Update on the suspension thermal noise modelling of the ET-LF cryogenic payload

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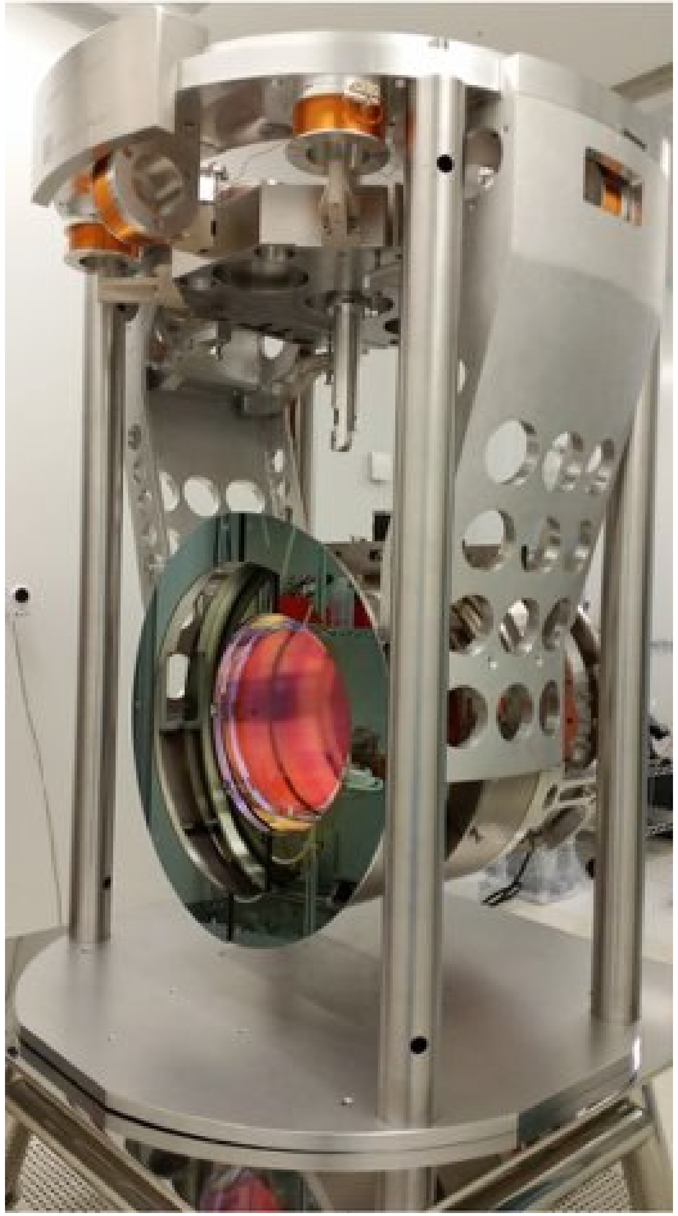
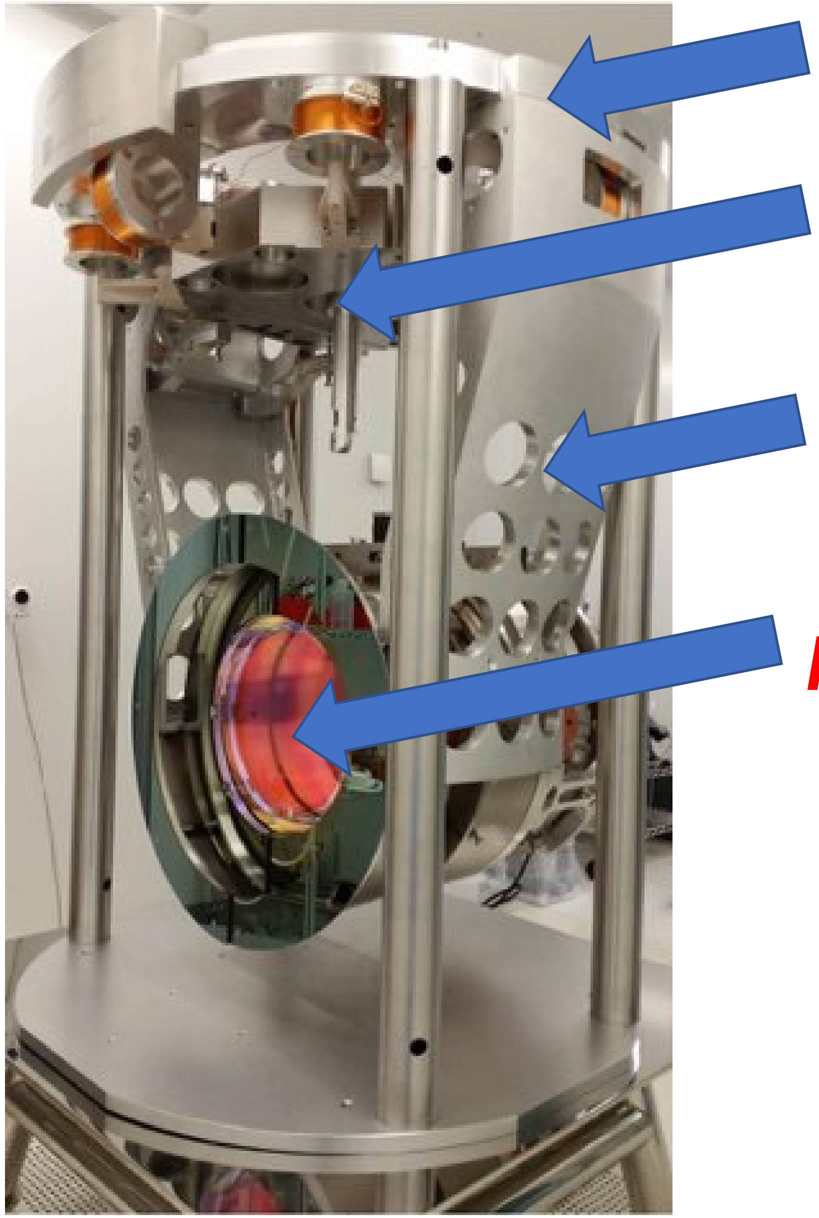


