Cryogenic Suspension and Isolation

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- Cryogenic suspension has a good chance of achieving major advancement in low frequency sensitivity.
- Modest R&D would answer some of the crucial questions.

LIGO-G980049-21-M

Compare signal to noise
with a frequency sensitive method

Noise power is represented in the usual way
$S_h(f)$, for each source

Quantify signal as a "signal power" $S_S(f)$
defined as the measure of signal strength that
determines the signal/noise ratio.
Has the same units as $S_h(f)$, so
they can be plotted on the same graph.

$$\left(\frac{S}{N}\right)^2 = 2\int_0^\infty \frac{\left|\tilde{h}_s(f)\right|^2}{S_h(f)} df \equiv \int_0^\infty \frac{S_s(f)}{S_h(f)} \frac{df}{f}$$

Overall Figure of Merit: DETECTION RANGE,
defined by changing distance to a source until it is
just detectable, which is $(S/N)^2 = 25$

The 'standard source' used here:
inspiral of pair of 1.4 Msol neutron stars

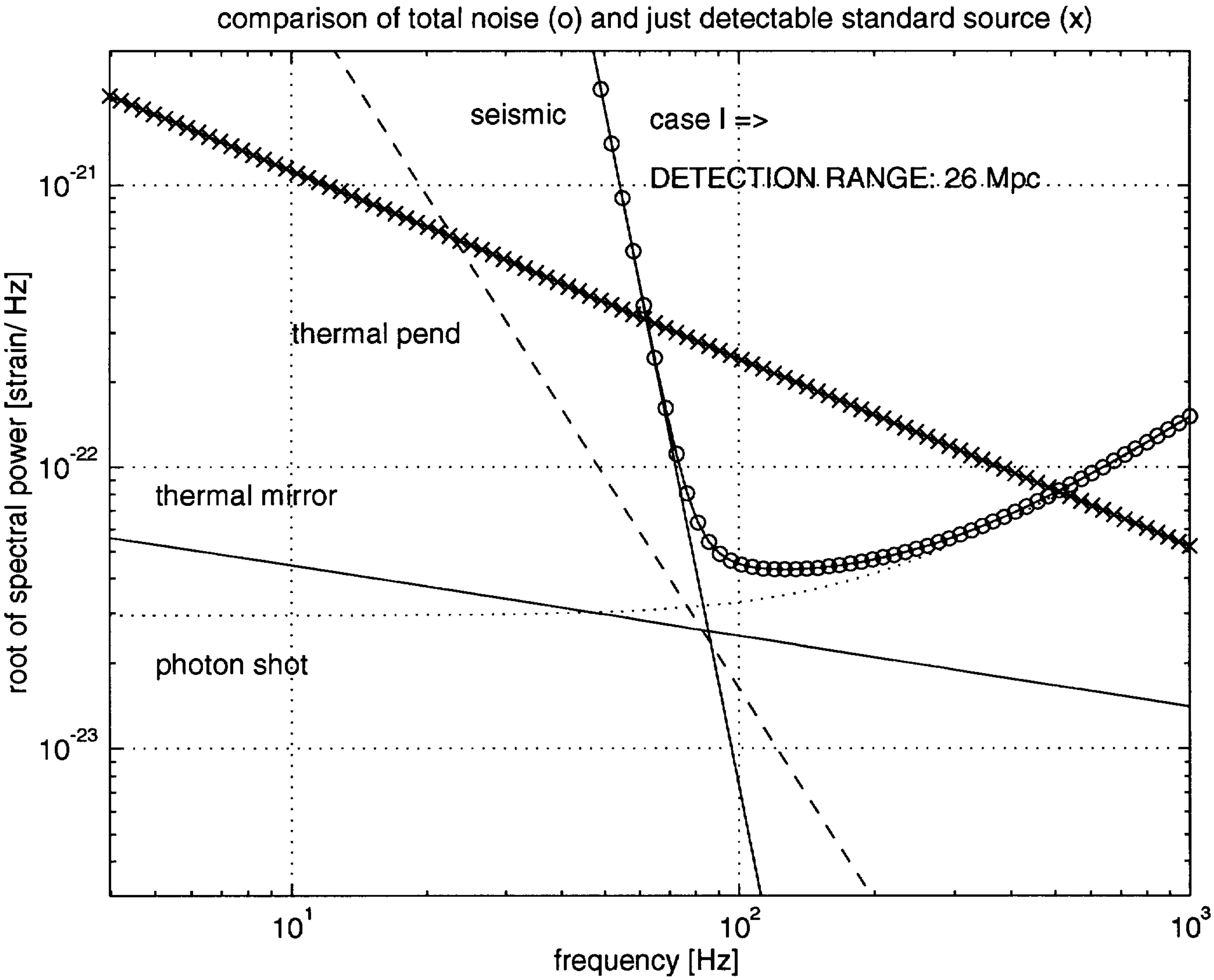
unofficial LIGO I

Laser Power 10 W

