Development of a CO_2 laser machine for pulling and welding of silica fibres and ribbons

D. Crooks for the GEO 600 collaboration

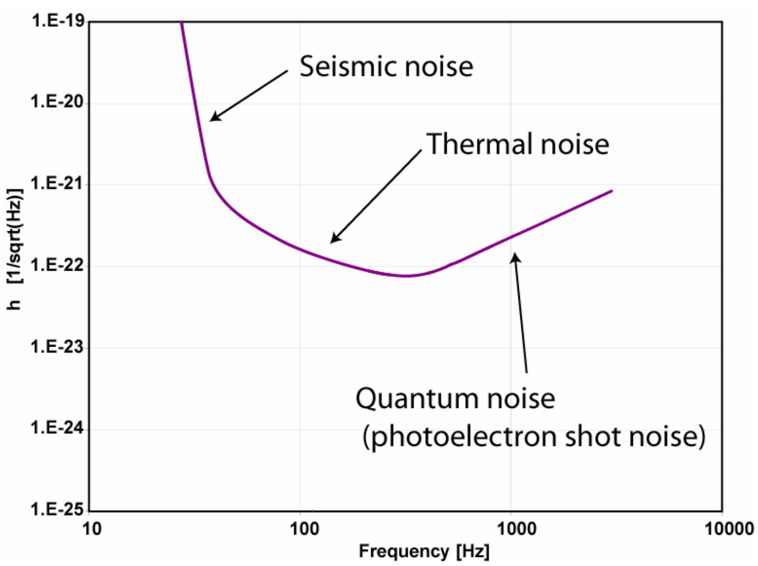
Aspen January 2005

LIGO-G050024-00-Z

Isolation of test masses: mission

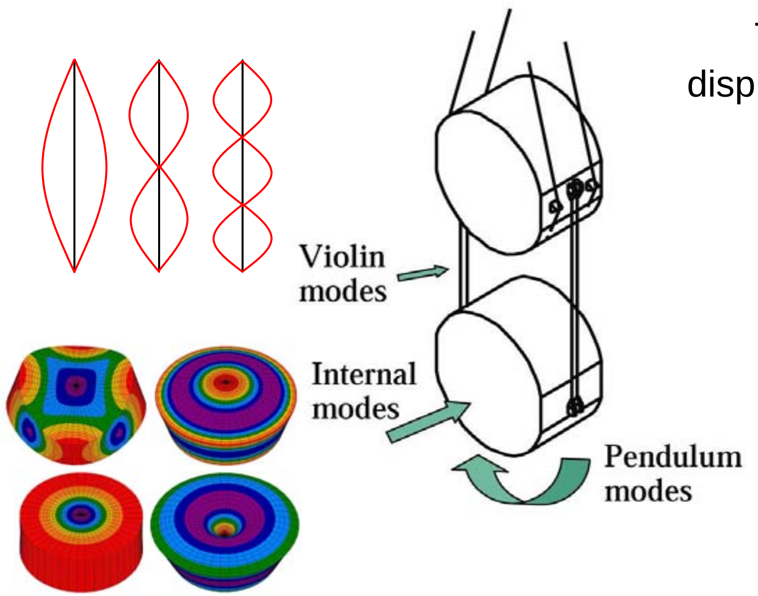
- Provide isolation of the test masses from seismic noise whilst minimising thermal noise
  - seismic noise:
    ground motion inversely proportional to frequency squared: seismic noise important below ~ 50 Hz
  - thermal noise:
    most significant noise source in current detectors at low frequency end of operating range (~ 50 Hz to a few hundred Hz)

