Incremental improvements in the initial interferometer: estimates of mid frequency noise one could achieve in LIGO after S5

R. Weiss; August, 2005 (Revised Sept 6, 2005, Sept 9, 2005)

The note discusses improvements that could be made in the initial LIGO noise spectrum at frequencies in the band 50 to 150Hz with modest changes in the system. There has been some work on estimating the improvements that could come from using a higher power laser and a DC readout for the antisymmetric gravitational wave signal. Both of these steps would be in the direction of technology development for advanced LIGO. This note concentrates on the improvements that would enhance the amplitude sensitivity in the band for the detection of black hole coalescences.

The improvements that could be possible with new suspension fiber materials and geometries are discussed. There would also need to be a change in the test mass coil drive and bias electronics with low temperature operation of the series current limiting resistors and revised input stages in the opamp/PA85 circuits. To open more low frequency bandwidth, an external elastomer filter to reduce the transmission of pillar oscillation would be useful. No one of the changes being considered is a big step but in combination they could result in a factor of 3 to 4 improvement in amplitude sensitivity over the SRD in this critical band for the detection of black hole coalescences.

Suspension Thermal Noise.

Table 1: Fiber material properties for Zener damping at 300K

material	Young's modulus	density	tensile strength	useful tensile strength	poission's modulus	specific heat	thermal conductivity	expansion coeff.
	dynes/cm^2 1 x 10^{12}	gm/cm^3	dynes/cm^2 1 x 10^9	dynes/cm^2 1 x 10^9		erg/gmK 1 x 10^6	erg/sec/cmK 1 x 10^6	1/K 1 x 10^{-6}
fused quartz 1	0.73	2.2	0.48	0.48	0.17	7.4	0.138	0.55
fused quartz 2			0.94	0.94				
fused quartz 3			7.7	7.7				
fused quartz 4			9.0					
sapphire	3.4	3.98	21	7.0	0.29	7.5	3.7	5.8
boron	4.1	2.57	36	10				
steel (LIGO)	1.76	7.8	13.4	6.71		4.5	4.6	11
invar	1.46	8.0	7.07	6.6		5.0	1.0	1.7
super invar	1.44	8.15	4.8	2.8	0.23	5.0	1.3	0.63

fused quartz 1: GE tables
fused quartz 2: Cagnoli et al PRL **85** 2442 (2000)
fused quartz 3: Planned LIGO suspension
fused quartz 4: Achieved at Glasgow (Norna Robertson) in round fibers (number given is 1/2 breaking stress)
steel(LIGO) wire used in current test masses diameter is 0.30 mm, tensile strength listed is 1/3 breaking stress
invar: data from tables provided on the web by Goodfellow. Paper by Cagnoli et al Physics Letters A **255** 230 (1999) shows upper limits and large spread in values for mechanical loss. No information about sudden stress realease and acoustic excitation. Need to look at super invar and to try a pendulum violin mode damping experiment for both invar and super invar.

Thermal noise from the pendulum support for 4 test masses given in terms of equivalent interferometer displacement noise is

$$x(f) = \left(\frac{2k\,T\,g}{m\,L\,(\pi f)^5}\right)^{\frac{1}{2}}\left(\frac{Y\,N\,\kappa^2 A}{2mgL^2}\right)^{\frac{1}{4}}\varphi(f)^{\frac{1}{2}}$$

