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Pathfinding towards a cryogenic interferometer for LIGO

The homework

- To explore possible futures for LIGO, (supposedly cryogenics)
  - Got mostly obvious answers
  - Got some surprising ones
- It will be a tough long way to a cryogenic interferometer
- It is (almost) obvious that the
  Ultimate Gravitational Wave Interferometer
  will be cryogenic!
- But what about the next evolution?

Preliminary Observations

- First conclusion is that it is almost impossible to mate a hot and a cold interferometer in the same pipe
    - Space reasons in existing buildings
  - Would have to junk advanced LIGO first ! !
    - I guess that we are not ready for it yet.
- Second, any cryo Interferometer will be heat evacuation limited
  - Radiative cooling is not an option because it behaves like T^4
- Will need to use crystals (sapphire) both for mirrors and suspension mechanics
  - Heat conduction in crystals behaves like T^3 but Sapphire peaks at 20-30^{o}K
  - Heat conduction in metals increases with lower temperature but metals have low quality factors (except Niobium, but low conductivity)

Present expectations from a cryogenic interferometer

- To improve the thermal noise of the mirror and of the suspensions by
  - Brute force, reduction of T.N. with $T^{-1/2}$
    - Factor of 3 at 30°K, (factor of 10 at 3°K)
  - Taking advantage of the mechanical Q factor improvements at low temperature
    - Factors of 5 - 10 - more? - pitfalls ?
  - Using larger beam spot sizes

Quantum requirements to take advantage of cryogenics

- To reach the thermal noise floor need
  enough power in the stored beams
  - Heat extraction problem quadratic with frequency,
  - Fades out somewhat at low frequency
- Increasing power to
  - reduce shot noise at high frequency
  - increases radiation pressure fluctuations at low frequency
- And vice versa

A naturally split personality?

- The last consideration leads to:
- high-power/high-frequency and

  low-power/low-frequency

  cryogenic interferometer would look quite different

  – Long skinny suspension members to push lower in frequency the suspension thermal noise at low frequency

  – Short stubby members to best evacuate heat for the high power brother

The extent of the power evacuation problem

- Considering mirror coating losses only:
- 1 ppm absorption mirror coatings with
- 1 MW circulating power dissipates
- 1 W dissipated on each mirror surface
- PLUS
- assuming 40 ppm/cm bulk absorption, 1000 finesse, and a 25 cm thick mirror
- 1 W dissipated in the input mirror bulk