GEO 600

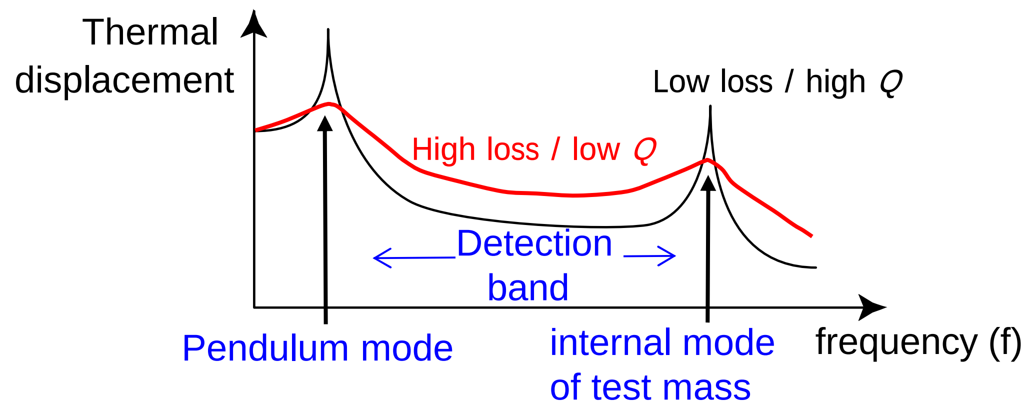


Multiple pendulum suspensions with low loss final stage

- Isolation from seismic noise:
  - Multiple pendulum suspensions, cantilever steel blades
    e.g. GEO 600 triple pendulum suspensions (isolation $1/f^2$ per stage)
- Minimise thermal noise:
  - Make final stage of low loss material e.g. GEO 600

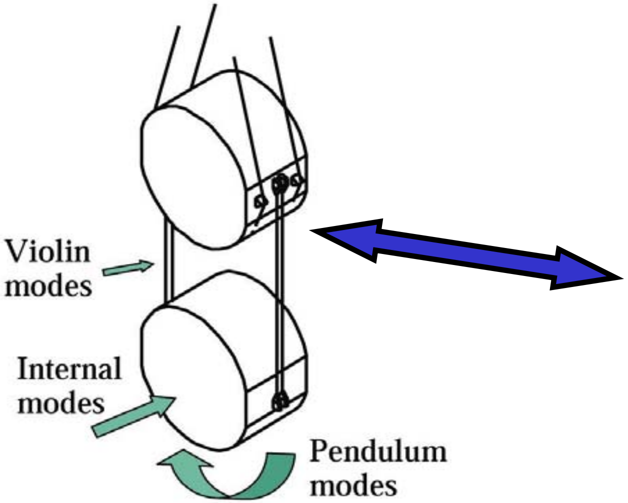


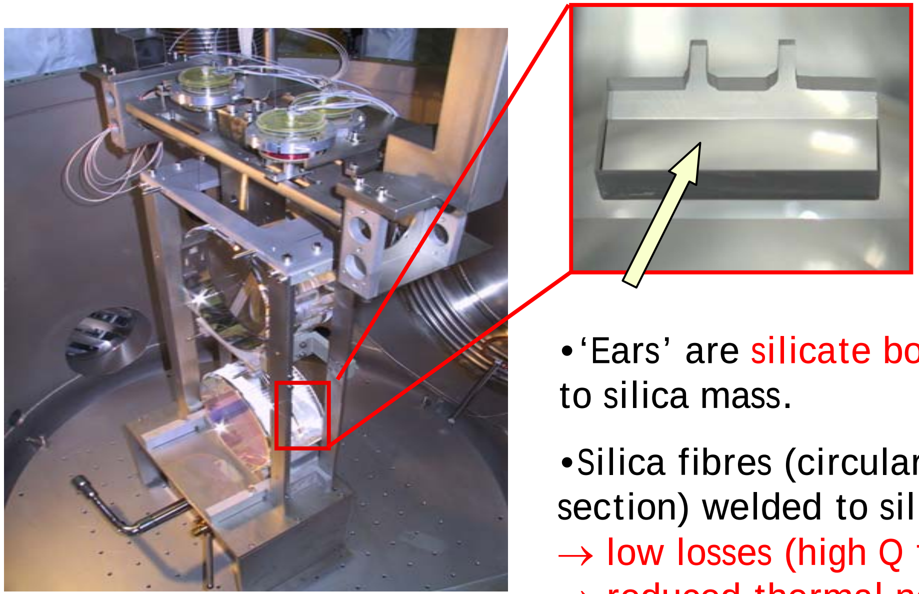
Each stage has pendulum, violin and test mass modes of vibration

