Composite mirror suspensions development status

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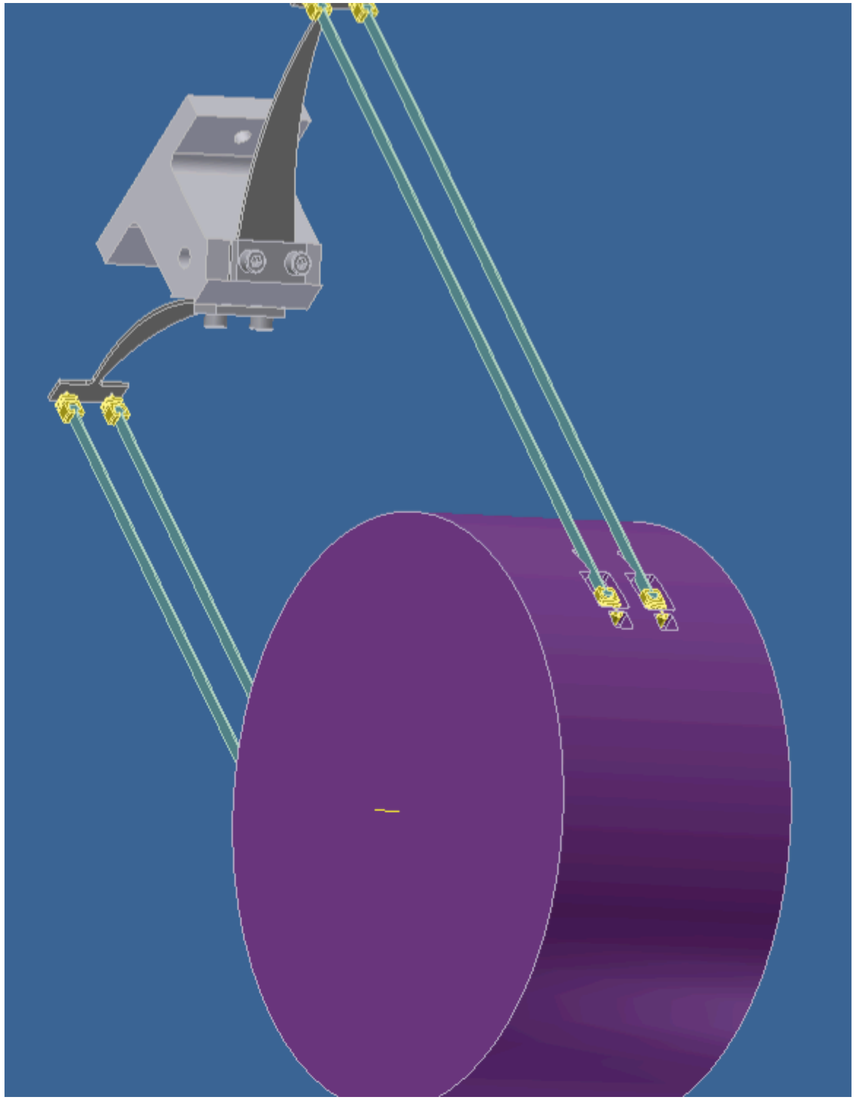
JGW-G1201265

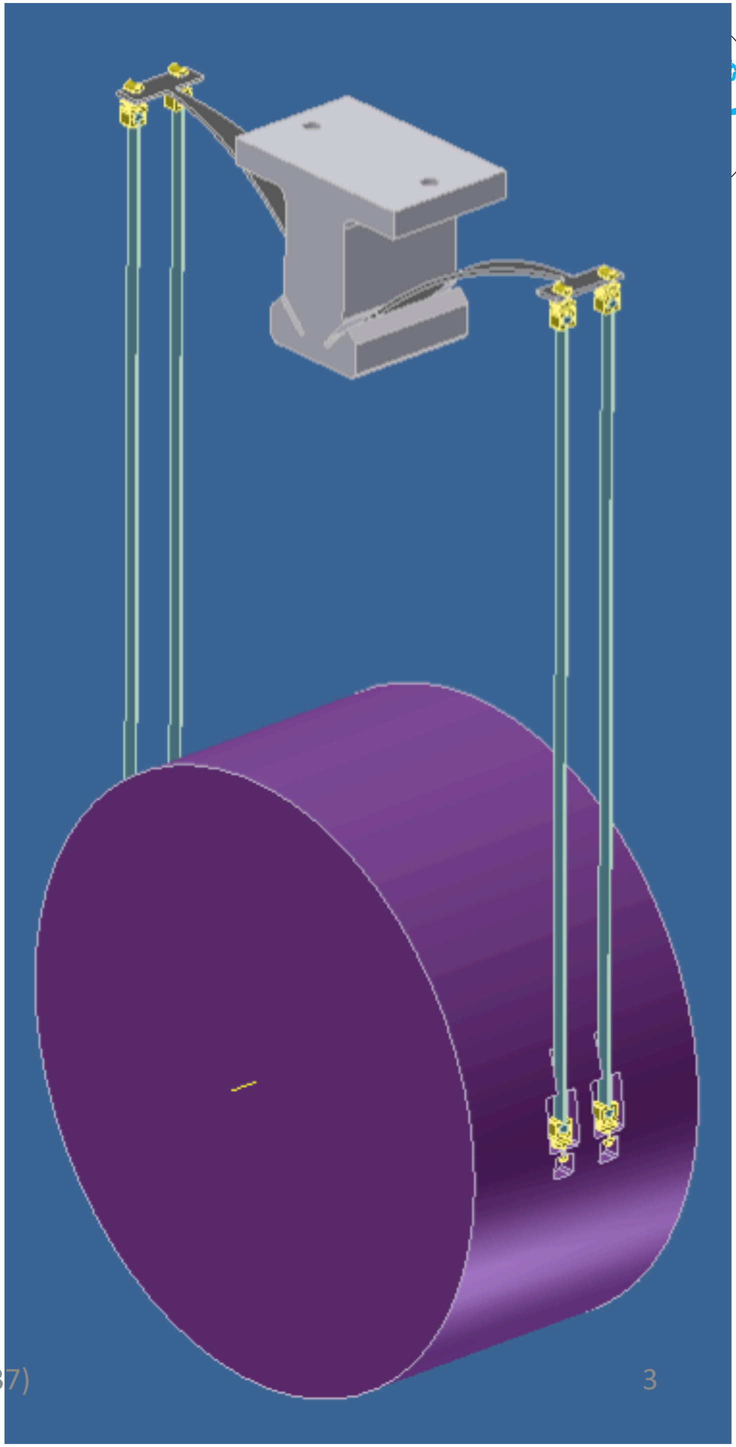
The idea

- A fresh approach to the design of low thermal noise mirror suspensions for KAGRA and ET



Key features:

- Composite structure
- Purely Compressive joints
- No shear noise
- No need for bonding
- Easy replacements
- Easily scalable to larger masses

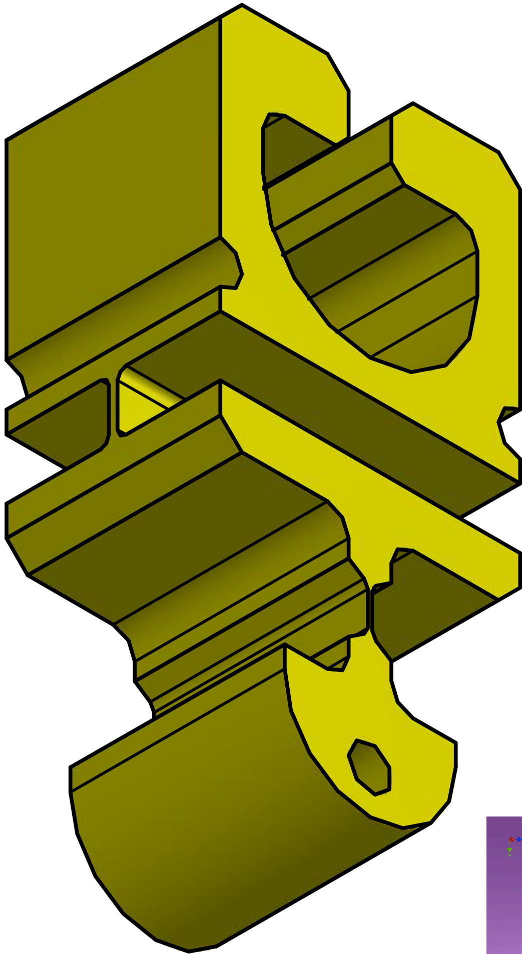


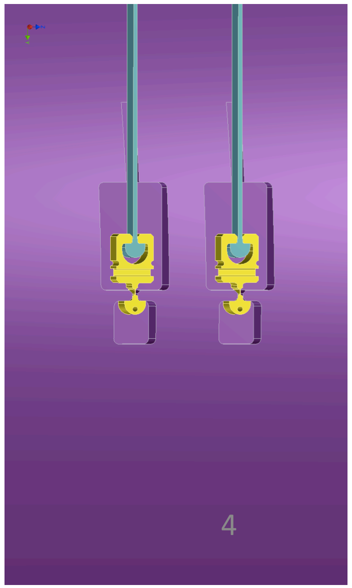
Flexure

Key features:

- Silicon flexures
- Intrinsic Q-factor $>10^8$
- Thermo-elastic $>10^6$
- Diluted Q-factor $>10^9$
- Before cryo gain !

