"Divided Function" Options for the KAGRA Cryogenic Suspension

Version 2, 9/13/12 – with revisions made after the talk

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Disclaimer: the KAGRA collaboration has not yet reviewed these conceptual design options.

Requirements	Proposed Solutions
• Heat removal	-> 1 thick sapphire ribbon
• Suspension of load	-> 2 thin metal ribbons

SEPARATE THE FUNCTIONS OF HEAT REMOVAL AND SUSPENSION

• Vibration isolation	-> thinnest possible ribbons
• Low thermal noise	-> thinnest possible ribbons
– material and temp	-> high Q at low temp
– ‘clamping’ loss	-> threaded-pin clamp
• High Q	-> thin-film metal bonding

Heat Link – sapphire ribbon

Single ribbon attached to top-front mirror surface, so it's vertical motion controls pitch.

This link does NOT carry any load, simplifying its attachment. Flat ribbon naturally allows a thin bond to flat mirror face.

Conductivity of sapphire and metal

- See viewgraphs below from Tomaru, et. al.

Heat Transfer of Several Materials at Cryogenic Temperature

■

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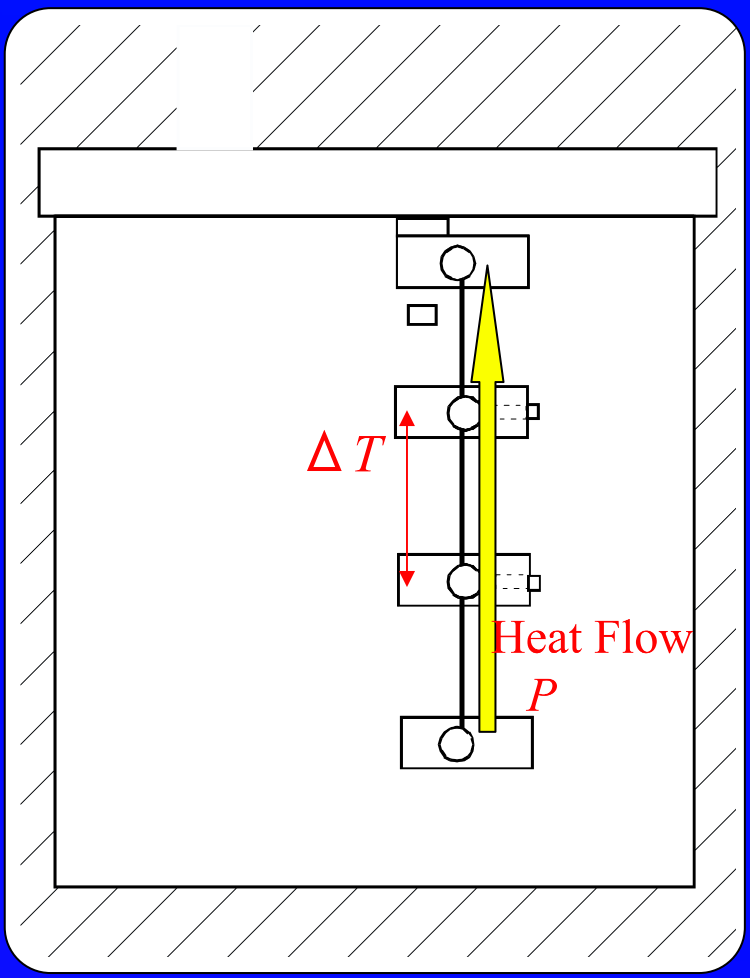
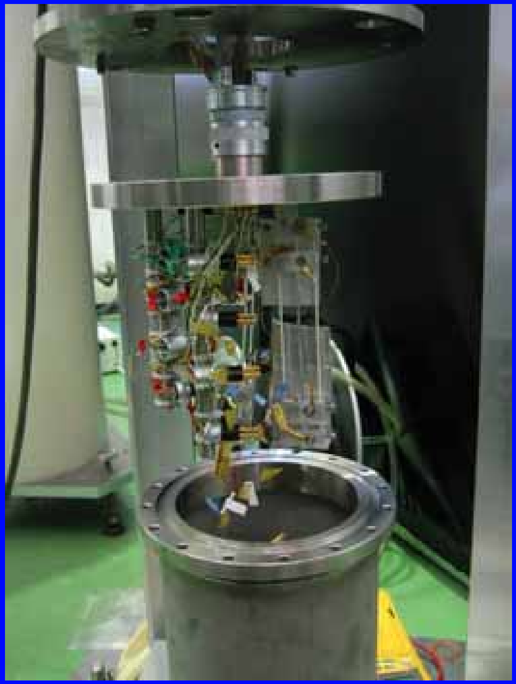
. Measurement Method of Thermal Conductivity

