A Cryogenic Suspension for LIGO

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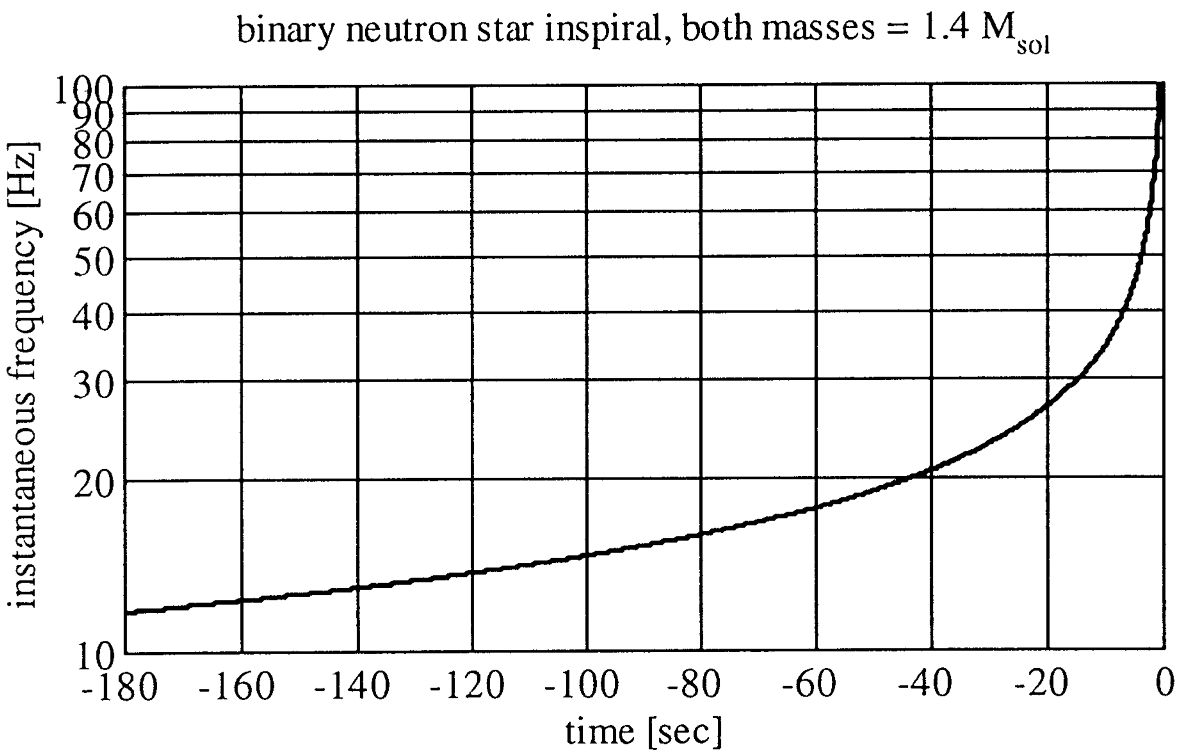
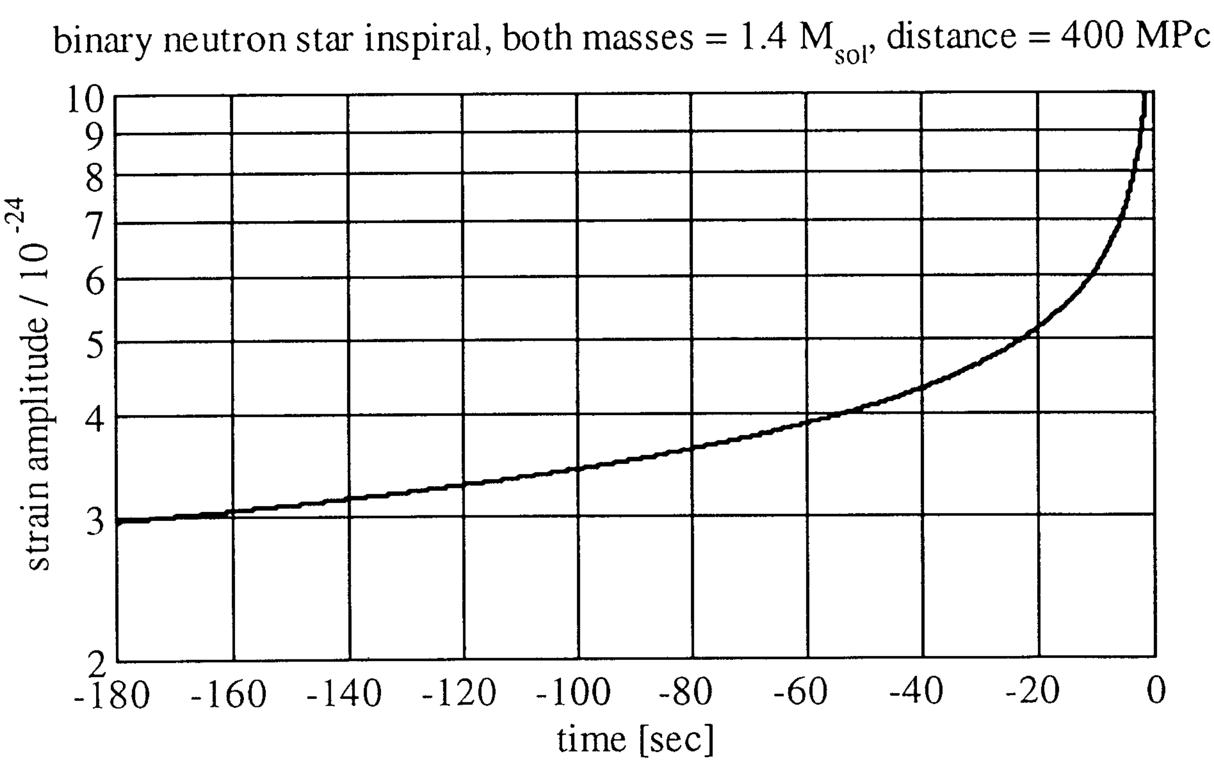
- The most likely gravitational wave source, an inspiraling binary neutron star system, is a <u>low</u> frequency source.
- The dominant fundamental noise source at low frequencies is *pendulum thermal noise.*
- It can be reduced by
    - increasing Q_P (or decreasing the elastic internal friction),
    - decreasing T (decreasing the temperature).
- Even a fused silica suspension will not be good enough for distant binary inspirals.
- A cryogenic suspension <u>should</u> be far better than any other, because it decreases T, and also because Q_P is greatly improved.
- We propose a systematic series of experiements to determine if a cryogenic suspension can be proven to be markedly superior.