The extent of the power evacuation problem 2

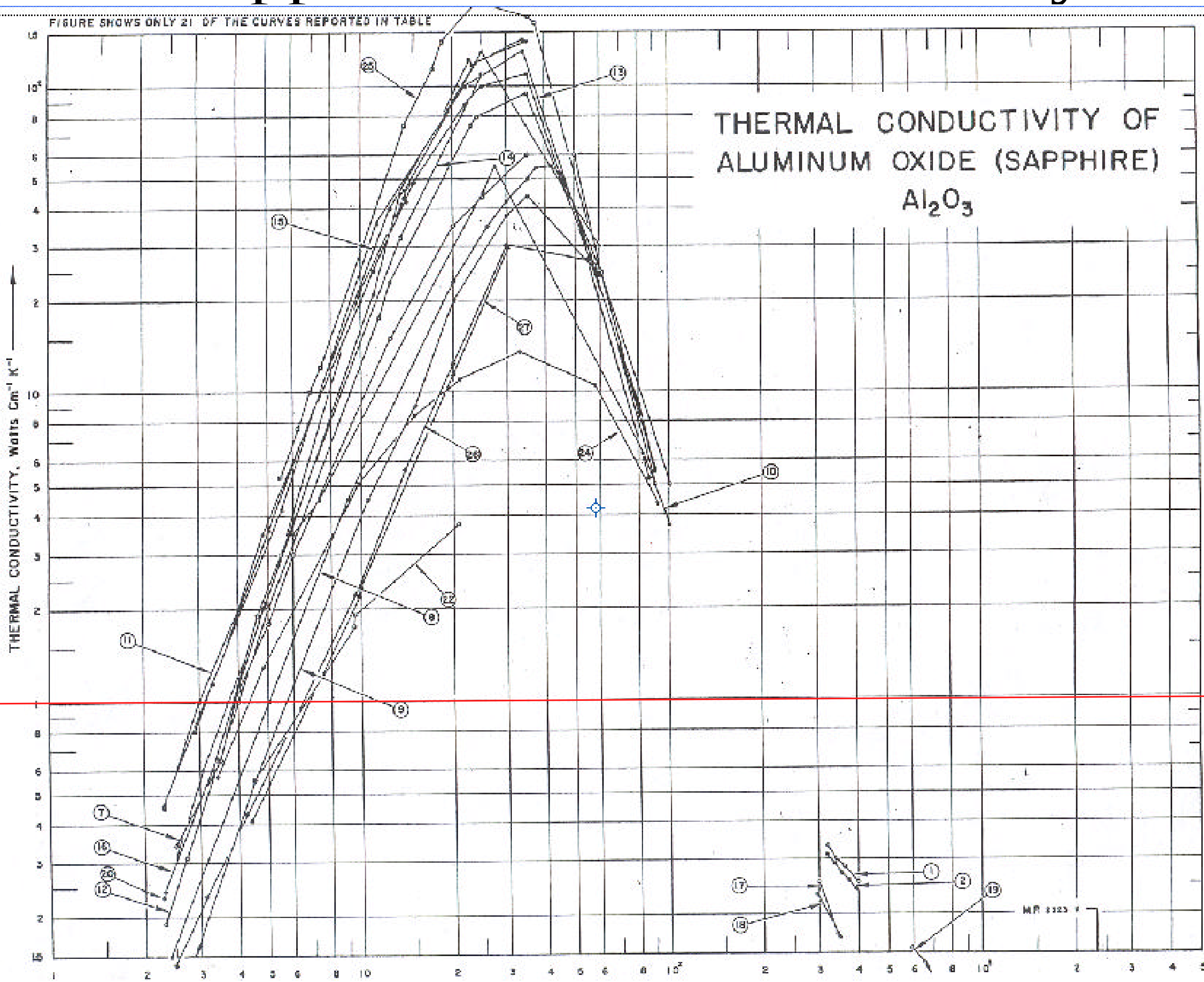
- At normal cryogenic temperatures 1 to 2 W is already problematic !!! BUT
- All power must transit through flex joints
- Conducting it through the thin isolation system is daunting.
- Must conduct all heat through crystalline struts
  - Need large cross sections for conductivity
  - Need thin flex joints for isolation and thermal noise
  - Classical conduction through ultra-pure and annealed copper or aluminum is excluded (Niobium?)

The present status of the power evacuation problem

- The LCGT test
- Used four 250 μm diameter 100 mm long sapphire fibers
- Extract of the order of 10-20 mW of power
- Thermal drop of order of 20^{o} K
- => Obtained a mirror above 25^{o} K

- Note, 20 to 30^{o} K is a magic temperature range due to the conductivity peak of sapphire

Sapphire thermal conductivity



Fibers
@25°K

Niobium
@ 4°K

R & D primary directions

- Energy conservation:
  - Substrate optical loss improvement R&D [1]
  - Coatings absorption reduction R&D [1]
- Thermal noise reduction aim:
  - Coatings substrate mechanical loss R&D [1]
- Heat conduction from mirrors
  - Flex rod development [2]
- Heat extraction techniques
  - Metal, Super-fluid He, Optical [3,4]

- Development prospects color code
  - parallel with Advanced LIGO [1]
  - LIGO direct contribution [2]
  - LSU, KEK, ICRR, Roma 1 /LNF, Fermilab [3]
  - Los Alamos, DOE support [4]

Conservation R&D
(parasiting Advanced LIGO)

- mirror coating R&D
  - to reduce coating absorption much below 1 ppm (0.1 ppm?, 0.05 ppm?)
- crystal growth R&D
  - to reduce Sapphire bulk absorption substantially below 20 ppm/cm

- mirror coating R&D
  - to develop lower mirror mechanical losses

Suspension R&D

- Sapphire suspensions from mirror leading to at least one recessed cooling stage.
  - Need cross section to carry heat
  - Need high quality machined and short flex joints
  - Need low defect crystals for higher conductivity
  - Need very high mechanical quality factors
  - The better TN you get, the more attenuation and power you need
  - Fibers are practically ruled out
    - Wrong aspect ratio (LCGT test)
  - Will need rods with short flex joints
  - But may lose in attenuation power
    - Mass of rods may limit isolation properties
    - Will need upstream an excellent seismic attenuation system

Why suspension rods and flex joints?

