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Proposal for baseline change from ribbons to fibres in
AdvLIGO test mass suspension monolithic
stage

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1 Introduction

1.1 Purpose and Scope

The suspension conceptual design for AdvLIGO, T010105-03, specifies a baseline of fused silica ribbons in the monolithic stage of the test mass quadruple pendulum, but notes that (round) fibres with a “dumbbell” profile could give comparable performance and could be considered as a fallback. This document makes the case that the baseline should be changed to dumbbell fibres for both the LASTI noise prototype and the final design.

1.2 Version History

4/09/08: Pre-rev-00 draft #1.

1.3 References

T020205-02, Models of the Advanced LIGO Suspensions in Mathematica™, M.A. Barton.

T010007-03, Cavity Optics Suspension Subsystem Design Requirements Document, M.A. Barton et al.

T050215-01, Monolithic Stage Conceptual Design for Advanced LIGO ETM/ITM, C.A. Cantley et al.

T010103-05, Advanced LIGO Suspension System Conceptual Design, N.A. Robertson et al.

T060283-02, Note on Design of the ETM Reaction Chain and ITM Reaction Chain in Advanced LIGO, N.A. Robertson

T020003-00, Dumbbell Shaped Fibers for Advanced LIGO Suspensions, P.A. Willems

P020040-00, Dumbbell-shaped fibers for gravitational wave detectors, P. Willems

Effects of nonlinear thermoelastic damping in highly stressed fibers, G. Cagnoli, P.A. Willems - Physical Review B, 2002 - APS

1.4 Glossary of symbols

In the discussion below the following symbols are used. The values are from IFOModel v4.1, except for Y , C , and l , where we use values recommended by Heptonstall. (These updated values have been approved for incorporation in a forthcoming update to Bench.)

Y : Young’s modulus of wire/ribbon/fibre material – 7.2×10^{10} for silica (IFOModel has 7.0 in the calculation of the stiffness and 7.27 in the calculation of the thermoelastic noise. New value is from spec sheet on grade of silica to be used.)

σ : maximum safe working stress – 7.7×10^8 for silica

D : dissipation dilution factor – a few 100 to a few 1000 depending on geometry and material

l : length of wire/ribbon/fibre – approximately 600 mm

m : mass of optic – 39.57 kg

ρ : volumetric mass density of wire/ribbon/fibre material - 2200 for silica

ρ_L : linear mass density of wire/ribbon/fibre

t : thickness of ribbon

W : width of ribbon

r : radius of wire/fibre

A : area of wire/ribbon/fibre

C : specific heat of wire/ribbon/fibre material – 770 for silica (IFOModel had 772; new value is from spec sheet on grade of silica to be used.)

K : bulk modulus of wire/ribbon/fibre material – 1.38 for silica

T : temperature – 290 K

α : thermal expansion of wire/ribbon/fibre material – 3.9×10^{-7} for silica (IFOModel had 5.1, but this is high according to measurements by Heptonstall and Willems)

$\beta = \frac{1}{Y} \frac{dY}{dT}$: 1.52×10^4 for silica

ϕ : bulk loss – 4.1×10^{-10} for silica

d_s : surface loss factor – 1.5×10^{-2} for silica

τ : thermoelastic time constant

δ : thermoelastic damping factor

$N = 4$: number of wires

g : local gravity – 9.81 m/s^2

2 Theory

The choice of fused silica in the first place, and thereafter of ribbons vs. fibres, is driven by the following factors:

- Load bearing capacity
- Bounce mode frequency
- Violin mode frequency
- Pendulum mode thermal noise

2.1 Load capacity

The load capacity is set by the strength of the material and the cross-section at the thinnest point. A safe loading with adequate margin is considered to be 770 MPa. For a 10:1 ribbon this implies a width of at least 1.1 mm (cf. 1.15 mm for the baseline ribbon) and for a fibre a minimum radius of 0.2 mm (diameter 0.4 mm).

