LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

- LIGO –

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Path-finding towards a cryogenic interferometer for LIGO

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Abstract

LIGO is exploring cryogenics as the ultimate weapon to reduce the thermal noise of mirrors and suspensions in Gravitational Wave Interferometric Detector (GWID). Some of the cryogenic or cryogenic related R&D made in LIGO are reported here. Some of the techniques being considered to make cryogenics possible may become useful even for room temperature detectors.

Introduction.

In the summer 2000 I was given the homework to explore the technical future of LIGO, with particular emphasis on cryogenics.

In the course of this study I arrived at some conclusions, some, obvious, at least a posteriori, some surprising. The content of this presentation should be regarded as no more than my very preliminary findings and, in part, my prejudices.

What is almost obvious is that the ultimate GWID will include cryogenics, what is less obvious is what will it look like.

So far the only serious and coordinated cryogenic GWID development effort is represented by the LCGT project[1] in Japan.

It should be noted though that the modern bar GW detectors[2] are cryogenic and their technology is well developed, but the technical problems involved are intrinsically different because they do not deal with any significant internal power dissipation.

From the necessity or large advantage of running GWIDs in global coincidence and from economical and technical considerations, there is an obvious interest that further development efforts be made under some sort of coordination.

The first, technical, consideration of GWID is that it is almost impossible to run a cryogenic and a warm interferometer in the same facility (at least not without building a separate building to physically separate the warm interferometer from the cold one by several tens of meters). Failing to do so would cause the cold interferometer to become the chemical sink for all out-gassing of the warm one and/or would expose it to an excessive level of thermal radiation. Therefore the installation of one or more cryogenic GWID in the LIGO pipes would require jettisoning the yet-to-be-built Advanced LIGO, an action for which few scientists are prepared at this moment. As it is difficult to think of the construction of a third (fourth counting Virgo) large vacuum envelope in the near future without having first a functionality proof of the cryogenics concept, the natural choice is to support and assist the existing cryogenic LCGT project. Then we would upgrade the LIGO sites to cryogenic GWIDs (or build brand new ones) after a successful testing of a first large scale interferometer at LCGT.

The second technical consideration is that any cryogenic GDID will be heat evacuation limited. Room temperature GWID dissipate the beam deposited power by simple heat radiation from each test masse. This heat is a sizeable fraction of the laser power, which is of the order of the Watt per mirror presently, and will be in the tens of Watts in some of the advanced interferometers. The current and advanced interferometer will run with test masses from a few to several degrees above room temperature. As black body radiation falls as T^4, an isolated test mass initially cooled near the absolute zero, would warm up to several tens of degrees Kelvin before finding a radiative equilibrium. Consequently any cryogenic detector will be cooled only through heat transport along its mirror suspension and vibration isolation mechanism.

Once it is accepted that high thermal conductivity and high mechanical Q factors are needed, it seems a foregone conclusion that any first generation interferometer should use sapphire both as its test mass[3] and for its suspension mechanisms[4]. Sapphire though, as any crystal, has thermal conductivity that peaks at low temperature, but eventually falls as T^3 towards 0^oK. This will automatically set working temperature of the first cryogenic GWIC at about 30^oK, taking advantage of the large (better than metals) sapphire heat conductivity peak between 20 and 30^oK.

Heat conductivity in a metal becomes better than that in a crystal at still lower temperatures so that eventually metal flex joints will win[5], but the metal quality factors start becoming substantially worse than that of sapphire. While, eventually metals will get a net advantage because of the $\sqrt{T}$ factor. This happens at temperatures one order of magnitude below $20^{o}K$[6]. This mirror working temperature must be achieved with non-negligible beam power absorbed on the mirrors and requires, for adequate heat conductivity, cross sections that are prohibitively large for proper mechanical suspension and isolation. For these reasons it is my personal prejudice that we should follow the example of the LCGT project, and not try to work substantially below $20^{o}K$ without, at the very least, making the intermediate step with sapphire suspensions at $30^{o}K$.

It is useful to remember that to reduce the mirror and suspension thermal noise one can take advantage of several factors.

- The brute force advantage of $\sqrt{T}$ with lower T.
- The increase of mechanical quality factors that ensues from a lower mirror and suspension temperature. This advantage is found to differ from sample to sample and even, in the same sample, from different processing histories. Taking best advantage of this factor will require the most R&D efforts.
- Make use of larger beam spot sizes which, averaging over larger mirror surfaces, bring in a thermal noise advantage varying as 1/r for coating induced thermal noise to $1/\sqrt{r}$ for bulk dissipation in the mirrors' bodies.
- Reduce the amount of mechanically stored energy in the suspensions by using flex joints[7] instead of round fibers (for suspension thermal noise only).

