^{-2}\,cm,$$

where L -is the distance between the locations of the test masses, ΔR is the local change of the distance between the surface and the center of the Earth (tipical values; $\Delta R \simeq 40\,cm - 60\,cm$).

b) The day-night and the seasons changes of the local temperature due to the thermal expansion coefficient of the soil produces

$$\Delta L_{(b)} \simeq (\alpha_{THERM})_{soil} \times L \times \Delta T \simeq 2\times10^{-5}(deg_2)^{-1}\cdot 4\times10^{5}\,cm\times1\times10^{-2}\,K \simeq 8\times10^{-2}\,cm,$$

where $(\alpha_{THERM})_{soil}$ - is the thermal expansion coefficient of the soil, ΔT- is the change of the temperature. It is likely that other effects (e.g. the displacements produced by the rain fall, by the change of the barometric pressure) are smaller than $\Delta L_{(a)}$ and $\Delta L_{(b)}$. The effects a) and b) have characteristic periods from 12 h to one year.

The estimate for the effect b) is based on the assumption that $\Delta T \simeq 1 \times 10^{-2}$ K during the whole year which will be provided by the use of a massive concret block on which the test masses have to be installed. I presume that the size of the block have to be 10^{+3} cm $\times 10^{+3}$ cm $\times 10^{+3}$ cm (total mass $\simeq 2000$ tons, the price $\simeq \$ 1 \times 10^{+5}$ which is equal to the price of five mirrors). The value $\Delta T \simeq 1 \times 10^{-2}$ K is recorded in the Russian Center of Seismometric research at the depth $\simeq 3 \times 10^{+3}$ cm, but I guess that even with lower depth ($\simeq 1 \times 10^{+3}$ cm) the variation of the temperature will be the same one.

c) The "high" frequency displacements of the location of the test masses will be produced by the local seismic noise which is not filtered out by the antiseismic filter ($f \lesssim 5$ Hz). It is difficult to predict the value of $\Delta L_{(c)}$ because it depends of the local conditions. For crude estimate I assume that $\Delta L_{(c)} \simeq 1 \times 10^{-4}$ cm. This "high" frequency displacement cannot be "predicted" unless it is recorded by an independent local seismometer.

Thus the sources a)+b) are responsible for $\Delta L_{(a)+(b)} \simeq 0.1$ cm and the source c) correspondingly for $\Delta L_{(c)} \simeq 1 \times 10^{-4}$ cm. I guess that a large fraction of $\Delta L_{(a)+(b)}$ may predicted if the calendar of local tide waves and temperature is available.

The compensation procedure

"Low frequency"

I guess that the compensation procedures have to be realized up to the level $\delta L_{compens} \simeq 0.2 \times \frac{\lambda}{F}$, where λ is the optical ~~[illegible]~~ wavelength and F is the finesse of the mirror. If in the first step of LIGO $\lambda \simeq 6 \times 10^{-5}$ cm and $F \simeq 3 \times 10^{+4}$ then $\delta L_{compens} \simeq 0.2 \times 6 \cdot 10^{-5}$ cm $\times 3 \times 10^{-5} \simeq 4 \times 10^{-10}$ cm. In other words the dynamical range of the compensating device has to be as large as

$$\frac{\Sigma \Delta L_{(a)+(b)}}{\delta L_{compens}} \simeq \frac{1 \times 10^{-1}\text{ cm}}{4 \times 10^{-10}\text{ cm}} \simeq 2.5 \times 10^{+9}. \qquad (1)$$

In the same time the compensation system has not to produce random force kicks which r.m.s. value is larger then

$$F_{grav} \simeq h\, M_{test}\, L\, \omega_{grav}^2 \simeq 4\times 10^{-22} \times 10^{+4}\, gram \times 4\times 10^{5} cm \times (2\pi \cdot 2 \cdot 10^{2} sec^{-1})^{2} \simeq 2\times 10^{-6}\, dynes. \quad (2)$$

I assumed here the 10σ reserve above the noise level which is expected in the first step of LIGO. The value F_{grav} has to be compared with the compensating force

$$(F_{compens})_{low\ frequ.} \simeq \frac{Mg}{\ell}\cdot \Delta L_{(4)+(6)} \simeq \frac{10^{4} gram \times 10^{3} \frac{cm}{sec^{2}}}{20 cm}\cdot 0.1\, cm \simeq 2.5\times 10^{+4}\, dyn \quad (3)$$

where ℓ - is the lengh of one of the fiber in the suspension, g - is the terrestrial acceleration, M - is the value of the test mass. Despite that $(F_{compens})_{low\ frequ}$ is almost a d.c. one nevertheless, the small fluctuation in the system which provides this force may create a random force of the order of F_{grav} or larger (the ratio $F_{compens}/F_{grav} \simeq 10^{+10}$!). Thus any scheme ~~to~~ of the feedback system has to take into account this circumstance.