- Example:
- If 3x3 rods instead of 250 μm Φ fibers
- => Gain of 180 in cross section (conductance)

- Flex joint over < mm (instead of ~300 mm fibers)
- =>Gain of >300 in lower thermal resistance
- Note, non multiplicative gains

- Low defect crystals
- => towards ballistic heat transport

Sapphire mechanics R & D

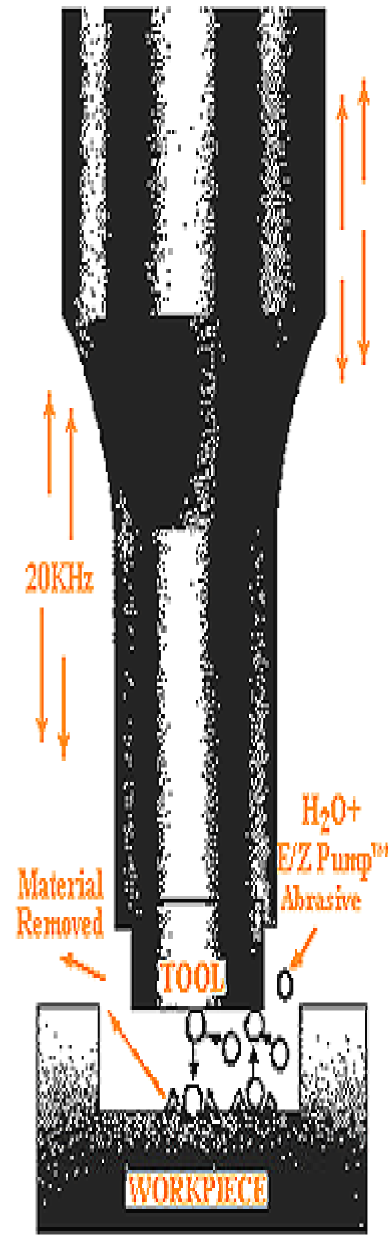
- How to make rods with
  - Flex joints
  - Using low defect crystal material

- Use UltraSound machining

- Surface treatments (to be tested)
  - (equivalent of flame polishing)
  - Ar-cluster polishing
  - Laser heating
  - Electron beam healing
  - Simple baking

