LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T050206-00-K *Advanced LIGO* 5th October 2005

Production and Characterisation of Synthetic Fused Silica Ribbons for Advanced LIGO Suspensions

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1 Introduction

This document summarises the current status of production and testing of the synthetic fused silica fibres that will be used as suspension elements for the test masses. In particular it gives details of the current status of the CO_2 laser based system being developed for production of suspensions as well as giving information gained from our experiences of producing the monolithic suspensions for the GEO 600 detector in Hannover.

2 Production of fused silica ribbons and cylindrical fibres

Detailed below are the two production methods that are currently used to produce silica suspension elements from a thicker stock material. The first method, that of using a hydrogen /oxygen flame to heat the stock material before pulling it down into a fibre, was used successfully to produce the 270μm cylindrical suspension elements for the GEO 600 detector. The second method, that of using a carbon-dioxide laser to heat the stock material, is currently being developed as an alternative method, which preliminary results have shown can produce fibres to a higher tolerance than using a flame.

2.1 Hydrogen / oxygen flame production of ribbons/fibres

For many years now research into producing fused silica fibres has focussed on using a hydrogen/oxygen flame, as the heat generated is quite substantial enough to melt the stock material from which a fibre is produced. At Glasgow several machines have now been produced using this principal, including that used to produce the suspensions for the GEO 600 detector. Once the stock material is heated the flame is removed and the material is pulled from both ends by motor driven arms. The heating and pulling cycle is controlled using a *LabVIEW* computer script which ensures that heating times and pulling speeds are identical each time the machine is run.

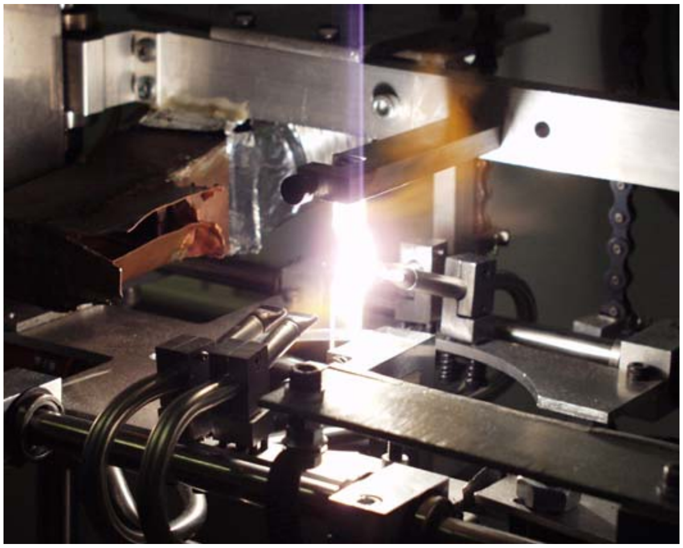

Figure 1 Ribbon being produced using a hydrogen / oxygen flame

The machine pictured above now uses solenoid valves to control shutoff of the flame, as well as a feedback controller on the motor to allow improved control of the pulling speed. The main limitation on reproducibility is how well the gas flow can be controlled, although other factors involving temperature changes in the machine as it warms up are also seen to affect the fibre dimensions slightly.

2.2 CO_2 laser production of ribbons/fibres

Current research at Glasgow is focussed on developing a machine to pull cylindrical and ribbon fibres using a carbon-dioxide laser. This system offers a number of advantages over the flame based machine which should result in higher tolerance and reproducibility of fibres.

Figure 2 Development work being carried out on the CO_2 laser based pulling machine

The CO_2 laser beam comes from a 100W laser, with work having been already carried out to power stabilise this using a feedback circuit. The stability has been measured to be 0.7% over a period of two and a half hours. The beam is then delivered using a series of gold coated mirrors onto the silica stock material. When producing ribbons the beam is dithered across the surface of the material using a galvanometer, as can be seen in ***Figure 3***. Using a laser also allows the heat to be directed only toward the stock material, and no warm up cycle is seen.