2.2 Bounce mode

The bounce mode is determined by the longitudinal elasticity, which is an average of the cross-section of the wire/ribbon/fibre over the length:

$$k = \frac{Y}{\int 1/A dl}$$

$$f_B = \frac{\sqrt{2}}{2\pi} \sqrt{\frac{Nk}{m}}$$

where the $\sqrt{2}$ allows for the fact that the penultimate mass also moves during the bounce mode, by about the same amount as the optic. The bounce mode frequency is required to be below 12 Hz (T010007-03, p7), and if at all possible somewhat below 10 Hz. The baseline ribbon achieves 9.11 Hz.

2.3 Violin mode

The fundamental violin mode is set by the length, the tension in the fibres and the mass per unit length in the central section:

$$f_v \approx \frac{1}{4\pi l} \sqrt{\frac{mg}{N\rho_L}}$$

The effective length is the actual length less one flexure length at each end. The fundamental violin mode frequency is required to be above 400 Hz (T010007-03, p7). The baseline ribbon achieves 481 Hz in longitudinal and 486 Hz in transverse.

2.4 Thermal noise

The pendulum mode thermal noise is required to be less than $10^{-19} \text{ m} / \sqrt{\text{Hz}}$ at 10 Hz, falling as at least f^2 above that (T010007-03, pp11,13).

The pendulum mode thermal noise is proportional to the product of the loss in the wire/ribbon/fibre material (ϕ) near the ends divided by a dissipation dilution factor (D) that measures the fraction of the energy in the pendulum mode in elastic deformation of the wire/ribbon/fibre material relative to the total energy.

The loss near the ends is the sum of three effects:

- Bulk loss
- Surface loss
- Thermoelastic loss

The dissipation dilution is in general a complicated function of the neck profile. For a neck that transitions instantly from an infinitely stiff base to a uniform section of moment of area I

$$D = \sqrt{\frac{4mgl}{YIN}}$$

This formula assumes identical necks at top and bottom. (For a pendulum mode with little pitch coupling, both necks contribute equally.) Typical values of D range from a few hundred to a few thousand.

2.4.1 Bulk loss

Per Bench, bulk loss is taken to be structural with a constant loss angle

$$\phi_{bulk}(f) = \phi_{bulk}$$

For silica, $\phi_{bulk} = 4.1 \times 10^{-10}$.

2.4.2 Surface loss

Again, per Bench, surface loss is structural with a constant angle

$$\phi_{surf}(f) = \phi_{surf} = \phi_{bulk} \frac{2 \times d_s (3NW + t)(W + t)}{(NW + t)Wt}$$

for ribbons or

$$\phi_{surf}(f) = \phi_{surf} = \phi_{bulk} \frac{4 \times d_s}{r}$$

for fibres. For silica, $d_s = 1.5 \times 10^{-2}$.

2.4.3 Thermoelastic loss

Thermoelastic loss is frequency dependent

$$\phi_{te}(f) = \delta \frac{2\pi\tau f}{1 + (2\pi\tau f)^2}$$

where

$$\delta = \frac{YT}{\rho C} \left(\alpha - \beta \frac{mg}{NAY} \right)^2$$

and

$$\tau = \begin{cases} \frac{\rho C t^2}{\pi^2 K} & \text{ribbons} \\ \frac{0.0737472 \times 4 \rho C r^2}{K} & \text{fibres} \end{cases}$$

3 Optimization of performance

Because silica is much better for all three forms of loss than metals, we are immediately pushed to either ribbons or fibres rather than wires.

Ribbons are better than fibres in terms of dissipation dilution, because the moment of area of a ribbon in the flexible direction is rather lower than that of a fibre of the same cross-section. This was the motivation for concentrating on ribbons originally.

On the other hand, fibres are better for surface loss, because the surface to volume ratio is less (again, for the same cross-sectional areas). (Bulk loss is small in comparison.)

As pointed out by Cagnoli and others, it turns out that because of the terms of opposite signs in the expression for the thermoelastic damping parameter δ , it is possible to contrive a cancellation by choosing the stress appropriately. The optimum stress is in the ballpark of $\frac{1}{4}$ of the maximum safe loading, so this can be conveniently achieved by roughly doubling the thickness and width, or the radius, of the ribbon/fibre. This was *not* attempted for the ribbon design presented in the conceptual design, because the design requirement had already been met. In this document we follow through on the possibility.