Longitudinal Heat Flow Method

$$\kappa \approx \frac{P\ L}{\Delta T\ S}$$

P: Heater power
L: Length between thermometers
S: Cross section of sample





3. Thermal Conductivity of Sapphire Fiber

– Size Effect –

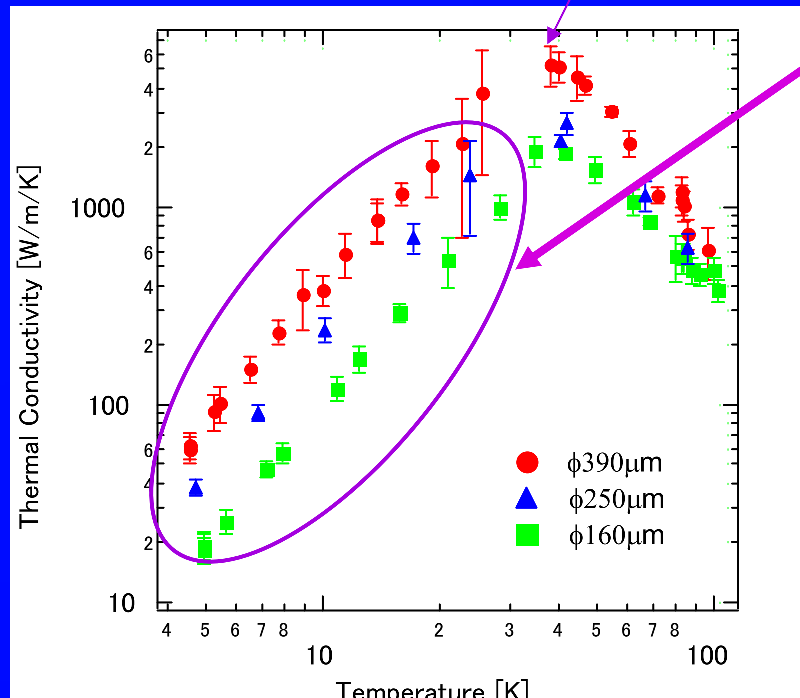
Produced by Photran LLC

lono-crystalline sapphire

FG method

$160, \phi 250, \phi 390 \mu$ m

Measured Results



Size effect

$$\kappa = \frac{1}{3} C_v v l$$

$$C_v \propto T^3$$

$$v \approx Const.$$

$$\kappa \propto C_v \propto T^3$$

$$@ < 40K$$

⇩

$$l \approx Const.$$

⇩

$$P_{max} \propto D^3$$

below 40K

- Estimated maximum heat transfer for the LCGT configuration ⇨ 340mW
- Estimated heat generation in the mirrors ⇨ a few W

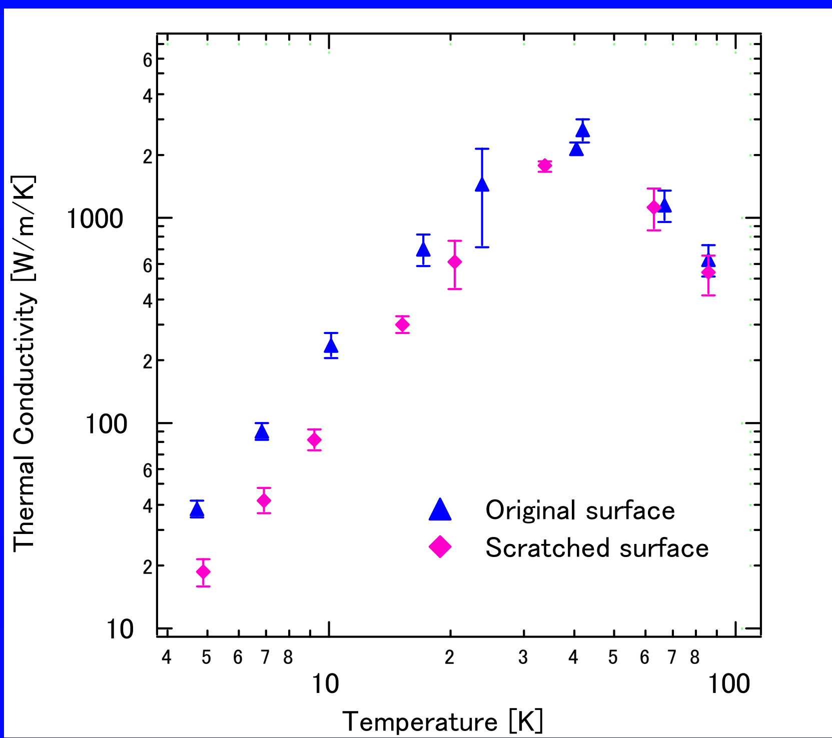
It is important to reduce optical absorption in the mirrors

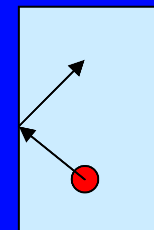
(For small pieces of sapphire, sufficient absorption level has been achieved.)

Possibility to enhance thermal conductivity

- Phonon Reflection Effect -

Φ250 μ m Sample





Original Surface

Scratched Surface

#8000
Diamond paste

Thermal conductivity of crystalline fiber can be enhanced at cryogenic temperature by increasing its surface quality.

. Thermal Conductivity of Pure Al and Cu

Requirement for the heat link:

- Large thermal conductivity
- Small spring constant

to make mechanically weak heat link

⇩

Key point

- Whether the size effect exists or not in metals.