Unlike the flame based machines described above, we use a feed and pull system here, whereby the stock material is slowly fed into the path of the beam while the fibre is pulled at a higher speed from the other end. The system reaches an equilibrium state where the volume of material pulled out is equal to that being fed in and it is possible to calculate the reduction in thickness based on the ratio of feed and pull speeds.

Also, unlike the flame based systems the pulling arms here are moved using a double ballscrew unit (similar to a lead screw, though using a re-circulating ball bearing race) mounted vertically and driven by two servo controlled motors through a reduction gearbox. This gives a substantial reduction of slack and backlash in the drive system compared to the chain drive of the flame pulling machines. Measurement of the position of the arms is made using a magnetised tape and readout head, giving a position accurate to 0.1mm. Again the system is controlled using a *LabVIEW* script, though it is now possible to also use this to collect information about the pull, such as the laser stability, pulling speed and final length for analysis.

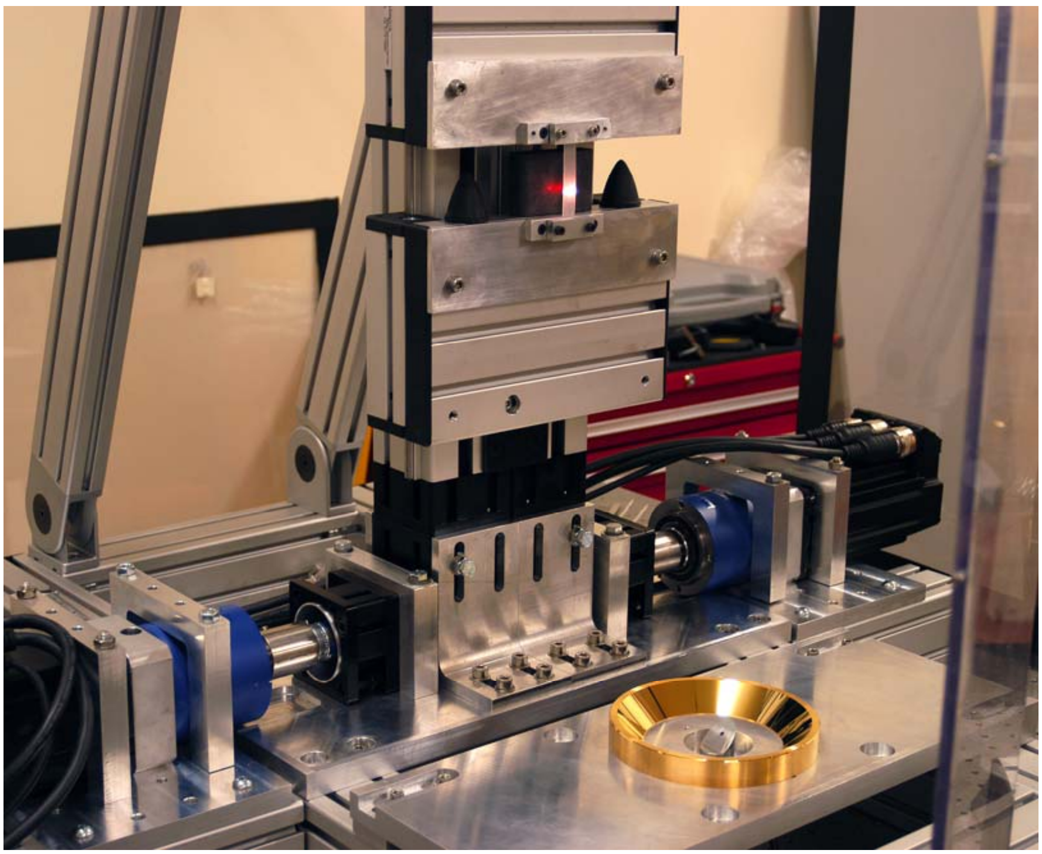

Figure 3 *Fused silica slide being heated using CO2 laser. Gold coated conical mirror used to produce cylindrical fibres also shown.*

Shown below are images of a cylindrical fibre and ribbon being produced using the CO_2 laser. These were produced using a prototype machine, which has now been replaced by that shown in ***Figure 2***. A final stage of construction of the machine will be to use conical gold coated mirrors, seen in ***Figure 3***, for the production of round fibres, allowing the stock material to be heated from all sides.