where

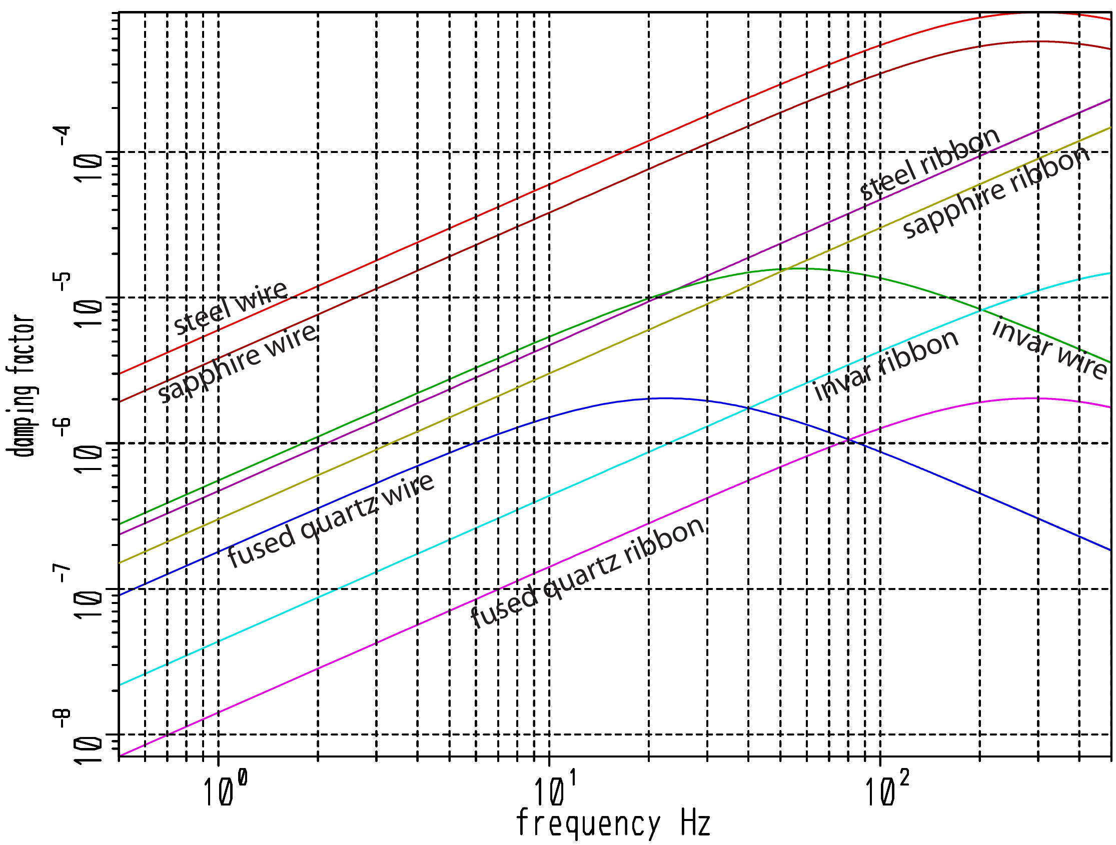
$x(f)$	equivalent displacement spectral density $m/\sqrt{Hz}$
k	Boltzmann's constant
T	temperature in K
g	acceleration of gravity
m	mass of the pendulum
f	frequency
Y	Young's modulus of elasticity of the material
L	length of the pendulum support
N	number of supports = 2 in all the calculations
A	cross-sectional area of support fiber
κ	support fiber radius of gyration = $(\frac{1}{A}\int z^2 dA)^{\frac{1}{2}}$
$\kappa^2 A$	circular wire diameter d: $= \frac{\pi}{64}d^4$, ribbon with width w and thickness d: = $\frac{wd^3}{12}$
$\varphi(f)$	dissipation factor of the fiber material at frequency f
k_{th}	thermal conductivity of the fiber material
c	heat capacity per gm
ρ	density of the fiber material

For circular fibers the diameter is given by $d = \left(\frac{4mg}{\pi S}\right)^{\frac{1}{2}}$ where S is the maximum allowed tensile stress. The corresponding relation for a ribbon is $d = \frac{mg}{SwN}$. The load per fiber assumed in all the curves is 5kg with N = 2 and the aspect ratio for the ribbons, w/d, is assumed to be 10/1

If the dissipation is thermoelastic damping (the Zener mechanism), the loss can be calculated from the tabulated values used in the following expression,