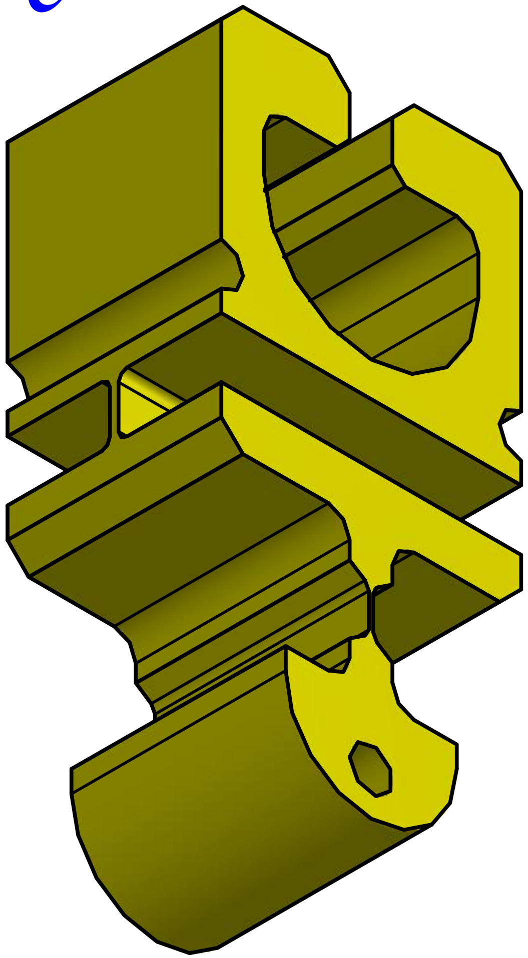
- Many Machining options available





Flexure structure

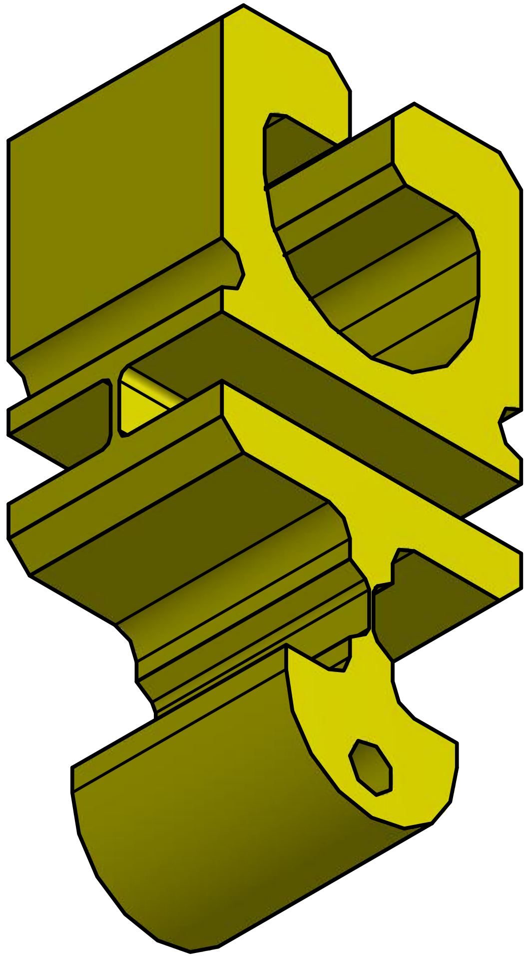
- Ultra-Sound Machined structure
- Etching of the flexure surface
- Sufficient 0.15 GPa b.p.
- Etching may increase the break point > 1GPa



Flexure structure

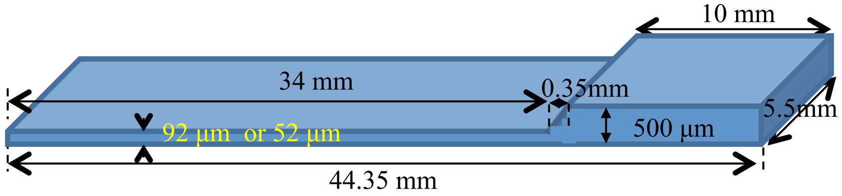
- Thin, short, etched flexure
- Small flexure aspect ratio

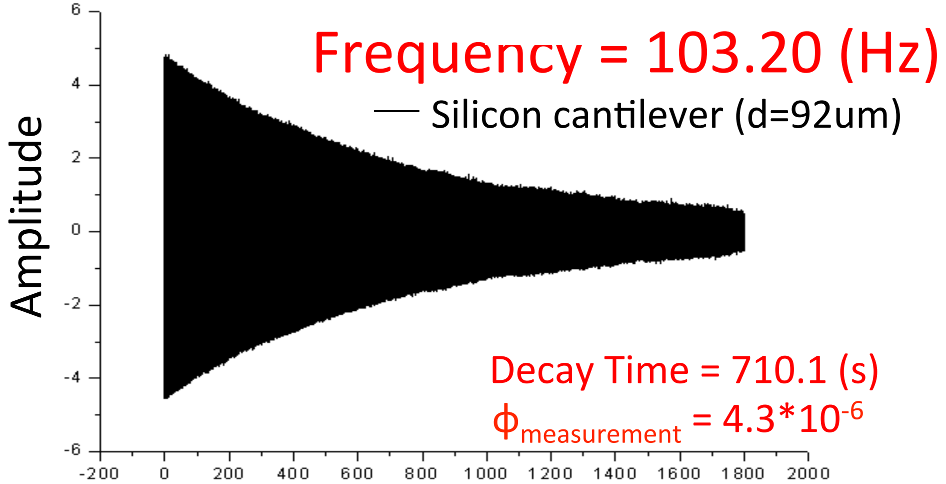
= > Large thermal conductance

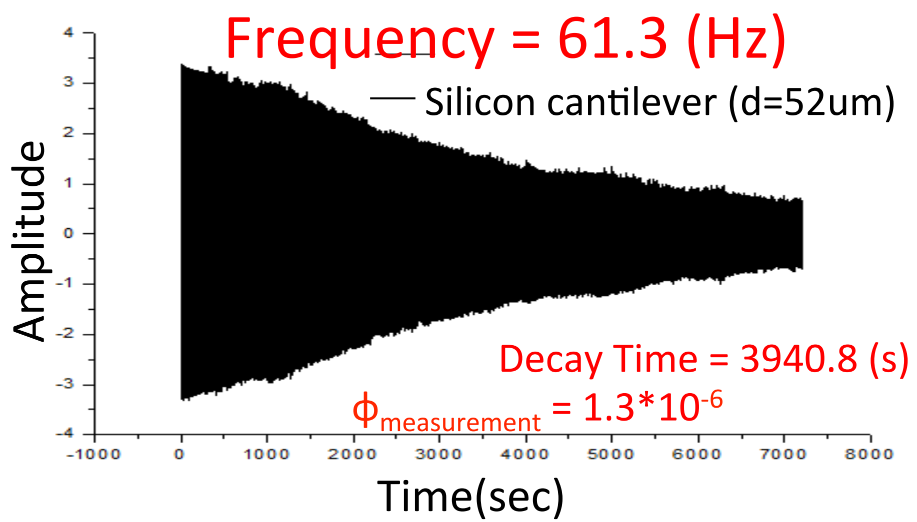


Chao Shiu laboratory, Taiwan
Silicon cantilever with KOH wet etching

4” un-doped double-side polished (001) silicon wafer,
500um thickness etched down to 92 and 52 µm