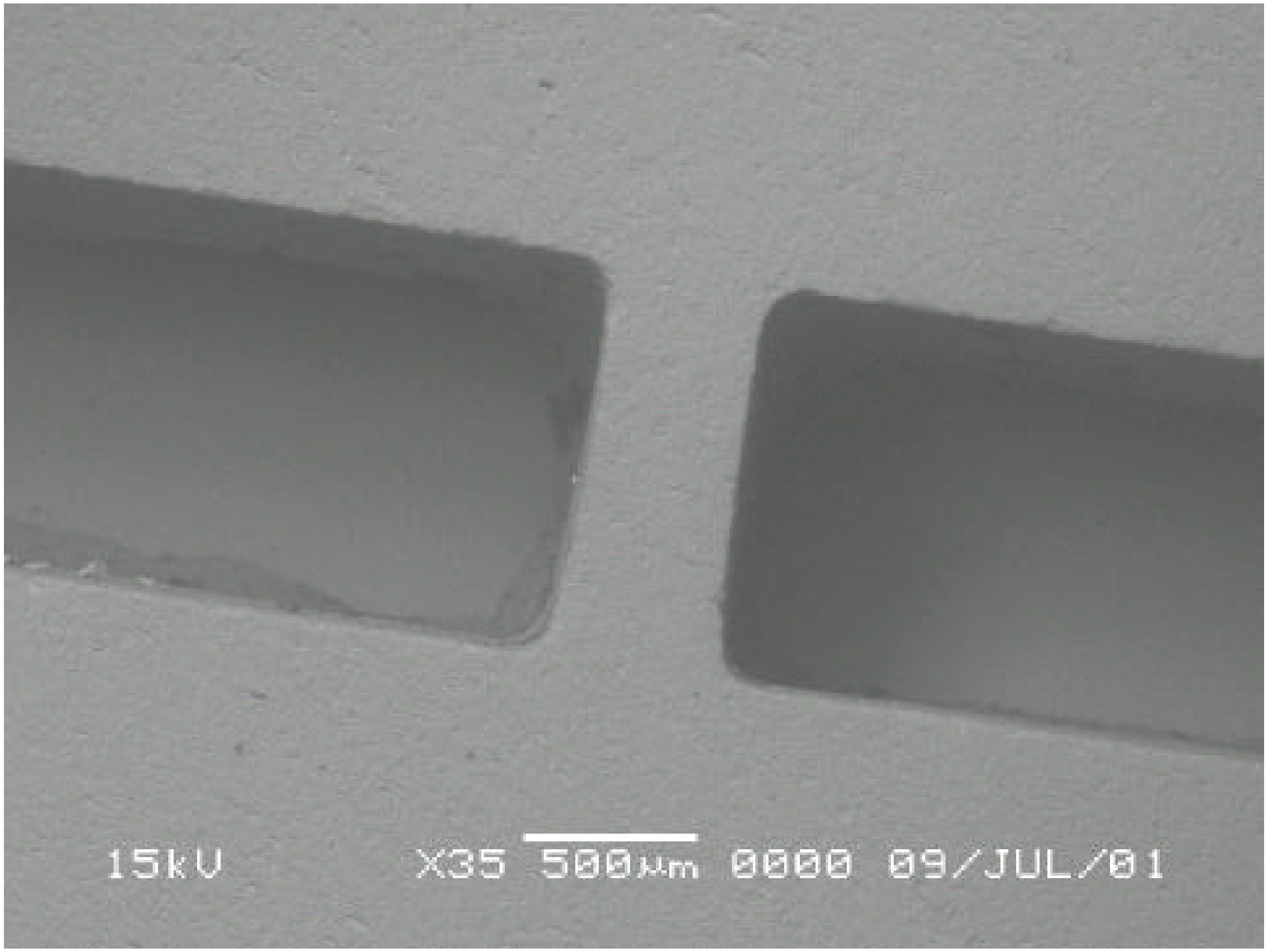
UltraSound machining of crystals

- Tool energized with U.S.
- Optical polishing powder carried in slurry
- Abrasive renewed by flowing slurry