I consider as one of the possible ways to get a force $(F_{comp})_{low\ fr.} \simeq 2.5\cdot 10^{+4}$ in the scheme which is presented on the FIG 1

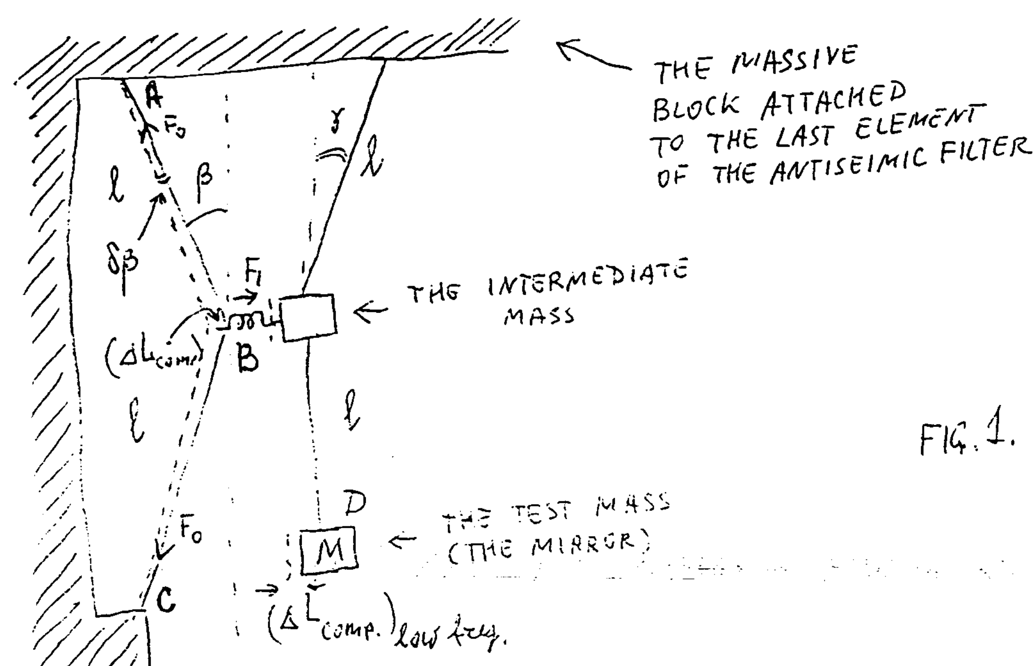


FIG. 1.

The idea is simple: the wire ABC in its midle is attached to the intermediate mass. By the heating the wire due to its thermal expansion coefficient α_{wire} it is not difficult to obtain

$$(\Delta L_{compens})_{low\ frequen} \simeq 0.1\,cm = \ell \times \delta\beta \qquad (4)$$

(see the FIG 1)

For $\ell = 20\,cm$, $\delta\beta \simeq 5\times10^{-3}\,rad$ the necessary change of the temperature

$$\Delta T \simeq \frac{\beta\cdot\delta\beta}{\alpha_{wire}} \simeq \frac{\beta \times (\Delta L_{compen})_{low\ freq}}{\alpha_{wir}^{*}\ \ell} \simeq \frac{5\times10^{-2}\times 0.1\,cm}{2\times10^{-5}\frac{1}{degr}\times 20} \simeq 25\,K \qquad (5)$$

In this example I assumed that

$$F_1 \simeq 3\times(\Delta L_{compens})_{low\ frequ}\times\frac{Mg}{\ell} \simeq 1.5\times10^{+5}dyn \text{ and } F_0 \simeq \frac{F_1}{2\beta} \simeq \frac{1.5\times10^{+5}dyn}{2\times5\cdot10^{-5}} \simeq 1.5\cdot10^{+6}dyn. \qquad (6)$$

If the wire has the diameter 2×10^{-2} cm and it is made of tungsten then the strain will be $5\times10^{+9}\frac{dyn}{cm^2} \simeq 10^{-3}\times$ (Young modulus of tungsten), which is a tolerable value. This wire with the above parameter will have the heat capacity $\tilde{C} \simeq 1\times10^{-2}\frac{Jouls}{degr} = 1\times10^{+5}\frac{erg}{degr}$ (for $\ell = 20\,cm$) and a relatively long thermal relaxation time τ^{*}_{THERM}:

$$\tau^{*}_{THERM} \simeq \frac{\tilde{C}}{4\sigma S T^3} \simeq \frac{1\times10^{+5}}{4\times5.6\cdot10^{-5}\times1\times(300)^3} \simeq 12\,sec, \qquad (7)$$

where σ - is the Stephan-Boltzman constant.