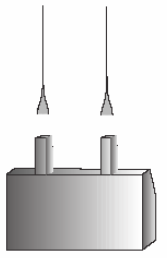


- *Quality Factor*, $Q = 1/\phi(\omega_0)$
- $\phi(\omega_0)$ is mechanical dissipation or loss
- want low $\phi(\omega_0)$, high Q

Unique GEO technology
- monolithic silica suspension for reduced thermal noise







- 'Ears' are silicate bonded to silica mass.
- Silica fibres (circular cross-section) welded to silica ears
  → low losses (high Q factors)
  → reduced thermal noise

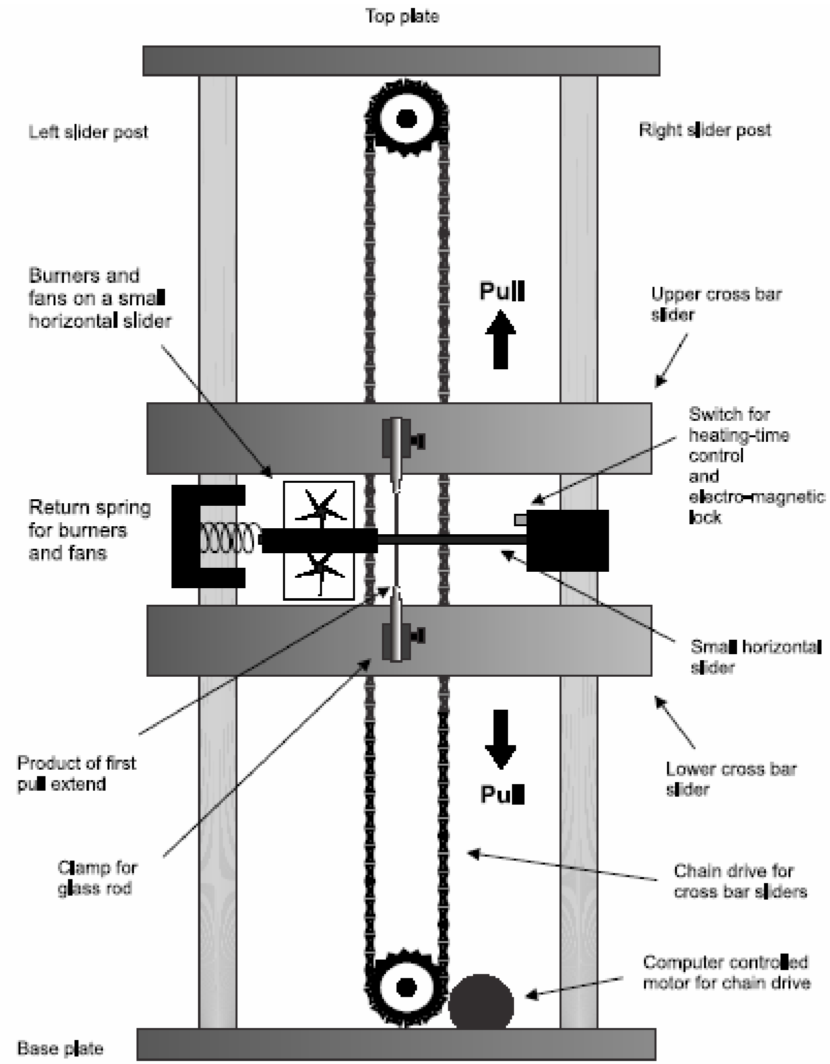
Dissipation due to bending of suspension fibres is 'diluted' by loss-less storage of energy. Hence pendulum and violin mode *Q*'s can be much higher than that of the material itself.