If we wanted to minimize the material loss before dissipation dilution, it would simply be a matter of zeroing the thermoelastic loss and exposing the structural loss, mostly in the surface. However since dissipation dilution decreases as I increases, the true optimum is slightly thinner, as well as slightly frequency dependent. We choose 20 Hz as the frequency to minimize at. The various components of loss are plotted as functions of ribbon/fibre dimensions in Figure 1 and Figure 2.

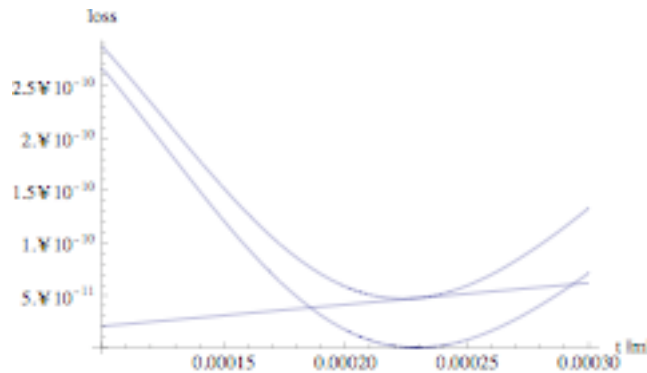


Figure 1: Optimization of total loss after dissipation dilution for 10:1 ribbons (surface+bulk, thermoelastic, total; $t_{\text{opt}} = 0.224$ mm; min. loss = 4.68×10^{-11})

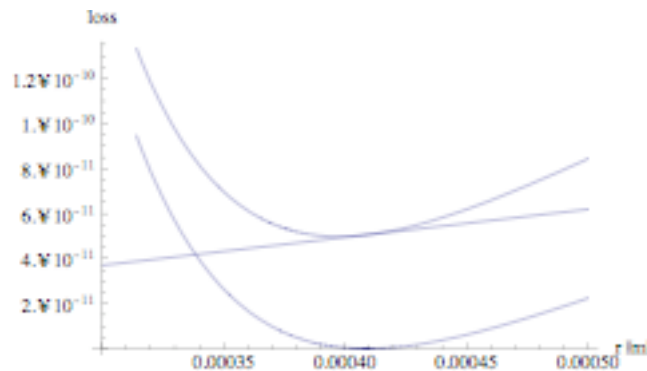


Figure 2: Optimization of total loss after dissipation dilution for fibres (surface+bulk, thermoelastic, total; $r_{\text{opt}} = 0.398$ mm; minimum loss 4.98×10^{-11})

The net result is that the total loss with optimized ribbons is about 5.3 times better than the baseline ribbons (2.48×10^{-10}), but only about 6.5% better than optimized fibres. The frequency dependence of the net loss and the improvement relative to a naïve optimization that merely zeroes the thermoelastic loss is shown for the optimized ribbons in Figure 3. The thermal noise for the baseline ribbons and the optimized ribbons and fibres (as calculated using Mark Barton’s Mathematica model) is shown in Figure 4.

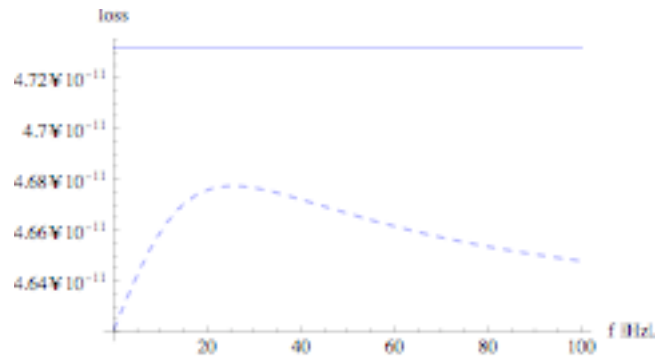


Figure 3: Frequency dependence of loss for optimized ribbons (dashed curve) and comparison to naïve optimization with thermoelastic loss zeroed (solid). Note narrow range of vertical axis (2.3%).