It is important to remember that, after lowering the thermal floor of the mirror, one has to store enough power in the interferometer's Fabry Perots to reach a matching length sensitivity. This generates heat and a heat extraction problem that gets more and more severe at high frequency, worsening with the square of the frequency of observation. A cryogenic GWID is intrinsically easier to design for a low frequency observation band.

Multi Frequency Interferometers?

The heat extraction problem is not the only one when operating a GWID at high stored beam power.

At a given test mass value the stored beam power level sets both the shot noise slope on the high frequency side and a radiation pressure fluctuations counter slope at the low frequency end. The thermal noise floor lies between these two quantum walls. The more one is successful in lowering the mirror and suspension thermal noise, the more the useful frequency range looks like a narrow cusp.

Almost automatically one gets to the important conclusion that at low thermal noise conditions, it will be necessary to run two, or maybe even more, GWIDs in parallel, each with its own stored power level and observable frequency band. Interestingly this fact starts being true even at room temperature for advanced interferometers.

Additionally, high frequency- and low frequency- optimized, cryogenic GWID will look substantially different, probably short and stubby mirror suspensions for high frequency to optimize large heat extraction, long and skinny suspensions for the latter for optimizing low-frequency suspension thermal noise behavior.

More on power limitations.

Let's make a practical example; we consider an interferometer with 1 MW of power stored in its Fabry-Perots and 1 KW injection power at its inner masses. We also consider 1 ppm absorption on the mirror coating and 40 ppm/cm absorption in a 25 cm thick sapphire substrate (absorption values common in currently readily available mirrors). The inner masses would have to dissipate 2 W each while each end mass would be subjected to only 1 W of losses. Extracting Watts is already difficult in any cryogenic system, while extracting it through an absolute minimum of one layer of low thermal noise suspensions borders the impossible with present techniques. The first priority must be to reduce the optical losses and the mirror thermal load.

To efficiently carry out heat one needs large cross sections and short lengths of high conductivity materials. To generate efficient mechanical attenuation and low suspension thermal noise, high mechanical quality factors and little elastically stored oscillation energy are required. One presently uses glass fibers or ribbons, which have negligible thermal conductivity.

One can in principle obtain good thermal conductivity AND preserve high mechanical quality factors by using crystalline materials, like sapphire, at the temperature of their peak thermal conductivity. Metals (except, maybe niobium) do not seem to have the necessary mechanical quality factors to be employed anywhere near the low thermal noise test masses.

To better understand the magnitude of the problem it is wise to consider the "success" of the LCGT test[8]. The LCGT team successfully cooled a test mass to 25-30^{o}K through 4 sapphire fibers 250 micron in diameter, 100 mm long. To do this they paid a price of roughly 1^{o}K/mW. They also used aluminum spaghettis to funnel the heat while isolating the mirror suspensions from most of the cold finger's chiller vibrations. While we should admire the technical prowess of the Japanese team, even allowing for the better conductivity that might be achieved by improved attachment of the fibers to the mirror, it is still far from a reasonably working point for a GWID and there is still a very large amount of R&D necessary for a technical design of a sensible interferometer. In particular it is important to realize that the fibers in the Japanese test behaved substantially below the best measured sapphire thermal conductivity and that it is therefore necessary to learn how to use sapphire at its best. The likely answer is the use of short sapphire flex joints linked to bigger fibers or rods.

The design of a cryogenic interferometer still requires a large amount of R&D homework to substantially reduce the mirror thermal load and to find a suitable way to build low thermal noise, high thermal conductivity and high performance vibration isolation suspensions at cryogenic temperatures.

The LIGO R&D activity.

Although just a fresh startup, LIGO is already very active in all these R&D fields, in large part due to similar requirements driving the Advanced LIGO R&D.

I will resume these activities in the following paragraphs.

· Mirror coating power absorption.

Advanced LIGO is also hampered by power losses and excess substrate thermal noise in its mirrors. An aggressive R&D program has started.

This large effort will be made in collaboration with Virgo and private companies to reduce the power absorbed in the mirror coating from the current ~ppm to 0.1 ppm or less in future. In the next future several tens of coating runs will be manufactured with varying coating parameters, techniques, evaporators and materials and measured with the aim to reduce the absorbed power by at least an order of magnitude and minimize the mechanical losses in the coatings. The most promising of these samples will be available for calorimetric tests in cryogenic environment.

- Sapphire substrate absorption.

Mono-crystalline sapphire crystals of the dimensions required by a GWID (40 Kg or more) are currently not available. Advanced LIGO also has base-lined sapphire as the substrate material for its mirror despite the fact that its relatively high power absorption in bulk sapphire (40 to 80 ppm/cm) introduces more thermal load than fused silica. To solve this problem LIGO is running two separate sapphire R&D programs in collaboration with 2 industrial partners, Crystal Systems in the USA and SIOM in P.R. of China.