4 stages of 5 Hz isolation + 1 stage at 0.7 Hz

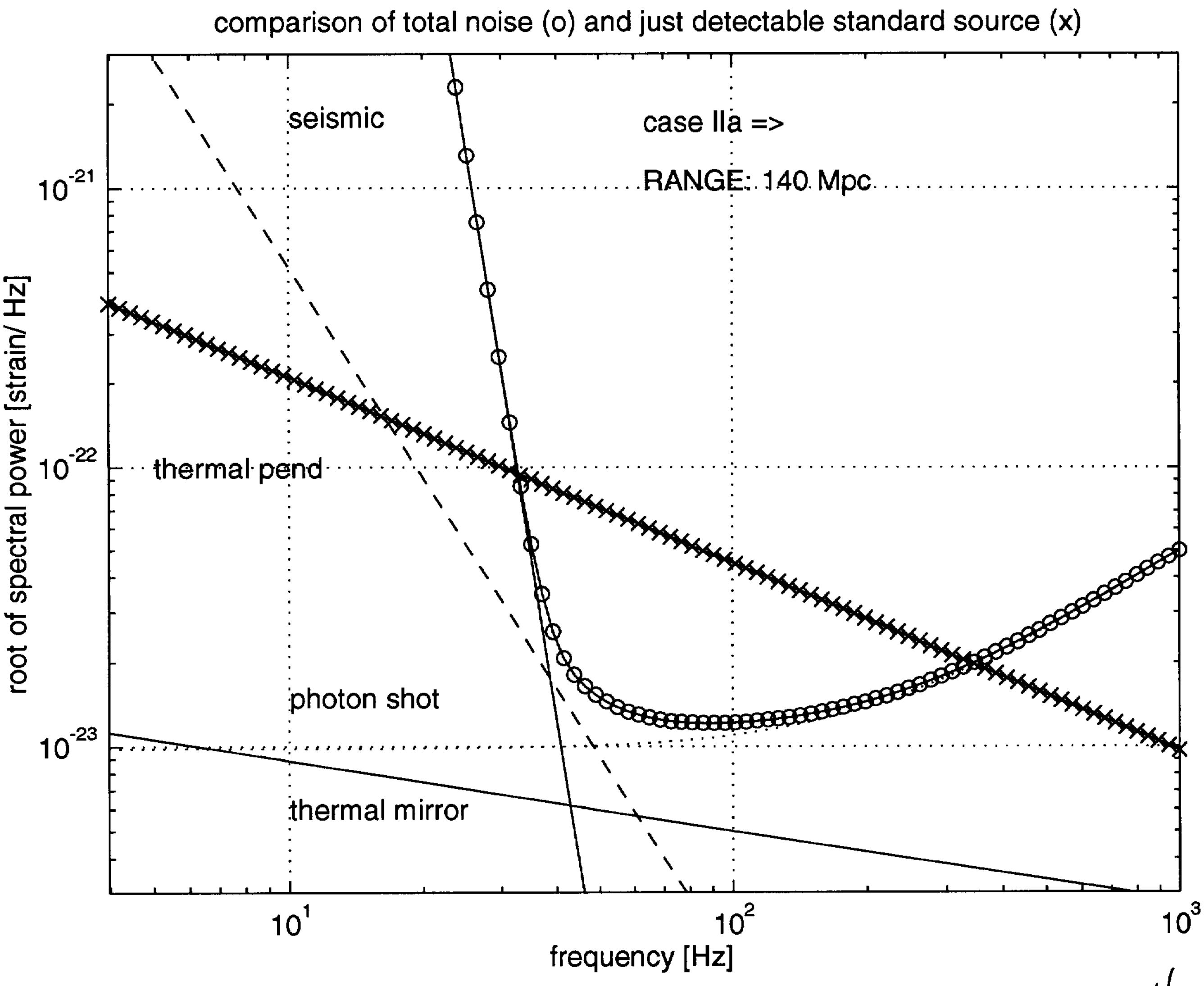
Qp = 1e6

Fused silica mirror



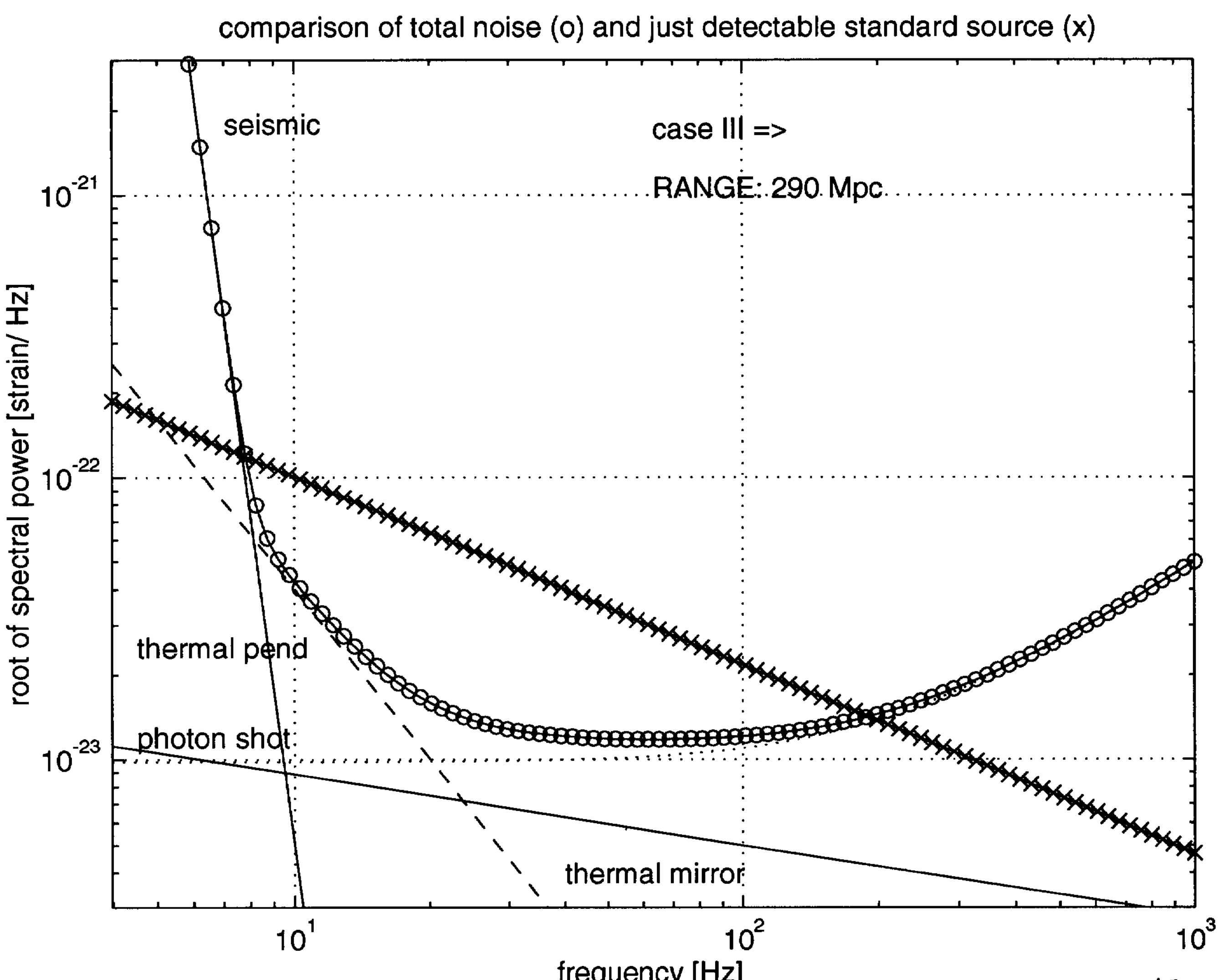
Improvements:

- 10 X Laser Power
- sapphire mirrors (assume $\sqrt{Sx}$ reduction by 5)
- Qp = 10^8 and structural
- add extra stage



Advanced

100 W laser
sapphire mirror (5 x better than fused silica)
suspension freq -> 1Hz
7 isolation or suspension stages
Qp = 10^11 at T = 300 K (& viscous damping)
or Qp = 10^9 at T = 3 [seems possible]