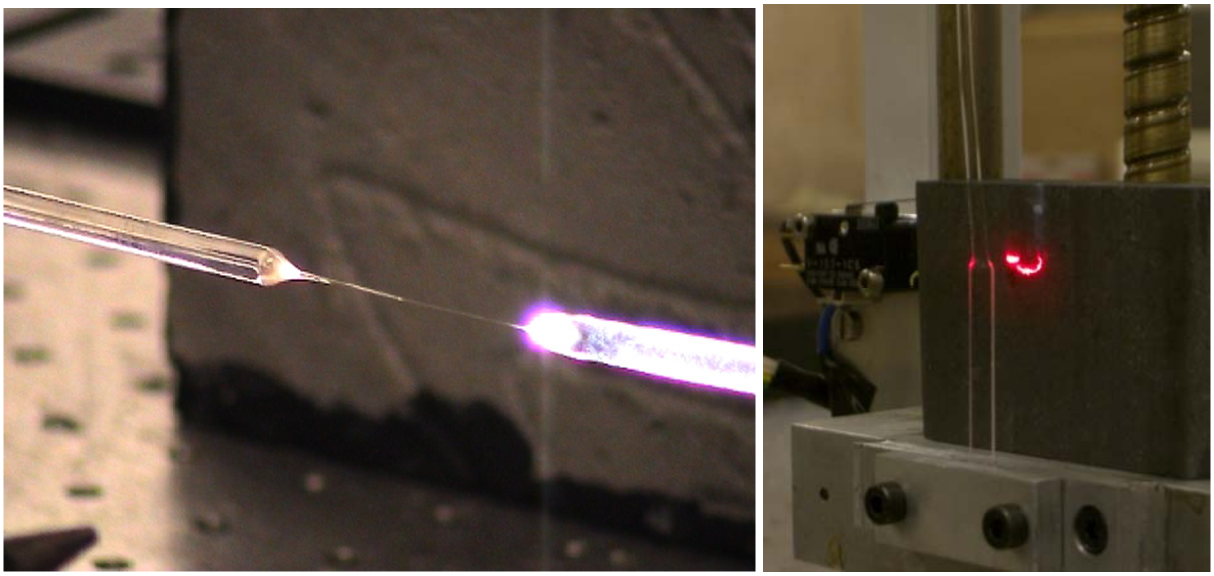

Figure 4 Cylindrical fibre (left) and ribbon fibre (right) being produced using CO_2 laser

3 Welding of suspensions

In order to construct pendulums from the silica fibres it is necessary to join them to the test mass in some low loss way. Welding has been used in GEO 600 for this purpose, giving monolithic suspensions, and it is the proposed method for the Advanced LIGO suspensions also. As with fibre production, it is possible to use either hydrogen / oxygen flame or CO_2 laser to weld the suspensions.

3.1 Welding using hydrogen / oxygen flame

It has been shown in GEO 600 that welding using a hydrogen / oxygen flame is an effective technique for jointing suspensions. In the case of GEO 600 this was essentially a manual process, performed using a hand held torch. The fibres were cut at the neck and then butt welded onto the ends of the ears. The tension in the fibres was then equalised by allowing a little weight to be put on them and reheating the joints.

3.2 Welding using CO_2 laser

Unlike flame welding which is a reasonably skilled task for the operator performing it, welding using a CO_2 laser is fairly simple by comparison. It is done by aligning the pieces to be welded and then exposing them to the laser beam for a period of time until the material has become continuous. As there is no gas being blown at the part to be welded there is less deformation than is associated with a flame. It is also possible to create overlap welds using the laser, which allows for easier alignment of the fibres. While it is possible to weld directly to the fibre, this tends to create a region of high stress, and current plans are instead to weld to the neck region of the fibres (thickened heads).

