Development and Characterisation of Fused Silica Ribbon Fibres for Gravitational Wave Detectors

Rencontres de Moriond

12th March 2007

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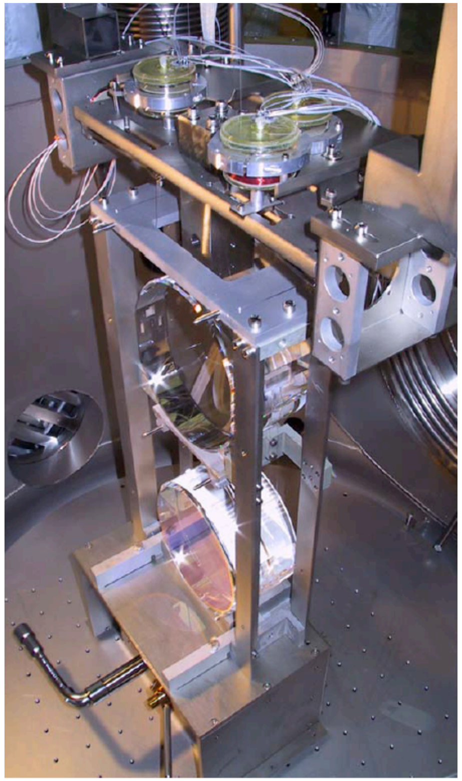
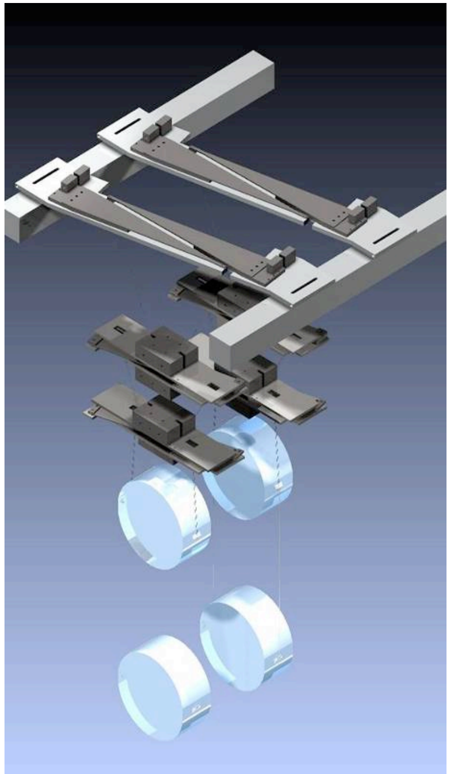
Heptonstall, Barton, Cagnoli, Cumming, Faller, Hough, Jones, Martin, Rowan, Strain, Zech

LIGO-G070196-00-Z

Monolithic suspensions for advanced detectors

- Development of monolithic suspensions is based on experience from the GEO600 suspensions
- This talk will cover aspects of production and testing of suspension elements suitable for Adv. LIGO and ‘Adv. Virgo’
- The criteria that must be met by ribbon fibres for Adv. LIGO:
  - Strength (x3 safety margin)
  - Thermal noise performance
- To meet these criteria we require
  - Breaking stress > 2.4 GPa
  - Intrinsic loss <3 x 10^{-11}/t, where t is the thickness of the ribbon





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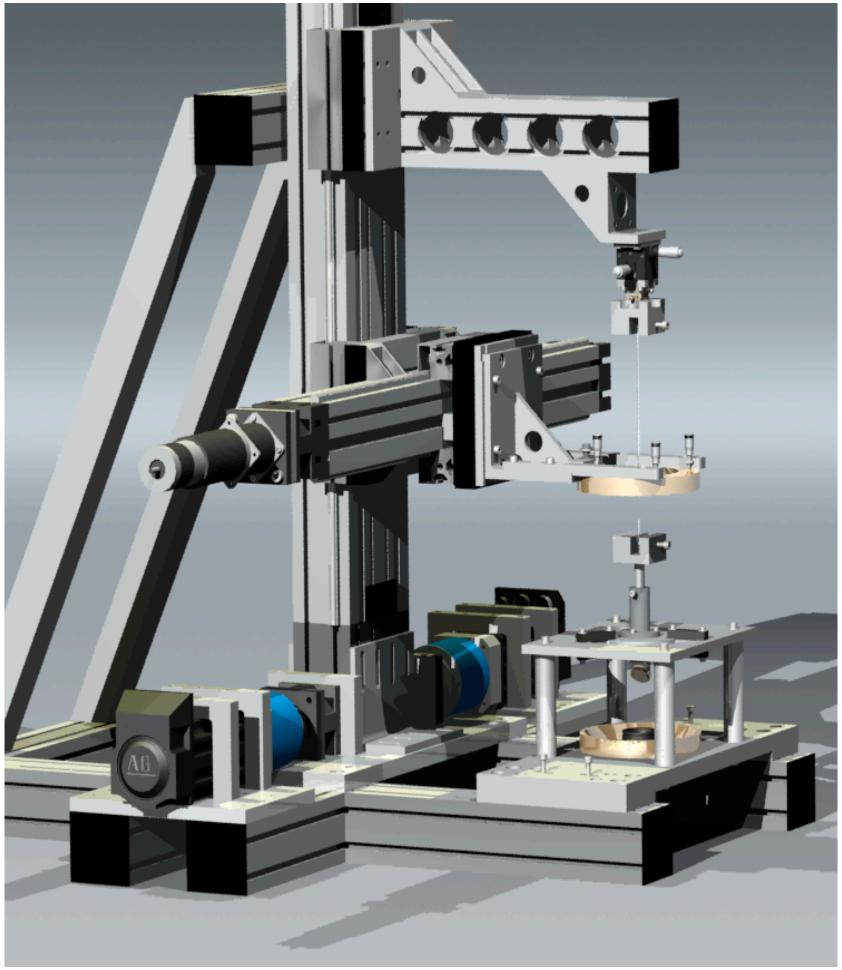
Improving fibre pulling technology

- Advanced LIGO suspensions require ±1.9% tolerance on fibre dimensions.
- This is a slight increase on the ±2.1% achieved in GEO600.
- Repeatability and tolerance in flame pulling machines is limited by gas regulation and slack in mechanical parts.
- A new machine was developed in Glasgow using a CO_2 laser and high precision drive systems
- Designed for both ribbon and cylindrical fibre production to be suitable for both LIGO and Virgo upgrades.
- The machine is also capable of welding fibres.



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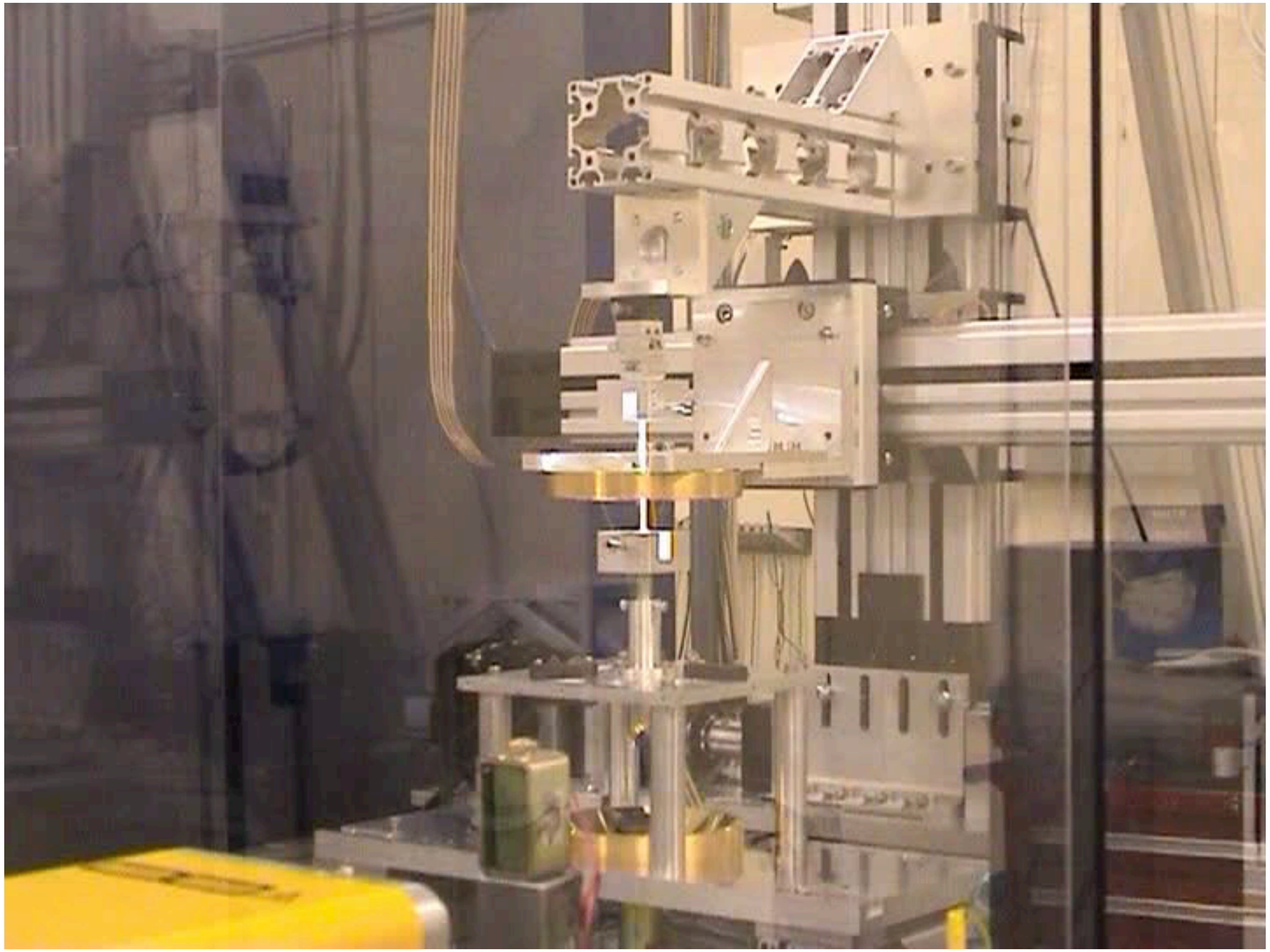
Pulling fibres using the CO_2 laser