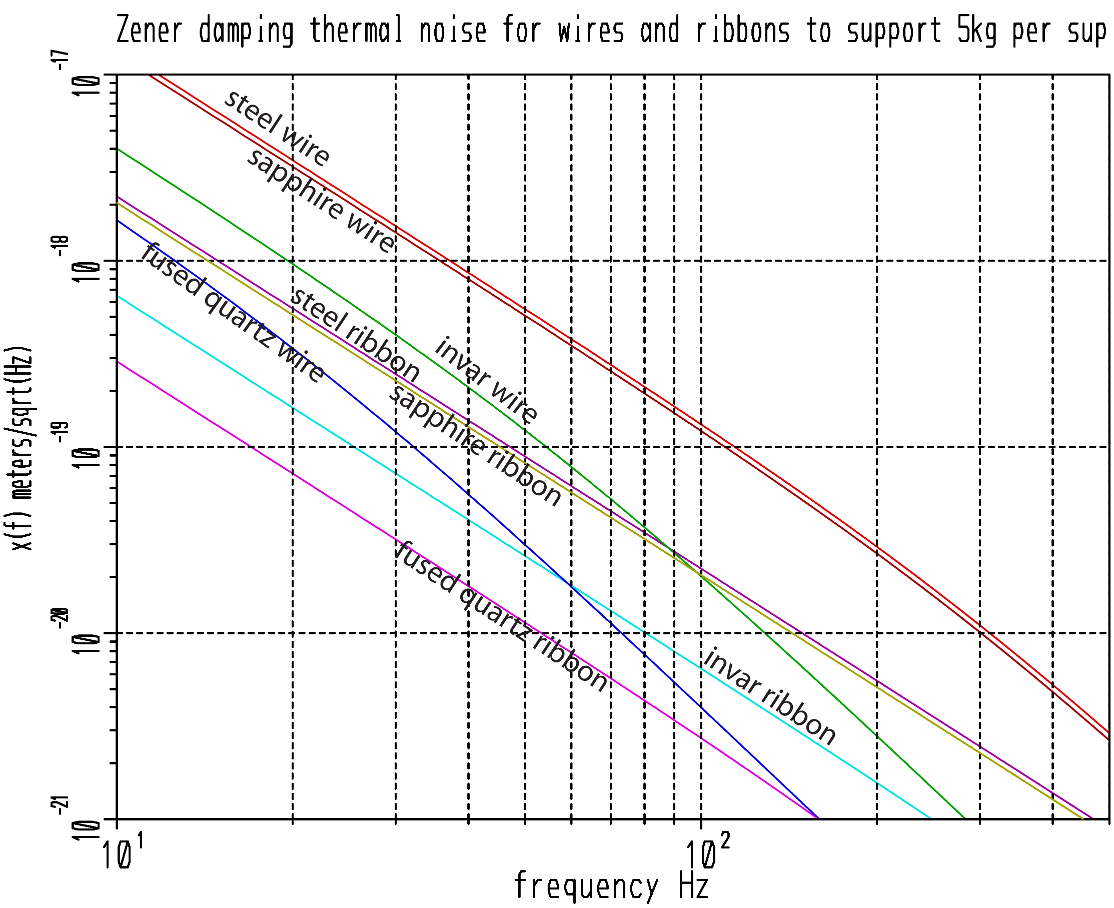
$$\varphi(f) = \frac{TY\alpha^2}{C\rho}\left(\frac{\sigma f}{1+(\sigma f)^2}\right) \quad \text{where} \quad \sigma = \left(\frac{2\pi}{13.55}\right)\left(\frac{c\rho d^2}{k_{th}}\right)$$

Zener damping for wires and ribbons to support 5kg/support



The interesting thing to note is that the steel fibers now in the test mass suspensions cannot have a damping factor less than 9 x 10^{-4} around 200 Hz since this is the value predicted by the Zener mechanism. The plot above does not include the additional contribution to the losses from structure damping. Without these invar looks like an attractive material. The loss data for invar in the Cagnoli et al paper lies between 0.8 to 1.6 x 10^{-4} in the 10 to 400 Hz band. The data is distributed without a discernible pattern and looking at the data for other materials in this paper, it could well represent an upper limit rather than a measurement of the dissipation. Violin mode Q of invar round and rectangular fiber are worth measuring again. The wire and ribbon can be purchased from Goodfellow or Espimetals. A possible hazard with invar is that it is ferromagnetic although we have a similar situation with the current steel wires. We should look at the violin mode Q of steel and invar wires and ribbons in the near future.