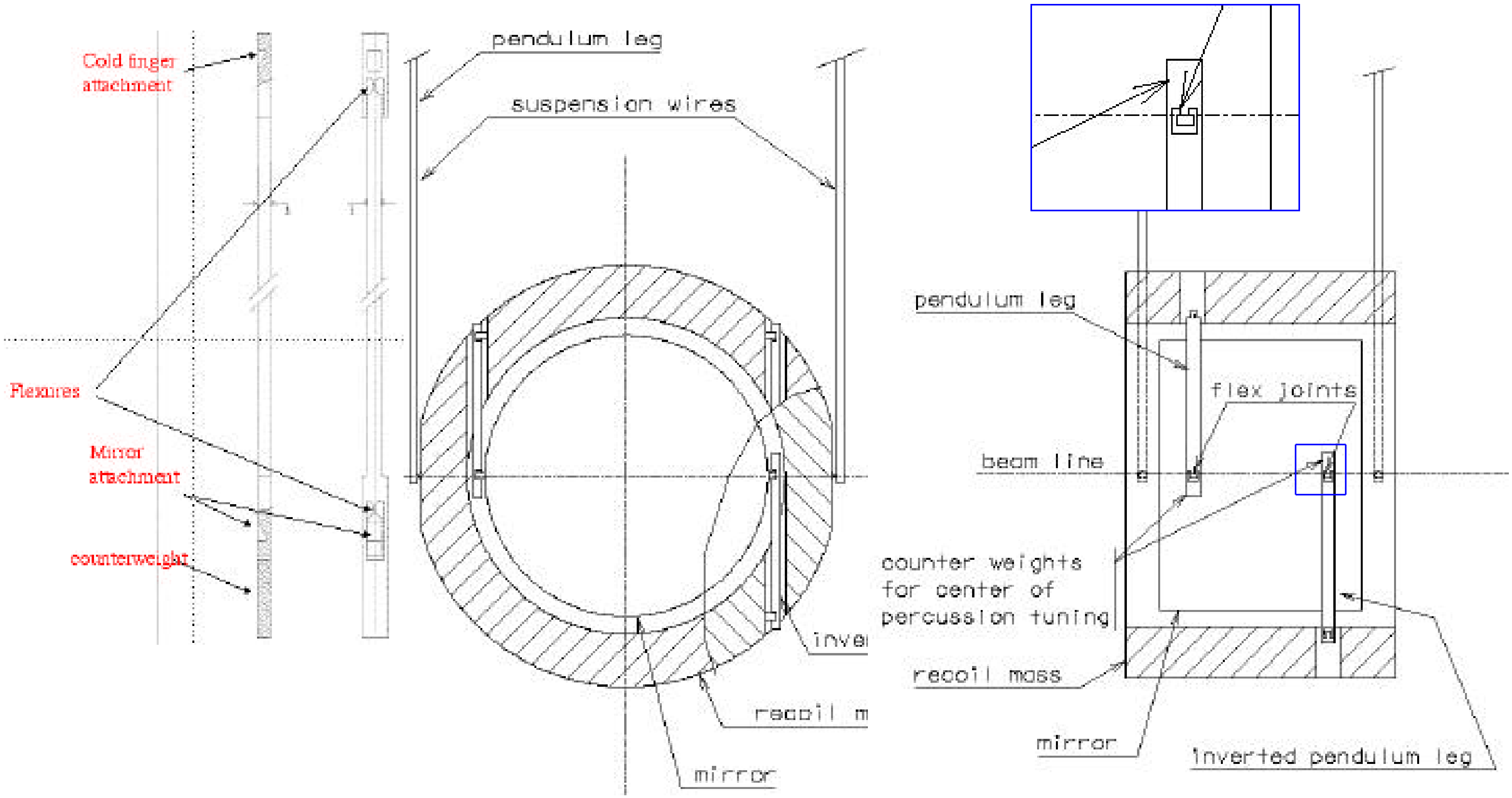
Sapphire flex joint for cryogenics

Ultra
sound
cut



- 0.04 cm thick
- 0.3 cm wide
- 0.15 cm long
- @10 to 100W/cmoK
- 0.6 to 6 W/^{o}K @ 30 ^{o}K