The Last Stage Suspension

The role of the Last Stage Suspension is to compensate the residual seismic noise and to steer the optical components maintaining the relative position of the interferometer mirrors.

Bernardini A., Majorana E. ,Puppo P. ,Rapagnani P. , Ricci F., Testi G. "Suspension last stages for the mirrors of the Virgo interferometric gravitational wave antenna." *Rev. Sci. Instr.* 70, no. 8 (1999): 3463.



Components:

Marionette: Mirror control with actuators (coil-magnets, electrostatic) between the upper suspension stage and marionette;

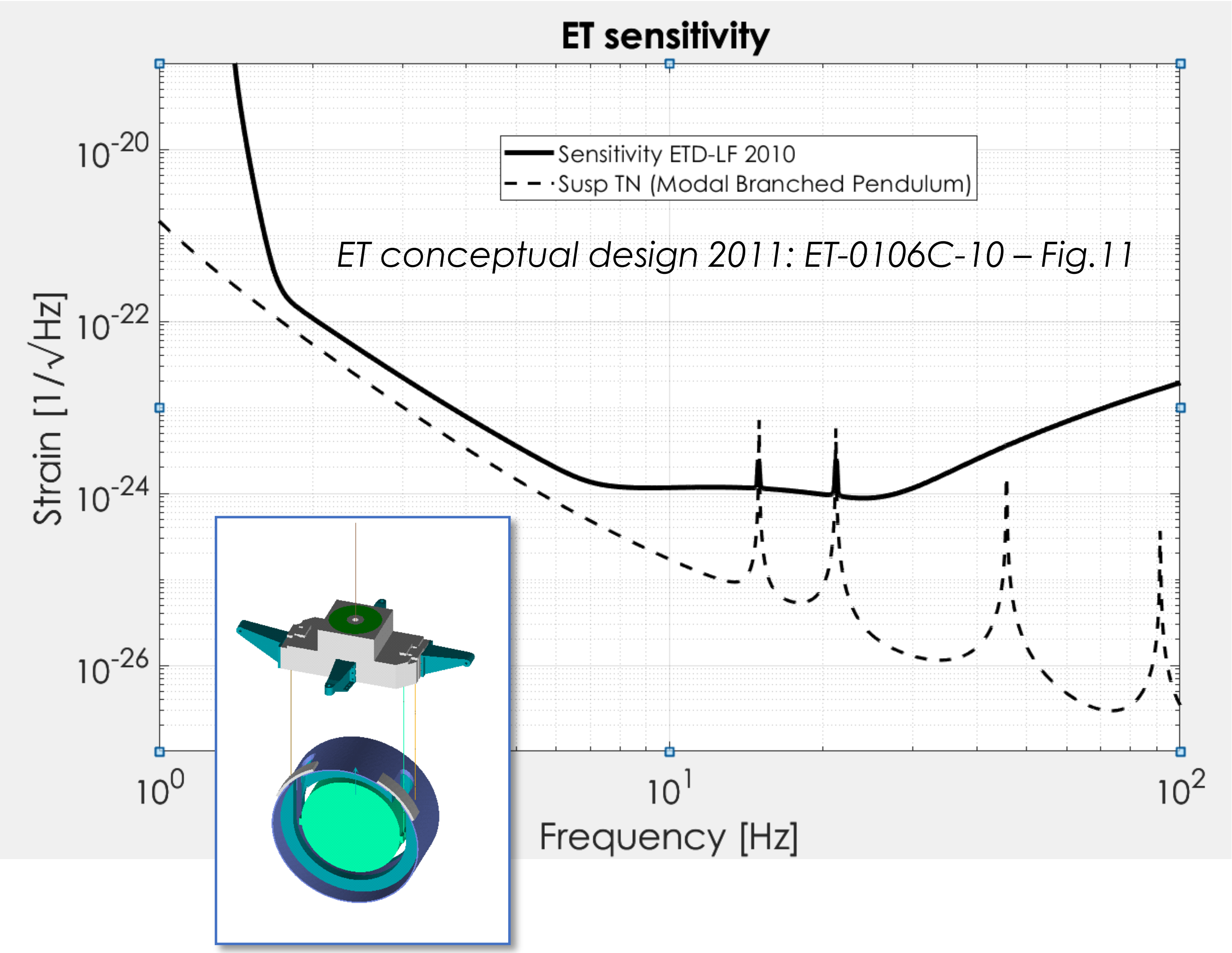
Reaction Mass (RM): Mirror steering with (coil-magnets, electrostatic) actuator between RM and mirror; Mirror protection; **in AdV replaced with the cage (screen)**