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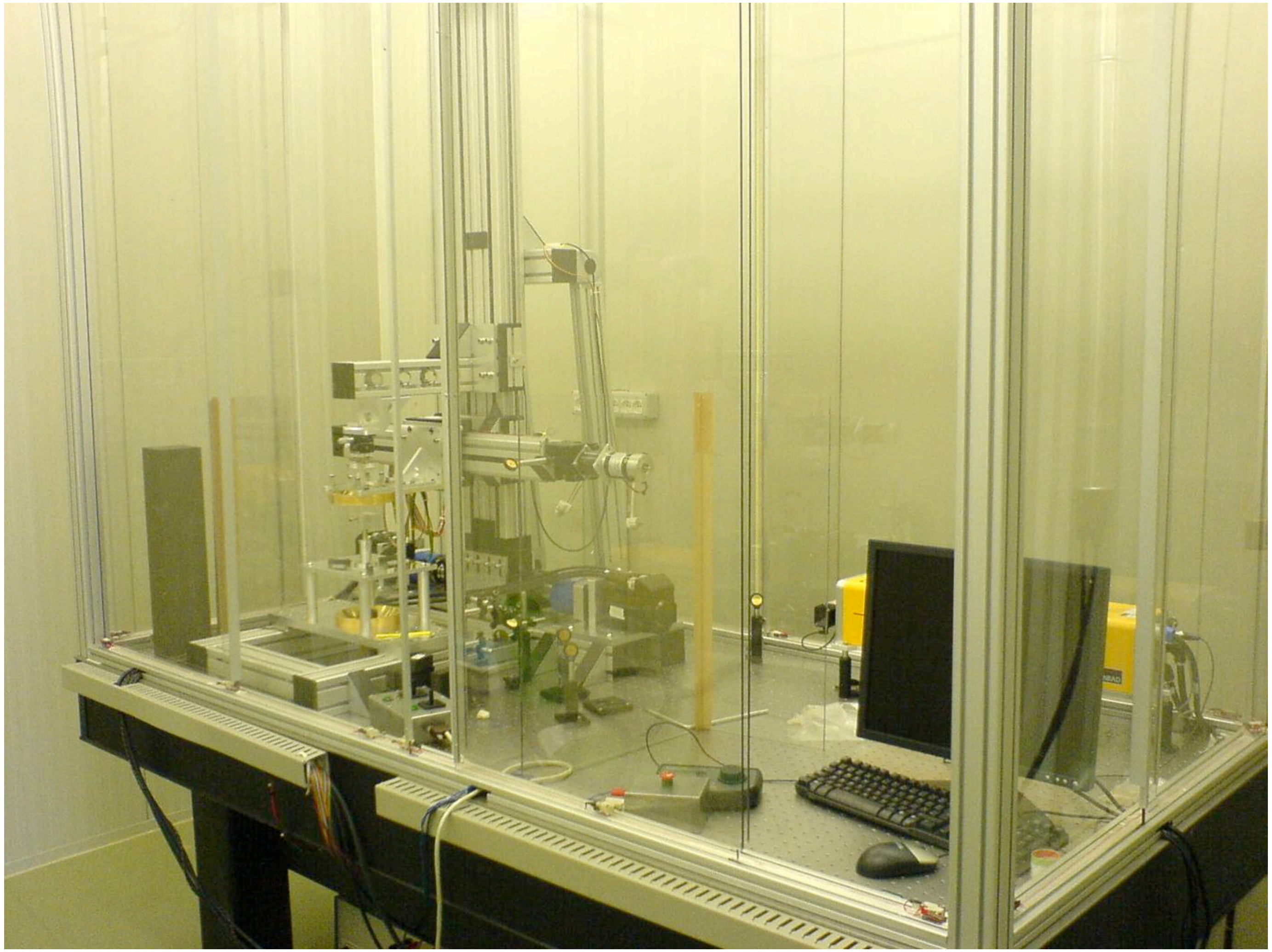
Virgo laser pulling machine installation



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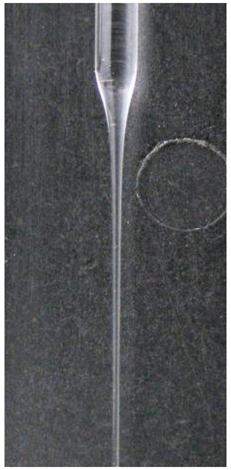
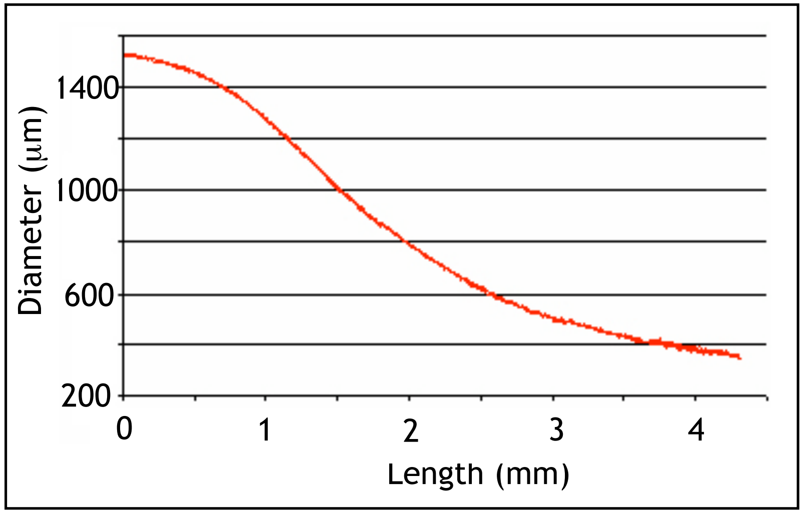
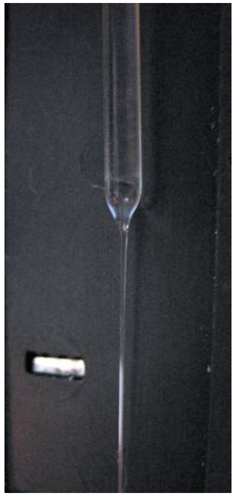
GEO 600