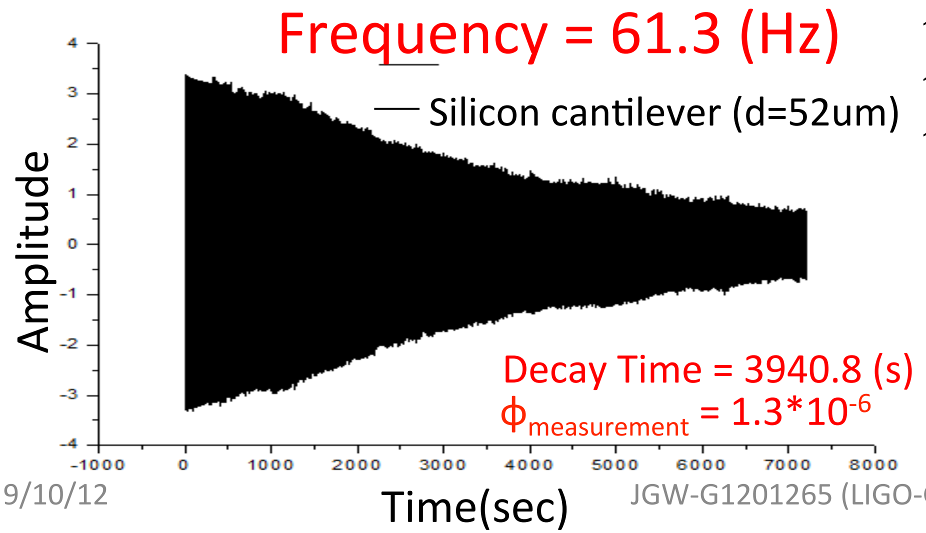


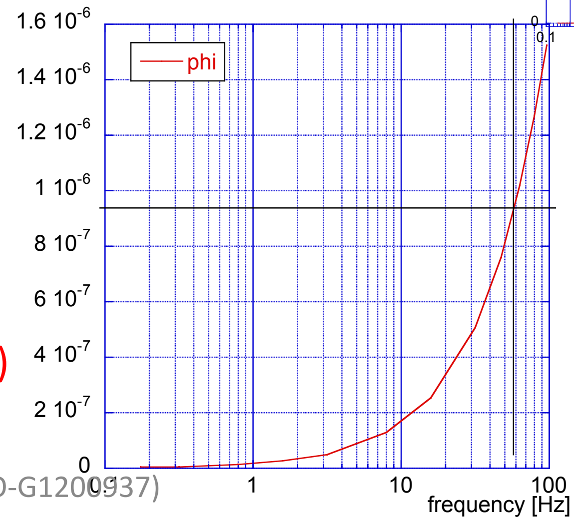


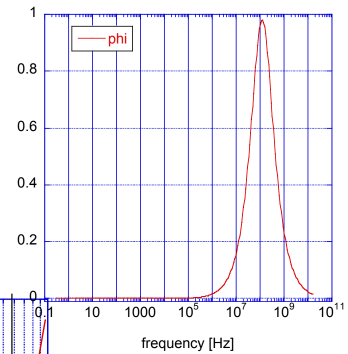
0.3 10^{-6} loss measured from residual gas

Thermo-elastic limit

- **@ 60 Hz 0.945 10^{-6} loss angle predicted (T.E.)**
- **1.3 10^{-6} measured** (-) **0.3 10^{-6} residual gas**
- **1. 10^{-6} loss angle measured**
- => Thermoelastic dominated

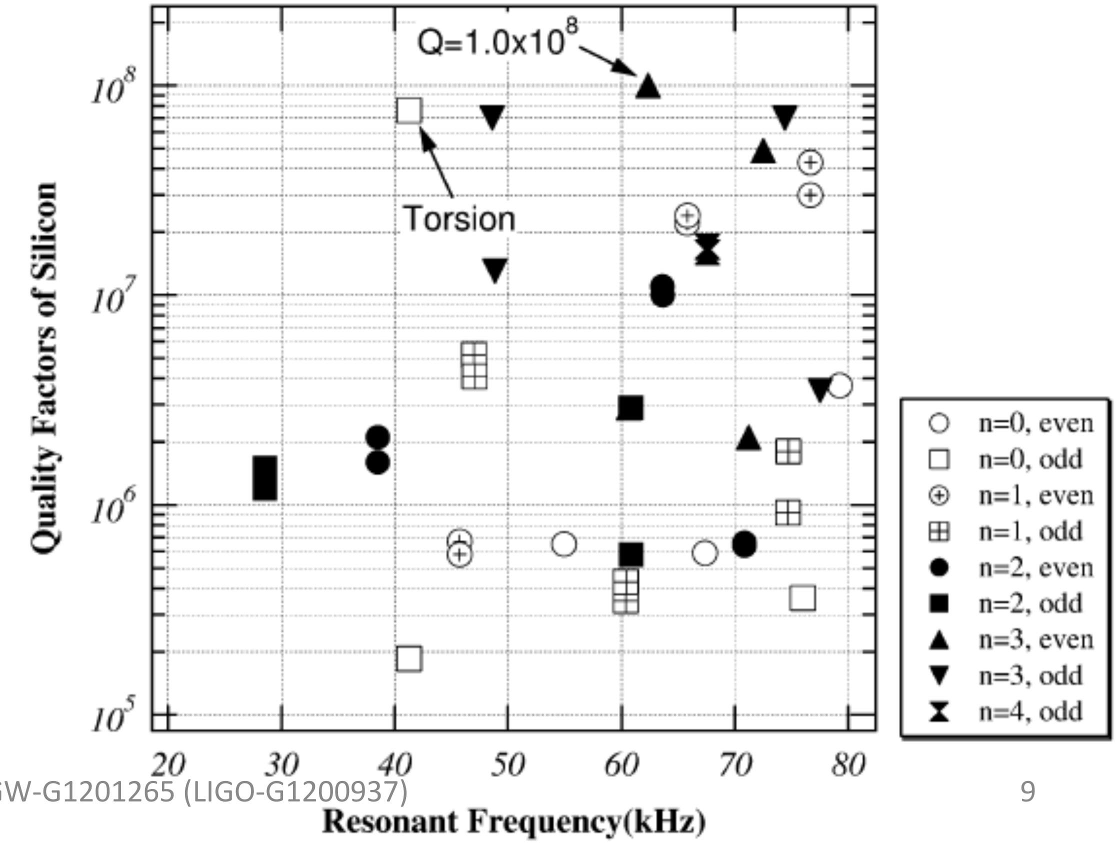






Kenji's Q-factor measurements

- Measurement on a mirror substrate
- 10^8 lower limit



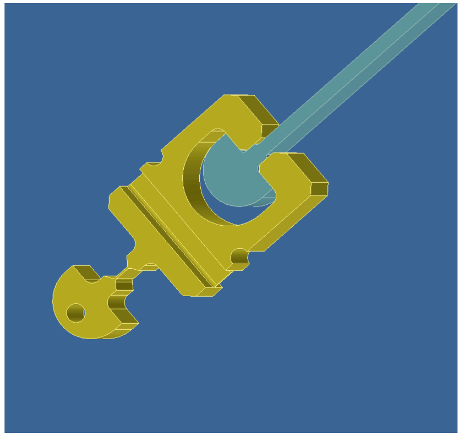
Ribbons

Key features:

- Compression joint attachment
- Machined-polished Sapphire ribbons

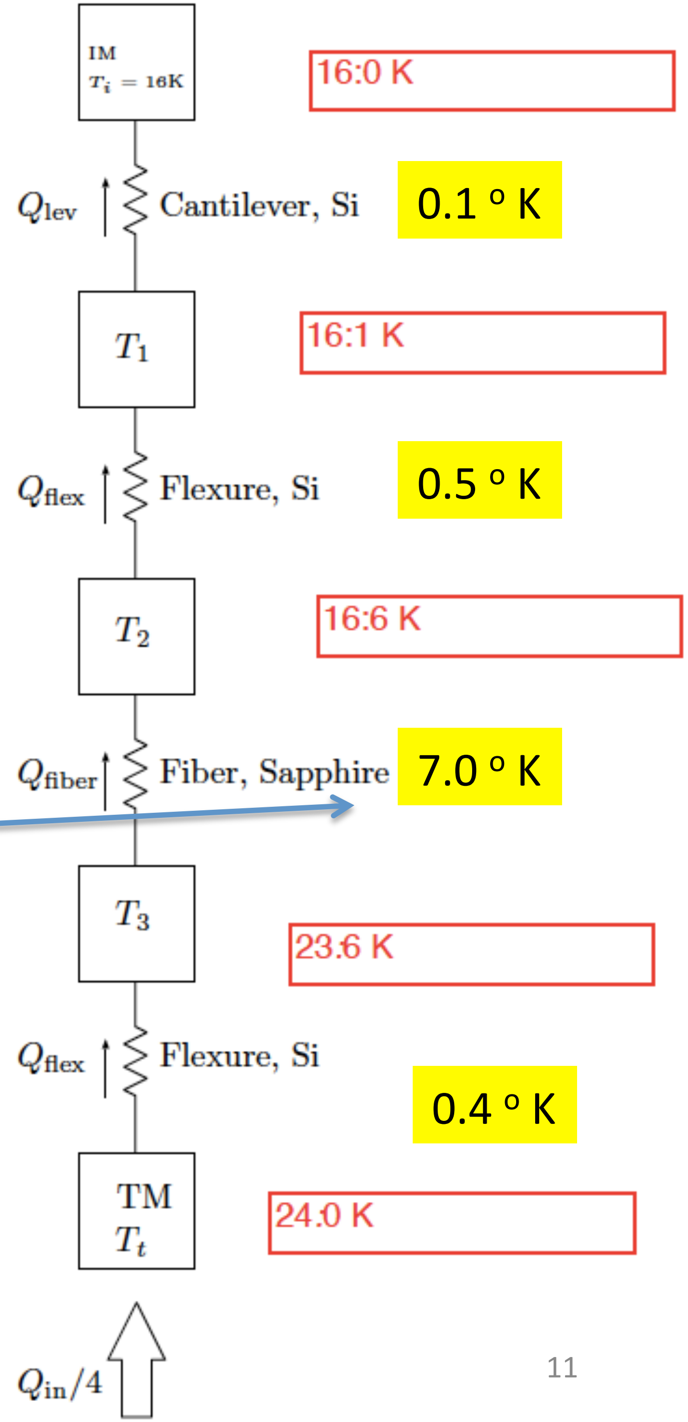
(from bulk, not grown)

- High quality sapphire
- High quality surface finish (sub-phonon defect size)
- => High thermal conductivity !