$$k = n \times K \frac{E\ d^4}{64\ l^3}$$

No size effect

$$k \propto \frac{P^2}{n}$$

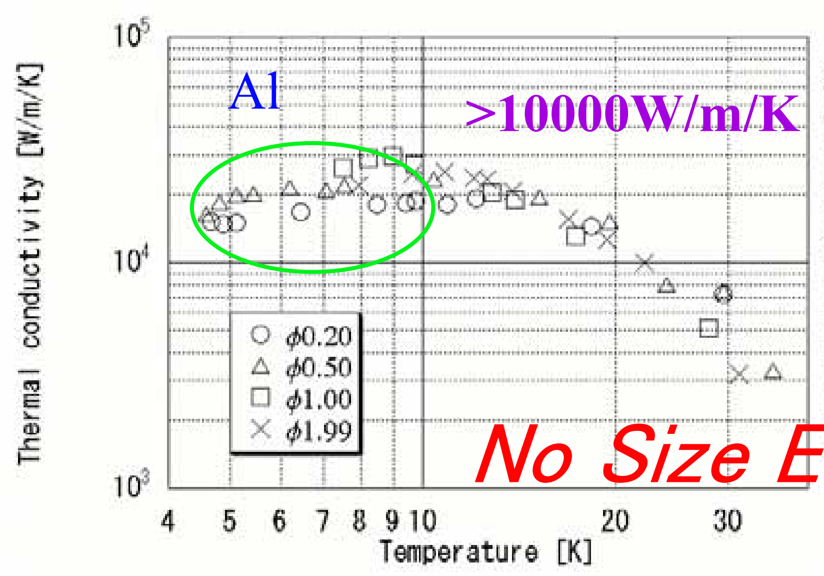
Size effec

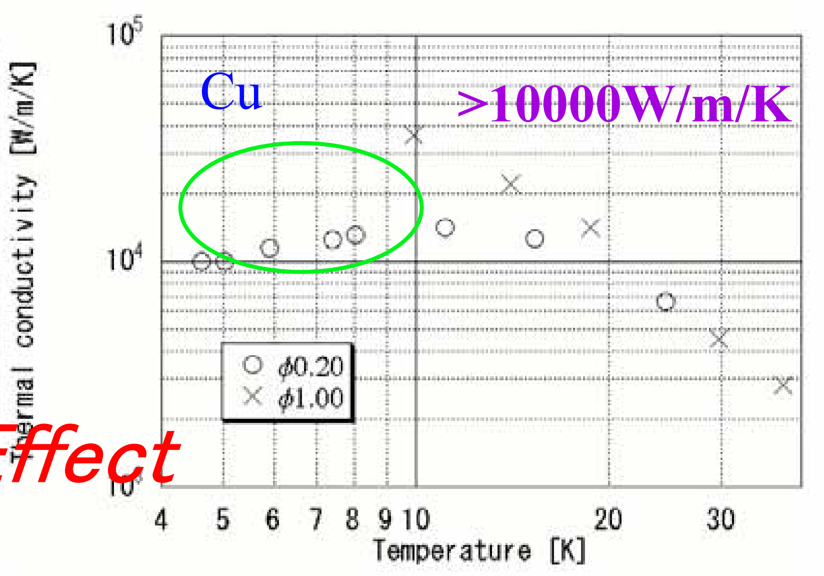
$$k \propto \left(\frac{P^4}{n}\right)^{1/3}$$

Sample

- Al: 99.999% purity
  ϕ 2mm, ϕ 1.5mm, ϕ 1mm,
  ϕ 0.5mm, ϕ 0.2mm
- Cu: 99.9999% purity
  ϕ 1mm, ϕ 0.2mm

Measured Results





No Size Effect

$$RRR = \frac{R_{300K}}{R_{4.2K}}$$

Sample	Aluminum				Copper	
	φ0.20mm	φ0.50mm	φ1.00mm	φ1.99mm	φ0.20mm	φ1.00mm
RRR	2900	4800	5500	6200	960	4100

$$\kappa^{(Al)} = \frac{1}{1.8\times10^{-7}\ T^2 + 1.1/RRR/T}$$

$$\kappa^{(Cu)} = \frac{1}{6.2\times10^{-8}\ T^{2.4} + 0.53/RRR/T}$$

It is effective to **use many thin wires** as keeping total cross section to make mechanically weak heat link.

Calculated heat transfer

Heat transfer $\dot{Q}$ and cross-section A are constant along heat link, but conductivity varies