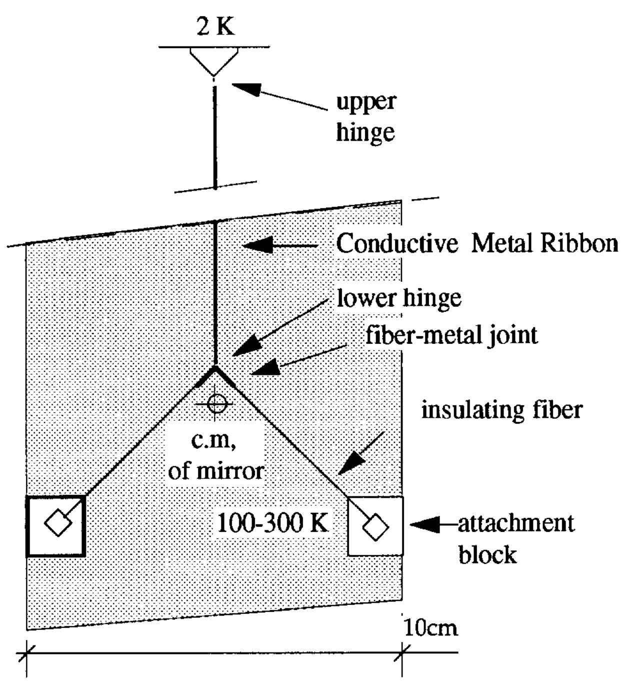
- Case III is apparently impossible to achieve with room temperature mirror suspension. [ref Kovalik and Saulson]
-
- ==> forced towards cryogenic mirror suspension
-
- Seismic noise wall needs to move down to 8 or 9 Hz, so suspension frequencies need not be much below 1 Hz.
- assumed sapphire mirror thermal noise matches the shot noise
- [radiation pressure noise is almost equal to pendulum thermal noise, so higher laser power is counter productive for low frequency sources]

Pendulum Thermal Noise

- Thermal noise force spectral density S_F (the Langevin stochastic force) is proportional to T/Q
- Temperature reduction might decrease S_F by a factor of 300K / 3K = 100
- But also reducing T often <u>also</u> increases Q
  - Thermoeleastic damping (the limit for most room temp metals) is gone at low T [see graph]
  - Two or three orders of magnitude improvement in other loss mechanisms is typical
  - [fused quartz is an exception]
- Some Al alloys and Cu alloys (including BeCu) have Q > 30 million at 3 K