NOTE: SEPT 9, 2005 found factor 1.4 error in ths plot. All values need to be divided by 1.4



For the same tensile stress, the violin mode resonances of the round and rectangular fibers are not the same. The rectangular fibers will have different frequencies for the modes that bend along the thin and the wide ribbon directions. The resonance frequencies are given by

$$f_n = \frac{n}{2L}\left(\frac{T}{A\rho}\right)^{\frac{1}{2}}\left(1 + 2\sqrt{\beta} + \left(4 + \frac{n^2\pi^2}{2}\right)\beta + ...\right) \qquad \text{where}$$

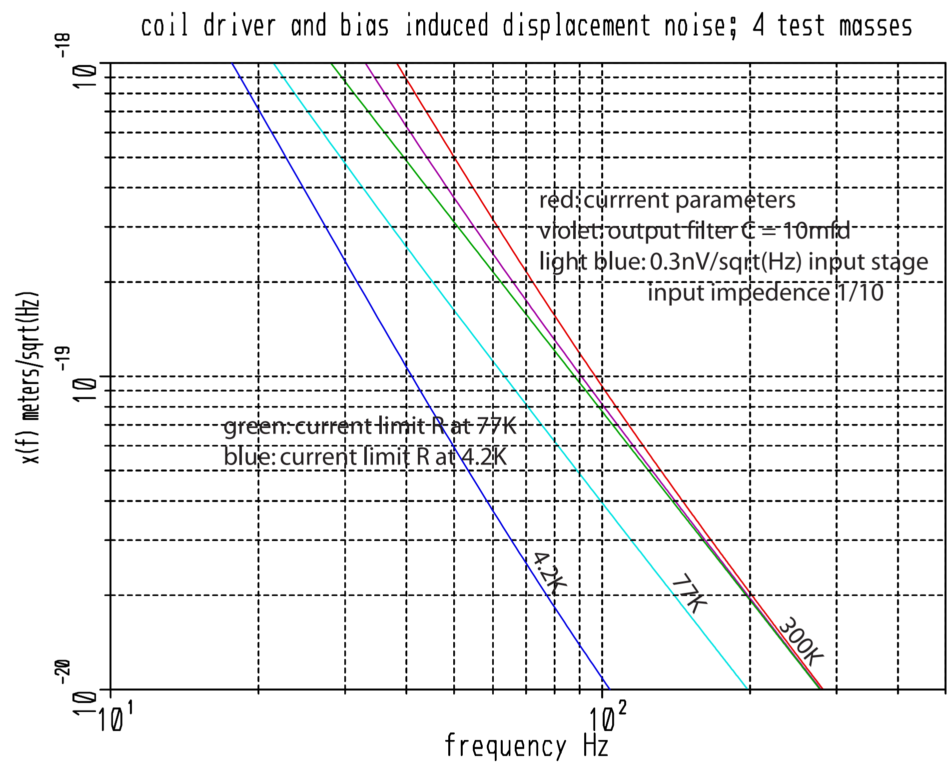
$$\beta = \frac{Y A \kappa^2}{T L^2}$$ n = harmonic number, T the tension in the fiber.

The radius of gyration, κ depends on the bending mode of the rectangular fiber with the fiber being stiffer for bending along the wide dimension. The table shows the stiff wire frequencies for a round as well as a rectangular stiff steel fiber bending along the hard and the easy dimensions. The load is 5kg and the fiber length 45 cm. The table shows that the ribbon does not cause the violin resonances to become unmanageable, but there are now more non-degenerate modes.