LIGO-G980135-00-M

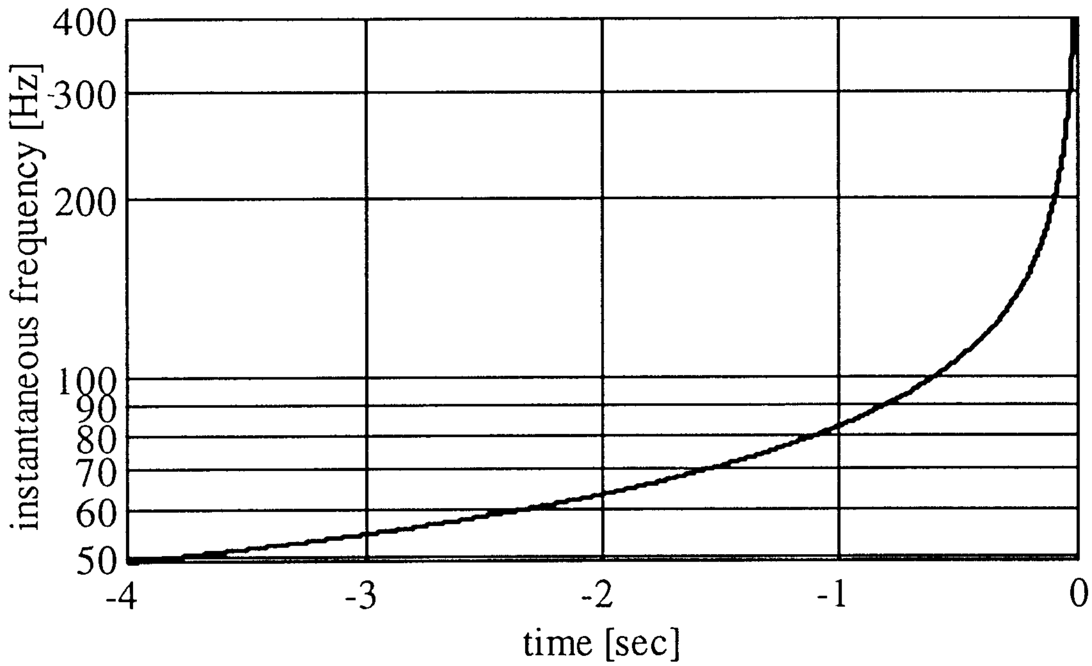
<u>Neutron star binary inspirals are low frequency sources.</u>