It is possible to use different heating systems to get $\Delta T \simeq$ in the range 10-50 K. Simpliest one is the use of a.c. electrical current in the wire ABC. To obtain the $\Delta T \simeq 25$ K it is necessary to apply the power W

$$W \simeq 4S\sigma T^3\Delta T \simeq 4\times2\times5.6\times10^{-5}\times(300)^3\cdot25 \simeq 2\times10^{5}\frac{erg}{sec} = 20\,milliwatt. \qquad (8)$$

I estimate the value of the transfer function between the point B and D at the frequency $\omega_{gz} \simeq 2\pi \times 10^2$ rad/sec of the order 10^{-5}. Taking into account that $(F_{comp})/F_{gzav} \simeq 10^{+10}$ one has to have the power fluctuation $\frac{\Delta W}{W} \lessapprox 10^{-5}$. The thermodinamical fluctuations of the temperature are negligible:

$$\sqrt{\overline{\delta T^2}} \simeq \sqrt{\frac{k\,T^2}{C}} \simeq 1 \times 10^{-8}\ K. \qquad (9)$$

I guess that other schemes of the compensation of the displacement $\Delta L_{(a)+(b)}$ based on the effect of thermal expansion may be used (e.g. like in the Galley-cell), but I prefer the shemes which do not differ substantionally from one discussed above because the latter one will not affect seriously the mechanical quality factors in the suspension.

"High" frequency

To compensate $\Delta L_{(c)}$ it is possible to use a direct force $\Delta F^{(c)}_{high\ freq.}$ produced by electrostatic pondermotive effect in a capacitor (see FIG 2)

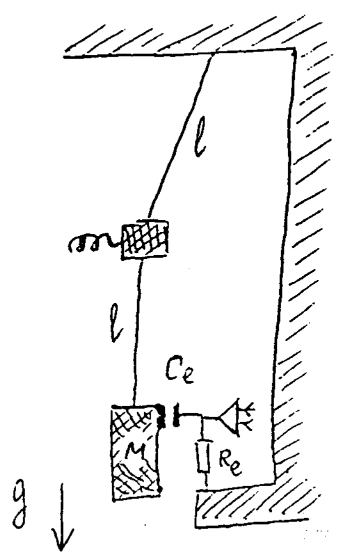


FIG 2

If the square are of the capacitor's plate is S and the distance between the plates is $d \simeq 2\times 10^{-1}$cm (two times larger than $\Delta L_{(a)+(b)}$) then the condition for the aplied potential U are:

$$\Delta F^{(c)}_{\text{"high" frequ}} \simeq \frac{Mg}{\ell}\Delta L_{(c)} = \frac{10^4\times 10^3\times 10^{-4}}{20} = 50\,\text{dynes} = \frac{S\,U^2}{8\pi d^2} = \frac{25\times 2}{25\cdot 4\cdot 10^{-2}}, \qquad (10)$$

where I assumed that $S = 25\,\text{cm}^2$ (5% of one side surface of the mirror is "sacrificed" to produce $\Delta F^{(c)}_{\text{high frequency}}$) and $U = 1.4$ CGSE $\simeq$ 400 volts.

Because $\Delta F^{(c)}_{\text{high freq}}$ is directly applied to the test mass the value of δU has not to fluctuate at the level

$$\frac{\delta U}{U} \lesssim \frac{F_{grav}}{\Delta F^{(c)}_{comp}} \simeq \frac{2\times 10^{-6}}{50} \simeq 4\times 10^{-8} \qquad (11)$$

in the bandwhidth $\Delta\omega_{grav} \simeq \omega_{grav} \simeq (1-2)\,2\pi\cdot 10^2\,\frac{rad}{sec}$.