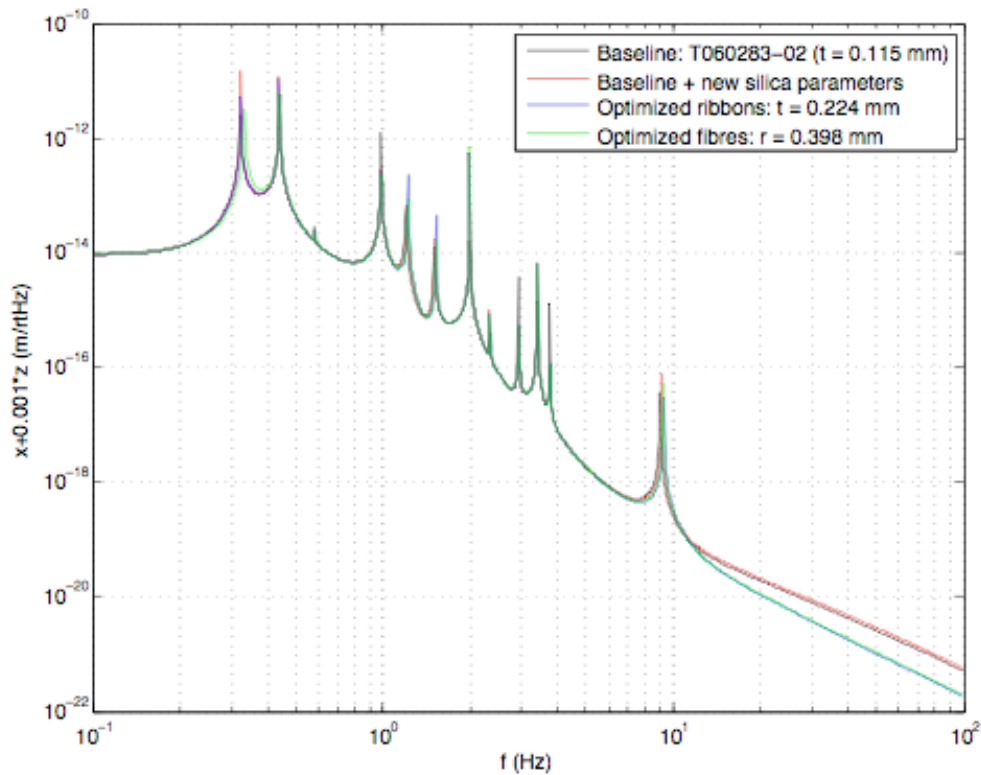


Figure 4: Thermal noise for baseline ribbons with old parameters, baseline ribbons, optimized ribbons and optimized fibres

Given that fibres give nearly as much margin on the requirement as ribbons and have certain practical advantages (see below), this suggests that the decision to go with ribbons should be reconsidered.

4 Practical Issues

The ribbon R&D has progressed fairly well relative to expectations and we are confident of being able to produce ribbons of sufficient strength and of being able to weld them to the ears. However the recipe for good ribbons has turned out to be a very sensitive function of a large number of variables and it will be difficult to reproduce it at LASTI or at the sites without a lot of tweaking by experienced personnel (i.e., Alastair Heptonstall).

Also, work by Alan Cumming and Rahul Kumar (see forthcoming PhD and Master's theses) has shown that the shape of the neck is much more critical than originally anticipated. The ideal ear/neck transitions abruptly from a region of very high rigidity to the dimension optimized for loss, and then a few flexure lengths later to the dimension optimized for bounce and violin mode frequencies. Current ribbon profiles are not very satisfactory in this regard. The slide from which the ribbon is pulled is not very rigid, so the neck length that can be tolerated is shorter than for fibres, whereas the neck length that has been achieved in an otherwise satisfactory ribbon is longer. Very possibly this could be corrected with further work but it remains a technical risk.