Conductance budget

- Preliminary conductance budget from Sakakibara with 1 W load
- Thin ribbon responsible for bulk of loss ! ! !
- Plenty of space for parametric optimization

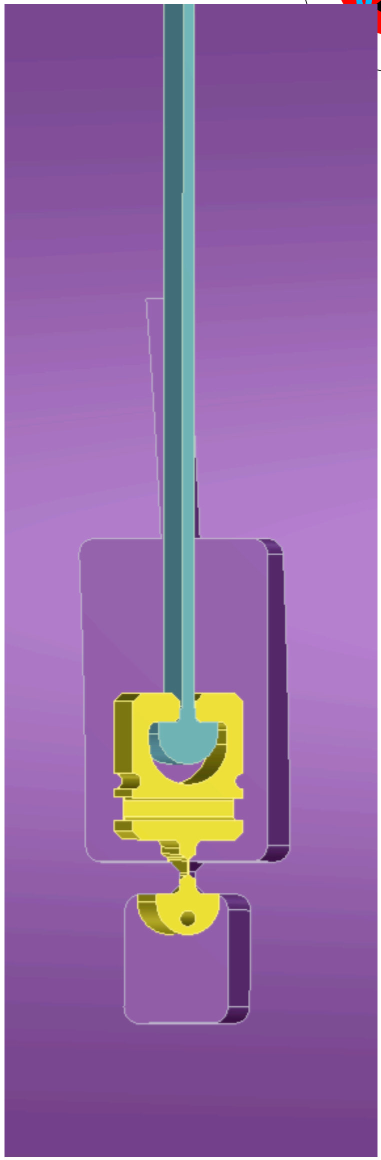


KAGRA

Mirror attachment

Key features:

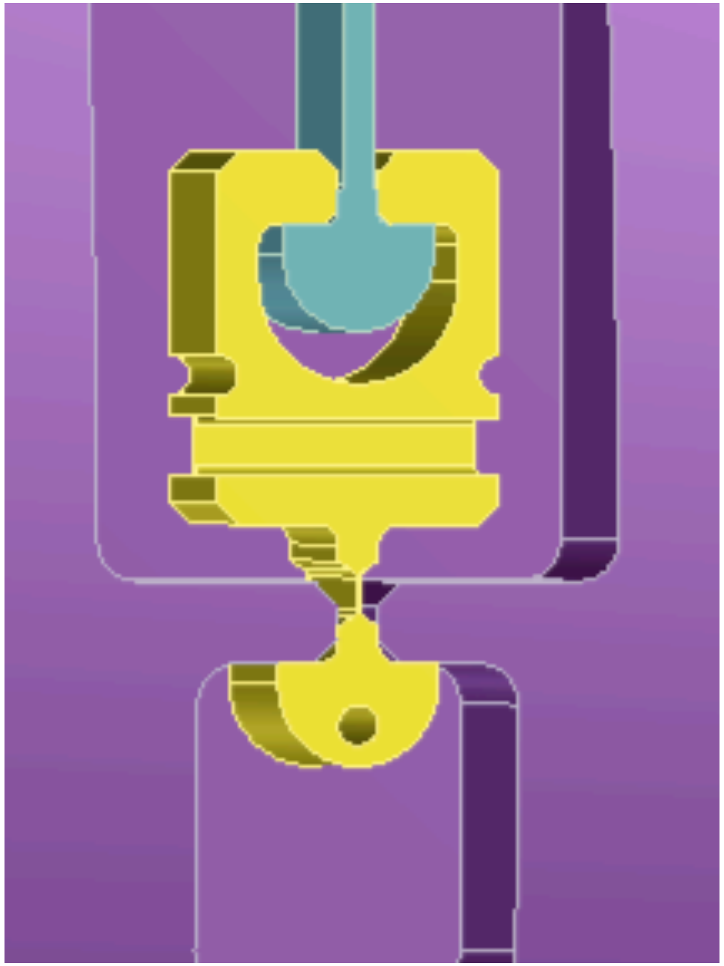
- Mini-alcoves (low volume machining)
- Machining before coating deposition
- Minimize substrate induced stress
- Recessed attachment, Low vulnerability
- No bonding shear noise
- No flats on mirror barrel
  => 100% of mirror front surface available



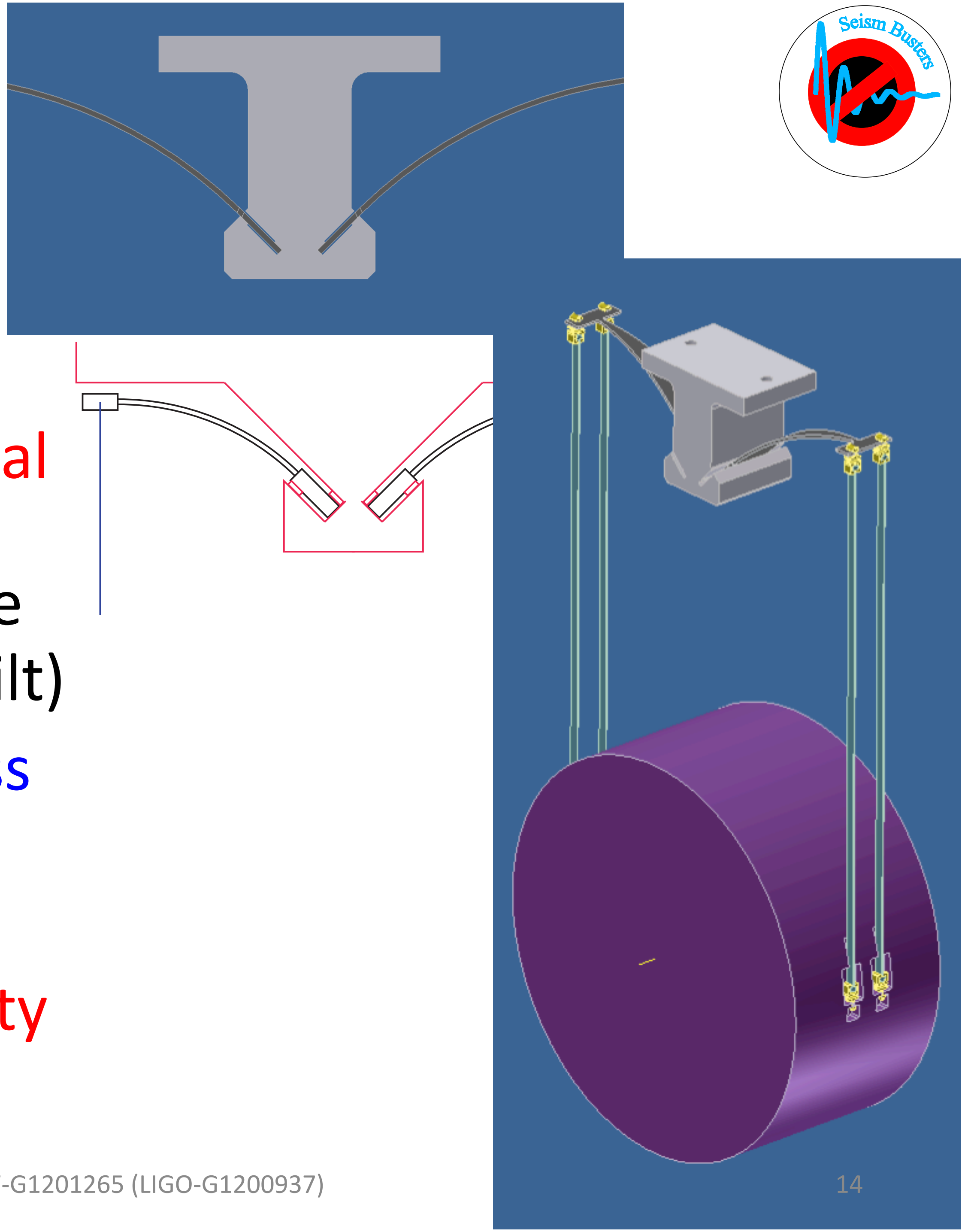
Connections

Key features:

- Purely compressive joints
- Direct silicon-sapphire contact
- => No energy loss for bending
- Problem: Lateral slippage between hard surfaces
- Sub-μm Indium or Gallium gasket
- Elimination of stick and slip noise (credit: Vladimir Braginsky)
- Perfect heat conductivity
- Easy replaceability



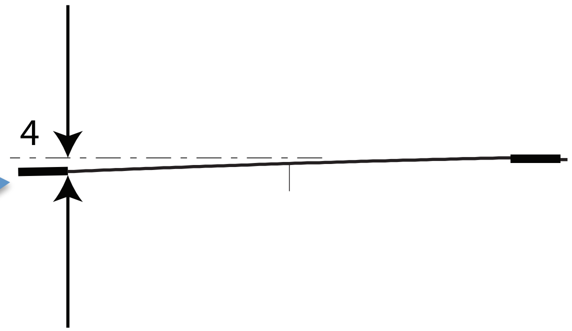
The need for Springs



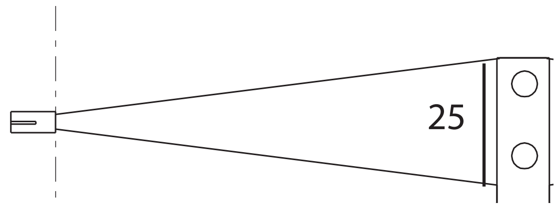
- Elimination of vertical suspension thermal noise (necessary due to KAGRA's tunnel tilt)
- Equalization of stress on wires
- Removal of bounce mode from sensitivity range

Cantilever blades vs. stress

- With 0.15 GPa only deflection is limited to 4 mm

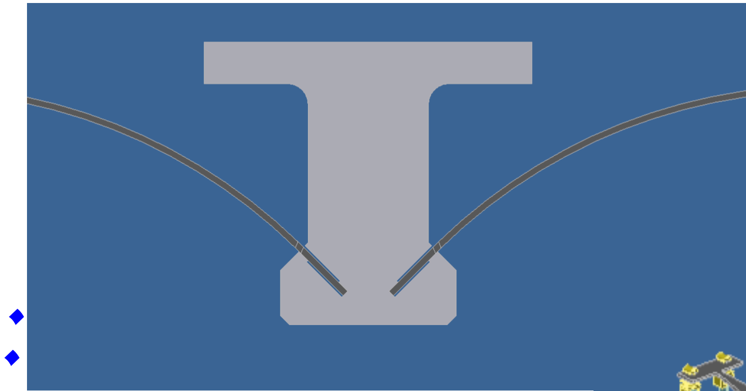


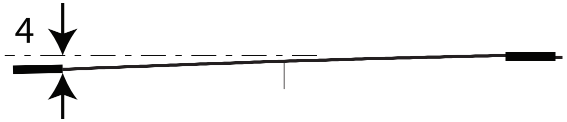
$$f = \frac{\sqrt{\frac{g}{h}}}{2\pi} \approx 8\,Hz$$



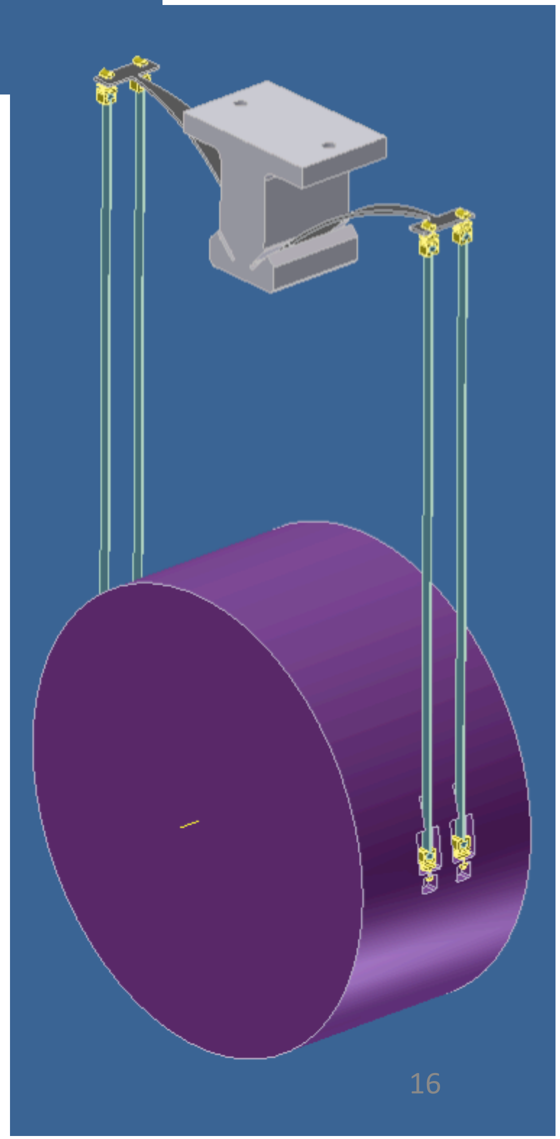
KAGRA

Springs
Key features:



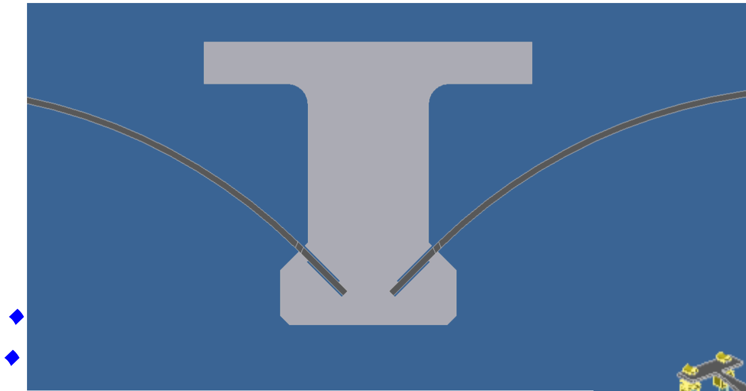


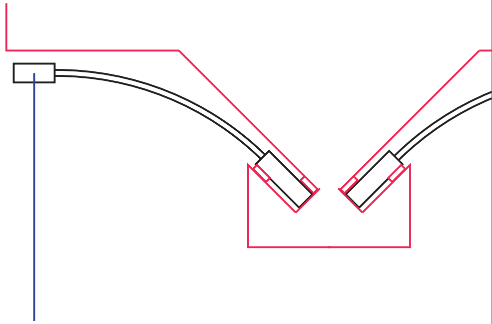
- Silicon springs
- 0.15 GPa break point
- Sufficient to equalize stress and shift bounce mode outside bucket
- Higher stress necessary to mitigate vertical thermal noise

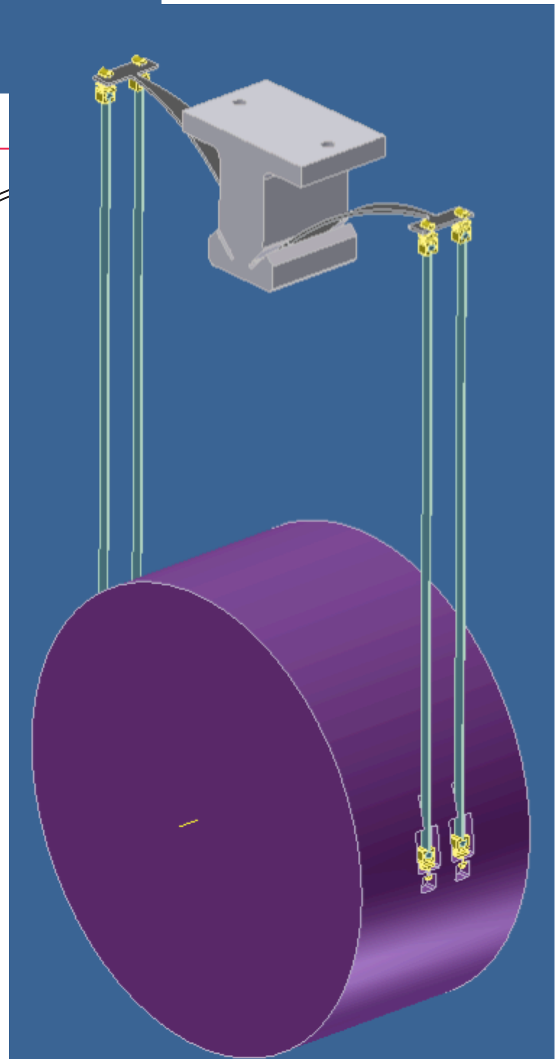


KAGRA

Springs
Key features:



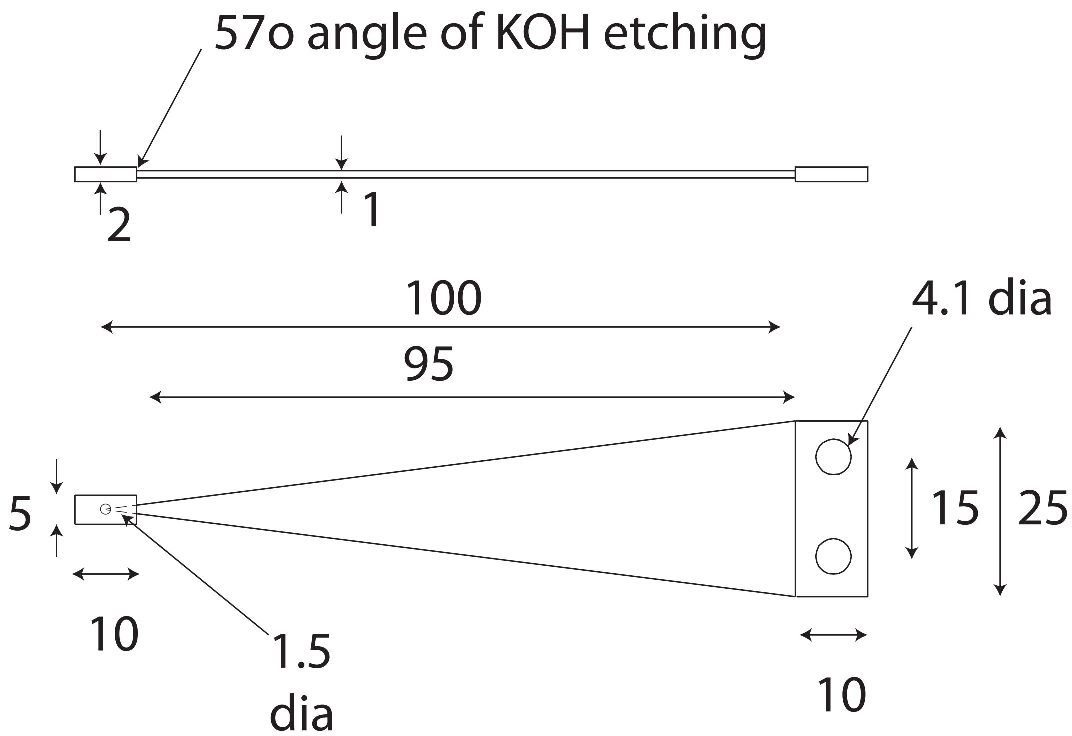




- How much stress allowable?
- In etched MEMS 1.4 GPa OK
- Defects etched away
- Allowable surface stress may be > 1 GPa
- To be confirmed for this geometry

NIKHEF test

- Produce a number of samples



- Measure bending breaking point

Jena-Glasgow test

- Pull ribbons with different surface treatments to determine
-
- longitudinal stress breaking point

Why Gallium

- Indium proved extremely effective to eliminate friction noise in compression joints (Vladimir Braginsky)
  - How it works? it impedes slippage between hard surfaces
- Problems:
- Melts at 160°C
- Requires heating of mirror at relatively high temperature for assembly and disassembly

Indium vs. Gallium

Property	Unit	**Indium**	**Gallium**	**score**	
Solid density (near r.t.)	g·cm^{-3}	7.31	5.91		
Liquid density @ m.p.	g·cm^{-3}	7.02	6.095		
Expansion at melting		1.041	0.9696	G	< 1
Melting point	°K	429.7485	302.9146	G	
Melting point	°C	156.60	29.77	G	
Wetting silicates		Yes	Yes	X	
Boiling point	K	2345	2477	G	
Vapor pressure	Pa	1 @ 1196°K	1 @ 1310°K	G	
Vapor pressure	Pa	10@1325°K	10@1448°K	G	
Elec. resistivity (20 °C)	nΩ·m	83.7	270		
Thermal conductivity	W·m^{-1}·K^{-1}	81.8	40.6	I	
Therm. expansion (25 °C)	µm·m^{-1}·K^{-1}	23.1	18.0	G	
Young's modulus	GPa	11	9.8	X	
Poisson ratio			0.47		
Brinell hardness	MPa	8.83	60	G	
Atomic radius	pm	167	135		
Magnetic ordering		diamagnetic	diamagnetic	X	