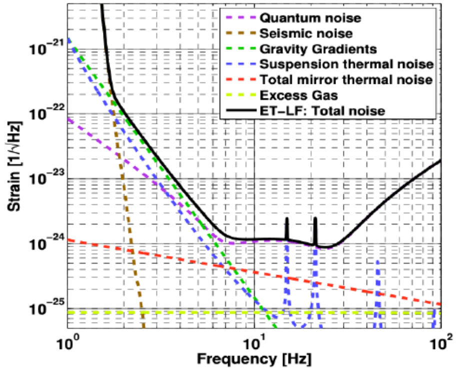
Mirror: with monolithic suspension.

Bernardini A., Majorana E. ,Puppo P. ,Rapagnani P. , Ricci F., Testi G. "Suspension last stages for the mirrors of the Virgo interferometric gravitational wave antenna." *Rev. Sci. Instr.* 70, no. 8 (1999): 3463.

ET-LF Payload Design Parameters
Starting point: Branched system

	Marionette	Reaction Mass	Test Mass
Mass (kg)	211	211	211
Wire diameter (mm)	3	3	3
Wire length (m)	2	2	2
Material	Ti6Al4V	Silicon	Silicon
Losses	10^{-4}	10^{-9}	10^{-9}
Temperature (K)	2	10	10
Wire Tension (MPa)	**866**	70	70





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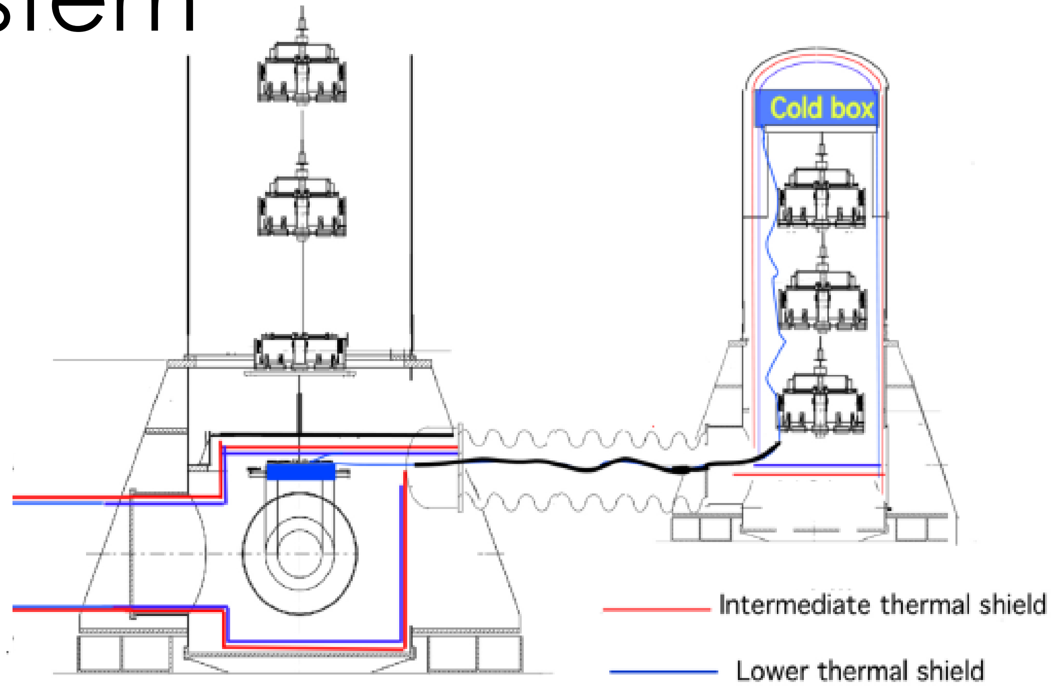
Mirror diameter 450 mm
Maximum power absorbed 100 mW