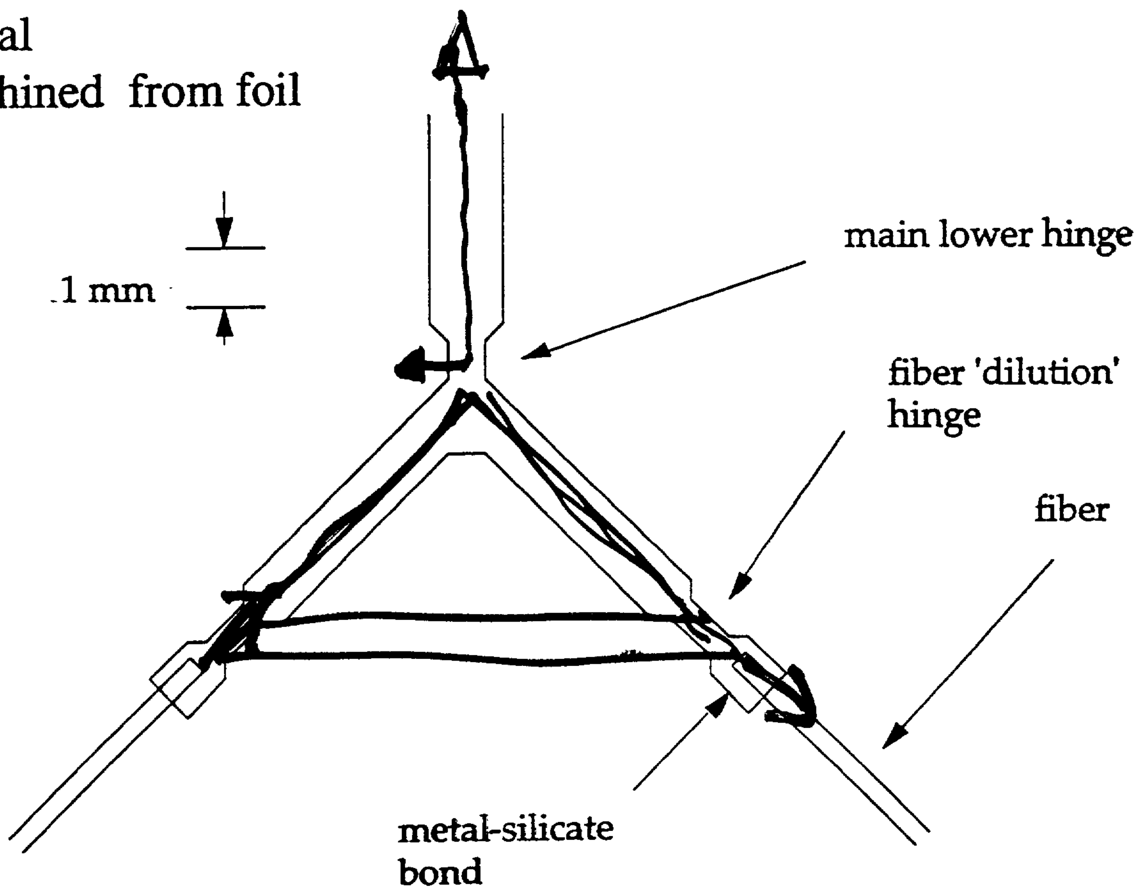
Cold metal suspension

- Only the suspension 'hinges' need to be cooled
  - This is where the noise forces on mirror CM are generated.
- Use long conductive metal suspension wire to cool the hinge
- <u>Insulate lower 'hinge' with fused silica fiber bridle</u>
- Keep mirror warm (290 K)



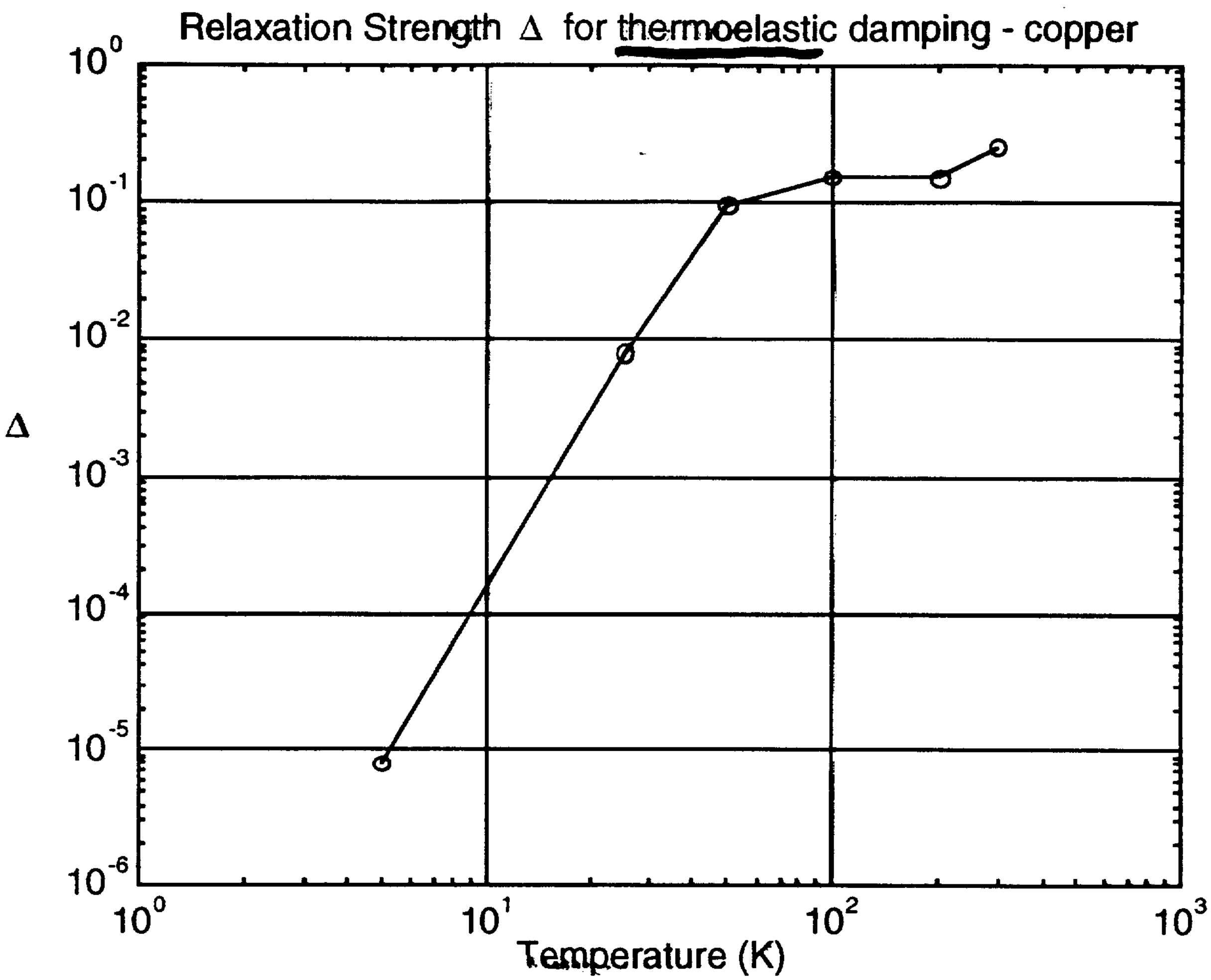
Dissipation dilution

BeCu metal
micromachined from foil



- elastic dilution factor = Utot/Uelastic — Q_P
- estimated dilution factors — Q_{met}
  - main hinge -- 300 x 100 (elastic & temperature) — $10^7 \rightarrow$ — 3×10^{11}
  - fiber flex -- 30,000 — $10^7 \rightarrow$ — 3×10^{11}
  - fiber stretch -- 5,000 (not enough!) — 5×10^{10}