S. Goßler *et al.*, Classical and Quantum Gravity , Vol. 21 , p 923 (2004)

GEO 600 silica suspension fibres – fabrication & welding technique

- Circular fibres pulled using oxy-hydrogen flame pulling machine. Manual flame welding.
- Successfully installed in GEO 600 late 2002.
- Limitations
  - Conductive/convective heating
    - Vaporisation of material on outer surface
    - Surface defects/contamination by combustion products can limit strength
  - Shape control - limited
    - Unsophisticated - melt and pull before silica cools down
    - Increased noise couplings, limited performance
  - Reproducibility - limited

VIDEO CLIP OF FLAME PULLING OF RIBBON
by A. Heptonstall



Picture: S. Goßler

Improved silica fibre technology for advanced room temperature detectors

- Advanced detectors require higher specification fibres than GEO 600 – must push silica technology to the limit at room temperatures

  e.g. Advanced LIGO baseline is to use ribbons (thinner, more compliant, higher dilution factors) or dumbbell fibres.

- Improvements to be made in:
  - Shape
  - Reproducibility
  - Surface quality
  - Level of contamination
  - Weld profile

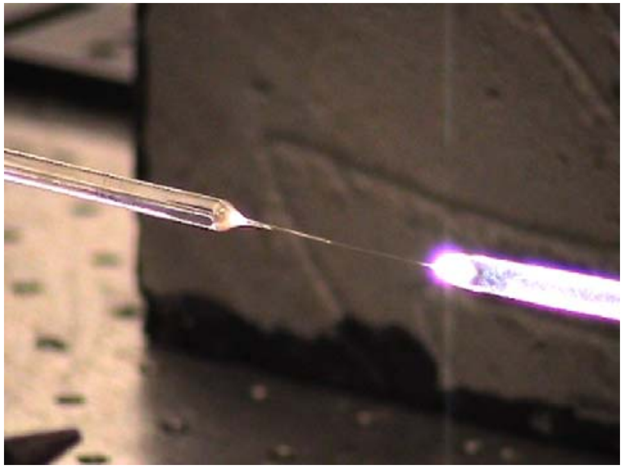
- Use CO_2 laser machine for pulling & welding of fibres/ribbons
  R & D already part funded by EGO organisation and by the UK funding agency PPARC

EGO European Gravitational Observatory

INFN - CNRS Consortium

PPARC

CO_2 laser pulling & welding of silica fibres/ribbons



- Use CO_2 laser radiation (10.6 μm) to melt silica
- Potential advantages of laser fabrication & weld:
  - Very fine control of quantity and localization of heating
  - Reduced contamination
  - Improved shape control by feed & pull (although can also be done by flame)
  - Diameter self-regulation effect
  - Rapid energy control – fibre diameter feedback control possible
  - Re-correction of shape, stress relief/annealing afterwards
  - Precision welding – improved weld shape

Diameter self-regulation

- Heat gained by absorption ($\propto$ vol) balanced by heat lost by radiation ($\propto$ area)
- As fibre is pulled the surface to volume ratio increases
- Material automatically cools as diameter decreases and pulling will cease
- For a given power of laser and constant axial tension should be able to reproduce fibres of identical diameter
- Question:
  Can this effect be exploited for pulling our advanced fibres?