Table 2: Violin mode frequencies

mode number	round wire	rectangular fiber (easy)	rectangular fiber (hard)
	d = 3.0 x 10^{-2} cm	w= 8.4 x 10^{-2} cm, d = 8.4 x 10^{-3} cm	d= 8.4 x 10^{-2} cm, w = 8.4 x 10^{-3} cm
1	333.01	331.8	337.4
2	666.11	663.6	675.6
3	999.9	995.5	1015.2
4	1332.7	1327.7	1356.9
5	1666.0	1659.0	1701.6

Electronics noise



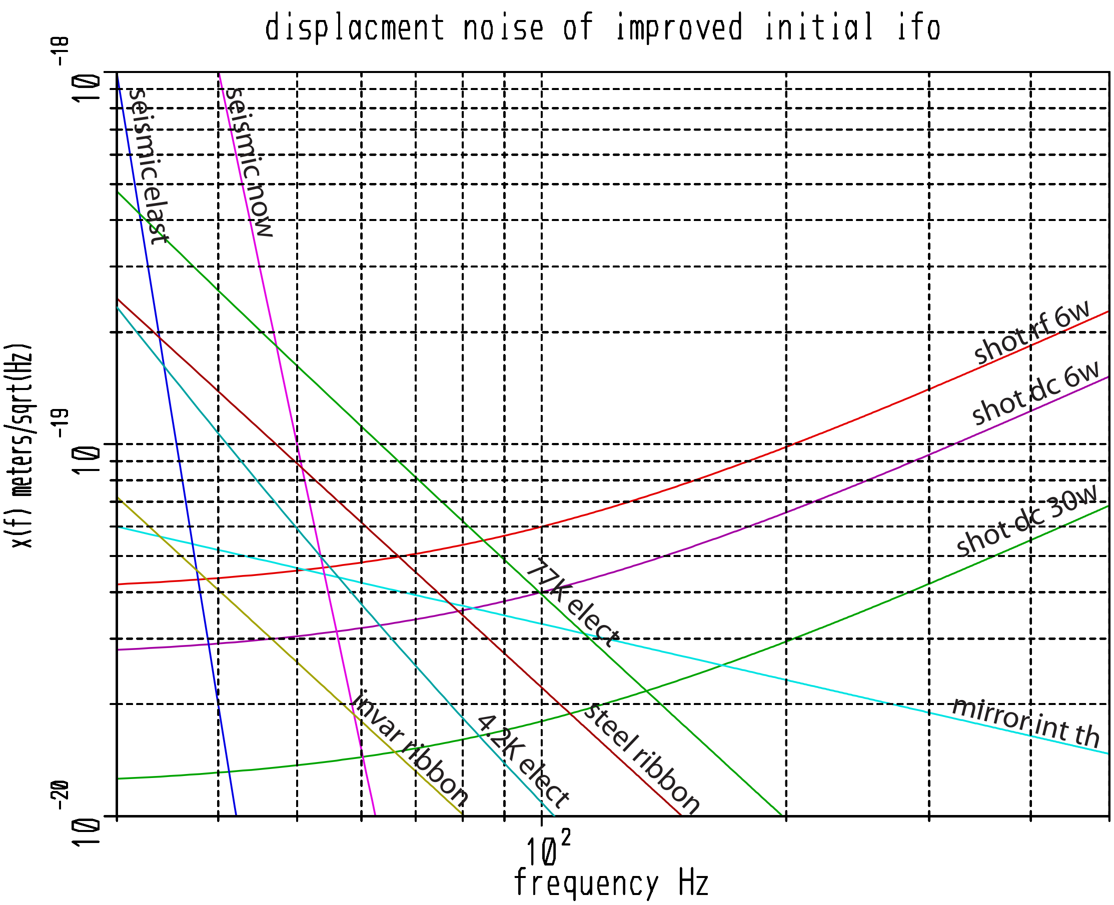
The electronics noise would need to be reduced in the bias and coil driver circuits to gain past the SRD. The figure shows a set of steps that could be taken to improve the noise. If one assumes that the same current range is needed to hold the interferometer in lock, it will be necessary to keep the same current limiting resistors in the bias and coil driver circuits. One could increase the voltage but we are already plagued by high voltage troubles with 150 volts. The parameters for the curves in the figure are