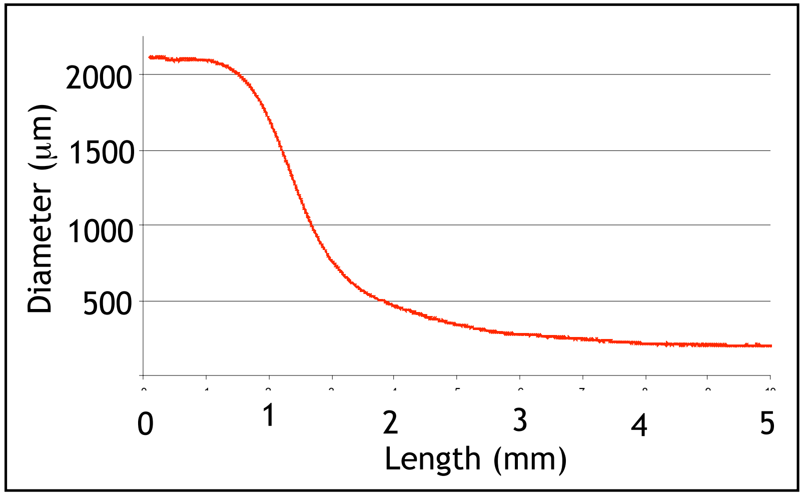
IGR

Controlled shaping of the neck









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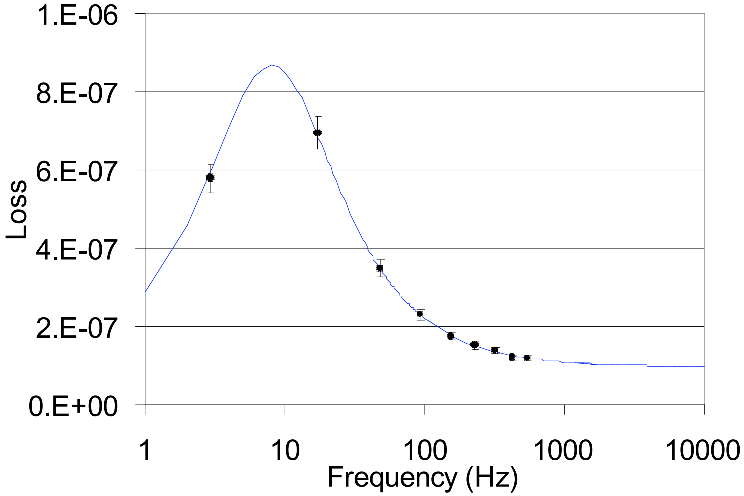
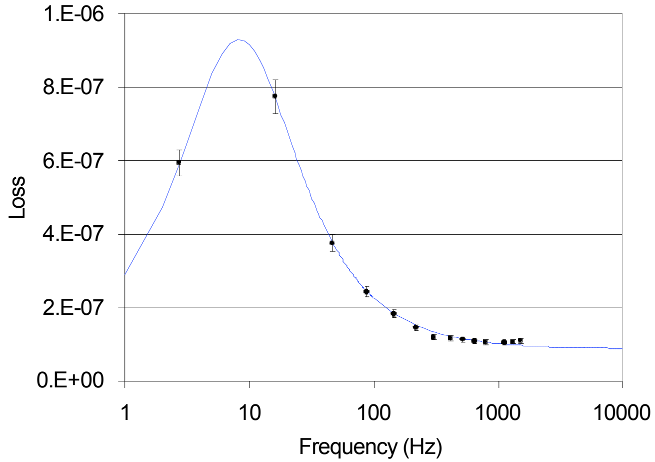
Mechanical loss in CO_2 laser pulled fibres





- Four Suprasil 300 fibres of diameter ~470μm were measured
- Initial analysis of losses shows a surface loss consistent with:

$$h\phi_{surface} = 4.7 \times 10^{-12}\,\mathrm{m}$$

- From Penn et al we can calculate values:

for suprasil 2 $\quad h\phi_{surface} = 6.05 \times 10^{-12}\,\mathrm{m}$

for suprasil 312 $\quad h\phi_{surface} = 3.25 \times 10^{-12}\,\mathrm{m}$

- Suprasil 300 is not necessarily expected to be similar to 312 or 311 as it has a different manufacturing process and a lower OH content

GEO 600

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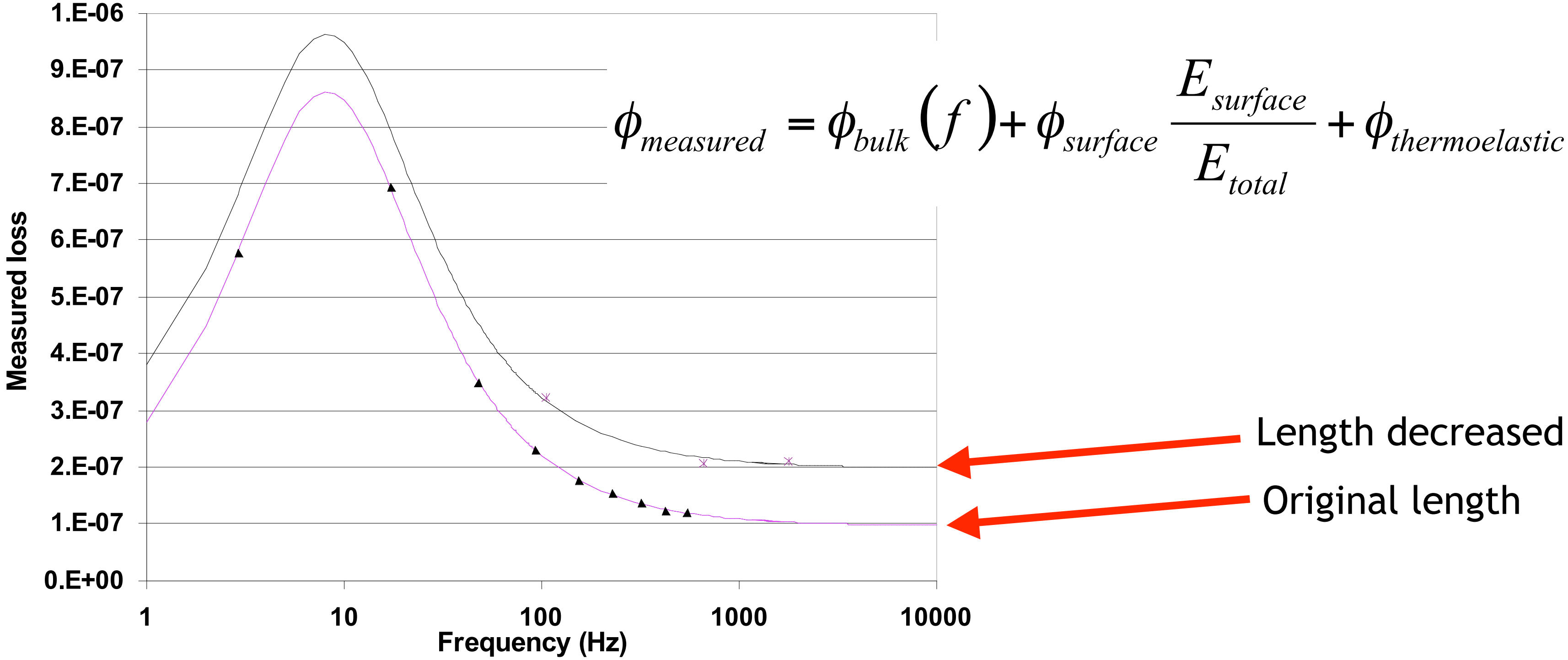
IGR

Measured loss as a function of length



$$\phi_{measured} = \phi_{bulk}(f) + \phi_{surface}\frac{E_{surface}}{E_{total}} + \phi_{thermoelastic}$$

- Loss of higher frequency modes not dominated by thermoelastic loss
- $\phi_{bulk} \sim 2.4\times10^{-9}$ (using model by S. Penn)
- Do not expect surface loss to be length dependent
- Measurements show some extra source of length dependent loss

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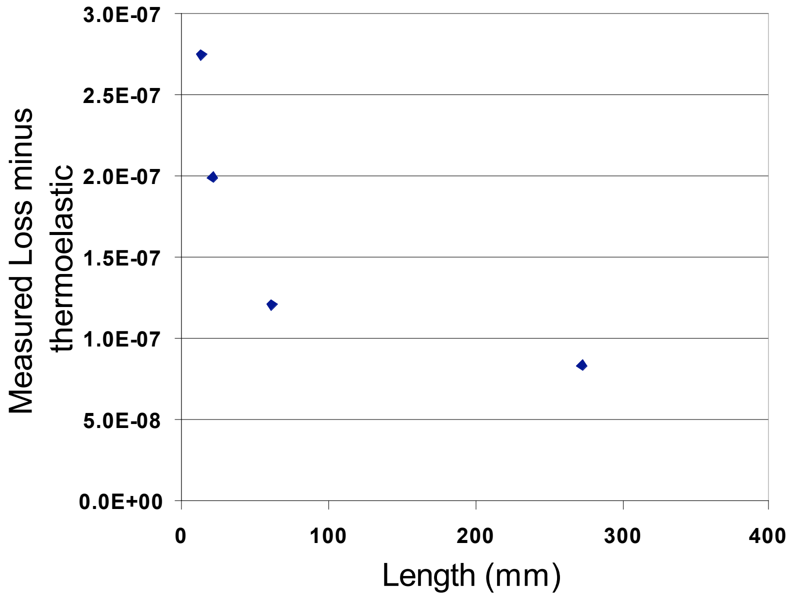
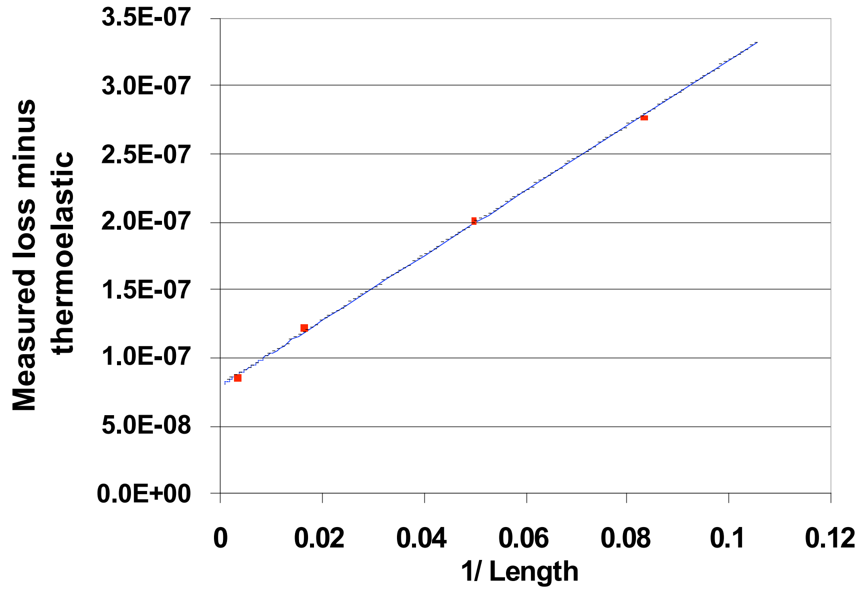
Measured loss as a function of length