This condition is not a very tough one because for $R_e = 10^{+4}$ ohm (the output impedance of the amplifier) the value of $\sqrt{\delta U^2_{therm}}$

$$\sqrt{\delta \overline{U^2_{therm}}} \simeq \sqrt{4\kappa T R_e \Delta f} \simeq 1\times 10^{-7}\ \text{volts} \qquad (12)$$

and $\sqrt{\delta \overline{U^2_{th}}}/U \simeq 2.5\times 10^{-10}$. In other words the conditions for the S/N in the feedback loop are not very severe ones. Correspondingly with the above ~~par~~ parameters the friction produced by this feedback loop will be ~~[illegible]~~ small. This value may be described by the equivalent quality factor $(Q_M)_{equiv}$

$$(Q_M)_{equiv} \simeq \frac{m\,\omega_M^2 d^2}{C_e\,U^2}\times\frac{1}{\omega_M R_e C_e} \simeq 5\times 10^{+8} \qquad (13)$$

The above numerical examples, as it seems to me, demonstrates that this scheme may be considered as a candidate.

The conclusion (the recomendations)

1. With the large scale LIGO the system of compensation of the displacements of the test masses's locations has to be regarded as one of the important part of R and D program.

2. Taking into account the large dynamical range of the compensation two feedback loops system looks more attractive than one loop system.

3. All above estimates have to be considered as preliminary ones. I guess that it will be very reasonable to offer the task of the analysis of all effects in the compensation system to a PhD or to a graduate student expecting much more careful and more accurate calculations

4. After this analysis will be performed it is likely that some results of this analysis have to be tested on special simulators.

5. I am sure that for the advanced LIGO the noise from the feedback loop system as well as the ways of its implementation will be as important as the problem of thermal noise in the suspension.

To professors R. Vogt and S. Whitcomb
from V. Braginsky

October 31st, 1994.

Dears Robbie and Stan,

I take the liberty to prepare these notes concerning the design of the antiseismic filter. I hope that probably a fraction of these notes may be of some use for the project.

I. I propose to substitute the last element of the stack isolation system (the last upper platform) which is made from stainless steel by a copper one. The argument for this is simple.

The stainless steel usually has magnetic susceptibility $\mu \simeq 1$ and the random change of the magnetic field δH will produce the acceleration of the platform a_{magn} which is approximately equal to

$$a_{magn} \simeq \frac{\mu\, H_{D.C.}\, \delta H}{4\pi \cdot \rho \cdot l_{char}} \simeq \frac{1 \times 0{,}5 \times 1 \times 10^{-2}}{10 \times 10 \times 10^{+2}} \simeq \frac{1}{2} \times 10^{-6} \frac{cm}{sec^2}, \quad (1)$$

where ρ - is the density of the steel, $H_{D.C.}$ - is the value of the local terrestrial magnetic field, l_{char} - is the charachteristic length which depends on the shape of the platform and of the magnetic enviroment near it. In the numerical estimates I assumed $l_{char} \simeq 10^{+2}$ cm and $\delta H \simeq 10^{-2}$ Öe (the typical value of the change of the magnetic field during a strong magnetic storm which last $\simeq 10^{-2}$ sec). It is necessary to add here that in an ordinary lab the value of $\delta H_{A.C.}$ is close to 10^{-3} Öe and when somebody switch off or on a piece of equipement then the changes of $\delta H_{A.C.}$ are of the same order.

The value a_{magn} has to be compared with the acceleration produced by the gravitational wave:

$$a_{grav} \simeq \frac{1}{2} h_{RMS} \times L \times W_{gr}^2 \simeq \frac{1}{2} \times 4 \times 10^{-22} \times 4 \times 10^{+5} \times (10^{+3})^2 \simeq 1 \times 10^{-10} \frac{cm}{sec^2}, \quad (2)$$

where W_{gr} - is the mean frequency of the gravitational burst, L - is the distance between the test masses, h_{RMS} - is the expected sensitivity (the RMS value of it) in the first version of the LIGO project.

The key argument in favor of the use the copper istead of the stainless steel is simple: it is unlikely that the ratio $a_{magn}/a_{grav} \simeq 10^{+4}$ may be compensated by the value of the tramsfer function of the wire suspension.

In addition to the above proposal I would like to recommend to install a coil nearby the test mass (outside the vacuum chamber) and with this coil to immitate a strong magnetic storm to calibrate the response. The same coil (better to have several ones, with different orientation) may serve to monitor the magnetic „activity" nearby the test mass.