Table 3: Circuit parameters for the curves above

curve	V(f)	i(f)	rin	rf	r1	r2	C	rb	Tsr
color	nv/sqrt(Hz)	famp/sqrt(Hz)	ohms	ohms	kohms	kohms	mfd	kohms	K
red	3	1000	470	7200	3	4	5	7.2	300
violet	3	1000	470	7200	3	4	10	7.2	300
green	0.3	10	47	720	3	4	10	7.2	300
light blue	0.3	10	47	720	3	4	10	7.2	77
blue	0.3	10	47	720	3	4	10	7.2	4.2

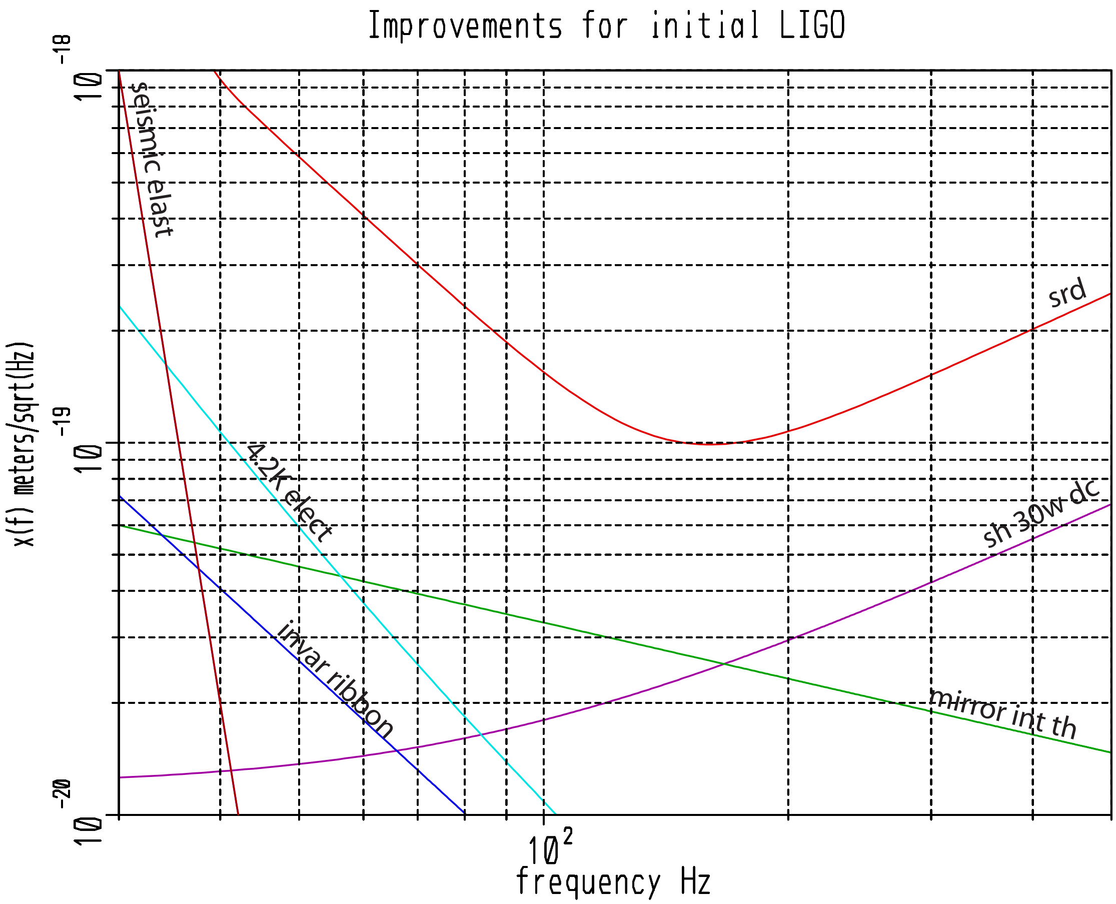
The red curve is the present situation. The most significant changes occur with a new front end amplifier for the PA85/LT1128 pair. A trial amplifier with the voltage and current noise needed has been tested. One envisions a daughter card put into the coil driver chassis which includes the low noise FET front end for each of the channels. The present coil driver circuit will not need to be rebuilt. The feedback resistor at 720 ohms is low and it may be necessary to change the relay for acquisition with an additional pole to allow switching to a higher impedence during acquire. The most perturbative change is that the series resistor for the bias and the coil driver will be operated at cryogenic temperatures. It may be enough to operate the resistors in liquid nitrogen storage dewars with several month lifetimes before refilling. Operation at liquid helium temperature will require more thinking. It would be most convenient to not transfer helium. The physics teaching laboratories at MIT have used liquid helium storage dewars for immersable experiments for many years,. the students never transfer helium. The storage dewars have wide mouths (2 inch diameter), a 50 liter dewar will last about a month. Liquid hydrogen at 20K, and higher enthalpy than helium, would serve well but will probably be considered too hazardous. Note: the estimated noise assumes that the bias module itself is filtered well enough not to generate any noise more than the thermal noise of the cooled current limiting resistor. The circuits currently do not have this property but there is no reason that they cannot be modified with enough filtering to be noise free in the 50 to 300 Hz band.