- Weld represents a possible source of excess loss
- Model would then be:

$$\phi_{residual} = \phi_{surface} \frac{E_{surface}}{E_{total}} + \phi_{weld} \frac{E_{weld}}{E_{total}}$$

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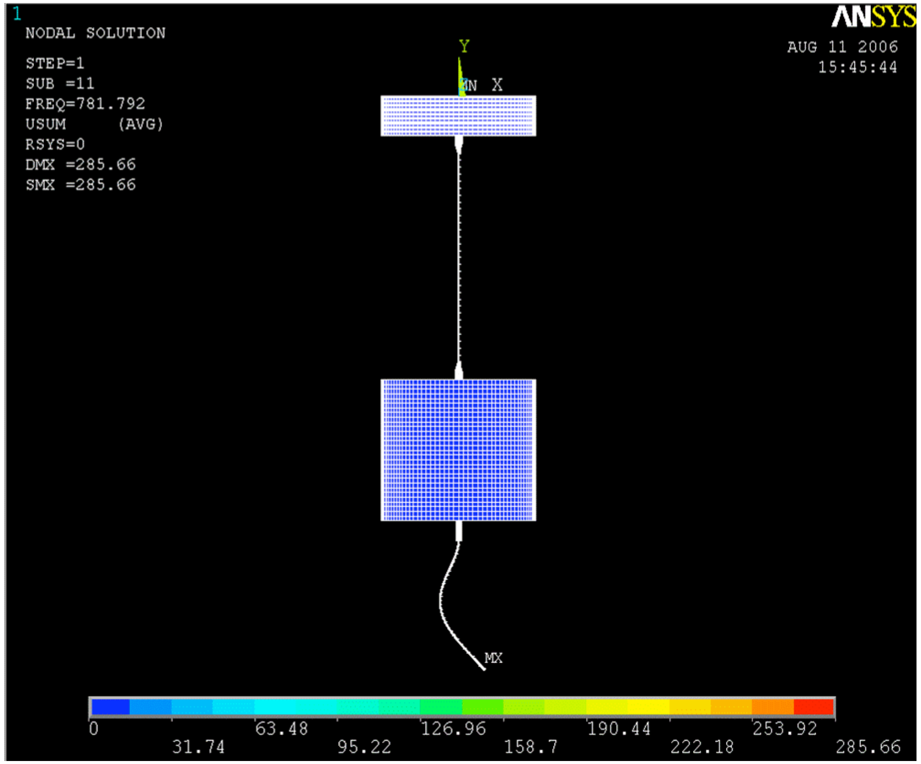
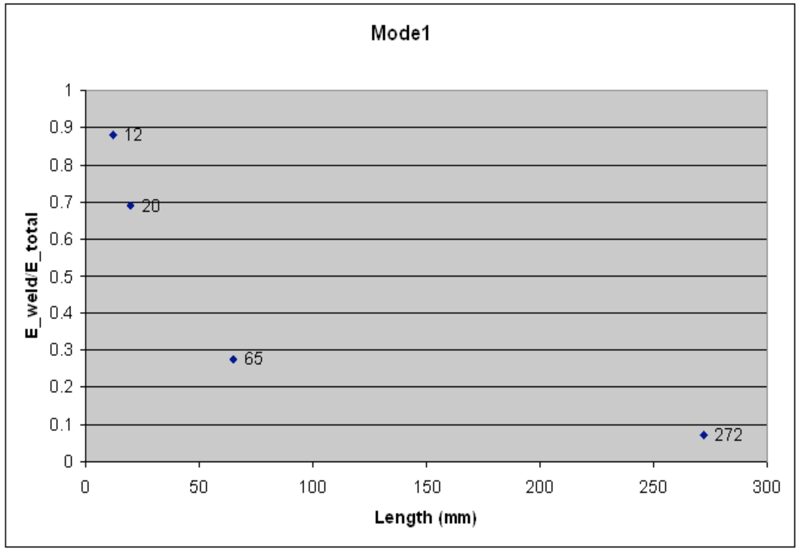
Finite element analysis of energy storage – *Steven Zech*, international summer student from Embry-Riddle University via NSF REU program

- FEA -investigate the length dependence of energy stored in last mm of fibre





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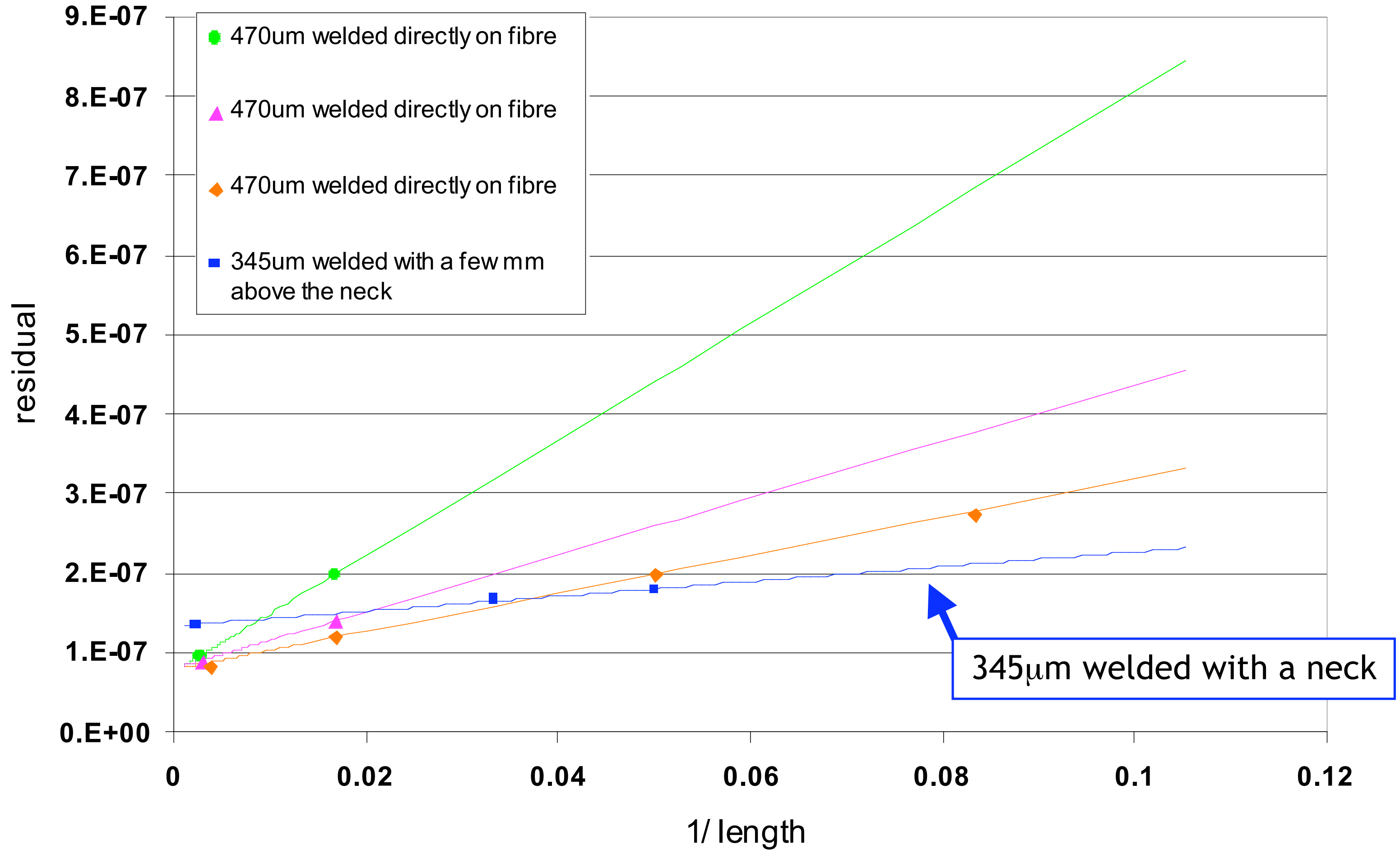
Analysis

$$\phi_{residual} = \phi_{surface} \frac{E_{surface}}{E_{total}} + \phi_{weld} \frac{A}{l}$$

where *A* is a constant

- For each fibre we can subtract the thermoelastic contribution and plot $\phi_{residual}$ vs 1/*length*
- Intercept provides information on magnitude of surface loss
- Gradient gives information on magnitude of loss associated with weld: $\phi_{weld} A$