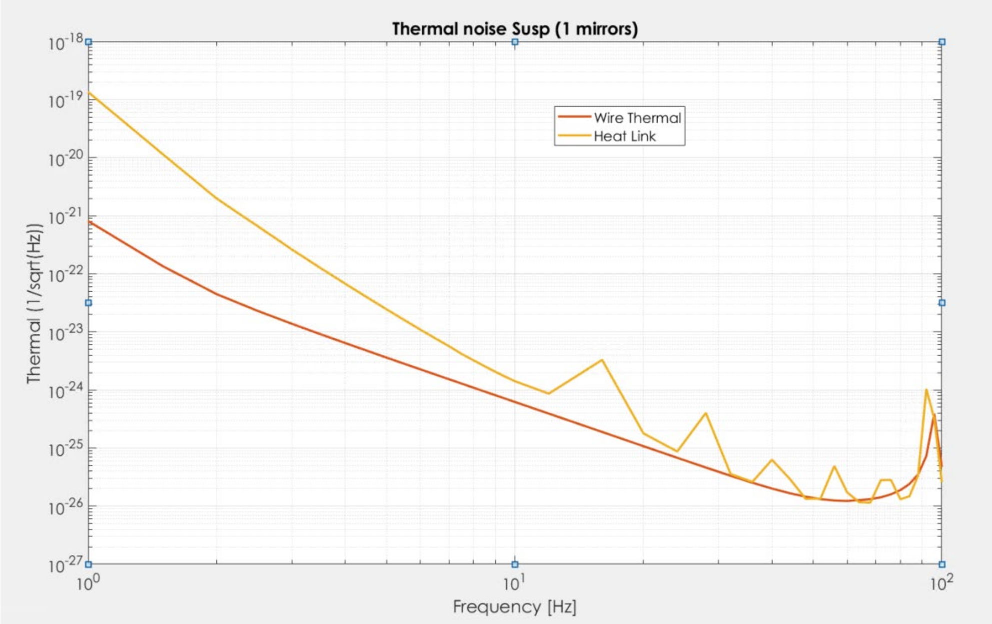
ET conceptual design 2011: ET-0106C-10 – Fig.11

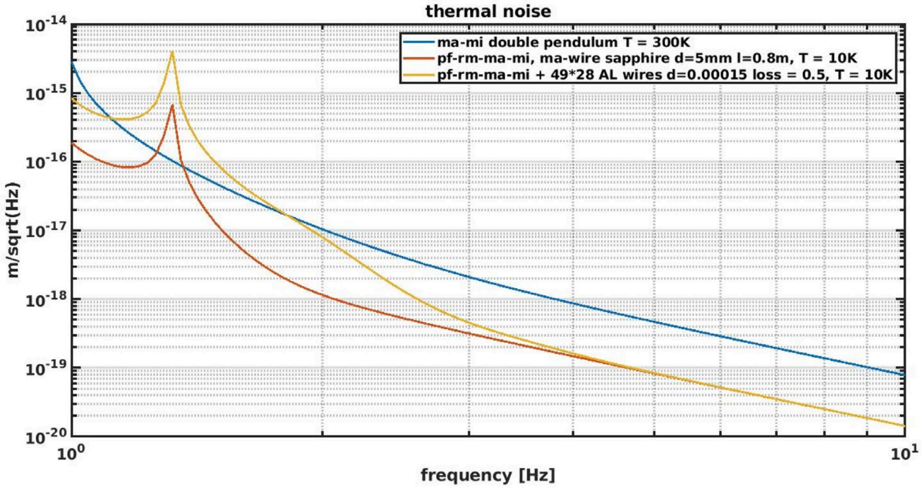
Starting concept for cooling :
dampened heat link directly connected to the marionette.