The final 3 minutes of the inspiral :

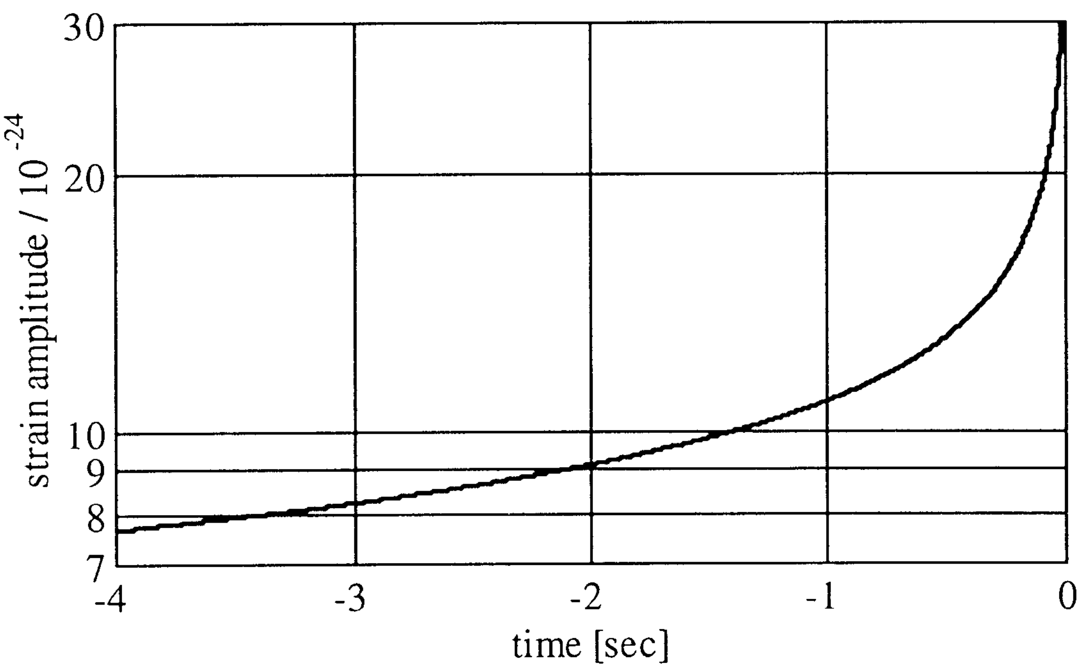




binary neutron star inspiral, both masses = 1.4 M_{sol}



binary neutron star inspiral, both masses = 1.4 M_{sol}, distance = 400 MPc



Pendulum Thermal Noise

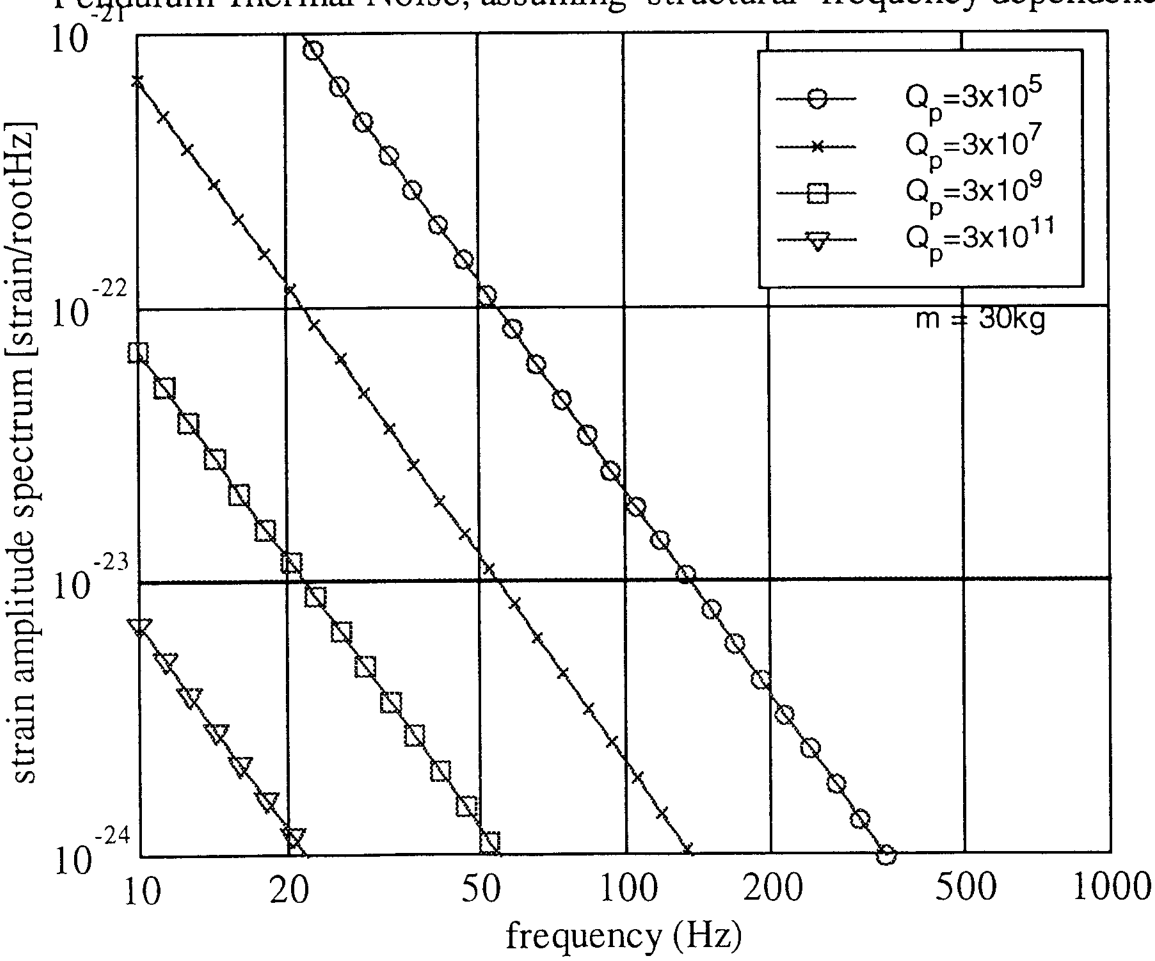
Mechanical equivalent of Johnson-Nyquist electrical noise generator

Cause of Brownian motion

Fluctuation-dissipation theorem says : the measured level of dissipation determines the minumum level for fluctuations :

$$\delta x(\omega) = \sqrt{S_x(x)} = \frac{\sqrt{S_F(\omega)}}{m\omega^2} = \frac{\sqrt{4k_bT\,\mathrm{Re}(Y)}}{m\omega^2} = \sqrt{\frac{4k_bT}{m^2\omega^4}\frac{k}{\omega Q_P(\omega)}}$$