Absorption depth in fused silica at λ = 10.6 μm

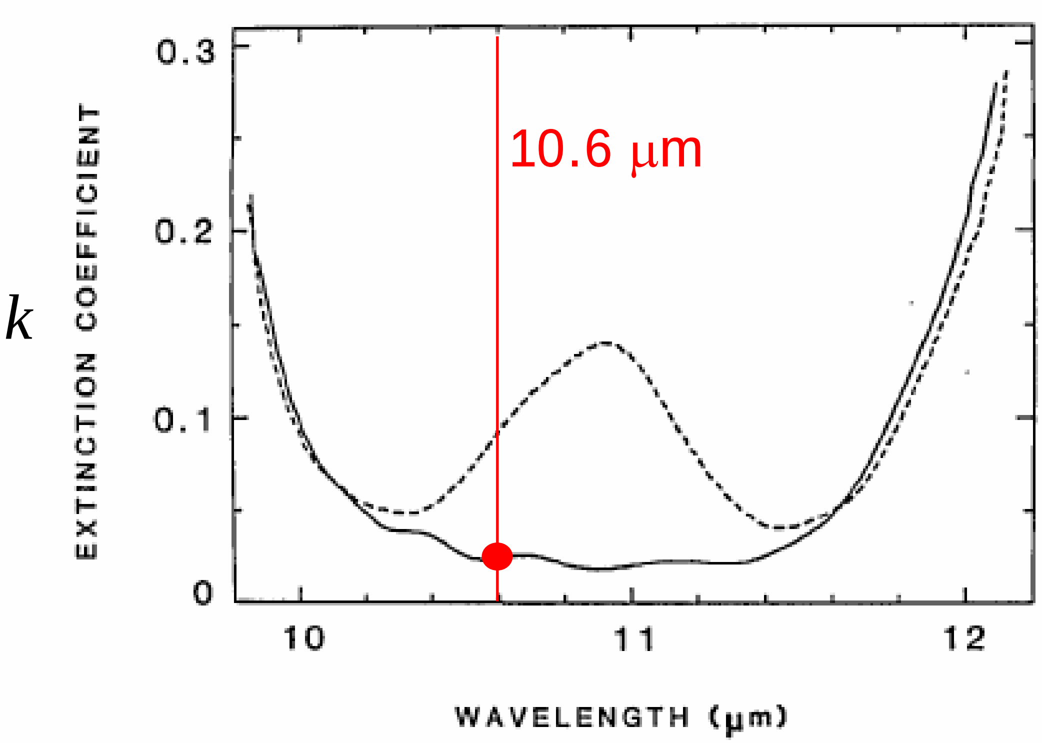


Fig. 3. Values of the extinction coefficient calculated from the data of Fig. 1: ——, pure fused silica; - - -, Vycor. The values were calculated from spectrophotometer transmittance measurements at 25°C.

(McLachlan & Meyer, Applied Optics, Vol 26 No. 9, 1987)

k = extinction (or attenuation) coefficient

n^* = complex index of refraction

$$n^* = n + ik$$

absorption depth β (intensity reduced to 1/e)

$$\beta = \frac{\lambda}{4\pi k}$$

β = 34 μm at 25°C

Diameter self-regulation: potential for exploitation?

- Q: Can this effect be exploited for our application?

  e.g. Advanced LIGO ribbon dimensions
  [600 mm x 1.12 mm x 112 μm]

- β only ~ 34 μm at 25°C for 10.6 μm (McLachlan & Meyer 1987)

- A: NO, dominated by surface heating without any substantial absorption of the radiation in the bulk of the material

- Applicable to manufacture of thinner fibres e.g. optical fibres, torsion balance fibres

VIDEO CLIP OF SELF-REGULATION by D. Crooks

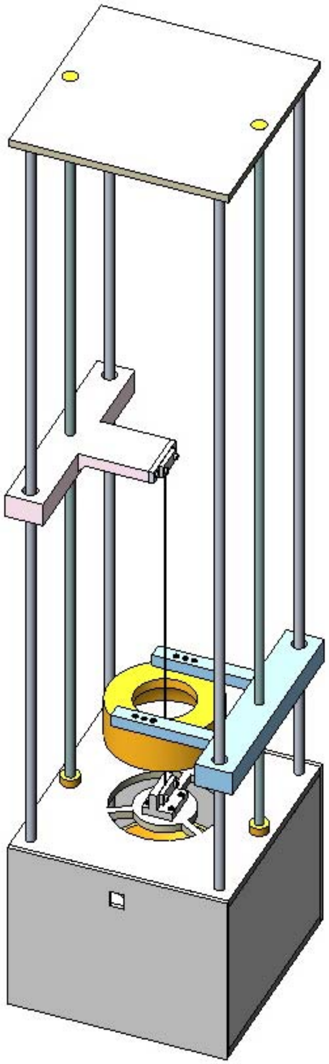
Feed and Pull

- A key change proposed for advanced pulling process is to use 'feed and pull' technique (established technique).
- Silica stock is fed gradually into the laser beam while fibre is drawn out of the resulting melt. Final fibre diameter given by:

  $(v_{initial}/v_{final}) = (d_{final}/d_{initial})^2$ with v, velocity and d, diameter
- Prototype manual machine has been constructed to test feasibility. Ratio $v_{initial}/v_{final}$ ~ 1/17 so diameter of pulled fibre ~1/4 that of stock

VIDEO CLIP OF MANUAL PULL

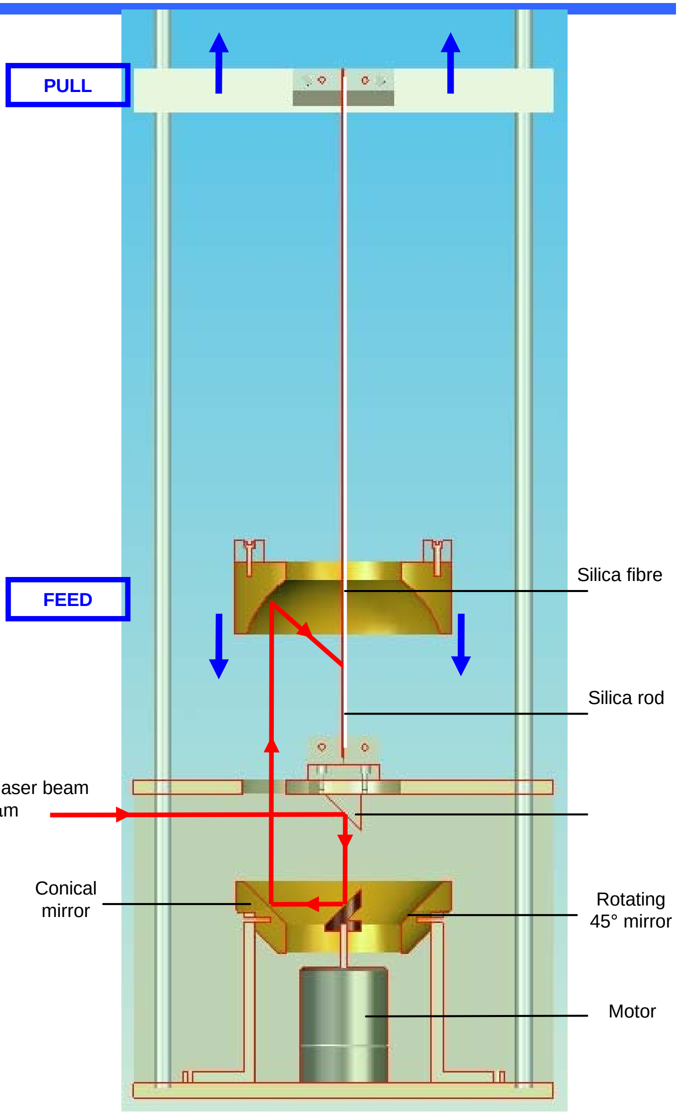
Pulling machine conceptual design



3D CAD representation

Current conceptual design of cylindrical fibre machine

- fibre stock clamped to base of machine
- focus of laser (ring) moved downwards to progressively melt stock
- upper stock clamp moves upwards to draw fibre
- For ribbons jitter laser beam using 2-mirror galvanometer



Concept Schematic

Characterisation

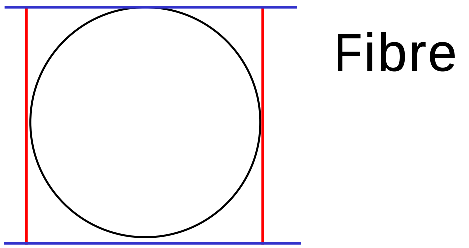
- Require to characterise the pulled suspension elements:
  - Mechanical dissipation
  - Strength
  - Key resonant modes