II I recommend to made the copper platform with the shape similar to one presented on the below figure 1

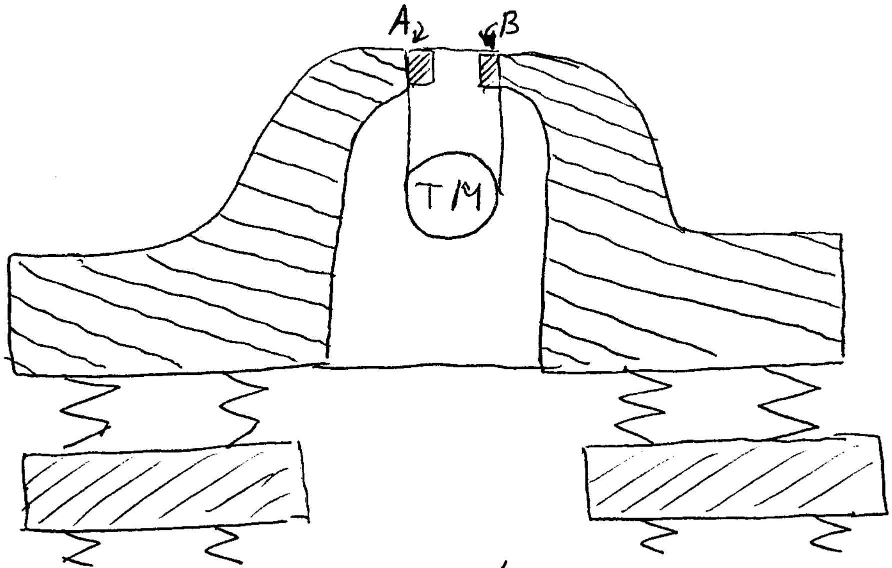


FIG 1

The idea of the design is simple:

a) to evade as possible the bolts and nuts in the suspension of the test mass: the strain in them may acts as sources of the excess noise (the discharge of the strain will produce a creep effect).

b) to make as high as possible all eigen mechanical frequencies of the supporting system and thus to realize better missmatching of the impedances between the wires and the platform itself. I guess that the platform's shape has to resemble the shape of a bell with thick walls and small windows.

In addition it would be reasonable to test all important eigen frequencies of the platform.

I also may recommend to <u>weld</u> the wires (in area A and B) to the upper part of the "bell" by means of hard alloys (based on silver with melting point > 400 K).

III I propose to substitute the elastomer springs between the upper platform and the next one below by a metalic spring. The reason to do so is the possible effect of the conversion of low frequency oscillations of seismic origin (5–8 Hz) in the stack into high frequency oscillations (e.g. 100 Hz) due to the <u>nonlinearity of the elastomer spring</u>. The elastomer has the Young modulus much smaller than any metal and it permits much large deformation (like rubber) and thus it has to have much larger nonlinear dependence of the displacement from the applied force.

It is reasonable to expect that near 5–8 Hz the stack will have the amplitude of vibrations $\simeq 10^{-4}$ cm due to the seismic noise and the displacement of the test mass which has to be detected is $\simeq 10^{-16}$ cm. If the nonlinearity of the elastomer is enough high the <u>cascade</u> process of conversion may overlap the gap between 5 Hz and 100 Hz (only the 20^{th} harmonics) with the efficiency larger than $\frac{10^{-16}\,cm}{10^{-4}\,cm} \simeq 10^{-12}$.

It is possible to make the metalic spring also from copper by carving a cooper cylinder (by a special drill)

[signature]

SOME comments on the conditions for LIGO project (IF ONE WANTS TO REACH h_{SQL})

$$\text{I.}\quad h_{SQL} = \frac{2}{L}\sqrt{\frac{\hbar \tau}{2m}} = \frac{2}{4 \cdot 10^{5}}\sqrt{\frac{10^{-27} \cdot 10^{-3}}{2 \cdot 10^{4}}} \simeq \frac{1}{3} \cdot 10^{-5} \cdot 10^{-17} = 3 \cdot 10^{-23}$$

$$\text{II}\quad \left(\frac{\Delta\omega}{\omega}\right)_{\substack{LASER\\PUMP}} \lesssim \frac{h_{SQL}}{\beta} = \frac{3 \cdot 10^{-23}}{10^{-4}} \simeq 3 \cdot 10^{-19}$$

β ← LEVEL OF COMPENSATION (equality of arms)

TO REDUCE $\left(\frac{\Delta\omega}{\omega}\right)_{\substack{LASER\\PUMP}}$ IT IS POSSIBLE TO STABILIZE THE LASER FREQUENCY BY AN EXTERNAL STABLE ~~QUALITY~~ RESONATOR.