Analysis of losses at welded interface



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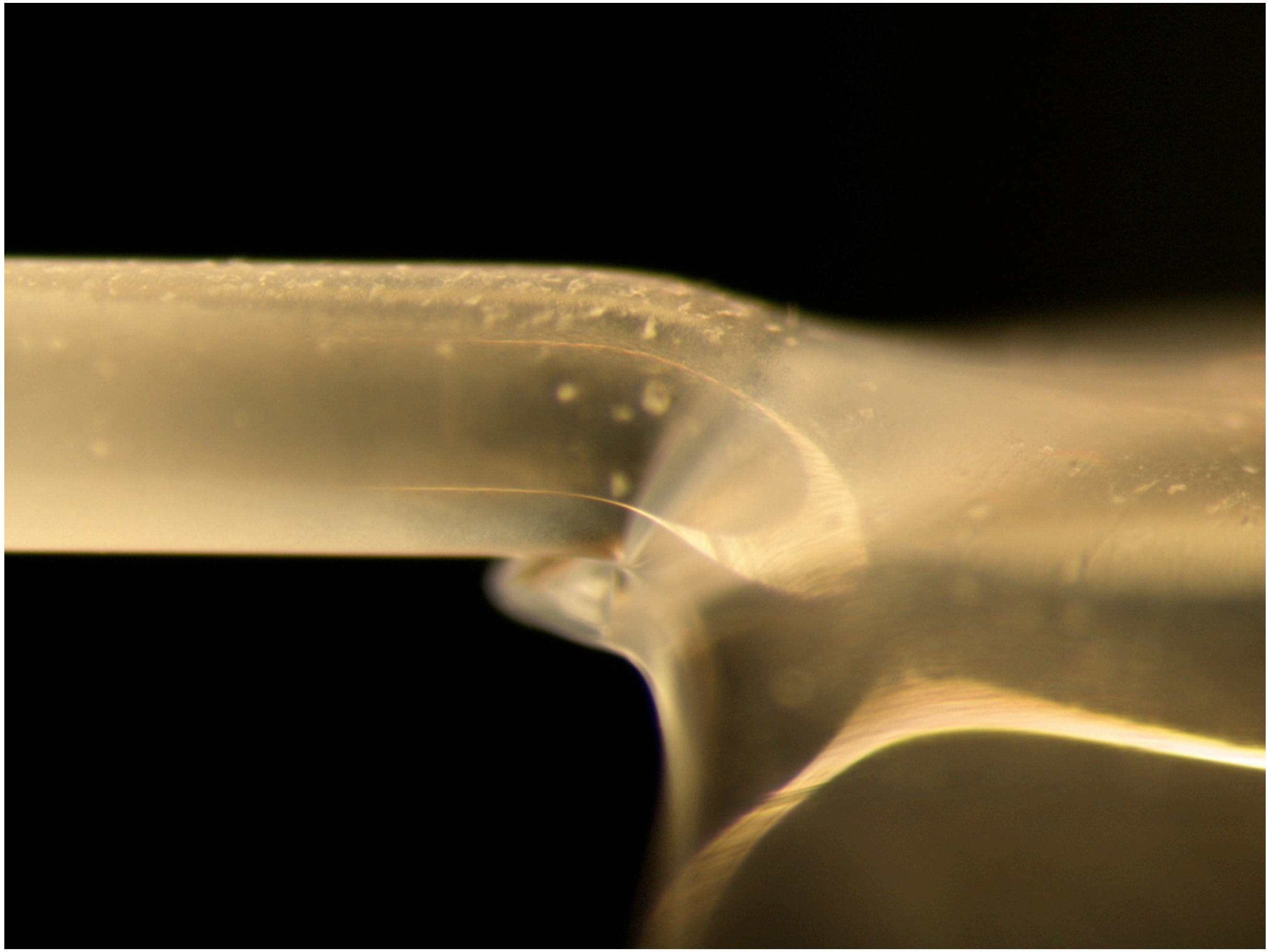
Interpretation

- Fibres of the same diameter clearly tend to same surface loss limit.
- Length dependent loss does appear at different levels in all fibres.
- If we assume a length for lossy section of 1mm we can calculate loss at the weld to be $\phi_{weld} \sim 6 \times 10^{-7}$ for the best weld seen here.
- Fibre welded above neck shows lowest gradient (or the lowest effect due to welding)

First fibre measured



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Second fibre measured

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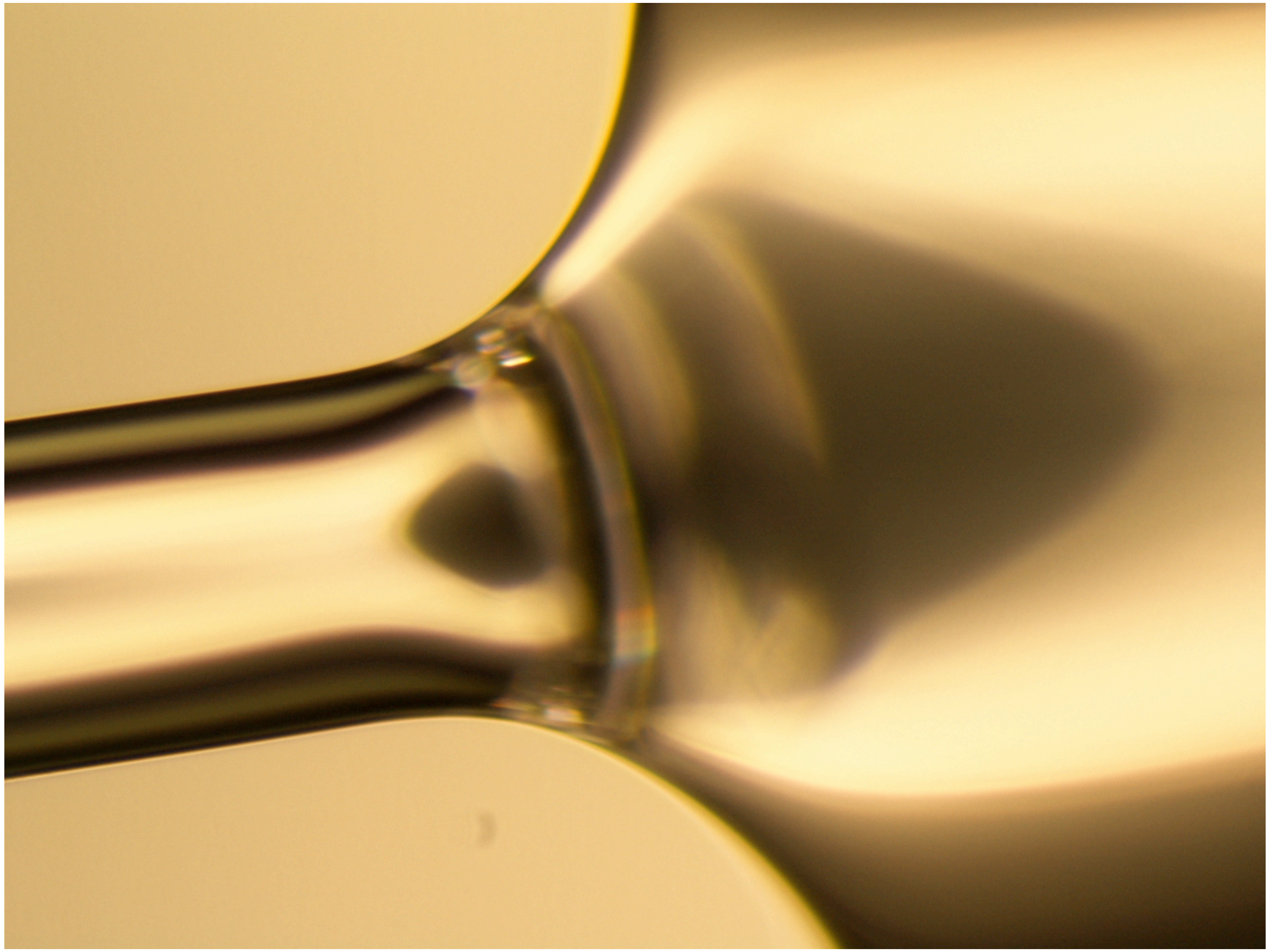
Third fibre measured