The beam for welding will be delivered using a 2D galvanometer to allow accurate positioning and dithering across the weld. This has already been tested using a 1D galvanometer, with a 2D giving the possibility to spread the beam slightly and improve the heat delivery.

4 Strength testing

An important part of building reliable suspensions is to perform strength measurements. Two types of tests are being performed at Glasgow, these being destructive tests and long term tests. As the CO_2 laser pulled fibres are still being developed strength data is currently only available for flame pulled fibres and ribbons and CO_2 pulled round fibres.

4.1 Destructive strength testing

Two facilities for strength measurements are to be available at Glasgow. The first, shown in ***Figure 5*** is already in place, and is for use in measuring the strength of ribbons and fibres. It is constructed of steel and uses linear bearing track to ensure the load is only applied along the length of the fibre. The drive unit must be both strong and smooth, hence a double reduction gearbox is used along with a linear ballscrew. A commercial piezo readout system is used to measure the applied load.

Figure 5 Breaking strength measurement facility

Although this setup has been used to perform preliminary measurements of bond strengths and welds, a dedicated unit for this is to be made. This second facility, for which parts are already being shipped, will be similar but smaller and will be mounted on an optical bench to further increase stiffness.

Measurements made on flame pulled cylindrical fibres, of the type used in the GEO 600 detector, gave an average breaking stress of $3 \pm 1.5\,\mathrm{GPa}$. Below are the initial measurements for flame pulled ribbons and CO_2 laser pulled round fibres. These give an average breaking stress of 2.6 GPa for the flame pulled ribbons, which compared to a working load of approximately 0.8 GPa for Advanced LIGO gives more than a factor of three safety margin. Three of the ribbon fibres had previously been touched before testing and were found to still achieve a strength which exceeded the Advanced LIGO working stress. The laser pulled round fibres that were tested gave an average breaking stress of 4.25 GPa.