$$\Delta = E \frac{\kappa^2}{C_v} T$$



Metal-silicate bonding

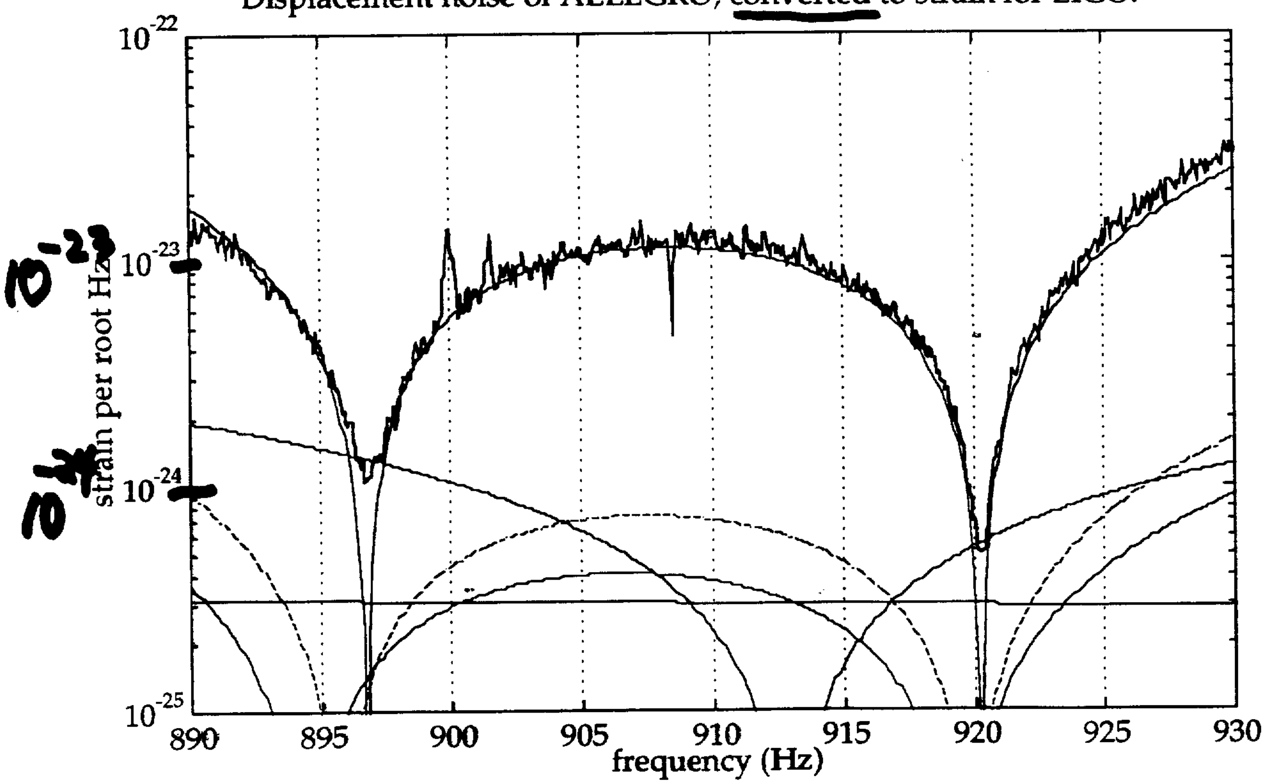
- Phil Adams has recently discovered a metal film that adheres extremely well to silicate glasses. He will test to see if it bonds as well to fused silica.
- A filler metal can then be bonded to the adhesion layer, and the filler bonded to the BeCu.
- These could be very high Q bonds (simple calculation suggests this)