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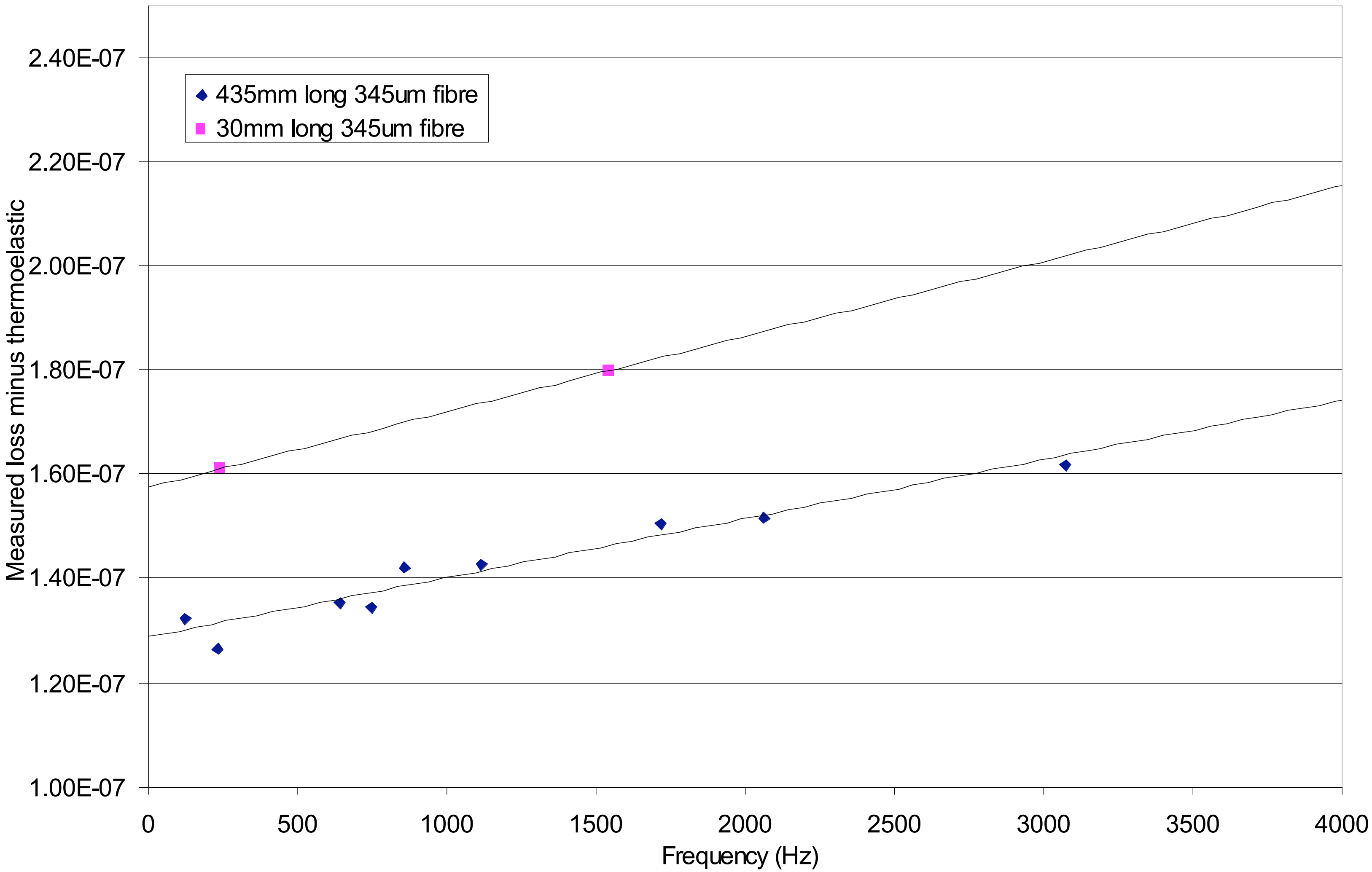
Analysis of residual loss once thermoelastic contribution is removed



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Frequency dependence of loss

- Some evidence of frequency dependence of loss in fused silica fibres seen for fibres of diameter greater than 1mm (A. Gretarsson PhD thesis)
- Here we see these effects in all fibres with diameters down to 320μm
- Well documented in bulk pieces (see eg. Penn et al or Numata et al)
- However here we would expect $\phi_{bulk} \sim 2.4\times10^{-9}$ (using model by S. Penn)
- This is dominated by loss from the surface layer by two orders of magnitude.
- Here level of contribution from the frequency dependent part of the loss causes an increase of $\Delta\phi = 3\times10^{-8}$ between 200Hz and 3kHz, a significant contribution to the loss at higher frequencies
- Frequency dependent dissipation is seen at similar levels in a number of fibres of different diameter
- To investigate source of this frequency dependent loss consider:

$$\phi_{measured} = \phi_{bulk}(f) + \phi_{surface}\frac{E_{surface}}{E_{total}} + \phi_{weld}\frac{E_{weld}}{E_{total}} + \phi_{thermoelastic}$$

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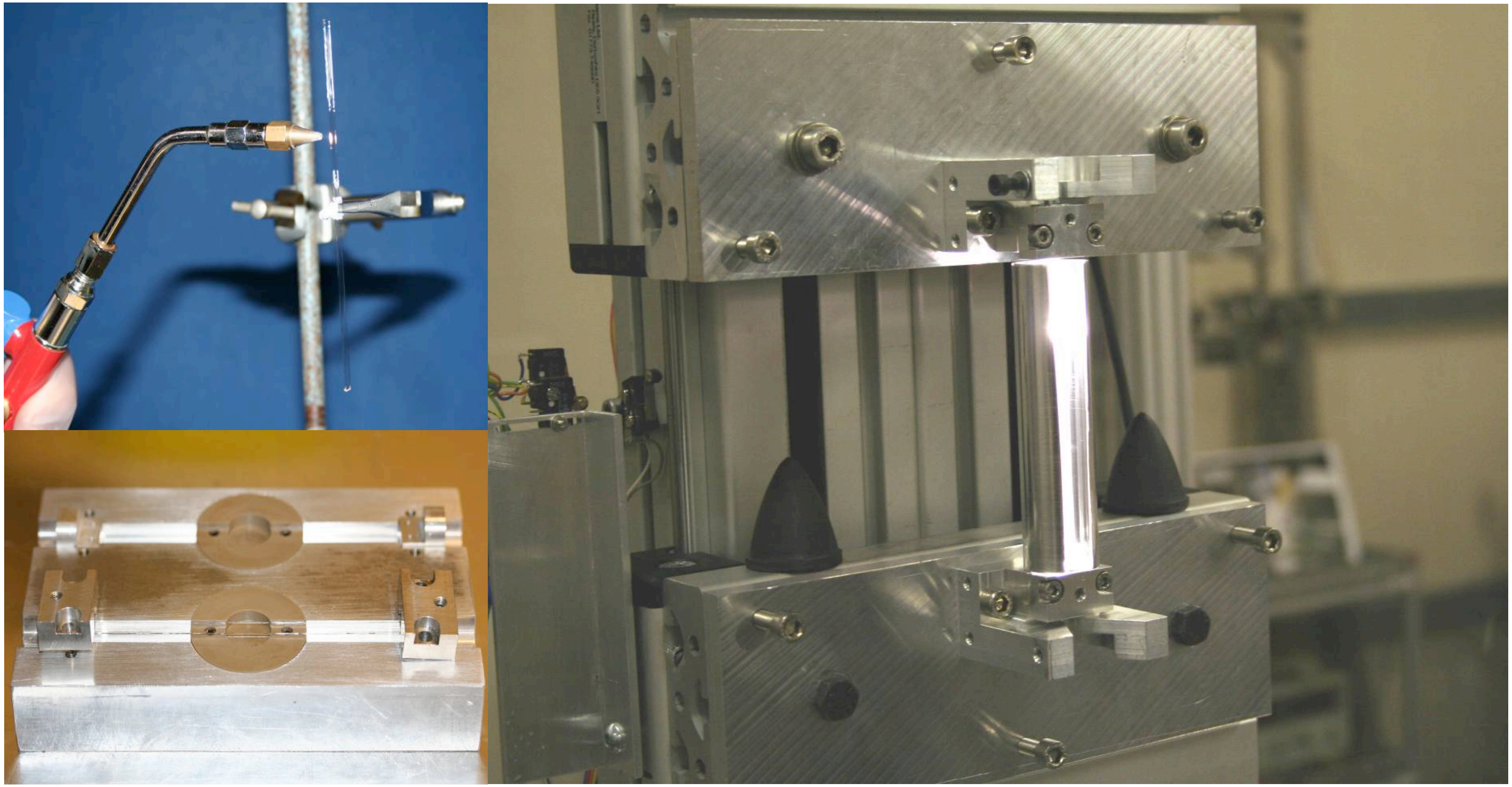
Ribbon fibre development



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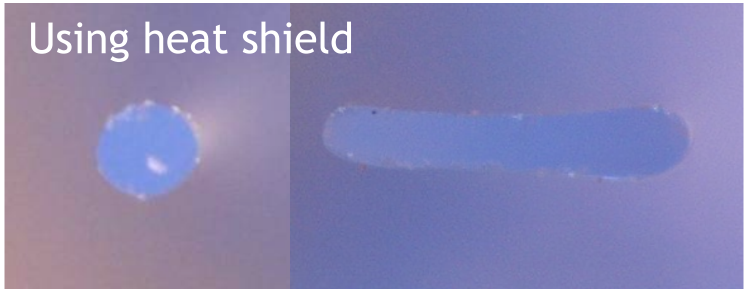
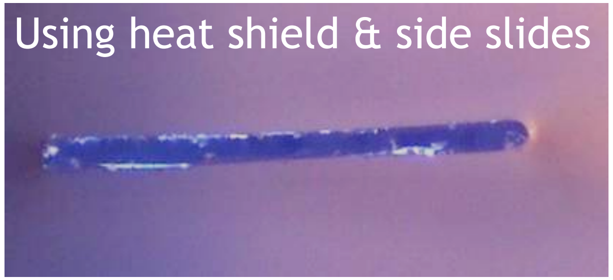
Ribbon cross-sectional shape development

