Notes about fused silica work in Glasgow
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Summary and Overall Impression

We should have patience with the fused quartz suspension. The pulling techniques and the welding are not as difficult as one first imagines. Excepting the tendency to fracture, fused silica is an easy material to work. It is forgiving and the skill required to weld and form it is not more difficult than to join metals, certainly easier than many other glasses.

The Glasgow group has now successfully constructed test suspensions several times. My assessment is that the difficulties experienced in hanging a suspension at MIT came from inexperience with the integration of the many steps involved. The steps individually had been qualified but the experience of the overall assembly had not been practiced enough.

I fully expect that we will be making successful hangs and achieving more reliability in the near future.

People and commitment

The Glasgow group has made a significant investment in the fused silica science, technology and fabrication methods. It is clear to me that they are eager to see the investment they have made through to a successful application in the detection of gravitational waves. The group developing the fused silica technology consists of:

Angus Bell
Alan Cumming
Liam Cunningham
Giles Hammond
Alastair Heptonstall
R. Kumar
Kirill Tockmackou
Marielle van Veggel

The different steps involved in the fused silica suspension were developed by different people in the group. Specific individuals became expert in the fiber pulling system, the welding techniques, the chemical bonding techniques, the design of fastners, the testing procedures and fiber modeling. It is only lately that all of this has come together. As a contingency, there is continuing work on flame welding. The current strategy is to develop a core group with experience in all the steps, who, if needed, can augment the LIGO staff responsible for suspension construction, assembly and installation.

A significant addition to the group is the arrival of Angus Bell after the loss of both Russell Jones and Ken Strain due to illness. Bell's experience is as an engineering physicist in industry and government laboratory on laser systems and precision measurement.

What went wrong at MIT

The two assembly and hanging failures at MIT came after the Glasgow group had only hung one complete trial suspension. In my opinion they tried to export the integrated process too soon. They were still learning how to do it and even now they are iterating the process.

Although there is not enough information to draw a definite conclusion of what went wrong at MIT, subsequent analysis and discussion by the Glasgow group led to a forensic report which looked at a range of possibilities. The environmental conditions in Glasgow, where there have now been several successful hangings, are not significantly different than those at MIT. Neither place uses clean room facilities nor is there control of humidity or air currents. The first hanging at MIT was done with almost the same techniques that were successful at Glasgow. The welding was done by the same person. The fibers were strength tested prior to welding although for 1 to 2 minutes at 12.5 kg (at MIT) and 5 minutes at 15 kg (at Glasgow). There is a possibility that the fused quartz ear was damaged prior to the welding and that this was the cause of the failure. A nick was found in an edge of the ear and no careful inspection was made of the glass with strong illumination in a search for cracks.

The second hanging at MIT was done in a hurry. There was no strength test done on the fibers prior to welding. In subsequent hangings at Glasgow it was found that for a variety or reasons 1 out of 3 fibers that had been formed and tested earlier failed the prewelding strength test. This test (until one understands more about the way the fibers become vulnerable) cannot be eliminated from the process.

My assessment is that the Glasgow group did not have enough experience with the steps in the hanging process before coming to MIT, They did not realize that the hanging process which includes not only the welding but also stress release and annealing and straightening steps as well as time to look at the welds from different angles and make judgements about rework, take longer than they gave themselves. It looks as though the hanging takes two days at the minimum in the hands of two experienced people.

Based on the current experiences in Glasgow, Angus Bell has urged the policy of pulling and characterizing 12 fibers for each hanging of 4 fibers and eight welds.

Assessment of working with fused silica relative to other materials
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I was particularly interested in the welding process as that will continue to be the one which needs the most skill and experience. It has never been easy in any material joining to automate the process although more attempts could be made with laser welding since all the commands given by the welder are recorded and there is more control in laser welding process than with a torch.

The most important property of the fused silica relevant for the welding process is that the glass is forgiving. The viscosity change over the temperature range where the welding can occur is small enough so that there are no time critical steps. One can work to flow the materials from the joining pieces together without danger of a fluid runaway or if one lets the material cool too quickly to lose the joint through thermal stress cracking. A weld can be made then cooled without annealling, inspected and reheated without incident. The weld can be worked and reworked limited only by the patience of the welder. The fused silica also acts as its own indicator of too high a temperature (and thereby a dangerous low viscosity) by evaporating, leaving a white silicon dioxide deposit on nearby cooler surfaces. The silicon dioxide "particle smoke" is easy to see even through welder's glass since its emissivity in the visible is higher than the fused silica. Working fused silica is significantly easier than other glasses many of which tend to break due to thermal stresses as they cool without sufficent annealing. They also have a much greater range of viscosities around the fusion temperatures. Determining if a weld is good, has full penetration and is free of cracks is actually easier with fused silica than metals. The material is transparent and one can see discontinuities in the melted region easily understrong illumination. The telltale for a good weld is the radius and continuity of the meniscus that has formed at the join. Again, visual inspection under good lighting tells the story. It may also be advantageous to use video cameras after heating to inspect the weld with magnification from different sides. The key issue is to see the continuous meniscus from the rod at the fiber end to the horn on the fused quartz ear.