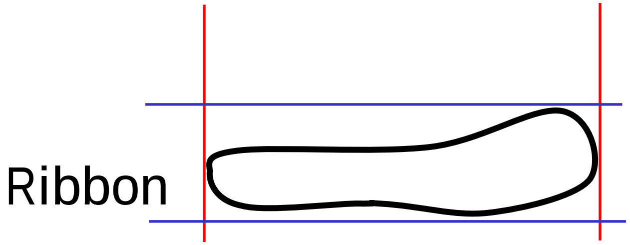
- Need to develop technique to characterise shape of silica fibre/ribbon
  - Offline characterisation
  - Potential online control - use to control machine during pull process

- 3 possible methods
  - Edge detection (shadow sensors/microscope)
  - Refraction
  - Absorption profile

Profiling

- Edge detection
  - Use either shadow sensor or camera picture to determine edges of element from which width and thickness can be determined. Gives overall dimensions but does not detect inner features.





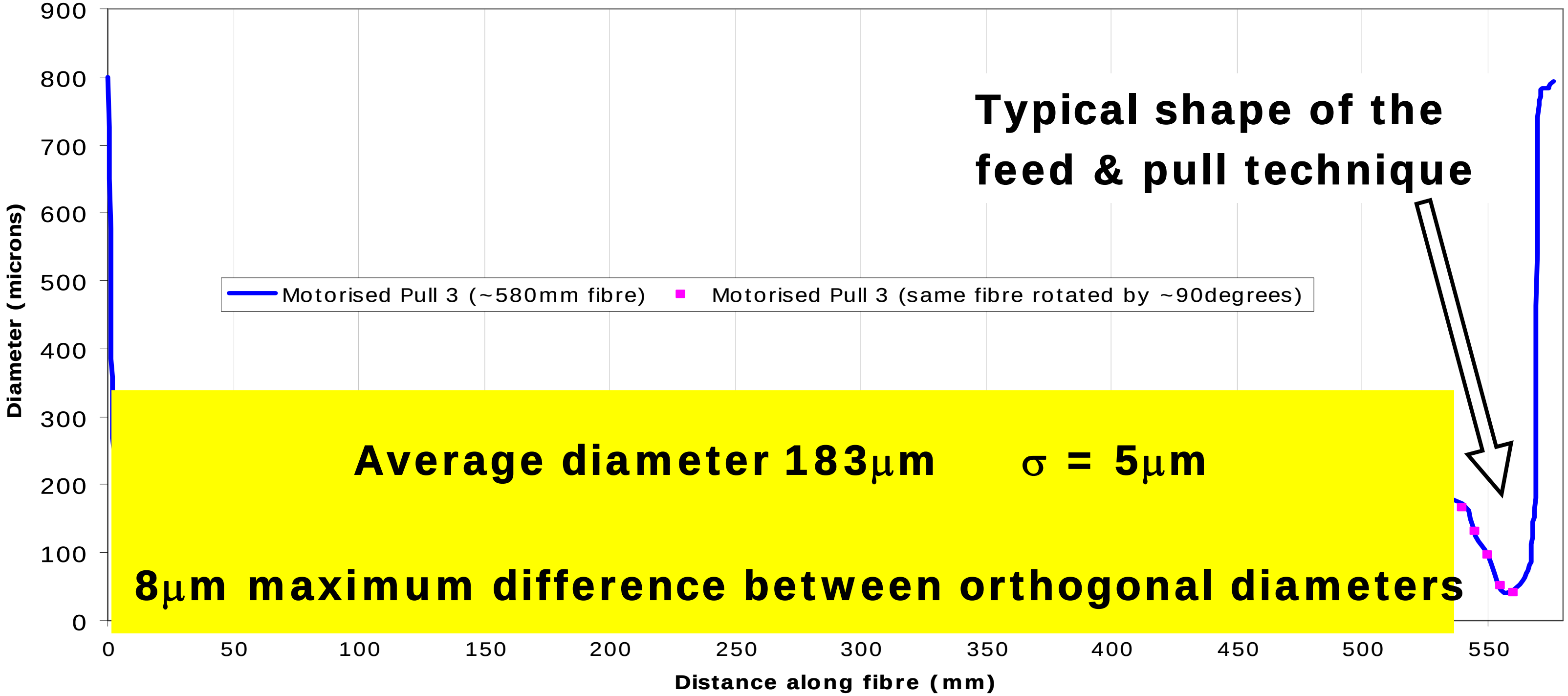
- Refraction
  - Take reference image and use machine vision to determine thickness profile from refracted image