IF ONE RESONATOR IS USED, THEN

$$\left(\frac{\Delta\omega}{\omega}\right)_{\substack{pump\\self\\oscill}} \cong \left(\frac{\Delta\omega}{\omega}\right)_{LASER} \times \sqrt{\frac{Q_{LASER}}{Q_{ADD.\,RESON.}}} \Bigg\}\ \text{Pound scheme.}$$

IF TWO RESONATORS ARE PROPERLY (OPTIMALY) COUPLED, THEN $Q_{LAS} \simeq Q_1 \ll Q_2$; IN OPTIMAL CASE

$$\left(\frac{\Delta\omega}{\omega}\right)_{\substack{PUMP\\SELF\\OSCILL}} \simeq \left(\frac{\Delta\omega}{\omega}\right)_{LASER} \times \frac{Q_{LASER}}{Q_2} \simeq 10^{-18} \cdot \frac{10^{8}}{3 \cdot 10^{12}} \simeq 3 \cdot 10^{-23}$$

Comparison with $\left(\frac{\Delta\omega}{\omega}\right)_{SQL}$:

$$\left(\frac{\Delta\omega}{\omega}\right)_{SQL} \simeq \sqrt{\frac{\hbar}{YV\tau}} = \sqrt{\underbrace{\frac{10^{-27}}{10^{12} \cdot 1 \cdot 10^{-3}}}_{\text{PRESENT STANFORD NUMBERS}}} \simeq 10^{-18}$$

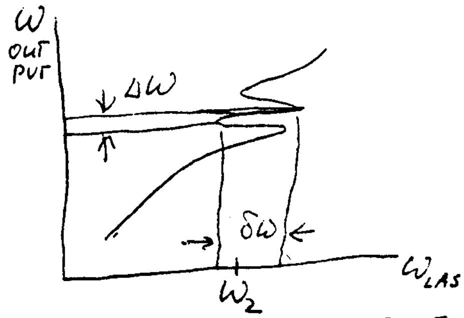
Y – Yong modulus, V – volume

IF

$$W_{OPTIMAL} \simeq \frac{YV\omega}{Q^2} \simeq \frac{10^{12} \cdot 1 \cdot 3 \cdot 10^{15}}{(10^{8})^2} \simeq 3 \cdot 10^{11}\ \frac{erg}{sec} = 3 \cdot 10^{+4}\ W$$

↗ HARD TO OBTAIN.

Van der Pol picture for three resonators autooscillator



$$\frac{\Delta\omega}{\delta\omega} = \frac{Q_{LAS}}{Q_2}\ \text{- FACTOR OF STABILIZATIC}$$

III LET compare THE REPORTED $h \simeq 1{,}5 \cdot 10^{-18}$ (ONE "ARM" USED AS A STABLE REFERENCE RESONATOR → THE CASE WHEN $\beta = 1$: NO BALANCE AT ALL)

THE ULTIMATE SENSITIVITY:

$$h \simeq \frac{\Delta\omega}{\omega} = \frac{1}{Q_{FP}\sqrt{N}} = \frac{1}{3 \cdot 10^{15} \cdot 10^{-3}}\sqrt{\frac{3 \cdot 10^{-12}}{10^{5} \cdot 10^{-3}}} \simeq 10^{-19}$$ – ONE ORDER LESS THAN $h \simeq 1{,}5 \cdot 10^{-18}$!

IF TWO CAVITY STABILISATION SYSTEM IS USED THEN IN IDEAL OPTIMAL CASE;

$$\frac{\Delta\omega}{\omega} = \frac{1}{\sqrt{Q_{LAS} \cdot Q_{FPR}}}\sqrt{\frac{\hbar\omega}{W\tau}} = \frac{1}{\sqrt{10^{9} \cdot 3 \cdot 10^{12}}}\sqrt{\frac{3 \cdot 10^{-12}}{10^{5} \cdot 10^{-3}}} = 3 \cdot 10^{-18}$$ – WORSE THEN $h = 1{,}5 \cdot 10^{-18}$.