so

$$\dot{Q} = \kappa A \frac{dT}{dx}$$

becomes

$$\dot{Q} = \frac{A}{L} \int_{T_0}^{T_L} \kappa(T) dT$$

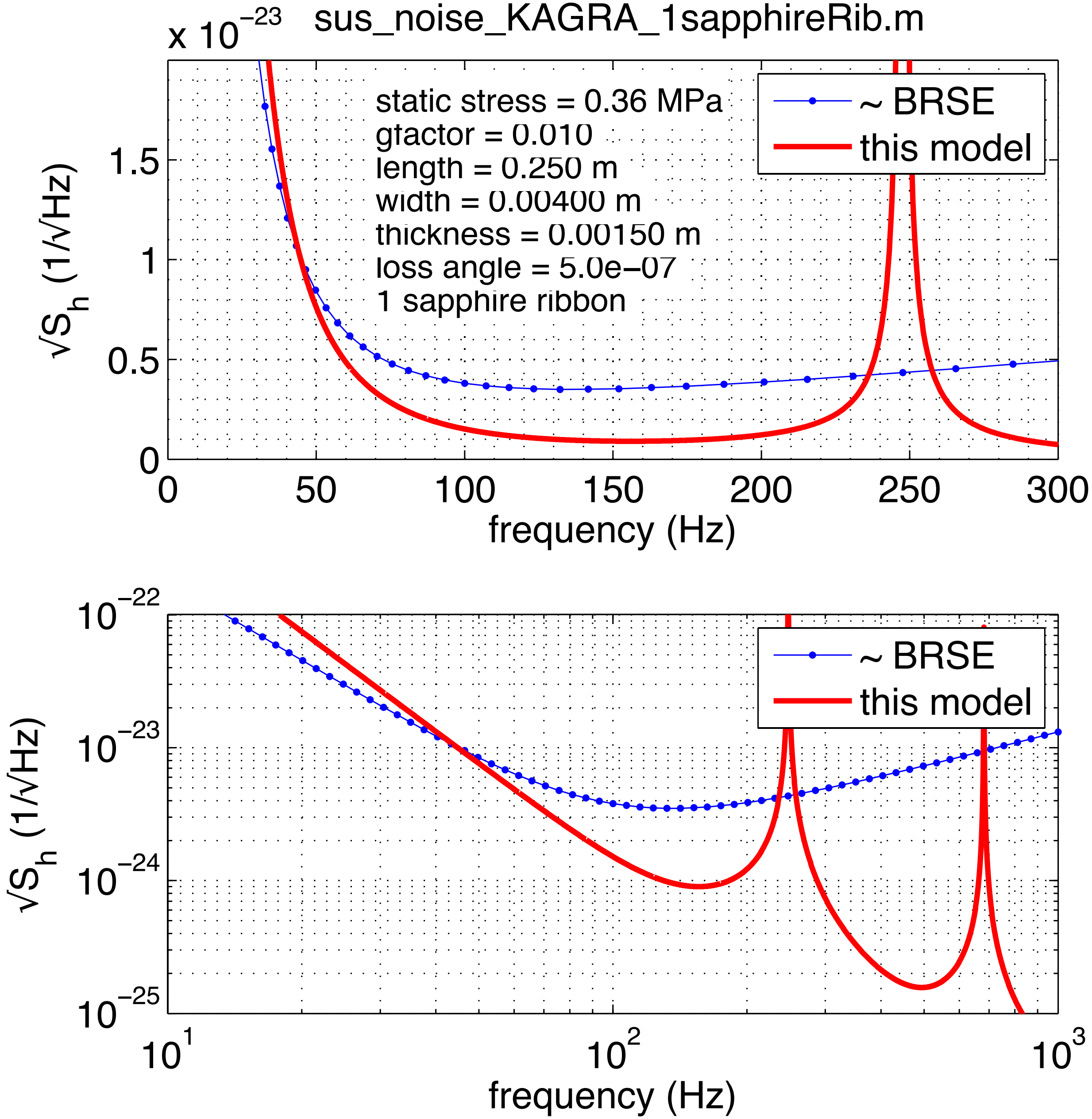
Tomaru results, scaled by size effect

$$\dot{Q} = \left(\frac{1.5}{0.39}\right) \frac{1.5\text{mm} \cdot 4\text{mm}}{250\text{mm}} \int_{10}^{20} \kappa(T) dT = 1.06 \text{ W}$$

So these dimensions, 1.5x4x250 mm, meet the heat extraction requirement.

Thermal noise from thick ribbon

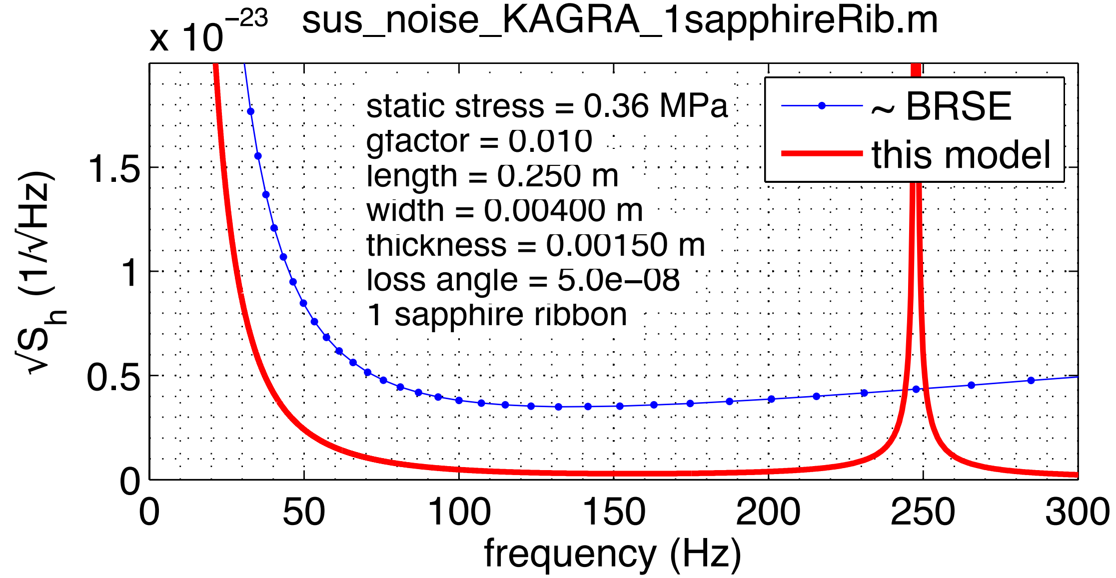
- Calculate Im(Y) for flexing-beam-equation under no tension [Gonzalez, Saulson, Levin, et.al.), use FD theorem.
- Assume $Q = 2 \times 10^6$ $T = 20$ K $m = 22$ kg

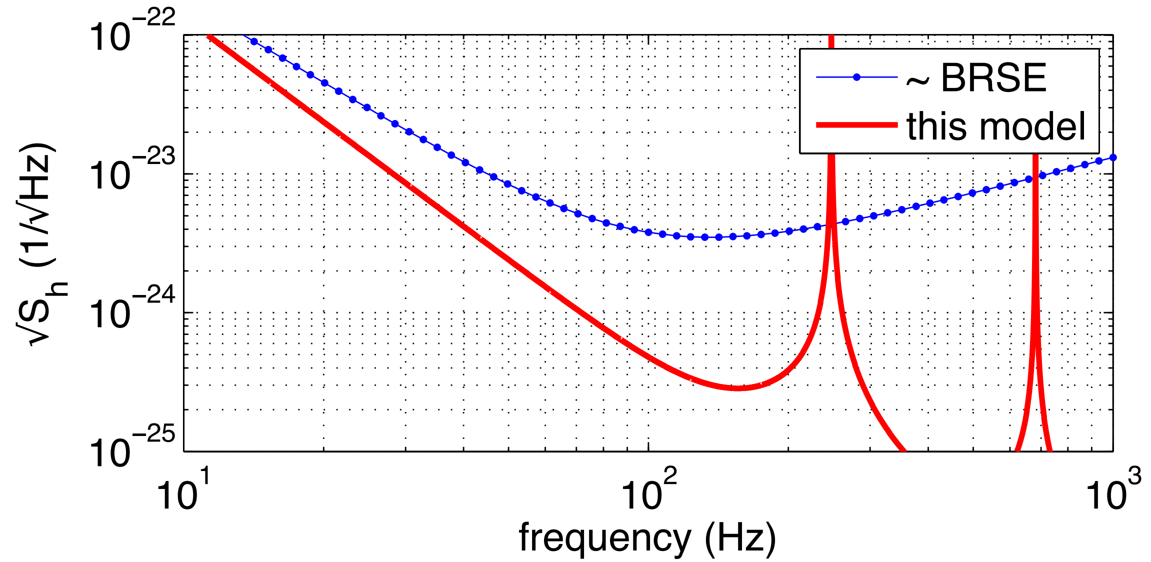


x 10^−23
sus_noise_KAGRA_1sapphireRib.m
static stress = 0.36 MPa
gfactor = 0.010
length = 0.250 m
width = 0.00400 m
thickness = 0.00150 m
loss angle = 5.0e−07
1 sapphire ribbon
~ BRSE
this model
√S_h (1/√Hz)
1.5
1
0.5
0
0
50
100
150
200
250
300
frequency (Hz)
10^−22
10^−23
10^−24
10^−25
~ BRSE
this model
√S_h (1/√Hz)
10^1
10^2
10^3
frequency (Hz)

result

- Using this low value of sapphire Q and high value of thickness, leads to thermal noise from the heat link to be larger than optical noise ("~BRSE") below 50 Hz
- The size of the peak at 250 Hz is partly due to the high mass of the thick and wide ribbon.
- So probably want sapphire fibers with higher Q, by a factor of 10, (see below) which other measurements indicate should be possible.