Violin mode mitigation

- Fiber-fed

Red-shifted

Fabry-Perot

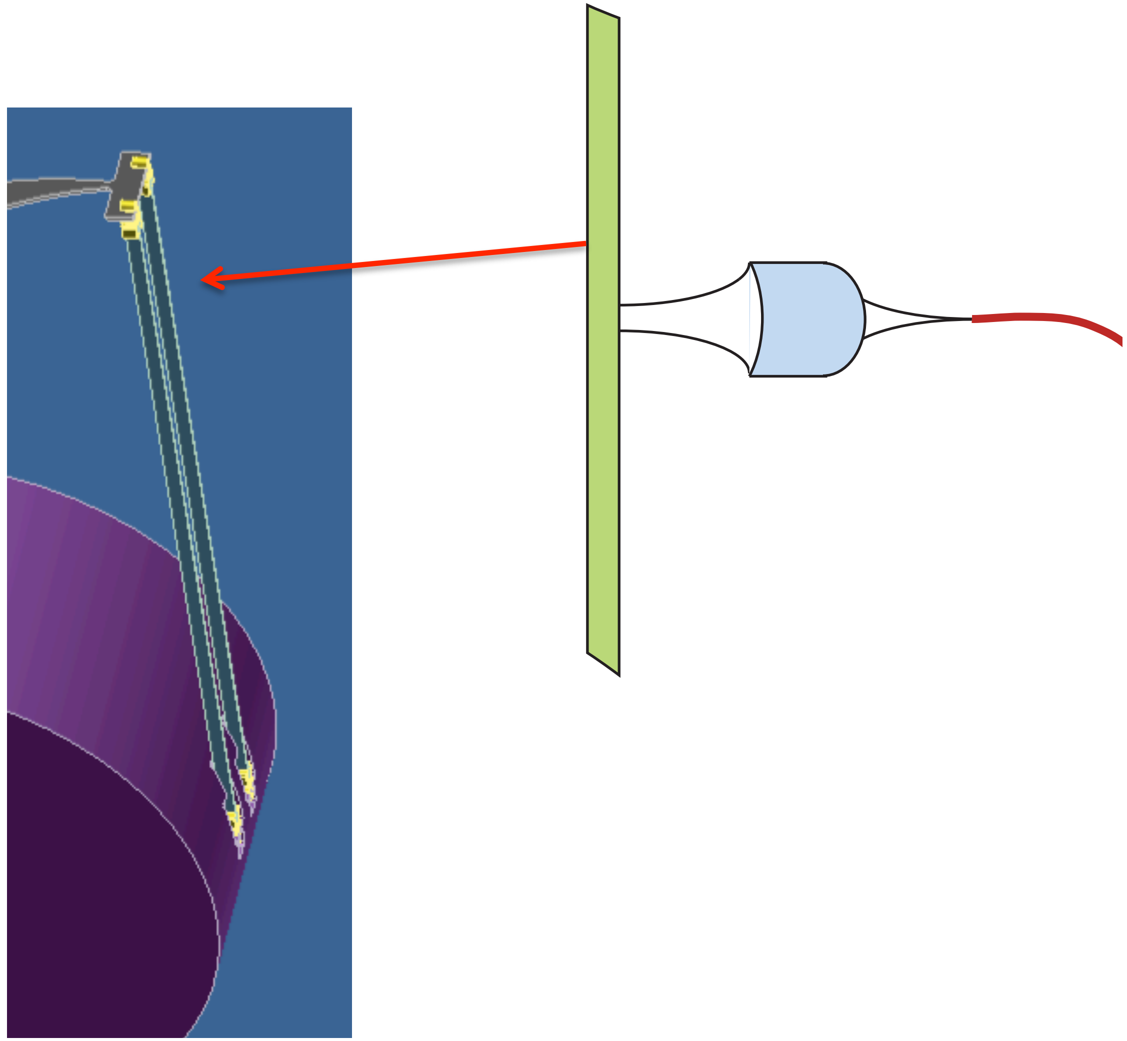
- Can cool

violin modes and

bounce modes

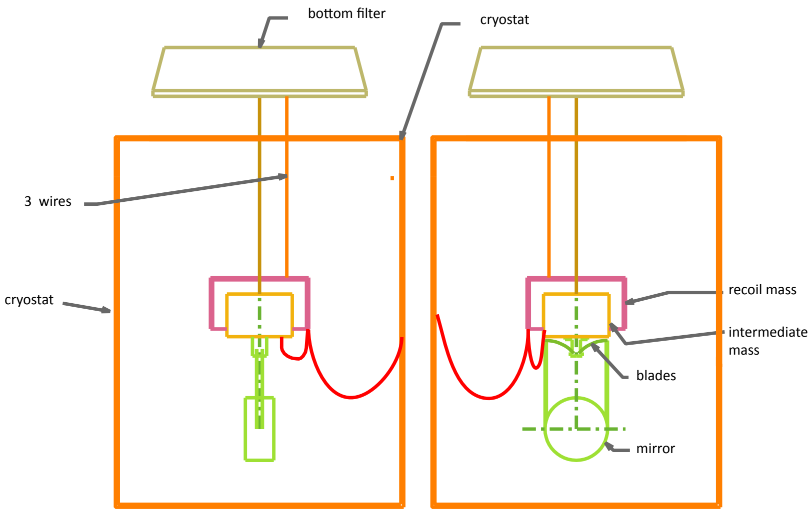
to mK level

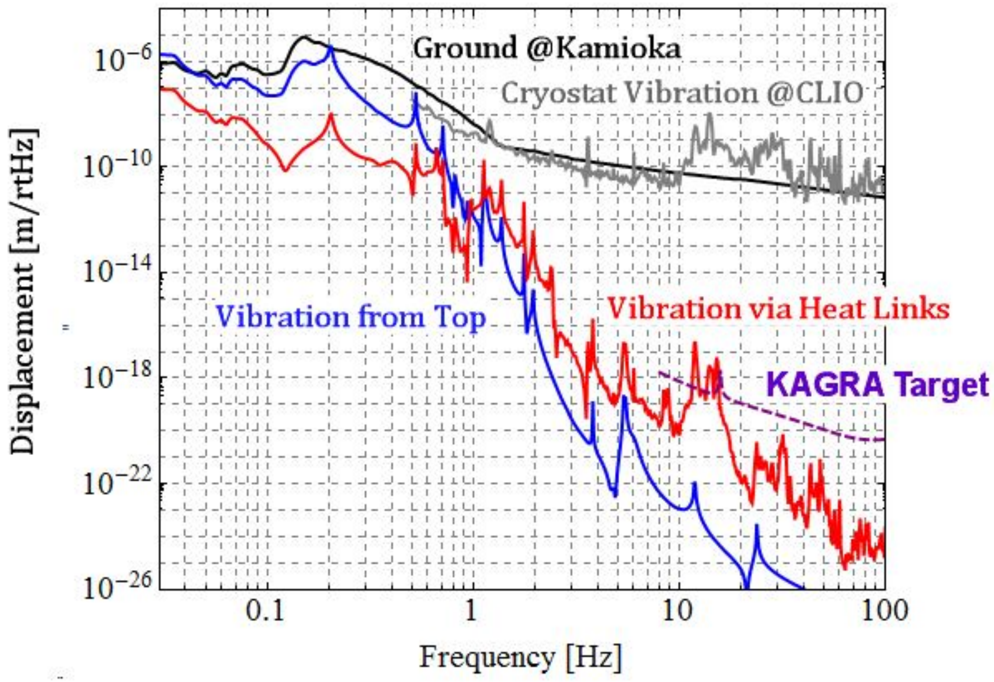
(Can we use the same idea for
Parametric instabilities ?)



Heat link limitations

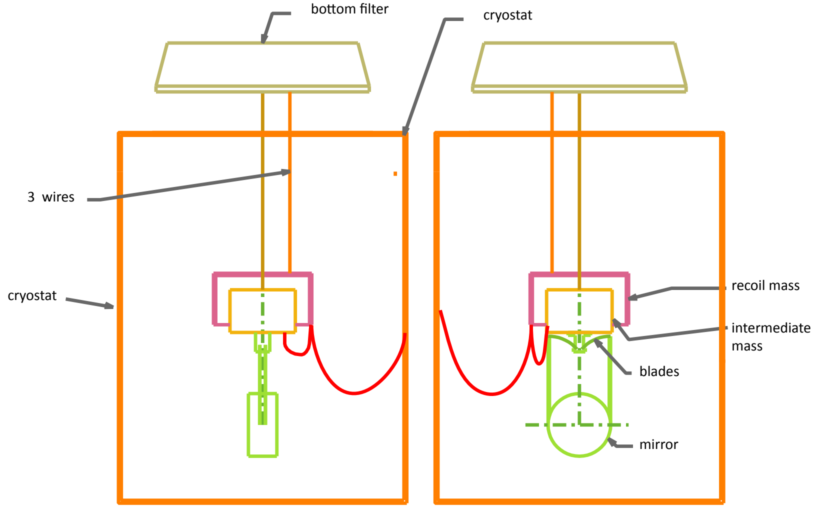
- Mechanical noise re-injection with two step heat link isolation
- Insufficient !





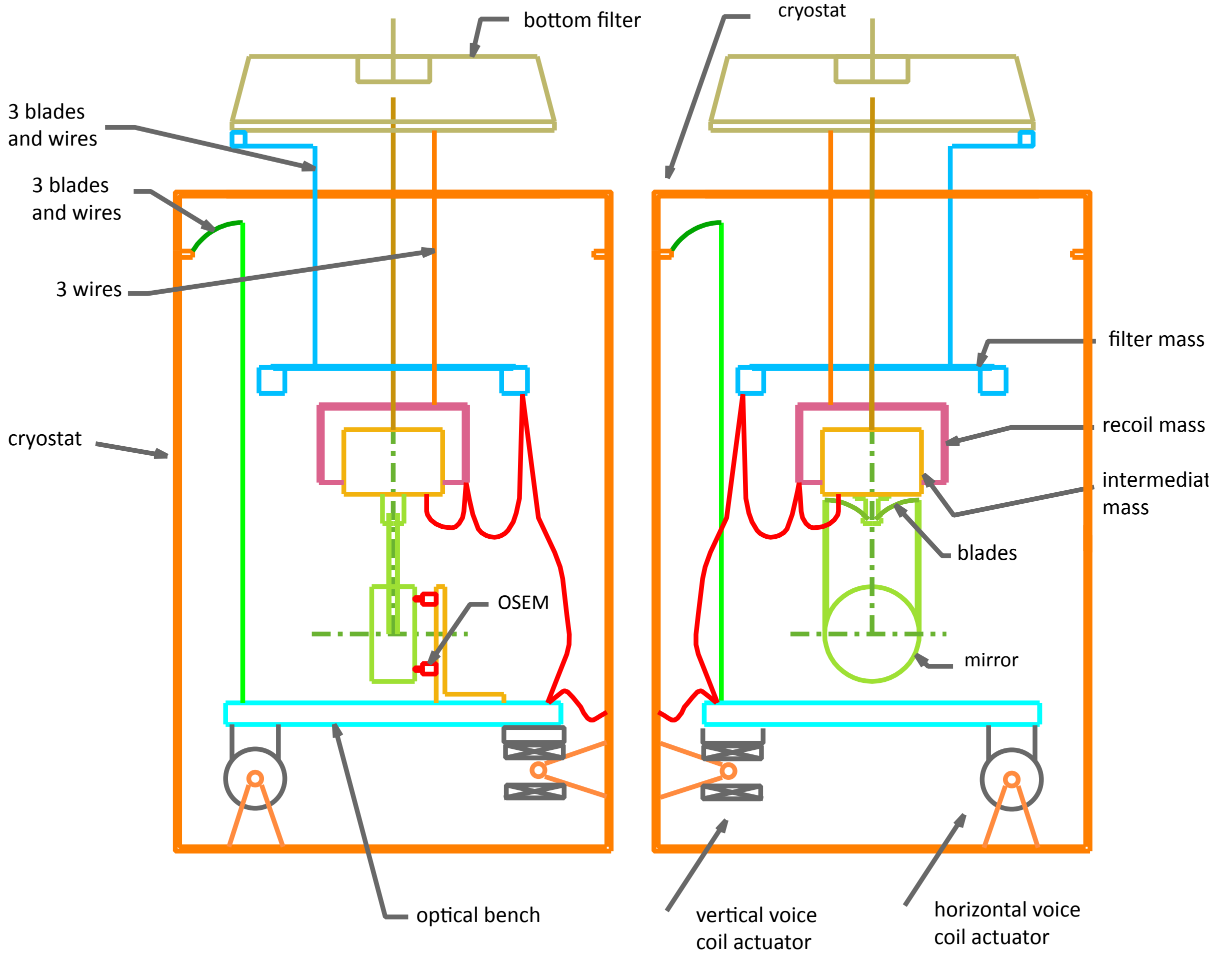
More Heat link limitations

- The heat links are soft above 10 Hz
- At 100 mHz they are 10^4 x stiffer ! ! !
- Microseismic peak noise reinjected into mirror actuators is a serious controls problem !
- Need a solution !