IF A FEED-BACK SERVO SYSTEM IS USED (WHICH INEVITABLY ADDS NOISE)

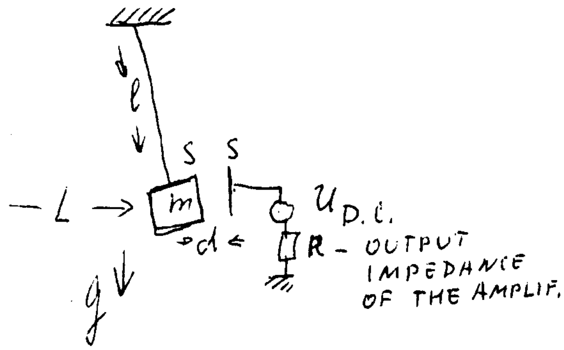
I DOUBT THAT THE LEVEL $\frac{\Delta\omega}{\omega} \simeq 10^{-18}$ IS POSSIBLE TO REACH.

TWO ARMS (AND $\beta \simeq 10^{-3} - 10^{-4}$) + INDEPENDENTLY COTROLLED LASER ARE MUCH MORE PROMISSING: IT IS POSSIBLE TO DISTIGUISH SOURCES OF NOISE.

IV CONDITIONS FOR THE FEEDBACK LOOP SYSTEM FOR $h \simeq h_{SQL}$

$\Delta L_{D.C.} \simeq L \alpha \Delta T \simeq 4 \cdot 10^{+5} \cdot 10^{-5} \cdot 2 \cdot 10^{-2} \simeq 0.1\ cm$; $\Delta L_{D.C.}$ - MAY BE PARTIALY COMPENSATED.

← OBNINSK STATION (~30 METERS)



$$F_{D.C.} = \underbrace{\frac{mg}{l} \cdot \Delta L_{D.C.}}_{\frac{10^4 \cdot 10^3}{10^2} \cdot 0.1 \;=\; 10^{+4}\ dyn} = \underbrace{\frac{S U_{D.C.}^2}{8\pi d^2}}_{\frac{10^2 \cdot (10^2)^2}{25} \;=\; 4 \cdot 10^4\ dyn} ; \quad d > \Delta L_{D.C.}$$

NUMERICAL EXAMPLES

$U = 1 \cdot 10^4 V$, $d = 0.3\ cm$; $E = \frac{U_{D.C.}}{d} = 3 \cdot 10^4 \frac{V}{cm} = 10^2$ es

$$\frac{1}{2} h_{SQL} M L \omega_{gz}^2 \geq \delta(F_{D.C.}) \cong F_{D.C.}\left(\frac{2\,\delta U}{U_{D.C.}} + \frac{\delta d}{d}\right)$$

$$\boxed{\frac{\delta U}{U_{D.C.}} \lesssim \frac{1}{4} h_{SQL} \times \frac{L \omega_{gz}^2}{g} \times \frac{l}{\Delta L_{D.C.}}} \qquad \boxed{\frac{\delta d}{d} \lesssim \frac{h_{SQL}}{4} \times \frac{L \omega_{gz}^2}{g} \times \frac{l}{\Delta L_{D.C.}}}$$

$$\frac{1}{4} \cdot 3 \cdot 10^{-23} \, \frac{4 \cdot 10^5 \cdot 10^7}{10^3} \, \frac{10^2}{10^{-1}} \simeq 3 \cdot 10^{-11};$$

IF $U_{D.C.} = 1 \cdot 10^4 V$, THEN $\delta U \simeq 3 \cdot 10^{-7} V$

IF THE ONLY NOISE IS THE NYQUIST NOISE, THEN

$$\delta U \simeq \sqrt{4kTR \frac{\omega_{gz}}{2\pi}} \simeq \sqrt{4 \cdot 10^{-23} \frac{J}{deg} \cdot 300^\circ \cdot 10^2\, ohm \cdot 10^{+3}\, Hz} = 4 \cdot 10^{-8} V$$

THIS CONDITION IS ALSO VALID FOR I-CURRENT IF MAGNETIC FORCE IS USED.

THE BARKHAUSEN EFFECT IS THE CAUSE OF VERY HIGH EFFECTIVE TEMPERATURE T IN THE EQUIVALENT NYQUIST FORMULA.

STORY about the church's behavior

V TO REACH h_{SQL} IT IS NECESSARY TO FULFIL THE CONDITION: $\frac{kT\tau^2}{\tau_M^*} \lesssim \hbar$ ← RELAX. TIME.