sus_noise_KAGRA_1sapphireRib.m
x 10^−23
static stress = 0.36 MPa
gfactor = 0.010
length = 0.250 m
width = 0.00400 m
thickness = 0.00150 m
loss angle = 5.0e−08
1 sapphire ribbon
~ BRSE
this model
√Sh (1/√Hz)
frequency (Hz)
0
50
100
150
200
250
300
0.5
1
1.5


~ BRSE
this model
√Sh (1/√Hz)
frequency (Hz)
10^−22
10^−23
10^−24
10^−25
10^1
10^2
10^3

Description of load bearing parts

- 2 metal wires support the entire weight of mirror. Use Cu:Be for high yield strength (~1 GPa).
- Wires are actually ribbons (annealed to `soft', rolled, and heat-treated to `hard' (high Q))
- Two clamp blocks connect a ribbon to the mirror.

rationale

- Metal is more “robust” than crystals (compare the *fracture toughness*)
- Mechanical loss can be quite small (at *cryogenic* temperatures) for the right metals.
- clamping ribbons (instead of round wires) can avoid stress concentrations. (=> Lower clamping loss ?)
- Thin metal films can be used to “weld” ribbons to sapphire clamp-blocks.

Here is metal with high Q (and high strength).

William Duffy, Jr. 2485

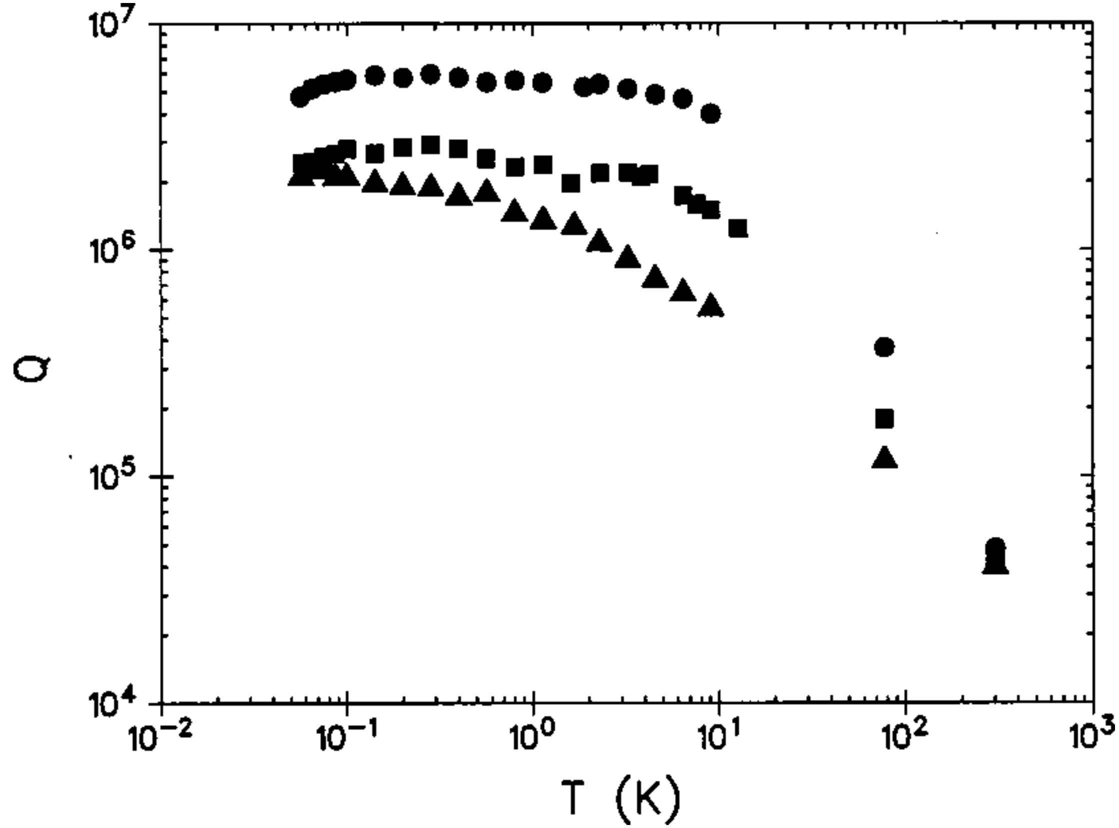
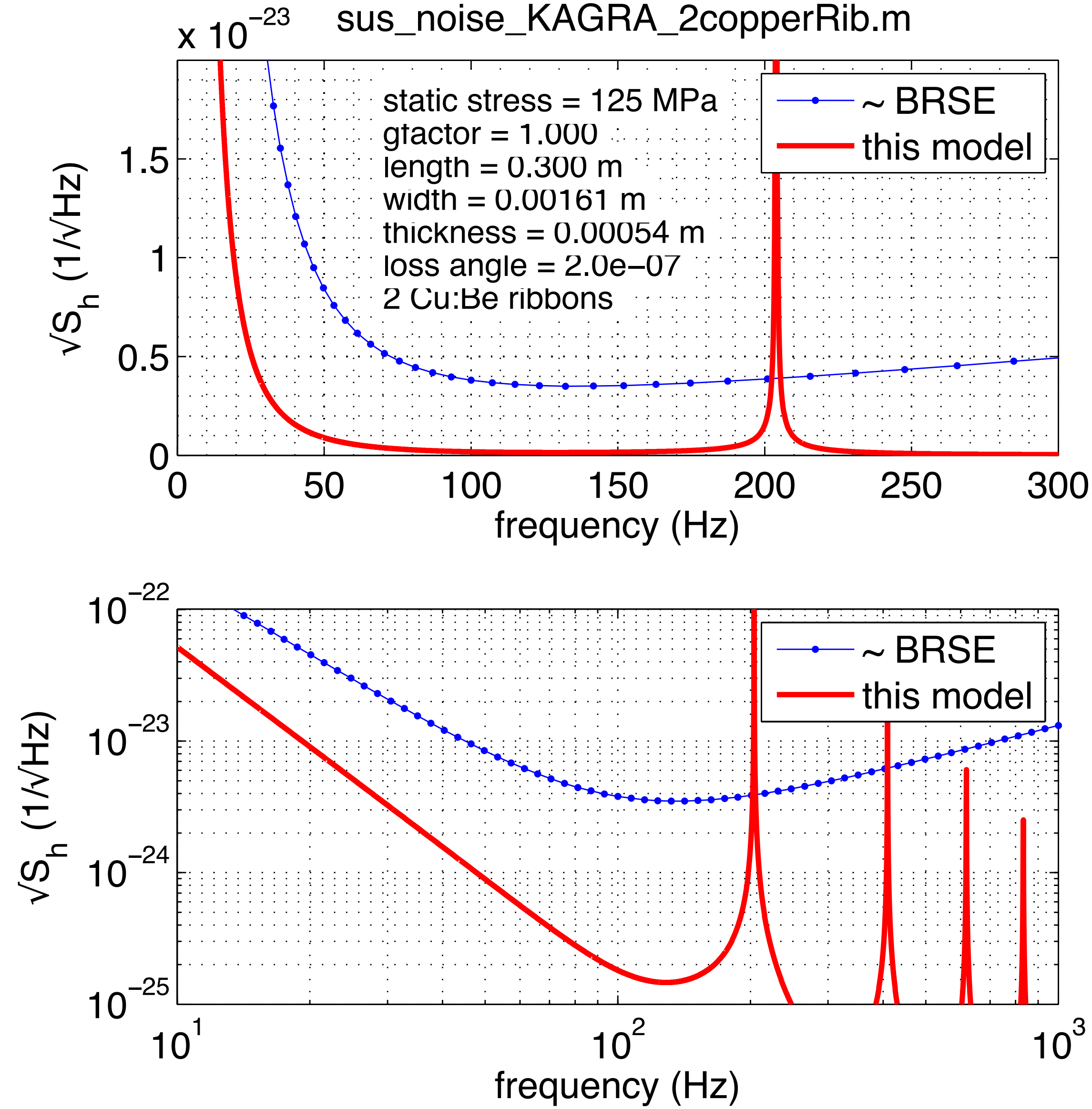
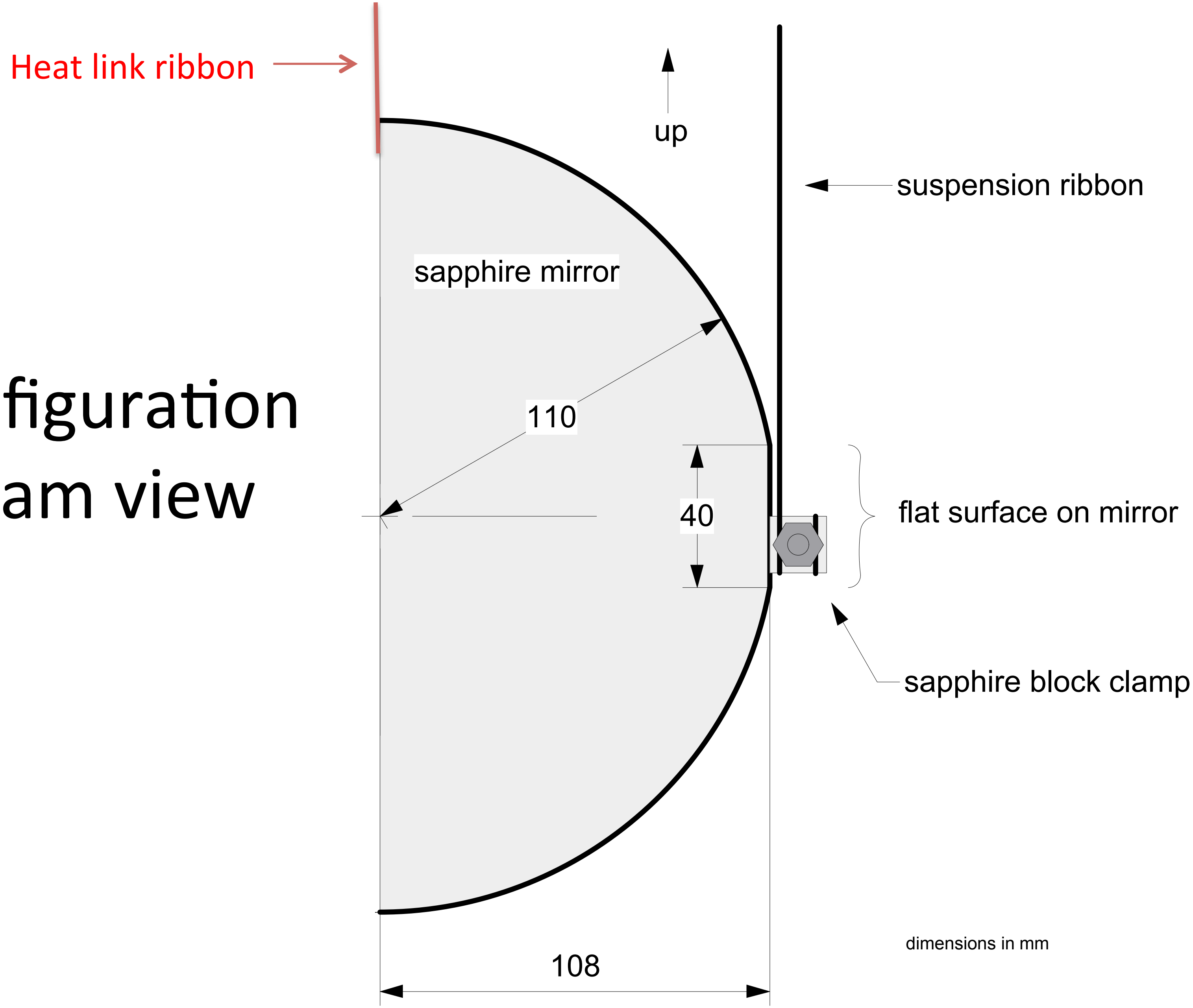