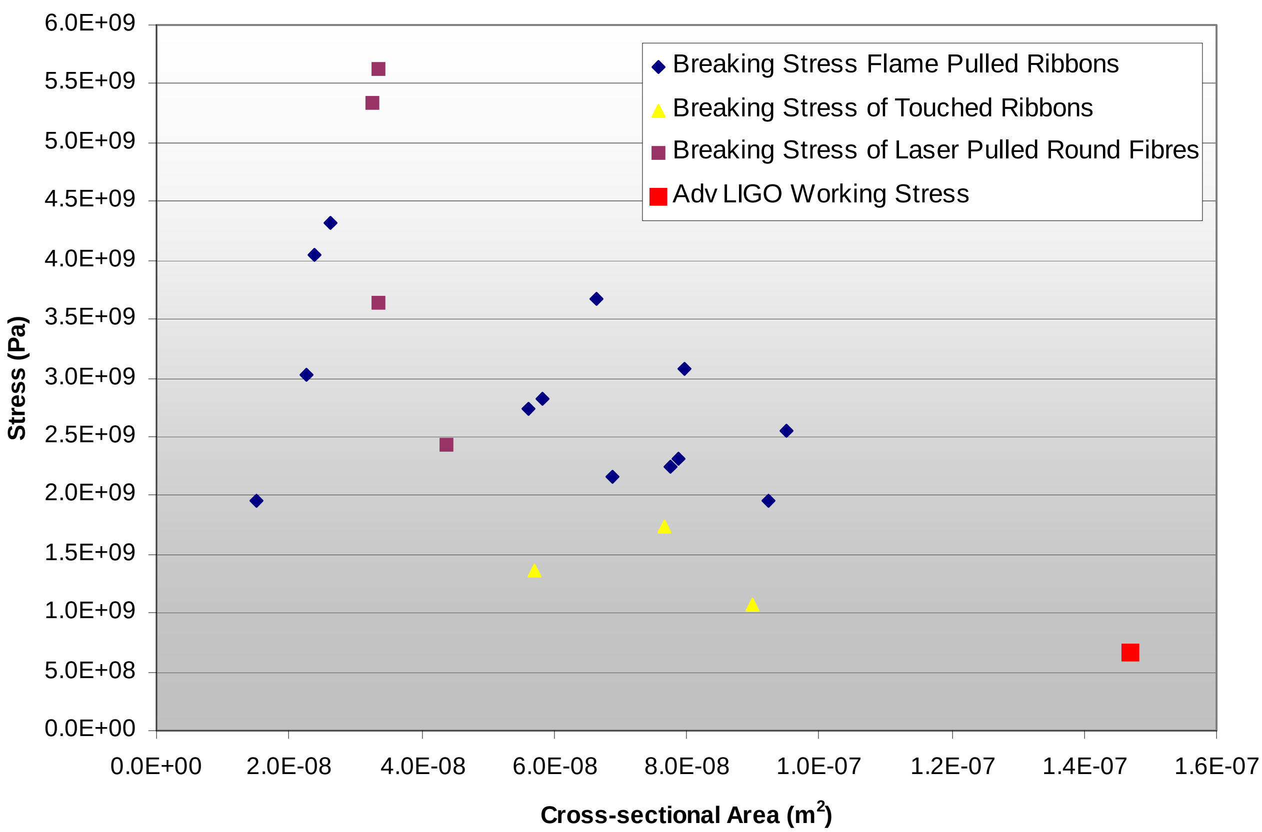

Figure 6 Measurements of breaking stress of flame pulled ribbons and CO_2 laser pulled round fibres.

4.2 Long term strength testing

Long term testing of the cylindrical fibres used in GEO600 was performed prior to creating the actual suspensions for the detector. Four cylindrical fibres of diameter 180 μm were welded onto bonded ears and were then used to suspend a mass of 10 kg for a period of 6 months. The stress on each fibre amounts to nearly 1 GPa. Similar tests will be performed on the ribbons/fibres for use in the Advanced LIGO suspensions, and indeed this test programme has already been started.

An initial test of flame pulled ribbons was performed, suspending 20 kg of lead on two fibres of the dimensions proposed for the Advanced LIGO suspensions. This was allowed to hang in air for a period of eight weeks. This is shown in ***Figure 7***. Designs for a more sophisticated test facility are now being made to allow testing of welded fibres and CO_2 laser pulled fibres.

Figure 7 Two fibre 20kg test suspension

5 Mechanical loss measurements

Measurements made on cylindrical flame pulled synthetic fused silica fibres have been shown through many published measurements to have extremely low levels of mechanical dissipation. For example the measurements made on fibres before installation at GEO 600 gave typical material loss values of $\phi_{material} = 1.4 \times 10^{-7}$. Due to the large surface area to volume ratio of these fibres most of the dissipation comes from a lossy layer on the surface, along with thermoelastic loss contributions, while loss in the bulk is relatively small.

Figure 8 One of the mechanical loss measuring facilities, with ribbon fibre being tested

Measurements of mechanical loss performed on silica ribbons have shown them to exhibit a similar level of surface loss to cylindrical fibres. Given that the thermal noise contribution from rectangular fibres is lower than for a similar cross section cylindrical fibre due to the increased dilution effect it is clearly advantageous to pursue this design.

Initial measurements of mechanical loss performed on cylindrical silica fibres produced using the CO_2 laser machine have shown that the surface loss is similar to that of flame pulled fibres.

6 Future research

The CO_2 laser machine is currently being developed in order to improve the shape of the fibres produced. The main part of this development work involves installing the gold coated mirrors for cylindrical fibre production, along with a new *LabVIEW* programme to allow greater control of the the shape of the initial section of the fibre.

A more comprehensive programme of strength testing of laser produced fibres and welds will take place soon, including both destructive and long term testing.