Pendulum Thermal Noise, assuming "structural" frequency dependence



Cryogenics has great potential

1) Temperature Reduction

From the flucuation-dissipation theorem, the net noise at any temperature T is determined by replacing Q_P by Q_P^{eff}

$$Q_P \rightarrow Q_P^{eff} \equiv Q_P(T)\frac{290K}{T} \approx Q_P(T)\frac{290K}{10K} \approx 30 \times Q_P(T)$$

For a pendulum, the $Q_p(T)$ can be function of many things, but in the best case it is given by

2) Improved Material Properties, especially Q_{mat}

–Thermoelastic damping (the fundamental limit for room temp metals) is reduced by 10^4 at low T [see next page]

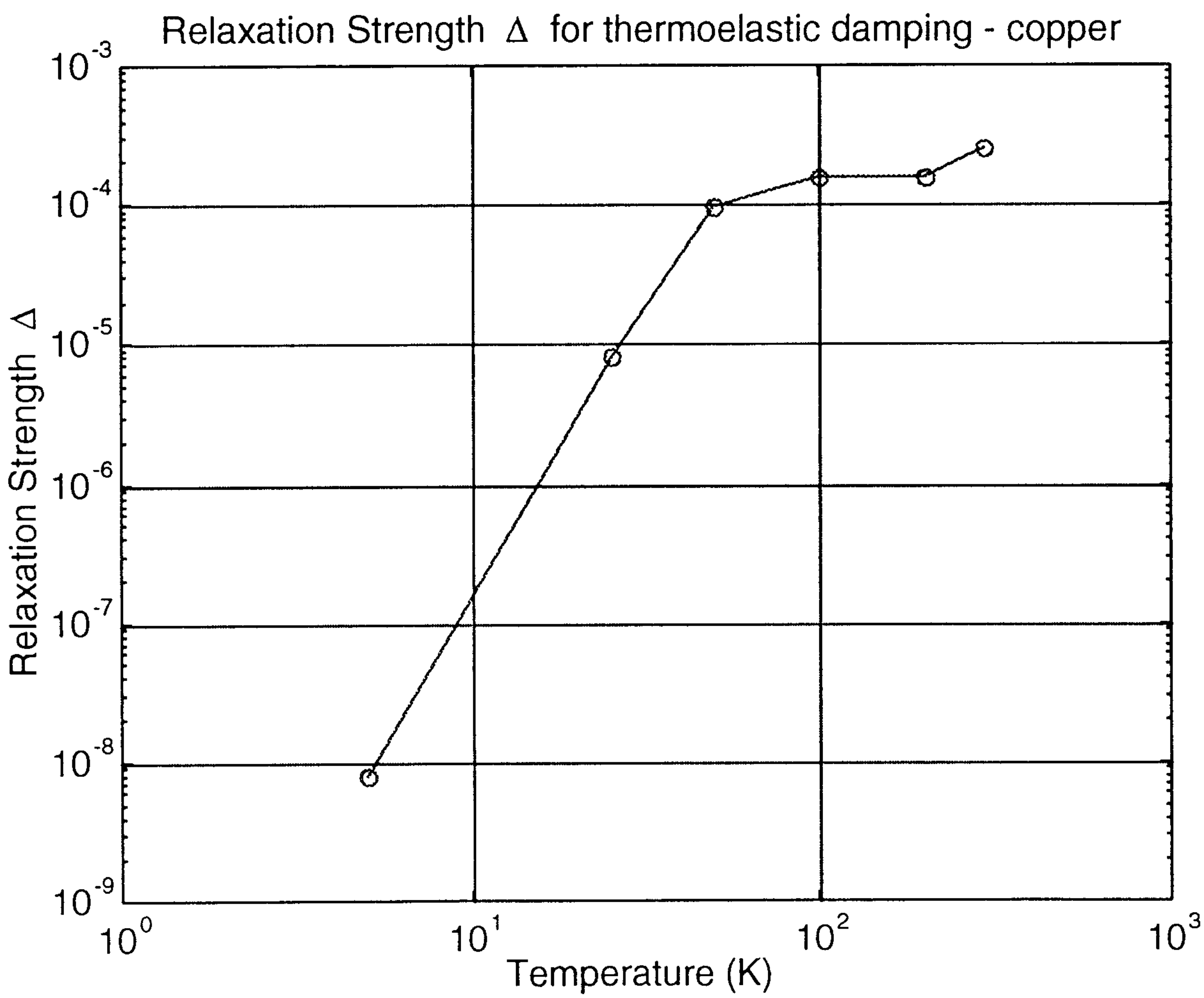
–Two or three orders of magnitude improvement in other loss mechanisms is not unusual, e.g., disclocation motion, grain boundary motion, impurity diffusion, etc.