BUT THIS IS an ISSUE

With heat links (a bad case)

Pure Aluminum Heat Link (loss angle: 0.5)

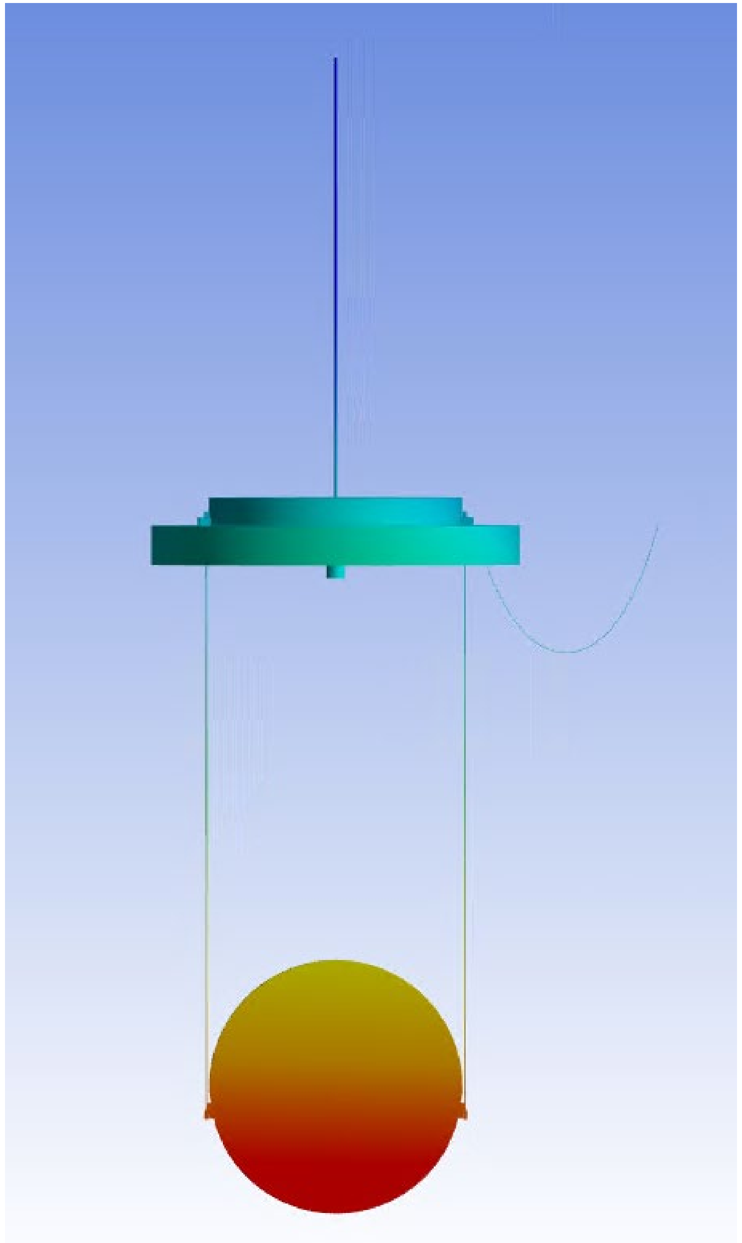




*from Ettore Majorana's talk at GWADW2021 May-18-2021

- The Heat Links cannot be directly connected to the marionette, they introduce vibrations and also increase the STN

- In agreement with the analitical study of the heat link effect based on the Saulson paper by P. Ruggi.