In my experience with glass working, welding and hard and soft soldering, I would rate the welding of fused silica in the ordered list below with 10 being the most difficult and 1 the easiest.

10 Aluminium welding
soft soldering without being able to move the piece
soda glass fusion with gravity assist
borosilicate glass fusion with gravity assist
hard soldering without being able to move the piece
hard soldering with gravity assist
fused silica welding
stainless steel welding
soft soldering with gravity assist
1 gluing

Specific technical issues and possible suggestions

Fiber breaking

The key problem with the technology is ease of breaking the fibers. The most likely source is surface damage and/or chemistry which causes a weakness to form that becomes a source for a propagating fissure. The energy to propagate the fissure and extend it comes from the work done by the tension in the fiber as the crack opens. It is a run away phenomena leading to a shock front. The optical fiber industry uses a plastic cladding to avoid the formation of surface damage. Coatings could be developed to inhibit the damage but it requires research to determine that the coatings do not compromise the fiber mechanical losses and increase suspension thermal noise. At this time the only means for reducing the probability of producing damage on the surface is to avoid contact with the fiber and to store the fiber in a benign atmosphere.

Here there is room for significant improvement to reduce the probability of fiber damage.

1) To facilitate handling in the pulling machine and in subsequent testing apparatus it would be useful to attach metal holders to both ends of the rod from which the fiber is pulled. The holders are made to be concentric with the rod and serve to align the fiber once pulled. They are removed only at the very end when the fiber with its rod stubs are cut to length for the welding. The holders need to be large enough so that there is no chance that a glove or knuckle can accidentally touch the wire as it is transported between the different measuring and testing rigs and storage bins. Glasgow is already adopting this improvement and it needs to be applied at MIT.

2) The long term storage of the fibers should be in dry hydrocarbon free nitrogen (boil off from liquid nitrogen) or better still vacuum (Sam Waldman suggestion). The storage of the finished suspensions should also be in vacuum or at worst dry nitrogen.

Damage from fiber breakage in the interferometer

There is significant energy stored in the loaded fiber, about 1/3 of a Joule is released When a fiber breaks, The shards can attain close to sonic speeds and can cause damage to objects in their path. It would be important to protect the optic surfaces from direct hits by the shards. LIGO will need shields to keep the shrapnel from a broken fiber contained and to avoid any direct hit on an optical surface or polished surface used in an actuator.

Tolerance to fiber length fit

Another factor that makes working with the fused silica fibers less onerous than I thought is the 1% stretch of the fiber between unloaded to loaded conditions. The fiber stretches 6mm. This serves to reduce the accuracy required in fitting the fiber length to equalize the fiber tensions. The technique with the current jigging establishes length equality to +- 1/2mm. After welding all four fibers on the test mass are put under small tension and the rod stubs are heated for a final anneal and length normalization. The results show good uniformity in the violin mode frequencies. Before seeing the process, I had assumed the distribution of the load between the fibers was a major concern. It is not.

Change in the ear and horn design

A small change in the geometry of the horn may pay dividends in ease of welding. Currently the rod is welded to the square horn directly. The cross section of the horn is larger than the rod and in the welding process more heat has to be applied to the horn than the rod to make a good weld. The meniscus between the rod and the horn is the critical part of the weld. A suggestion is to make a heat relief, as is done in metal welding. This could be done by extending the horn by several millimeters with a smaller piece (either round or square) with the same cross section as the rod. The heating during the welding would be uniform and the extra length of the horn would allow for more weld attempts should there be a fiber breakage. The meniscus between the welded sections would be easier to see.
The sacrifice in thermal noise does not look serious using the results in the published paper on fiber modeling.

Mechanism for loading the fibers after welding

An important point raised by Angus Bell is the possibility that the release of the lower mass is not uniform as the fibers begin to be loaded. The release is carried out by using a scissors jack under a table forced to move on ground rod guides. There may well be binding at these guides and it would be useful to measure the motion on release. Should it be a stick/slip motion it would be worthwhile to use Thomson linear bearings or teflon sleeves on these ground rods.

Welded rod misalignment

Need to understand how the misalignment of the fiber pull direction with respect to the axis of the welded rod can cause failure and if so what are the requirements for colinearity. A simple model of stress to balance the torques gives smaller stress in the rod than in the fiber for even a 10 degree misalignment. Is the ultimate shear stress significantly smaller than the ultimate tensile or compression strength?

If the alignment is truly critical it may well be worthwhile to sight along the rod and fiber with a magnifying theodolite or camera to measure the angles from two almost orthogonal directions. Currently one of the final annealing and alignment steps is to put the fibers under a gentle load and reheat the welded sections to straighten the welded connections (the same step used for load equalization of the fibers).

Information transfer and education

It would be useful for the Glasgow group to make a movie of the steps in the suspension assembly. The movie would be best with narration. An atlas of pictures showing good and bad welds would also help in training new people.