The results of these developments will be available for cryogenic tests and for any cryogenic GWID design.

These "parasitic" contributions are at present coming "for free"; at the end of the Advanced LIGO R&D they will have to be carried forward to finalize the results for cryogenic use.

Other efforts are made in LIGO specifically for cryogenics interferometers.

- Sapphire to sapphire bonds.

The construction of a sapphire suspension will be quite intricate and will require bonding of sapphire to sapphire. There are several promising candidates being presently tested to bond quartz to sapphire and sapphire to sapphire. Tests of sapphire to sapphire silicate bonds are being made in Caltech[9] in collaboration with ICRR.

- Flex joint development.

It is my prejudice that, because of fiber's unfavorable aspect ratio, we will not be able to build a good cryogenic GWID cooled through fibers.

Following the example of the U.W.A. group[10 11], we would like to focus on membrane flex joints.   Unlike them, though, we focus on crystalline flex joints. For this reason at Caltech we started, in collaboration with Universita' di Pisa, a development for sapphire machining using numerically controlled ultrasound grinders[12].

In ultrasound machining a "soft" metallic tool is energized by a powerful piezoelectric vibrator while a slurry of fine grit flows around it. The tool is hovered just above the material to be machined. The grit, energized by the ultrasounds, grinds any hard material without applying macroscopic efforts or vibrations. A first sapphire flex joint obtained with a coarse machining grit is shown in figure 1.

This first flex joint is slightly less than 400 micron thick over a width of 3 mm and a length of about a mm. After the coarse cut shown in figure we plan to reduce the still rough surface with a progression of passes with finer and finer grits. As ultra sound machining uses the same grits employed in mirror polishing, we expect to eventually obtain thin flex joints and good surface finishes.

The results achieved with different samples and techniques will be measured at Caltech. The best samples will be provided to ICRR for more in depth testing.

We hope with the ultrasound technique to achieve finer membranes than in conventional grinding techniques. We also plan to try treatment of superficial cracks and dislocations (that may limit the quality factors or hamper the thermal conductivity). We will use thermal treatments and/or ablation to apply a final molecular level polishing[13]. Using these and other techniques we hope to engineer very short flex joints with large aspect ratios to support the payload and carry the heat while reducing the elastic stored energy and depress the suspension thermal noise.

Suspension thermal noise can be pushed back, beyond the gravity gradient noise limit, by simply decreasing the suspension resonant frequency. This might be done using longer suspension struts. Longer suspensions will only go so far because of the limited overhead space and because longer struts can be achieved only at the cost of increasing their thermal resistance. Alternative geometries, like for example the folded pendulum[14], may allow arbitrarily low resonant frequencies with short struts. A possible folded pendulum mirror suspension geometry is shown in figure 2. Numerical Control Ultrasound milling may allow the design of intricate shapes of struts and counterweights to achieve sufficiently low suspension thermal noise while maintaining high thermal conductivities.

· Heat extraction techniques.

The sapphire flex joints will provide low thermal noise suspensions with large thermal conductivities. A couple of stages recessed from the test mass, it may be possible to build conventional thermal bridges towards a cold finger. Alternatively one could use, closer to the mirror, more exotic systems like the LASSOR optical chilling. Richard Epstein at LANL[15] seems confident that this technique, presently developed for liquid nitrogen temperatures, can be extended at the 20^{o}K level.

Conclusions

LIGO is starting to contribute to the development of Cryogenic GWID.

The long path towards a cryogenic LIGO passes through collaboration with the other GW experiments and R&D efforts.

One of the most surprising ideas coming from exploring the cryogenic problems is the realization that, considering the low thermal noise floor promised by Advanced LIGO, it may be advantageous already at room temperature to build two separate interferometers, one dedicated to low and one to high frequency detection ranges. This may well be the first payoff from LIGO R&D effort in cryogenics.