Design of the payload (recursive)

Mechanical design

- Materials → Mechanical, thermal properties, losses
- Breaking strength
- Interfaces → HCB, couplings
- Shapes of wires (diameter, length)

- Frequencies:
  - Must be outside sensitivity bandwidth
  - Must be compliant with control requirements

Thermal design

Cooling efficiency, cryostat design
Heat to be extracted

- 500 mW very conservative
- 300 mW possible with the known absorption properties

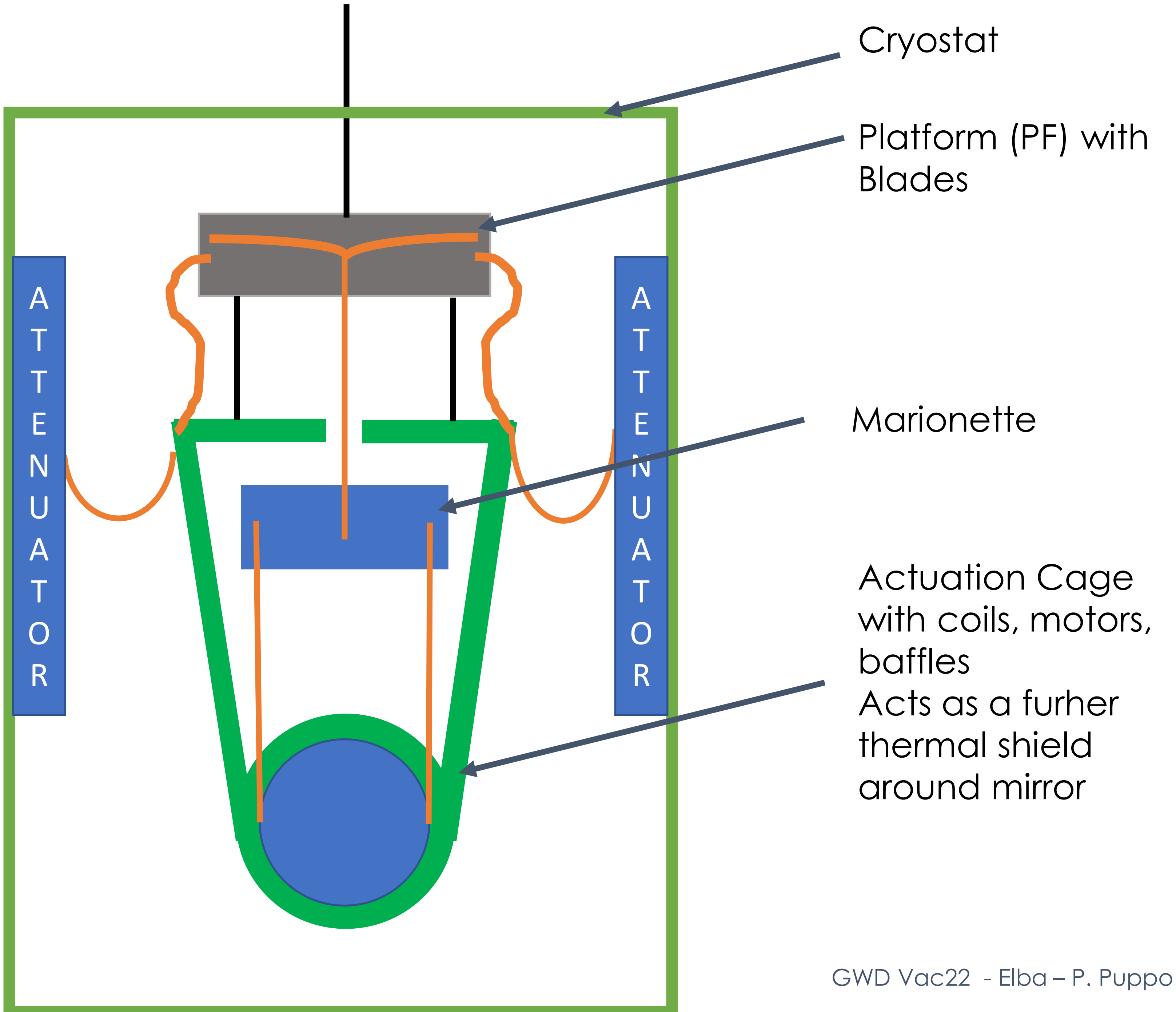
- Heat extraction
  - No noise injection form links
  - Thermal resistance of the interfaces as low as possible

Suspension Thermal noise

Strain noise limit : 5 10^{-25} 1/sqrt(Hz) @ 10 Hz

A cooling scheme for the payload

- Double pendulum
- Platform with blades for vertical attenuation
- Heat links on the screen
- Screen connected to PF with 3 wires (for angular control)
- Link cooled with PT Cryocoolers and attenuated with mechanical filters;
- Heat conduction through the marionette and mirror wires