Geometry under study

- Suspended actuation platform
- Four step mechanical noise filtering
- Actuation platform slaved to mirror

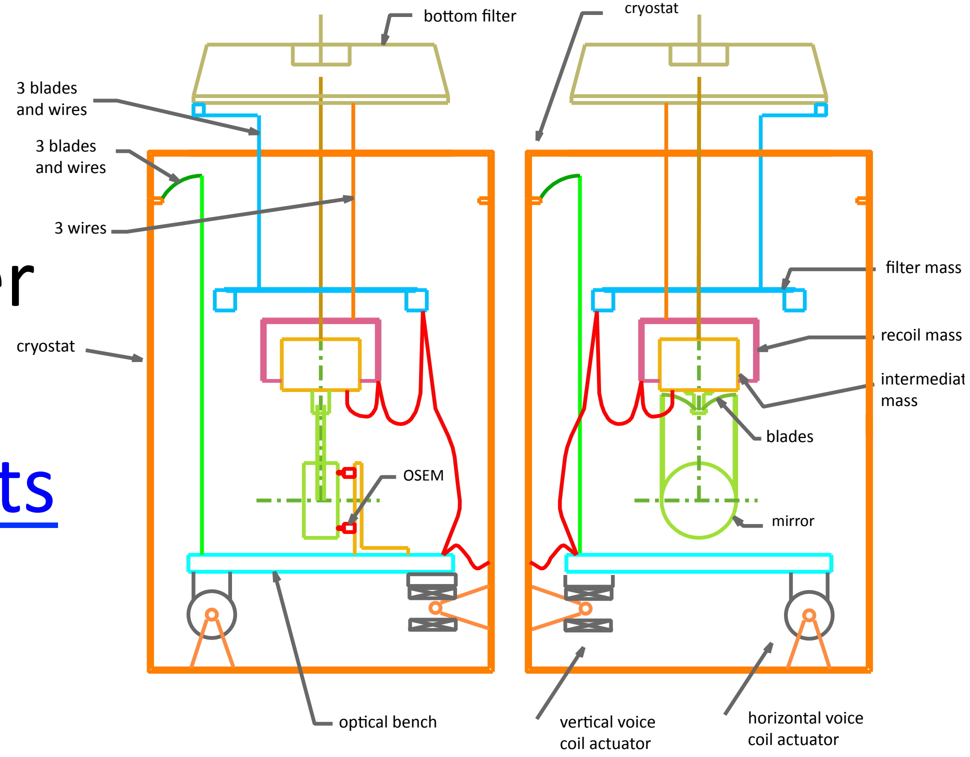


Filtering the heat pump noise

- The heat links are subjected to

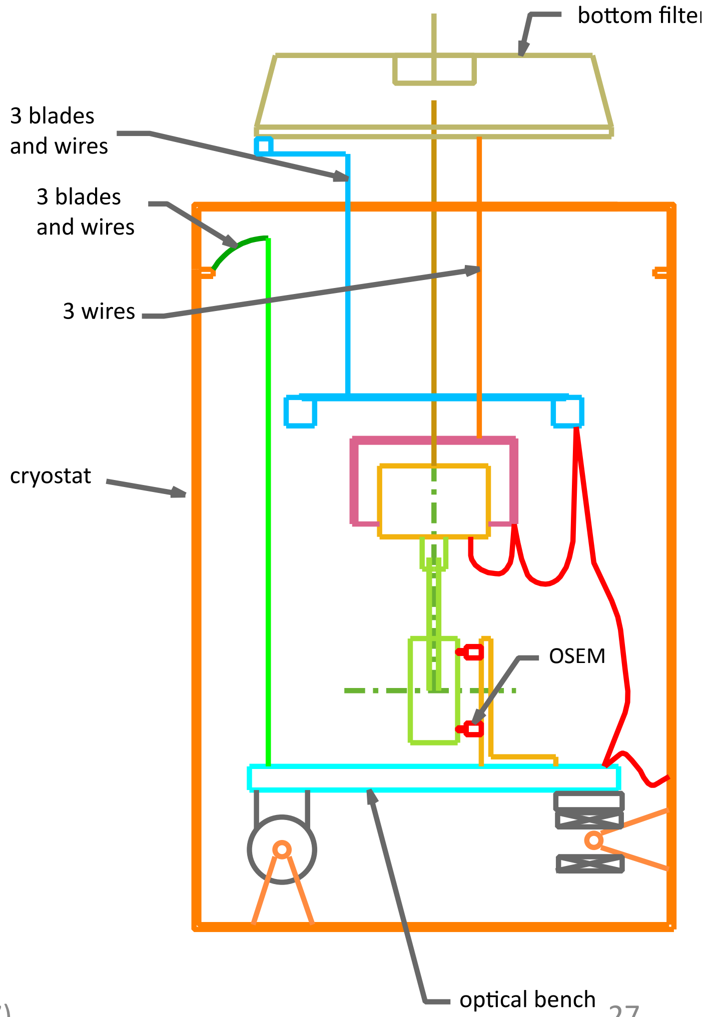
4 filtering steps (2 extra)

- Both seismic and chiller noise are filtered <u>way below the requirements</u> in KAGRA's sensitivity band (> 10 Hz)



External lock acquisition controls

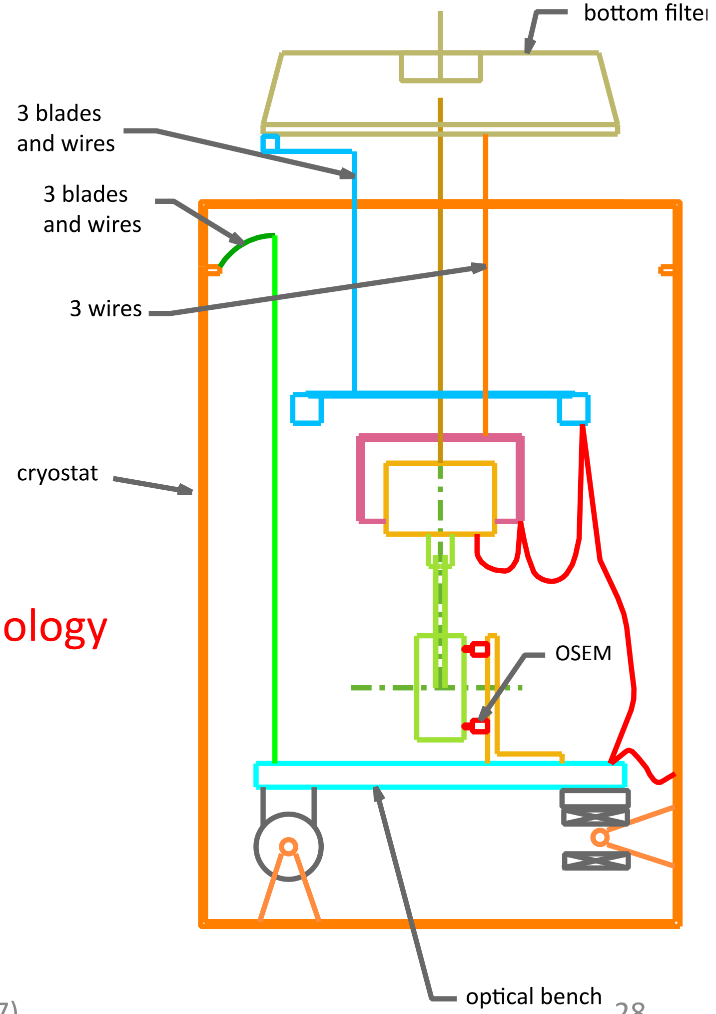
- Use Initial-LIGO-like controls for lock acquisition but from a suspended platform
- In this phase the optical bench actuators are used for viscous damping



In-lock controls

- Use Virgo-like marionetta controls during operation
- The mirror OSEM actuator are disconnected
- The OSEM sensors are used to slave the optical bench to the mirror
- The effects of microseismic noise on controls are neutralized

Borrowing AEI technology



Conclusions

- KAGRA was said to be : (with some reason)

  Mission Impossible!

- Now it is just "difficult", but feasible!
- KAGRA will be a great 2nd-1/2 generation GW Observatory

- It will also serve as the test-bed for all technology needed for the low frequency interferometer in the ET xylophone and for all 3rd generation observatories