Profiling

- Absorption profile
  - Use low power CO_2 beam to scan across element and use absorption to determine thickness.

- We are currently investigating all methods but will focus on machine vision methods.

Profile of CO_2 pulled fibre



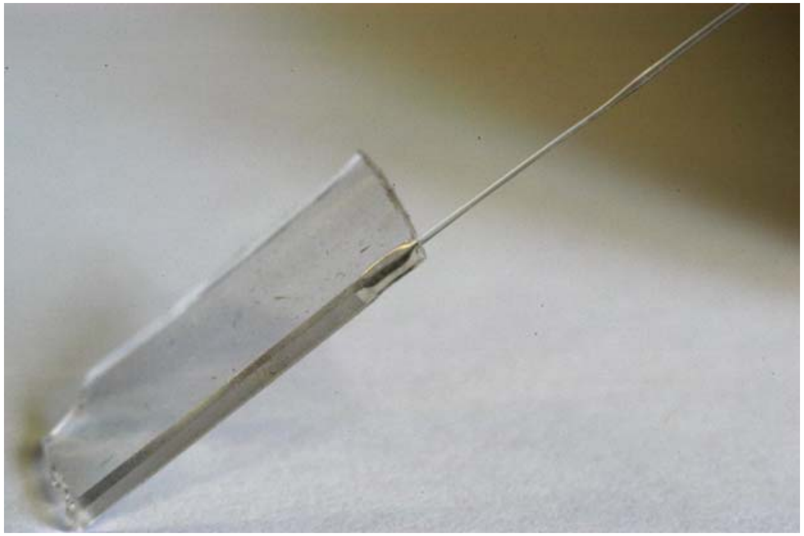
Average diameter 183μm σ = 5μm

8μm maximum difference between orthogonal diameters

Preliminary strength tests

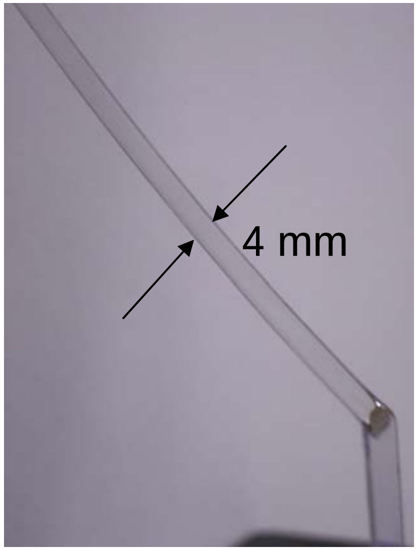
- Strength tests on drawn fibres
  - The fibres always break at the thinnest point yielding a breaking stress of 3GPa

- Strength test on welded fibres
  - ~500 Mpa breaking stress
  - No annealing done
  - Investigation in progress



Ribbon manufacture

- Earlier discussed need for dual capability machine able to produce ribbons as well as fibres.
- Use single axis mirror galvanometer to jitter beam across surface of rectangular stock using a triangular beam path
  - Important not to allow beam to linger on edges of stock
  - Allow beam to *overscan* the sample
- First test ribbon manufacture promising, strength testing to commence soon



- Gives proof of concept for beam steering in welding context.

Planned work

- Perform dissipation measurements with high quality silica stock
- Power stabilisation of laser
- Develop fully automated welding technique
- Further studies on the absorption of CO_2 laser radiation in silica
- Viscosity experiments
- Extend profiling methods