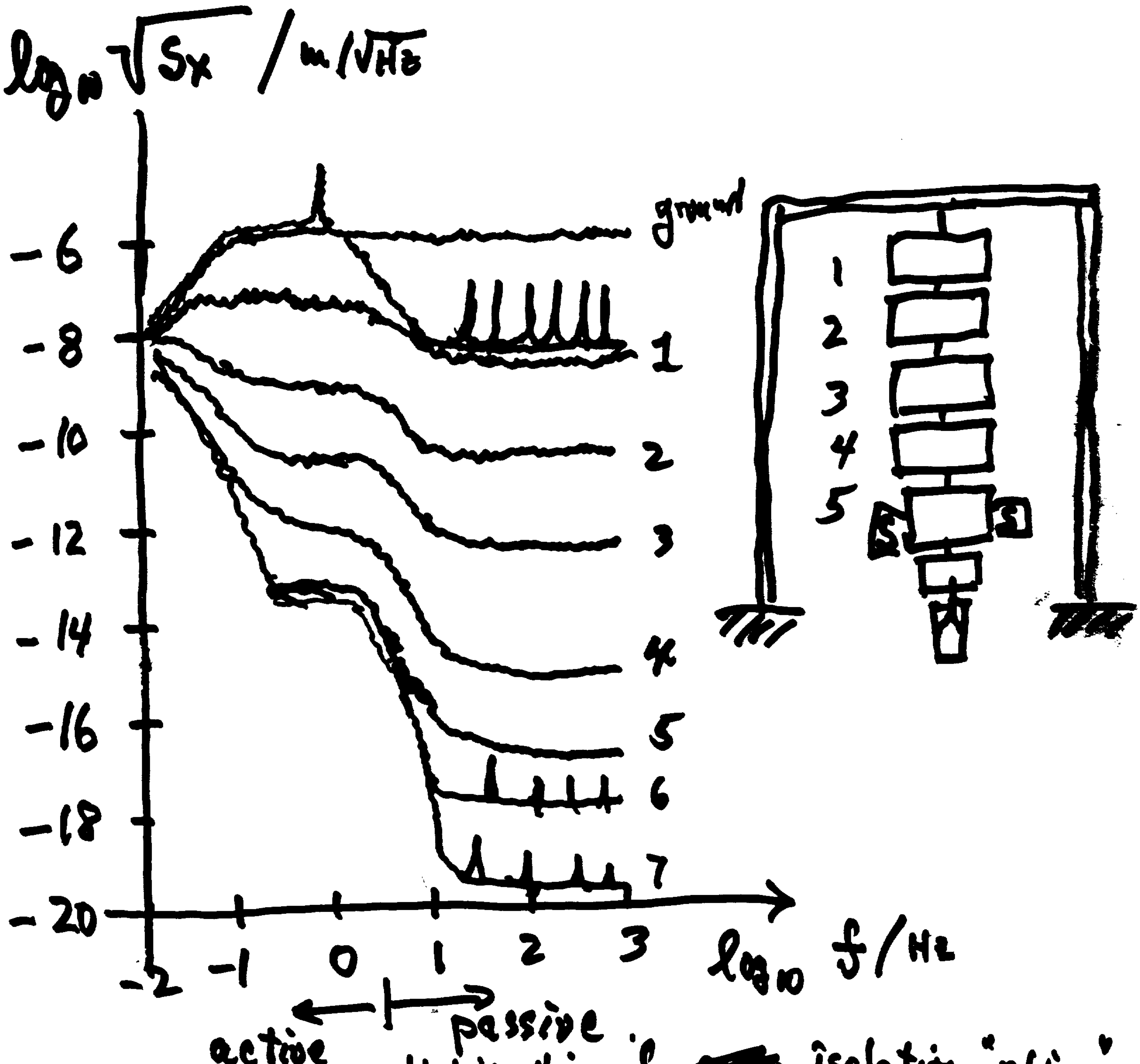
Low frequency seismic isolation. Prototype construction proposed

- works warm, or cryogenic
- 1 Hz suspension frequencies in all DOF
- passive isolation at 10 Hz and above - 50dB worst case
- active isolation from 0.005 Hz to 5 Hz
- combine the best features of VIRGO, JILA, and ALLEGRO isolators
- (over a narrow bandwidth ALLEGRO is one order better than needed)

$$\text{"}h\text{"} = \frac{\Delta l_{bar}}{4000\ m}$$

Displacement noise of ALLEGRO, converted to strain for LIGO.





distribution of isolation "effort"

Isolation features

- Guiding principles :
  - Use the simplest possible mechanics
  - Use many sensors and actuators to synthesize the mechanical response needed
- Choices considered for mechanical architecture:
  - LIGO stacks and downtube
    - 4 stacks per stage, many springs/stage
    - hard to reduce compression springs to 1 Hz
  - Virgo hanging stack
    - single vertical rod provides isolation for 5 out 6 DOF
    - 1 stack per stage
    - low frequencies easier
  - JILA nested stack
    - not enough stages
    - requires 3 vertical springs/stage