–[glassy materials, including fused quartz, are the exceptions]

-Q_{mat} for some alloys of Cu and Al is greater that 10^7 at 10K

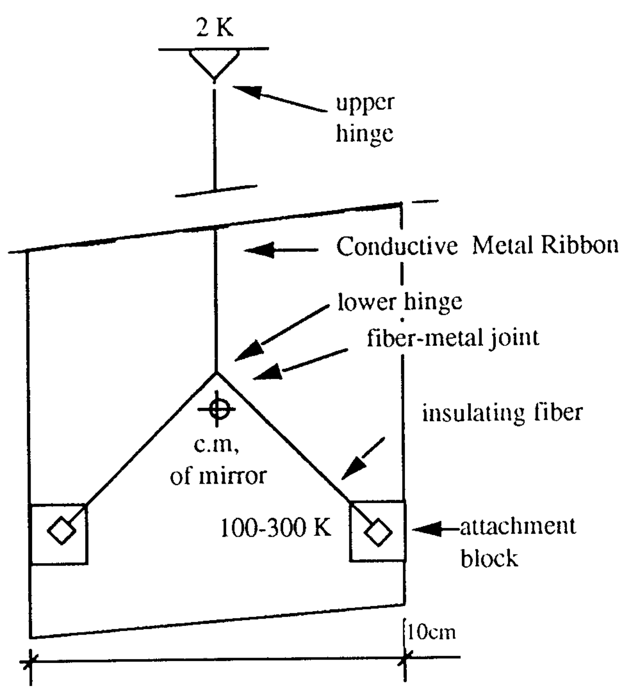
Relaxation Strength for Thermoelastic Damping of Copper

$$\Delta = \frac{E\alpha^2 T}{C_v} \qquad\qquad Q^{-1} = \phi = \Delta \frac{\omega\tau}{1+(\omega\tau)^2}$$