Important Parameters for the suspension of the test masses

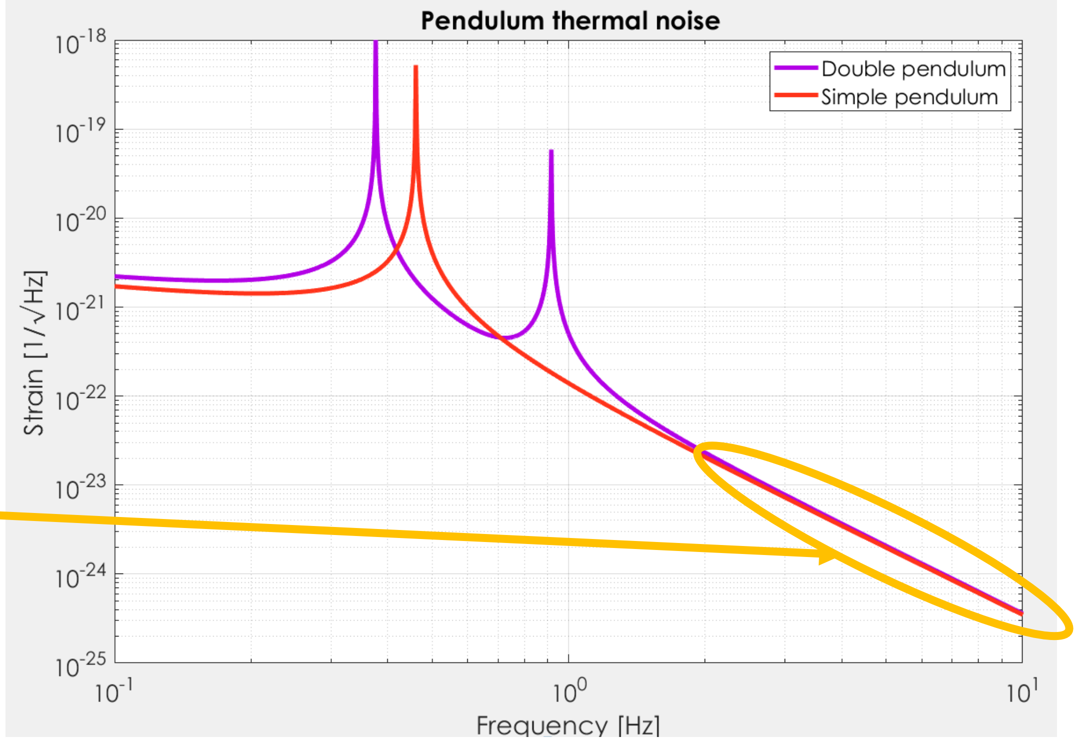
The dilution factor

$$D = \frac{1}{L_w}\sqrt{\frac{E\,I}{Tens}}$$

E: Young Modulus
I: Section moment of inertia
L_w: wire length

$$X^2_{therm}(\omega) = \frac{4k_bT}{M\omega}\frac{\omega_p^2\,\varphi_p(\omega)}{\left(\omega_p^2-\omega^2\right)^2+\left(\omega_p^2\varphi_p(\omega)\right)^2}$$

$$\approx \frac{4\,k\,T}{M\,\omega^5}\frac{\varphi_w}{D} \quad \text{for} \quad \omega^2 \gg \omega_p^2$$