THIS CONDITION IS FULFILLED IF $T = 300$, $\tau \lesssim 10^{-3}$ sec, $\tau_M^* \gtrsim 4 \cdot 10^{+7}$ sec

Q	$2 \cdot 10^7$	10^6	$5 \cdot 10^6$	$2 \cdot 10^7$	$2.8 \cdot 10^7$
ω	6	10^{+3}	10^5	10^4	10^4
m	10^2	10^{-5}	$2 \cdot 10^3$	10^2	10^2

THE BEST KNOWN AT MSU NUMBERS.

TWO GOALS AT MSU: i) Q (diameter, suspension, impurities, T)

ii) exess noise.

VI THE ULTIMATE SENSITIVITY OF LIGO FOR THE PRESENT $(1-R) = 10^{-5}$ →

$$\rightarrow \tau_e^* = \frac{L}{c(1-R)} = \frac{4 \cdot 10^{+5}}{3 \cdot 10^{10}\, 10^{-5}} \simeq 1\,sec; \quad h_{ULTIMATE} = h_{SQL}\sqrt{\frac{\tau}{\tau^*}} \simeq 3 \cdot 10^{-23} \cdot \frac{1}{30} \simeq \underline{1 \cdot 10^{-24}}$$

IF QND TECHNIQUE IS USED.

V. BRAGINSKY JAN. 21. 1991

To professors R. Vogt and R. Weiss
from V. Braginsky

Dears Robbie and Ray,

Kip told me that you both decided to prepare a proposal about the enhanced version of the detector. He also recommended me to share with you my views about this business. I took the liberty to write down several considerations on this subject expecting that not all of them you will regard as useless.

I. The justification of the proposal.

The accumulated experience about the properties and the features of the existing prototype of the detector and about the design of the detector for the first version of LIGO project allow to formulate the following:

1) Several elements of the suspension of the mirrors may be in principle substantially improved and due to this higher potential sensitivity may be obtained.

2) Several elements of the detector which „surround" the center of the test mass (in other words which influence the behavior of the test mass center) deserves deeper analysis and more tests because they may be a sources of additional noise which may affect the sensitivity of the antenna.

3) It is reasonable to perform several independent experiments, tests, analysis and modeling to prepare a set of new elements and new techniques which will allow to realize the enhanced detector with the ~~se~~ projected sensitivity substantionally higher than in the planned first version ~~of~~ (first step) of LIGO project.

II The key goals of the proposal.

1. To realize and to test a new full scale suspension system based on the fused silica fibers which (according to the experience accumulated in the MSU group on small models of such a suspension) is promissing the rise of about 3 orders of the quality factors (violin modes and pendulum mode) and due to this the supression of the thermal noise from these modes with the factor ≃ one and a half orders (in the units of the perturbation of the metric).

   The evident potential advantage of this version of suspension is not only in the supression of the thermal noise, but also in the fact that the existing steel wires will be substituted by a nonferroelectrical fused silica fibers and due to this the direct action of the fluctuation of the a.c. component of the magnetic field on the wires will be excluded.

2. To test and to analyze the excess noise in the fiber suspension (which was observed in the MSU group in the metal wire) and to estimate its contribution in the total sum of the noises.

3. To realize and to test new actuator based one the use of electrostatic force in the feed back system. The evident advantages of this device are: i) as soon as <u>no</u> D.C. magnets will be attached to the mirrors the quality factors of the internal modes will not be affected and due to this the contribution of their thermal motion to the sum of the thermal noise will be reduced, ii) the absence of D.C. magnets will diminish substantially the direct action of the fluctuation of the magnetic fild on the mirrors.

4. To design, to develop and to create a new ensemble of elements (the mirror, the suspension, the actuator system, the anti-seismic isolation) which has to promiss better sensitivity that the planned one for the the first version of LIGO.

III Specific problems which have to be solved.

1. To investigate the damaging effect of the welding of the fibers to the mirror (the possible distortion of the bulk) and the probably associated effect of the contamination of the mirror due to the welding. To find procedures which will allow to reduce these two effects (e.g. the welding using CO_2 laser, the protection of the mirror's surface etc).

2. To find the correlations between the stresses in the fibers, the quality factors of the modes and the mean level and the charchterists of the excess noise. To formulate the conditions for the final version of the suspension, to test the quality factors and to measure the level and other features of the excess noise and finally to estimate the ~~expected~~ sensitivity which may be expected from the results of the above tests.

3. To find in the test model the dynamical ~~ra~~ range of the electrostatic actuator and the conditions for the output noise, the necessary precautions for the electrostatic isolation and the possible damping effect (the reduction of the quality factors) due to the use of electrical field applied to the mirror.

V. Braginsky