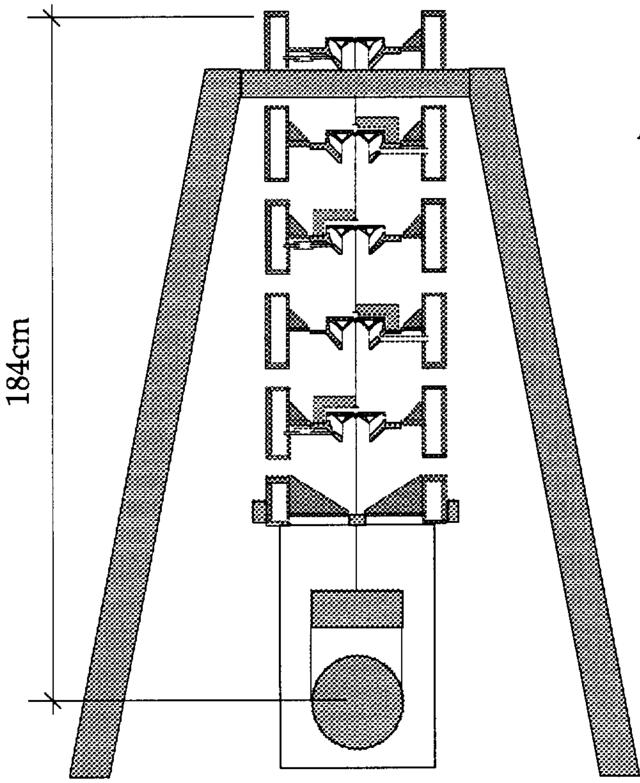
- VIRGO geometery looks simplest
- use following VIRGO features
  - top-down geometry
  - ~100 kgm / stage
  - single vertical rod/stage for compliance in 5 of 6 DOF
  - single vertical spring/stage
- differences from VIRGO
  - 25 cm stage length, instead of 100 cm
    - => 1 Hz horizontal frequency
  - use gas spring for vertical compliance (mechanically simpler, easier to get low frequencies, low stresses)
    - use height sensors as very sensitive thermometers
    - use heaters to control height
    - gas spring have best ratio of spring mass/load,which allows more attenuation/stage
    - Fall-back position: use the VIRGO blade springs

- ACTIVE CONTROL OF EVERY DOF in stack.

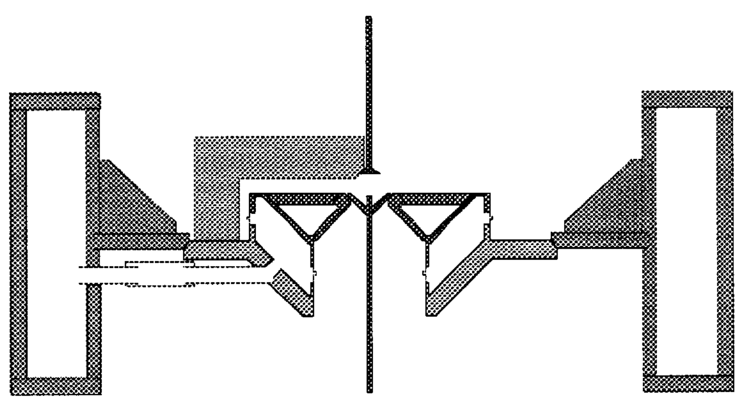
- Inertial reference for stage 5.

- use following JILA features
  - a local inertial mass as reference to stabilize the platform
  - distribution of control to many stages cascade
    - allows lower isolation/stage
- differences from JILA
  - will search for a better feedback topology
    - one easier to stabilize
    - with reasonable tolerance for gain drift and sensor offset
  - proposal: follow the leader (the quiet ref mass)
    - intuitively it works
    - simplified model works
    - Realistic model?
  - on paper, RF capacitor displacement sensors have
    - best commercial displacement sensors are capacitive(e.g. Queensgate), cost \$3K/channel, and have 10^{-12} meters/$\sqrt{\text{Hz}}$
    - some improvements lead to < 10^{-13} meters/$\sqrt{\text{Hz}}$?
- use ALLEGRO features
  - stringent mode control to 2 kHz
  - near monolithic construction
  - all welded or soldered joints (no loadbearing screws)
  - no high stresses ($\sigma <= 0.25\ \sigma_y$)

Schematic design



Active Pendulum
Isolation System



- 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 out of the way completely. Cryogenic piping is removed are reconnected through standard Conflat flanges.

Note 1, Linda Turner, 04/20/98 05:27:10 PM
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