- First ribbon fibres pulled had a non-rectangular cross-section due to heat loss from edges.
- Laser was run at close to maximum power due to heat loss
- Polished aluminium heat shield was developed to reflect heat back at edges
- Further improvements to the symmetry of the fibre neck and cross section were achieved by using slides on either side to reduce the edge effects





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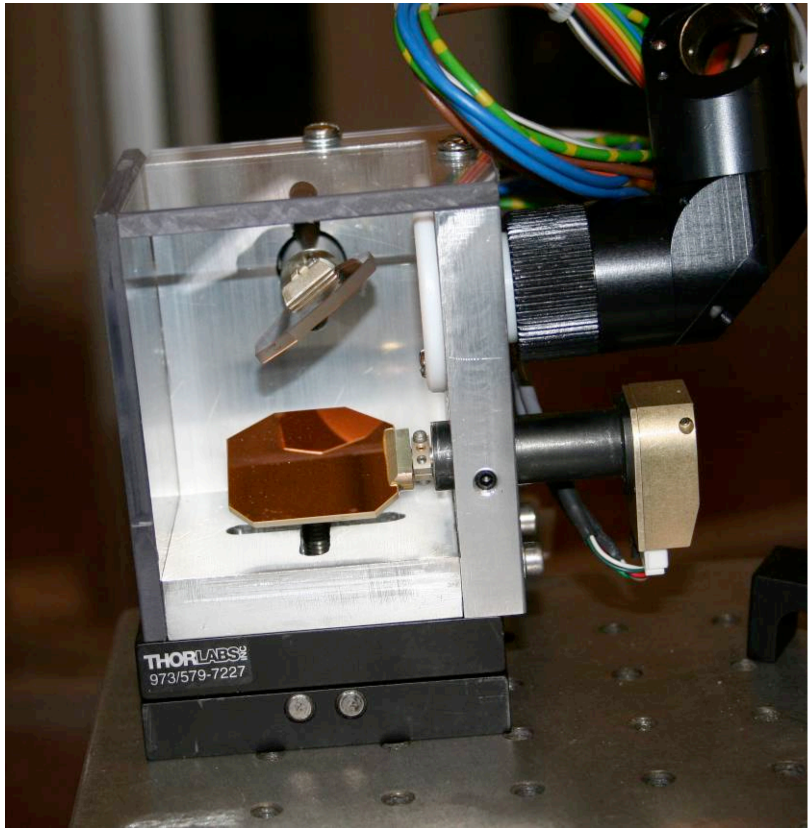
Welding technology



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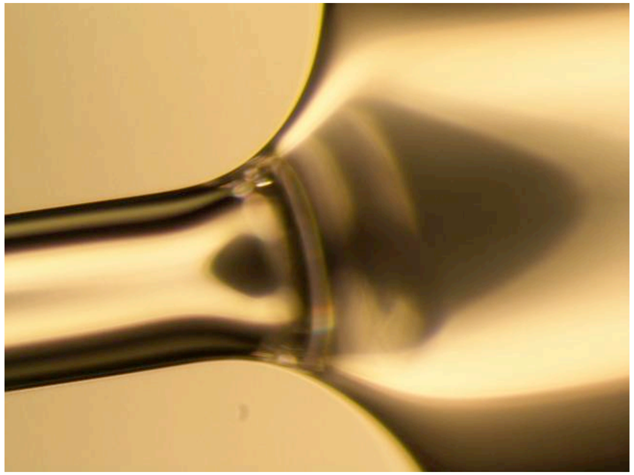
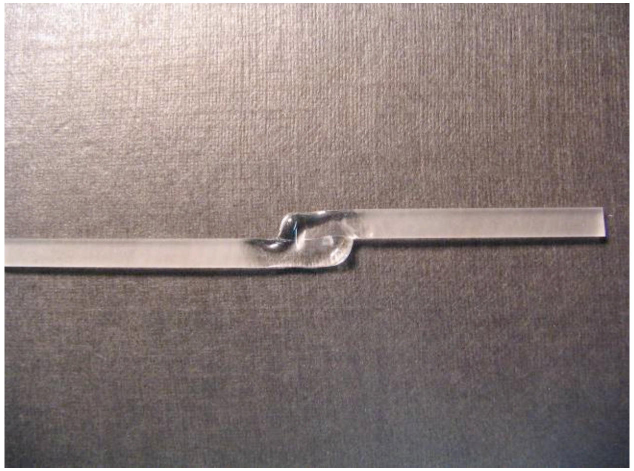
Laser welding and silicate bonding tests





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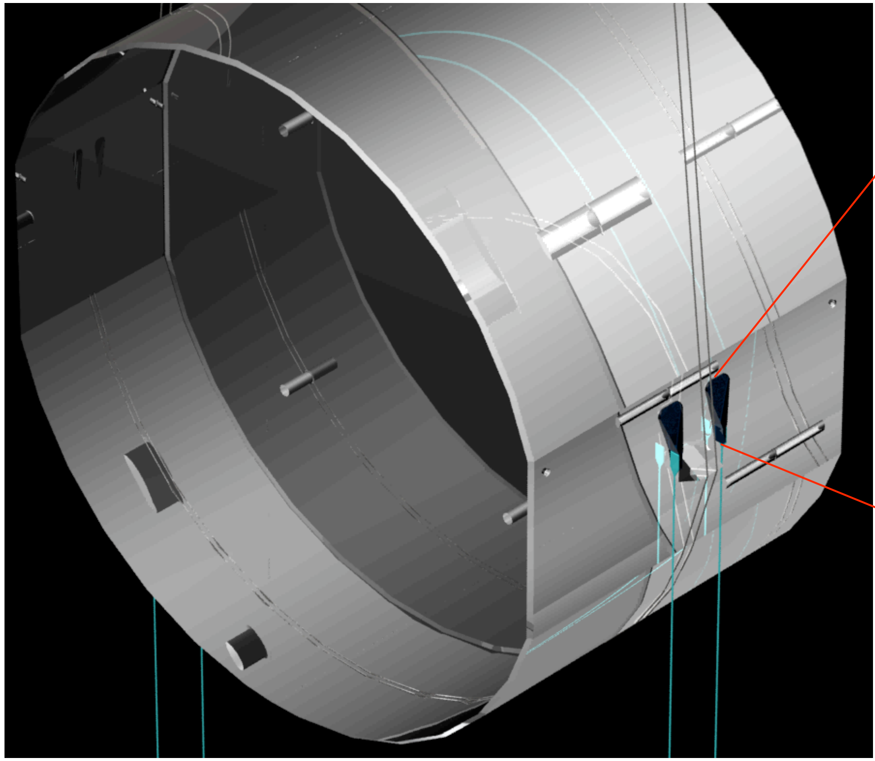
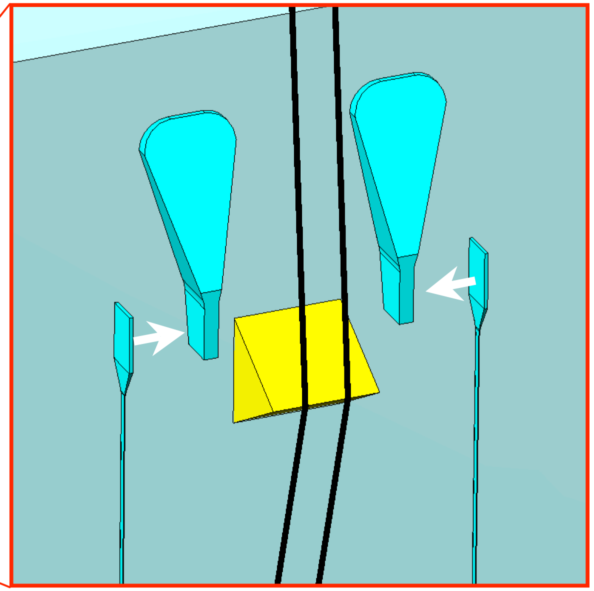
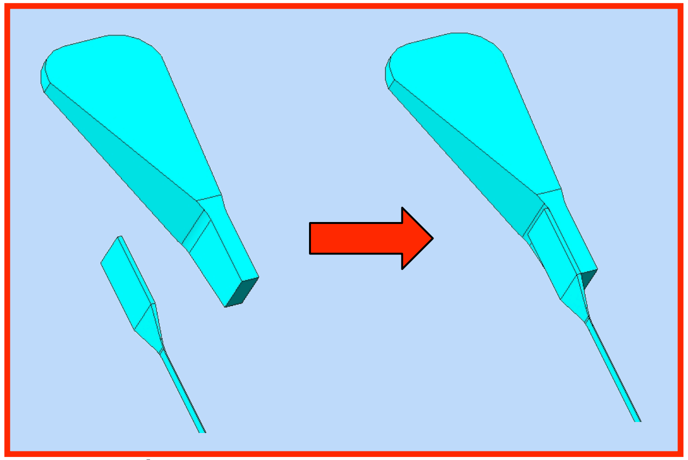
Improved ear design