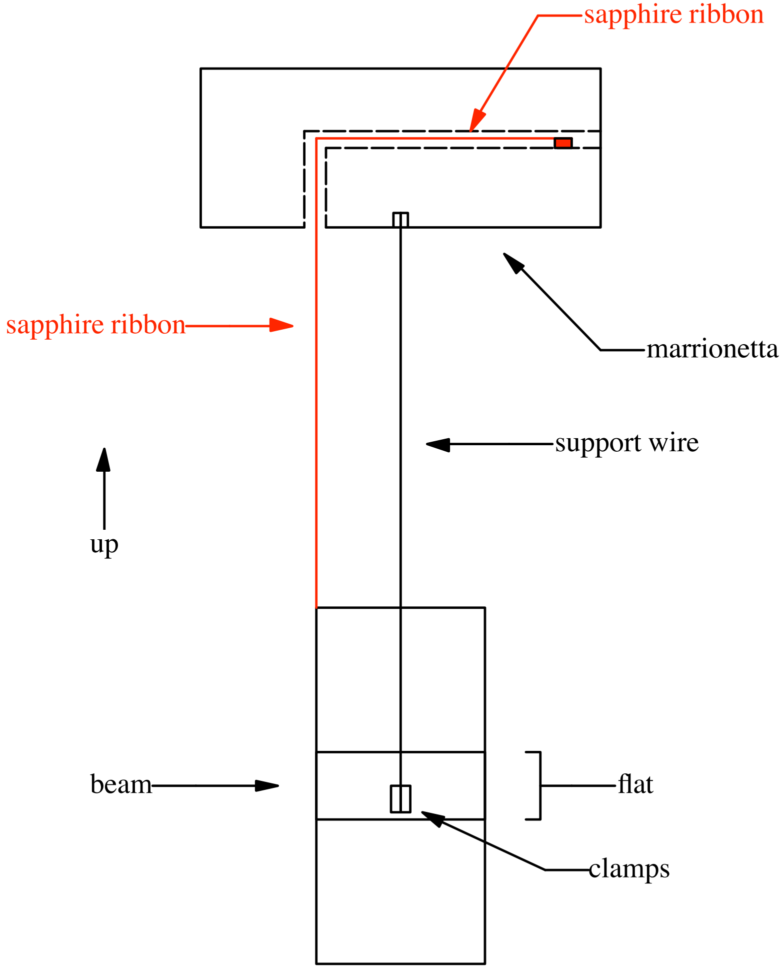
FIG. 2. Acoustic quality factor vs temperature of C17 500 Cu–Be–Co alloy, also commonly known as Alloy 10. Data shown are for as-machined material (■), heat-treated material (●), and doubly heat-treated material (▲).


sus_noise_KAGRA_2copperRib.m
x 10^−23
static stress = 125 MPa
gfactor = 1.000
length = 0.300 m
width = 0.00161 m
thickness = 0.00054 m
loss angle = 2.0e−07
2 Cu:Be ribbons
~ BRSE
this model
√S_h (1/√Hz)
frequency (Hz)
0
0.5
1
1.5
0
50
100
150
200
250
300
~ BRSE
this model
√S_h (1/√Hz)
frequency (Hz)
10^−22
10^−23
10^−24
10^−25
10^1
10^2
10^3