Possible (very preliminary) dielectric mechanics

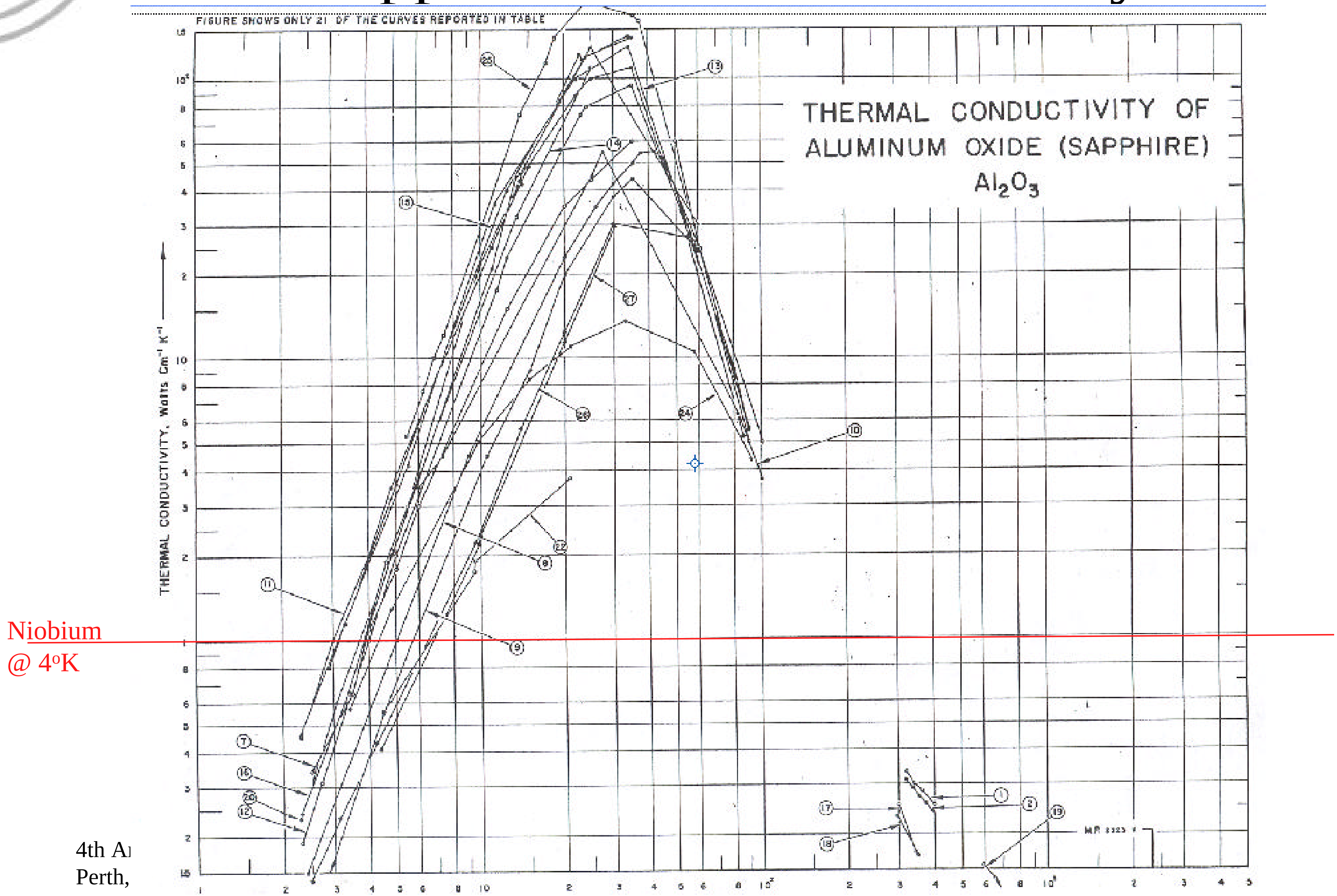


Flex joint maybe OK but rod?

- 0.3 cm x 0.3 cm square
- 30 cm long
- 0.06 to 0.6 W/ ^{o}K (between 20 and 35 ^{o}K)