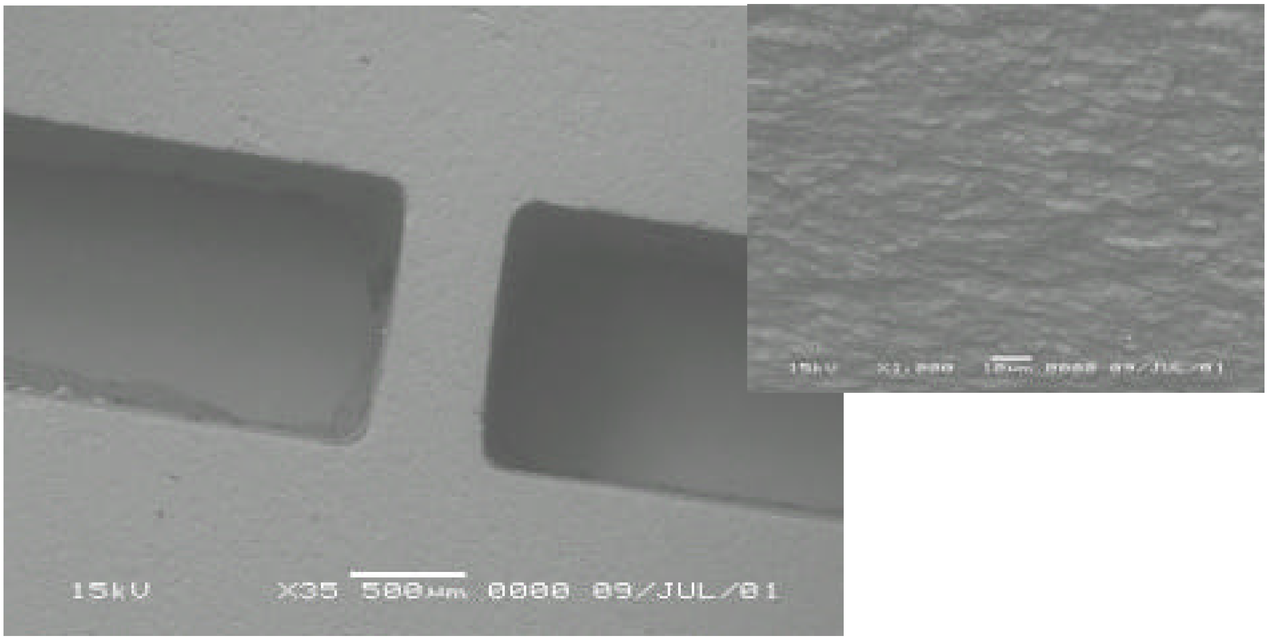

Figure 1: Feasibility test flex joint obtained by Ultra Sound machining. The insert shows the surface roughness obtained with coarse grits. Finer grits are expected to give better finishes. Polishing to optical levels will be necessary to make low noise flex joints.

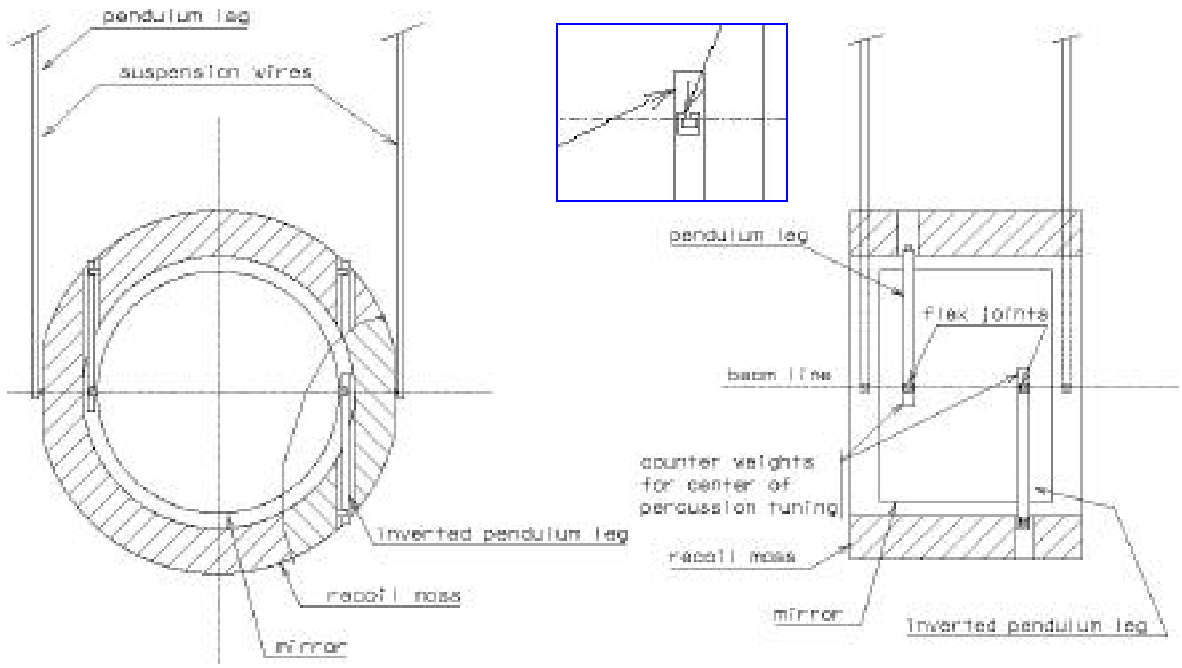

Figure 2: Folded pendulum suspension geometry study. Geometries like this are designed to push the suspension thermal noise to frequencies lower than the gravity gradient wall limit.

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