Configuration - beam view

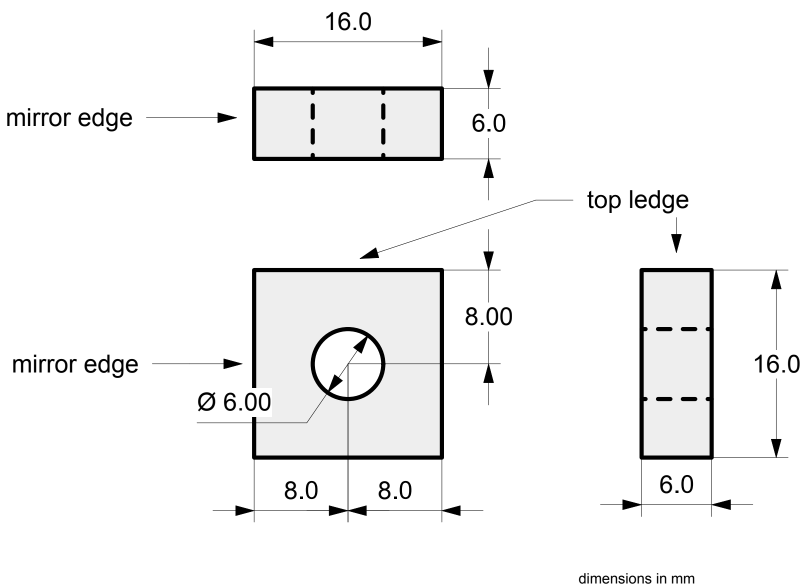


Configuration
- Side View

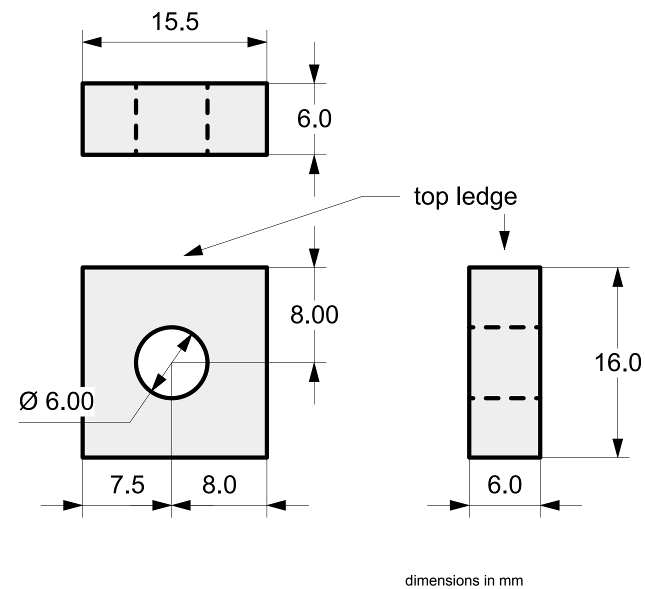


Two support metal `wires'.
One heat link ribbon (no load)
with a `blade spring' to
soften the connection to
the stage above (the "marrionetta")

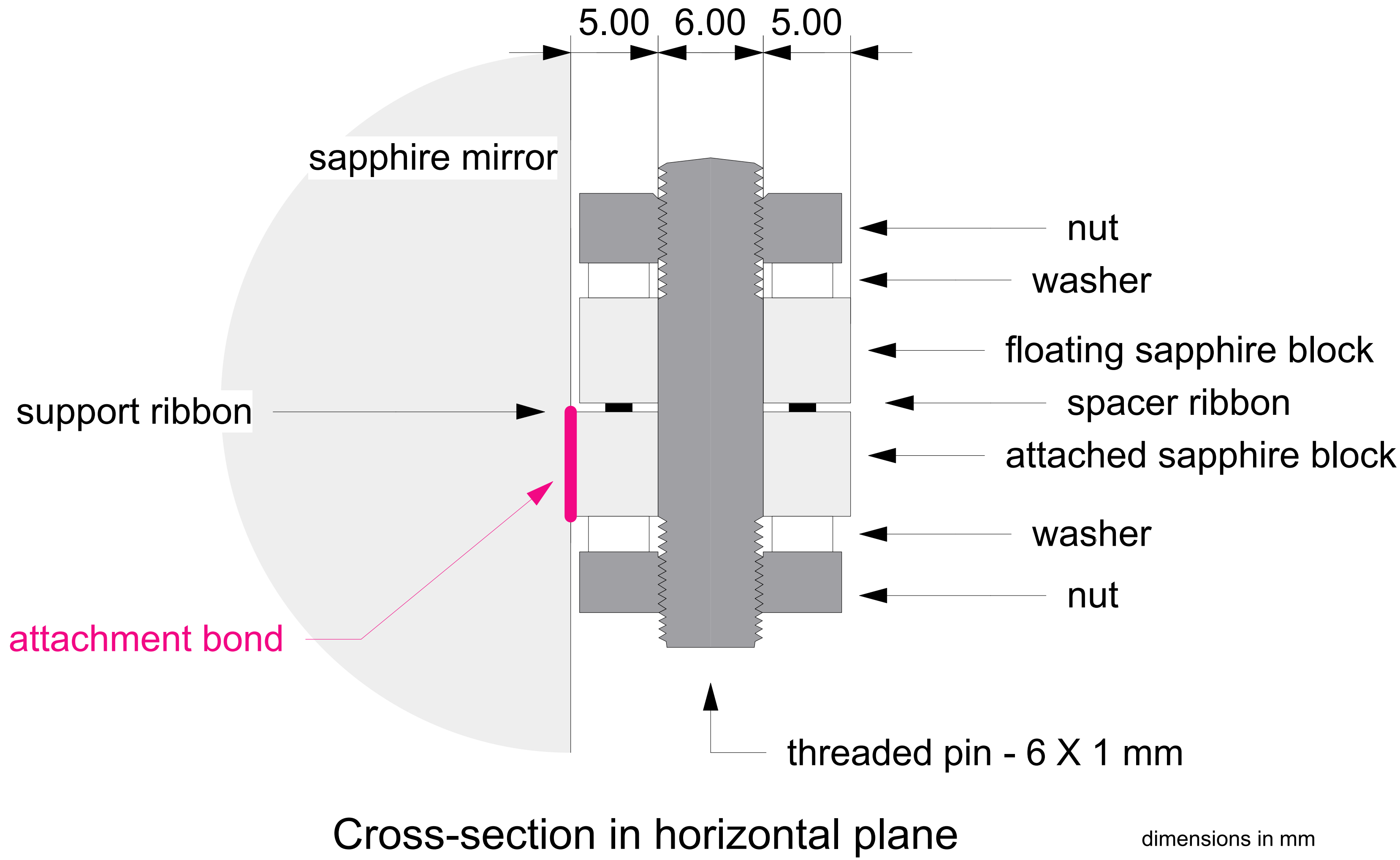
2 clamp blocks



attached block



floating block



single-threaded-pin clamp block

Further Options

- sapphire ribbon fabrication:

  EGF rod or ribbon, then lapped and polished

  (I have found commercial fabricators in US of such ribbons)

- metal thin-film bonds for joining sapphire to sapphire

  thin metal film deposition is an industry.

  Compress and heat two coated sapphire pieces to form molecular bonds.

- A speed-up for cooling in a vacuum (suggested by DeSalvo, Tanner)

  Grind and polish a flat surface on bottom of mirror, coat with “black”,

  make a movable cold-black surface for low-load touch
- Use (Cu:Be) blade springs to make vertical springs
  - Special consideration : Colder → stiffer → Lift
  - Solution: Adjust height with a lighter load, tuned for the room temperature.
- Differential thermal contraction

  Use to increase or adjust clamping force at low temp