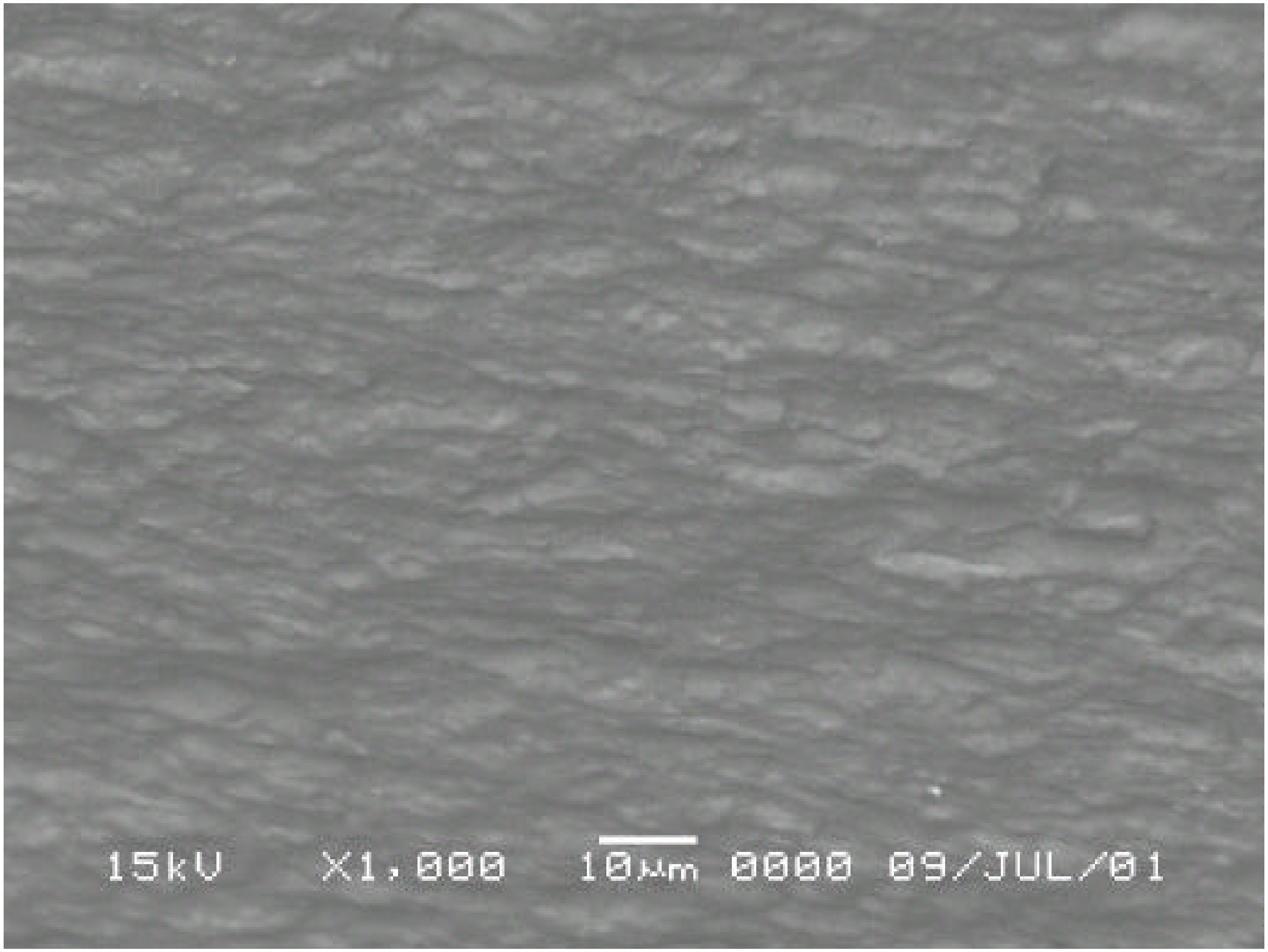
- Require already a larger temperature drop!