- Reduces stress in ear
- Improves access for welding
- Increases the overlap area for weld

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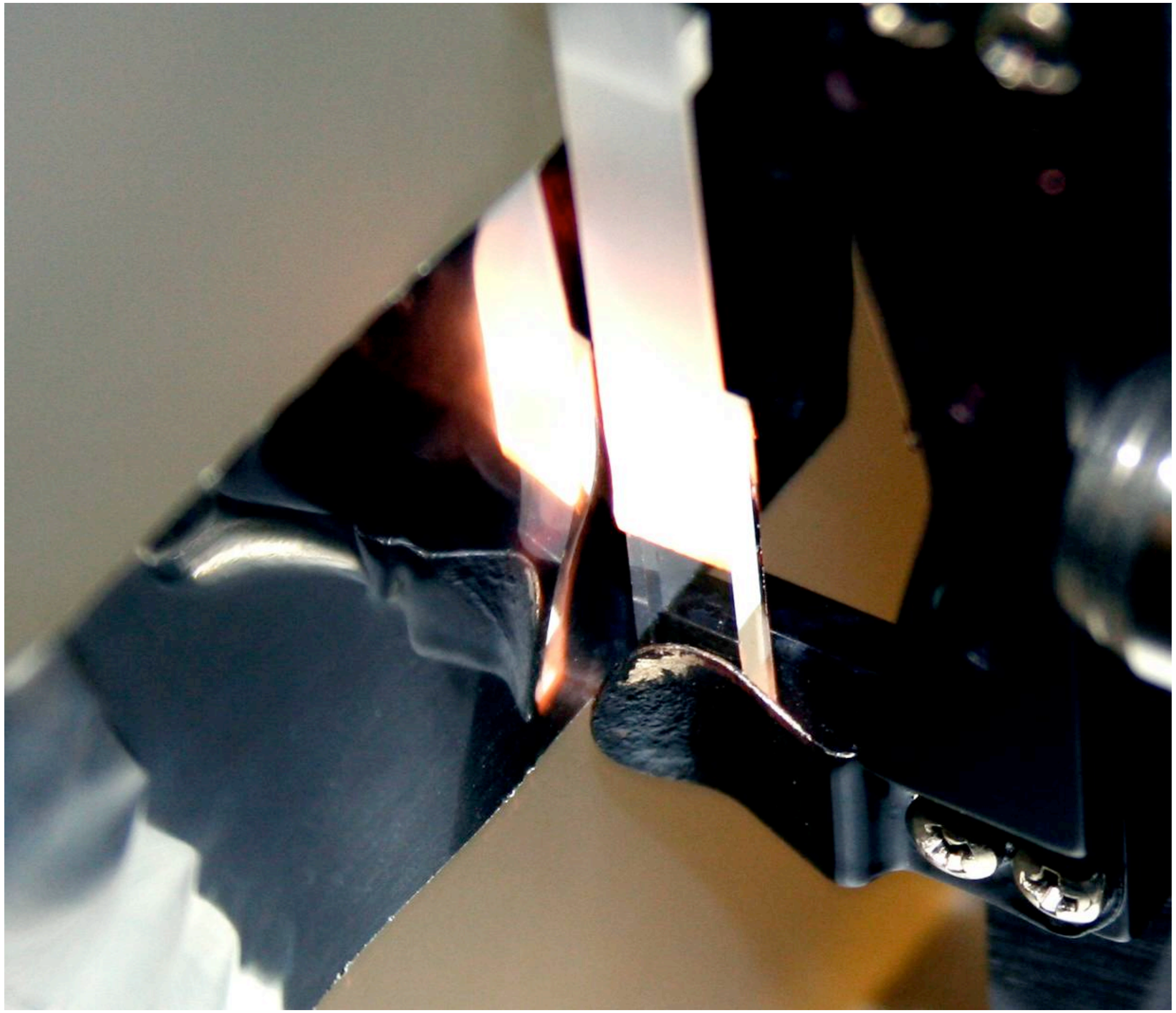
Reflection welding tests



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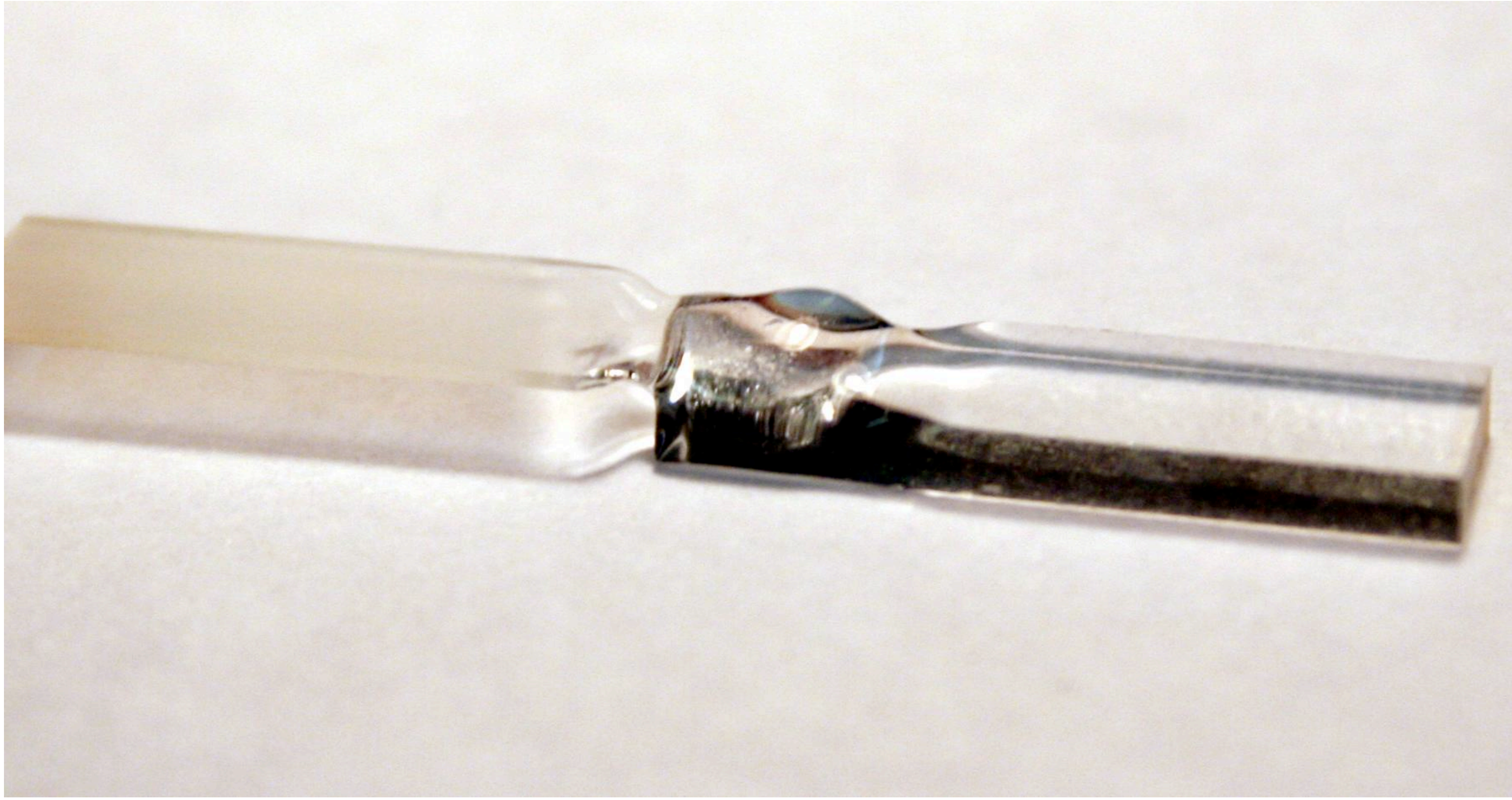
Reflection welding tests



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Conclusions

- Based on the experience of the flame pulling machines used for the GEO600 suspensions we have designed and built new fibre pulling machines using CO_2 lasers
- Laser pulled cylindrical fibres have a surface loss at a similar level to flame pulled fibres
- Data shows evidence of length dependent loss which appears to be related to the quality of weld
- There is strong evidence of frequency dependence in residual loss of fibres studied
- This appears to arise due to dissipation in the bulk of the fibre material but at a higher level of loss than is seen for larger 'bulk' samples
- **Both the above effects need included in any model of suspension thermal noise in monolithic silica suspensions**
- **Further studies in progress**