By contrast, fibres are extremely simple. The pulling machine was developed for fibres originally, and all the parts required for fibre operation have been delivered to LASTI and could be installed in a day or so. The necessary dumbbelling to keep the bounce mode frequency down and the violin mode frequency up can be produced by simply loading a different pulling velocity profile table. Neck lengths with fibres are naturally of order one radius of the stock material, which should be satisfactory. (With 1.5 cm neck regions and a mid-section cross-section as per the baseline, the bounce mode will be only marginally worse at 9.23 Hz (up from 9.11 Hz) and the violin modes will be marginally better.) Successful welding experiments have been conducted with likely stock material (1.5 and 2 mm rod) and objects with similar thermal mass to the ears.

The follow areas of completed or pending R&D have been considered for possible impacts:

Issue	Notes
Bounce mode frequency	Both optimized ribbons and optimized fibres would require dumbbelling to keep the bounce mode below 10 Hz. The thicker neck regions would only need to be about 1.5 cm long and the bounce mode would increase only very slightly, to around 9.2 Hz. Transitioning from thick to thin is simpler for fibres.
Violin mode frequency	Dumbbelling for the bounce mode would also raise the violin mode frequency slightly (i.e., a minor improvement), because extra mass at the ends has almost no effect, but the extra stiffness does.
Flexure correction	For the NP, ears are already in place to give effective $d_3 = d_4 \approx 1\text{mm}$ for ribbons. Achievable d 's with fibres and these ears are likely to be a few mm larger, increasing stiffness in pitch, but Peter Fritschel and Matt

	Evans from SYS have said this would be an interesting area of parameter space to explore.
Interface with RAL structure	Unchanged
Masses	Unchanged
Handling masses	Unchanged
Cleaning	Unchanged
Current ears	Ears have already been attached to the NP masses and there is no time to change them out. The current ears are probably not optimum for having fibres welded but are almost certainly usable. If laser welding fibres proves difficult, we have a electrolytic flame welding setup in place for use as a fall back.
Ear redesign	Some ear redesign needs to be done anyway because preliminary results of FEA work by Cumming and Kumar suggest that the current ears may not be stiff enough and may significantly degrade the dissipation dilution. Features to make it more convenient to weld fibres can be incorporated at the same time.
Ear cleaning	Probably unchanged.
Ear bonding templates	Minor changes in conjunction with post-NP ear redesign.
Bonding procedure	Probably unchanged
Ear bonding inspection	Unchanged
Prisms for penultimate mass	Probably unchanged, unless incorporated with ears in post-NP redesign.
Prism cleaning	Unchanged
Prism holders	Unchanged
Prism template	Aim to merge with ear template in post-NP redesign
Prism bonding procedure	Unchanged unless incorporated with ears
Proof/Bounce testers	If for some reason the “fuse” of stock material needs to be longer, both the proof and bounce tester cabinets would need to be reworked to be taller.
Profiler	Mostly unchanged. Could take the opportunity to exchange lenses to optimize resolution now that stock is ≈ 3 mm in both directions rather

	than 5 mm x 0.5 mm. If “fuse” cartridge needs to become longer, would need to swap out short ballscrew unit (Glasgow profiler only).
Pulling machine	LASTI unit would have to have dithering galvo removed and fibre-pulling attachment fitted (parts already at MIT; simple job)
Pulling machine clamps	Minor redesign required – already underway
Fuse cartridge gluing jig	Redesign required, but simple.
Welding fixture	Minor redesign required. (The possibility of changing the baseline has been kept in mind for some time.)
Welding setup (articulated arm, steering mirrors, baffles)	Unchanged.
Welding procedure	Probably no more difficult, and ribbon welding R&D is not particularly mature in any case.
Ribbon/fibre cutting tool	Currently being designed – will be dual use.
Fibre recipe	Trivial compared to re-debugging ribbon recipe for LASTI copy of pulling machine.
Neck shape	Preliminary results suggest rapid transitions from stock to end-section and end-section to mid-section are likely to be much easier with fibres.
Strength	Ribbons require onerous flame polishing of stock to approach strength of material (probably due to surface defects from mechanically polished slides). Fibres are much easier to make strong.
Schedule	Probable net time saving.

5 Conclusion

Fibres should have nearly as good performance as ribbons (very likely better when the effects of necks are taken into account), with much lower technical risk. Therefore it is propose to change the baseline to ribbons, effective as of the NP build in (hopefully) June 2008.