Sapphire thermal conductivity



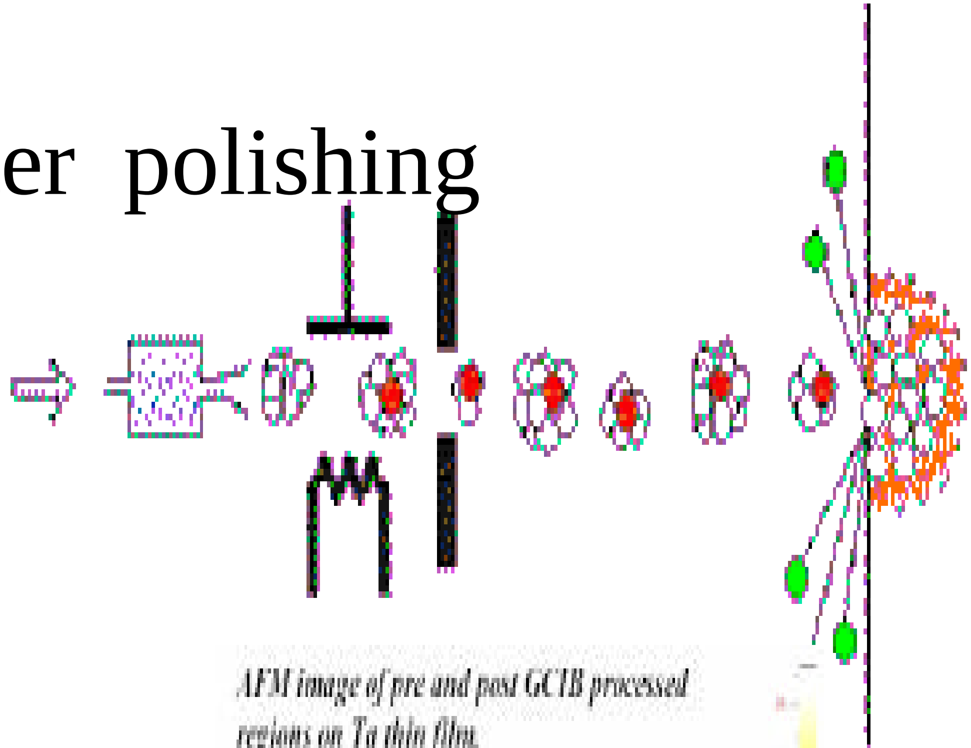
Sapphire flex joint surface finish

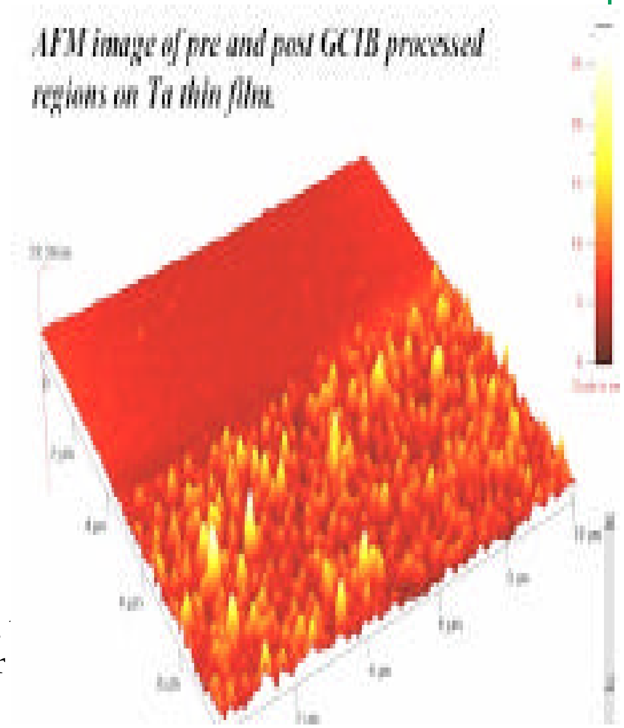
- First cut, no polishing treatment



Ar- cluster polishing

- A jet of Argon droplets electrostatically accelerated abrades the surface
  – (Gutta cavat lapidem)





Other differences between high and low frequency interferometers

- low frequency range
- lower shot noise requirements
  - Can reduce circulating power by factors of 10 to 100
  - Can increase finesse and further reduce input power
  - Maybe exotic cooling schemes

- high frequency range
  - temperature drop feed power across multiple isolation stages to noisy heat pipe.
  - Less isolation constraints
  - Could use shorter, thicker links for better conductivity

LIGO

Comparative advantages of a low/high frequency, low/high power interferometer

- Assuming that we can achieve
- 0.1 ppm coating absorption
- 3 ppm/cm bulk absorption 20^{o}K/30^{o}K
- Then:
- 1kW/25kW B.S. power
- 250/50 Finesse
- 250 kW/1.25MW circulating power

- 25+30 mW/125+750 mW deposited power
- Radiation Pressure Fluctuation / Shot noise limited

- May look feasible but still need lots and lots of R&D ! ! !

Is cryogenics LIGO's best next step? (my prejudice)

- It is (almost) obvious that the Ultimate Gravitational Wave Interferometer will be Cryogenic. But probably not immediately.
- It is practically impossible to marry a cryogenic experiment with a hot Advanced LIGO inside the present building
- Cryogenic interferometers will almost certainly have to be split in High frequency and Low frequency separate interferometers
- The NEXT LIGO step should use cryogenics only if there is no more ground to break (must throw away Advanced LIGO)
- Low frequency, room T. GWI is probably a better intermediate step.
- But we need to run an aggressive cryogenic R&D effort stating immediately if we want to be relevant on it
- We should support and complement the ongoing LCGT program as THE common cryogenic development effort for GWI.