Overall performance improvement



The seismic curves come from estimates made by Rana in July 2005 in preparation for a document he and Peter Fritschel are preparing for the LIGO project. The seismic curves may become noisier when full account is taken of the material properties of the VITON. The curves are determined measuring the seismic noise at the cross beams of the test mass chambers and multiplying by the transfer function of the stack system provided by Hytec. This model did not take into account the stiffening with frequency of the imaginary part of Young's modulus of the VITON. Actual measurements of this transfer function in situ at the sites would be useful both for the planning as well as the current noise modeling. The seismic curve labelled seismic elastomer is a concept that Rana has been considering in which an extra stage of elastomer isolation is applied externally between the support pillars and the cross bars. This additional stage may also be useful for advanced LIGO to make it easier to achieve the Advanced LIGO goal since the "amplification" of horizontal ground motion by the undamped pillar was neglected in the initial Advanced LIGO isolation system modeling.

I do not know the basis of the mirror internal thermal noise curve, this is the curve used in the noise modeling. I do not know if it includes the estimates for the coating mechanical loss. The three shot noise curves come from the estimates made by Rana in July 2005. The SRD curve should be in the figure but there are not enough plotting curves allowed in the program I am using. It is incorporated in the next figure which shows the “best” we could accomplish with the changes being considered. The suspension fiber loss is assumed to be only Zener damping.



The figure above shows the best one could hope for with the incremental changes being considered. It seems from the prior calculations that the electronics noise will dominate in the interesting observation band, so that steel ribbon or invar wire fibers may be enough to achieve this best case performance.

Summary and recommendation

At this moment we are still not at the SRD in the frequency band being considered. I assume that we will learn the nature of the problem we are facing during the S5 run since this will provide a good body of undisturbed data to analyse for detector performance. We may yet find that the dominant problem is scattering in this band. This will be very important to know both for any improvements being contemplated in the initial detector but even more important for Advanced LIGO. Knowing more, and especially getting better performance at these frequencies to find the problems at these frequencies, is in my opinion critical to a successful Advanced LIGO program.

In order not to miss opportunities that will open to us after the S5 run, it is important to prepare now for the possible changes that could be made. At the minimum we should determine the damping in the current steel fiber as well as in steel ribbons and invar wire and ribbons. If the prior estimates are correct there is no real advantage in going to fused quartz for these interim improvements. We should look hard at the changes that would need to be made in the coil driver and bias module electronics. These two programs are not currently in direct line with Advanced LIGO (though their results if applied and successful would be important in giving confidence that the Advanced LIGO is on the right track). The changes in laser power and the possible use of the DC fringe interrogation system are part of the current Advanced LIGO and there will be little controversy in going forward in these two directions. The elastomer improvement to the seismic isolation at the top of the support pillars could benefit both the interim improvements and ease the design of the Advanced LIGO isolation system. If the real problem is scattering, it may help a lot now.