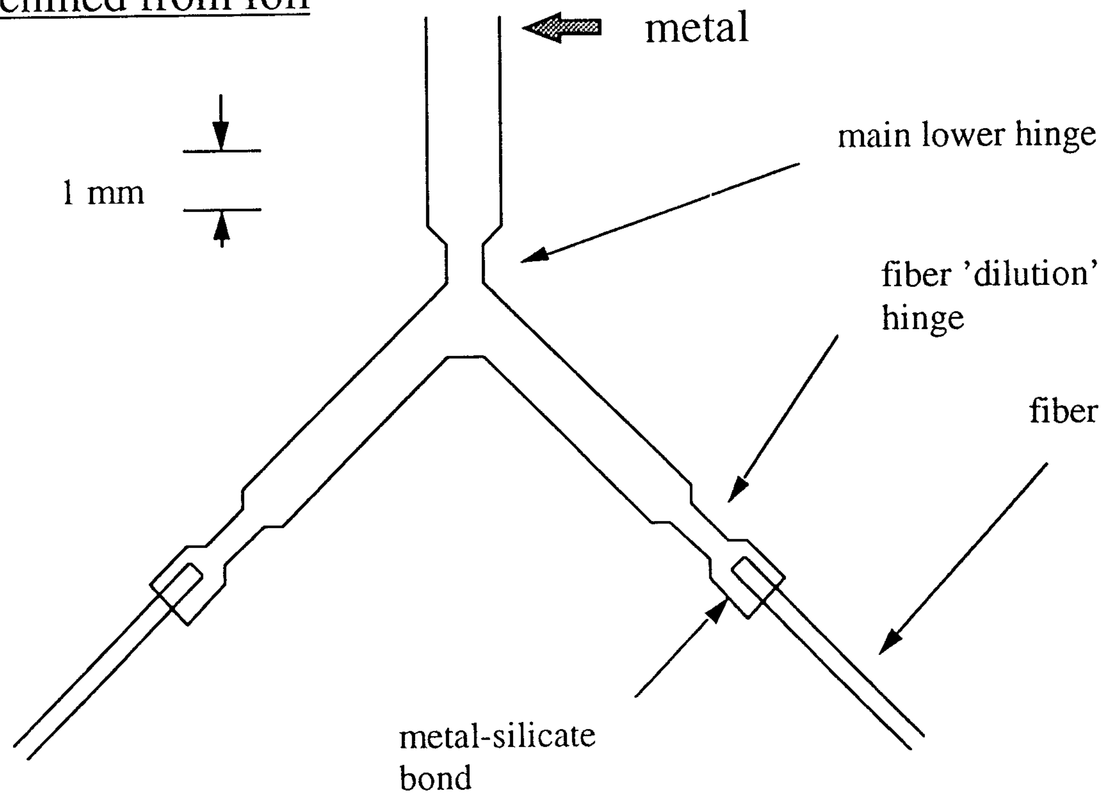
propose a cold metal suspension

- The suspension 'hinges' need to be cooled, because they are the main locations for elastic deformation
  - Therefore this is where the noise forces on mirror CM are generated.
- Connect upper hinge to cold mass.
- Make metal suspension wire with high thermal conductivity, so it can cool the lower hinge.
- <u>Thermally insulate lower 'hinge' with fused silica fiber bridle</u>
- Keep mirror warm (~290 K) to prevent the condensation of optically lossy material. [Will this really be neccessary?]



detail of bridle and metallic suspension

BeCu metal
<u>*micromachined from foil</u>



$$Q_P(T) = Q_{mat}(T) \times dilution\ \ factor \approx Q_{mat}(T) \times (100 - 1000)$$

- elastic dilution factor = η = Utot/Uelastic
- estimated dilution factors
  - main hinge -- η ~ 300 at reasonable stress (~25% of breaking), or
  - $Q_e = Q_b \times \eta \times (T_0/T) \sim 10 \times 10^6 \times 300 \times (300/10) \sim \mathbf{3 \times 10^{11}}$
  - fiber flex -- probably ok
  - fiber stretch -- not quite enough

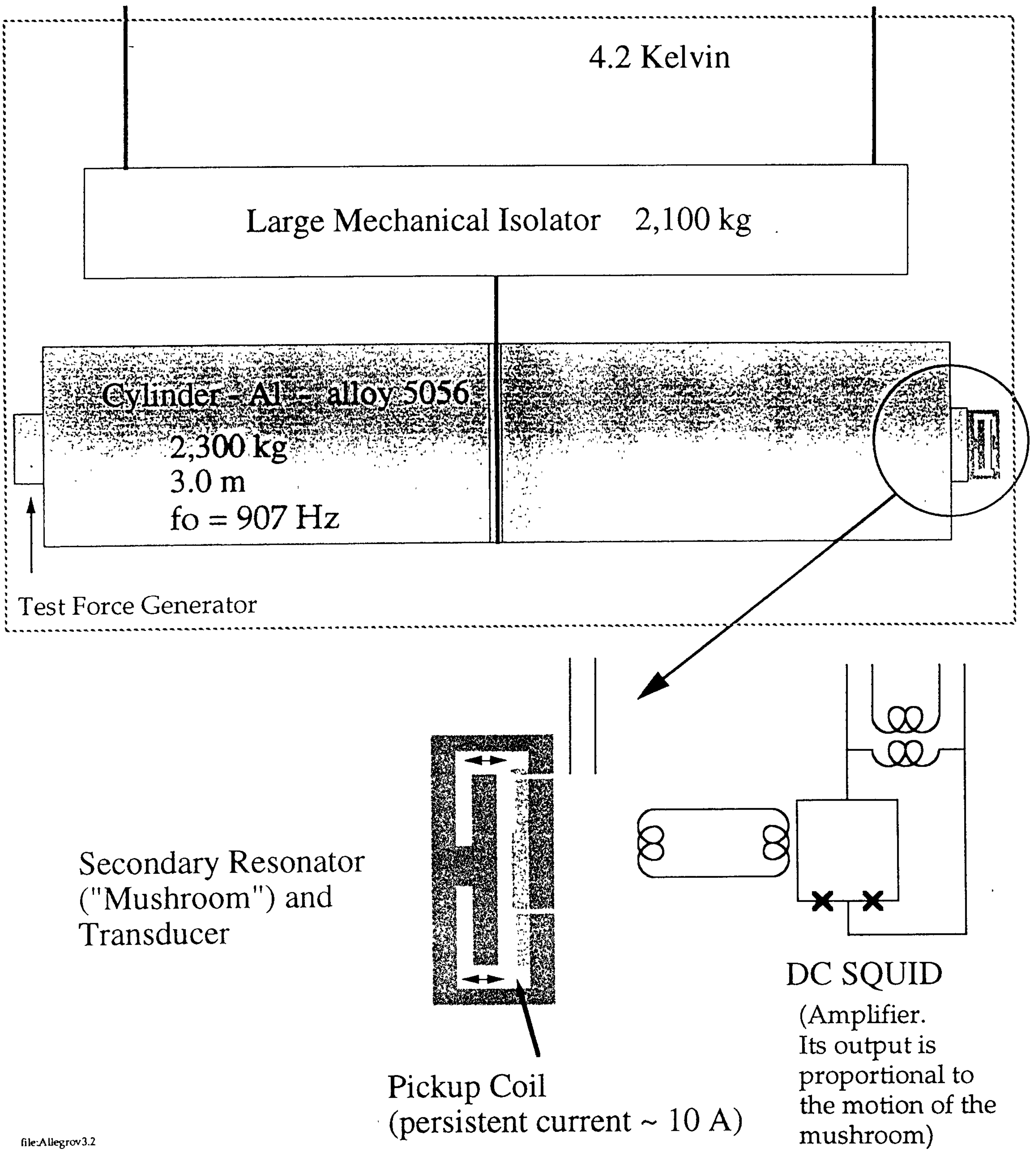
Metal-silicate bonding

- Phil Adams has recently discovered a metal film (Beryllium) that adheres extremely well to silicate glasses, at thicknesses of 2-5 nm. He will test to determine if it bonds as well to fused silica.
- A filler metal, perhaps 1μm thick, can then be bonded to the adhesion layer.
- Then heat, or a laser welding beam (transmitted through the transparent silica), can be used to bond these metal layers to a metal parts.
- Because they are stiff, and metal has reasonable Q, these should be high Q bonds

- Cryogenic Engineering
  - Cooldown
    - Use a vacuum tight pipe, carrying liquid He or N_2, to cool the jaws of motorized clamps, which grasp metal tabs protruding from all the large pieces. Retract them when all is cold.
  - Warmup
    - clamp on, and flow hot gas through the pipe.
  - Access
    - The cooled three layer thermal shield has copper panels which unbolt so that the shield has clearance to be lifted compeletly out of the way, without moving optics. Cryogenic piping is removed and reconnected through proven removable (Conflat) flanges.
- Damping
  - eddy current damping should be very efficient because of the much larger conductivity of normal metals -- side effects, ie magnetically coupled noise, can be calculated and also reduced drastically by good design.

ALLEGRO

A Louisiana Low-temperature Experiment
and Gravitational Radiation Observatory



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