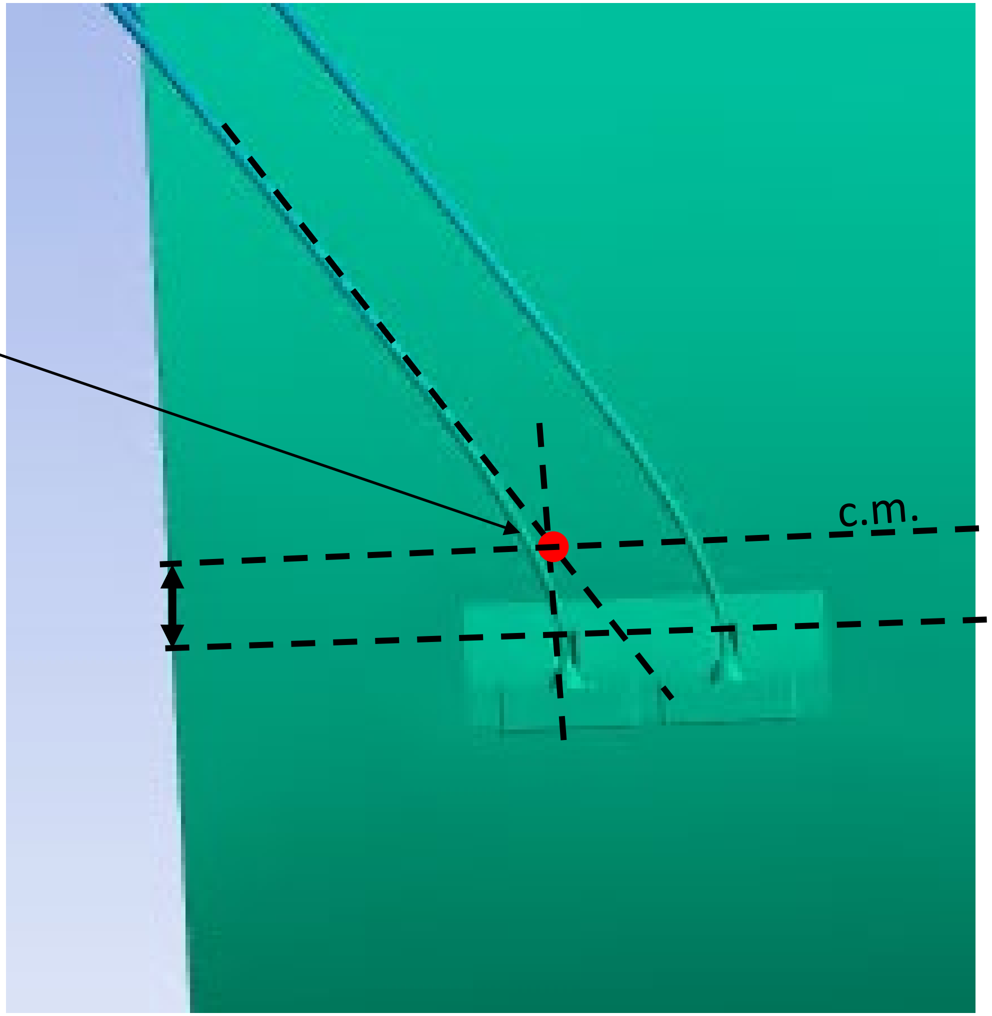
Larger dilution implies a lower level of noise

The bending point

The bending point → **wires length**

$$y_{bending} = \sqrt{\frac{E\ I}{Tens}}$$

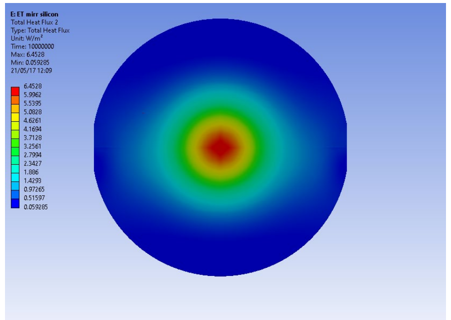
E: Young Modulus
I: Section moment of inertia
Tens: wire tension



The bending point must lay on the center of mass of the suspended body

$L = Lo + 2y_{bending}$ for mirrors

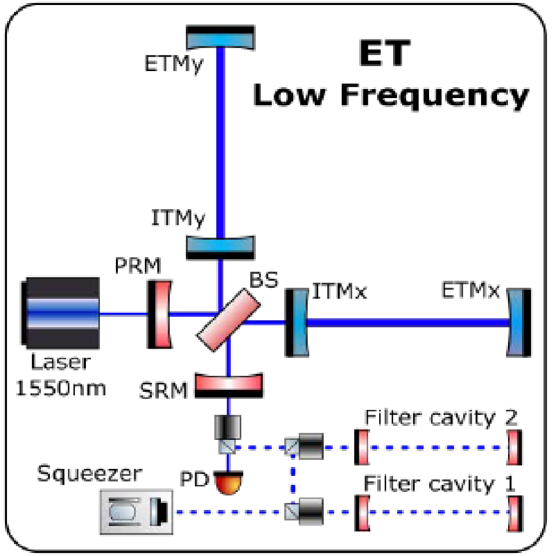
Heat extraction



Mirror mass 220 kg
Beam size 9cm
P in the arms 18 kW
Finesse 880
Recycling factor 21.6

P_{RC}=18kW/(2F/pi)=32 W (Power in recycling cavity)

	Sapphire Mirror	**Silicon Mirror**
Thickness (cm)	35 (diam 450mm)	36 (diam 550mm)
Substrate (ppm/cm)	50	10
Coating (ppm)	1	1
Pcoat (mW)	18	18
Psubstrate (mW)	112	12
Ptot (on ITMs)	**130**	**30**
Ptot (on ETMs)	**18**	**18**



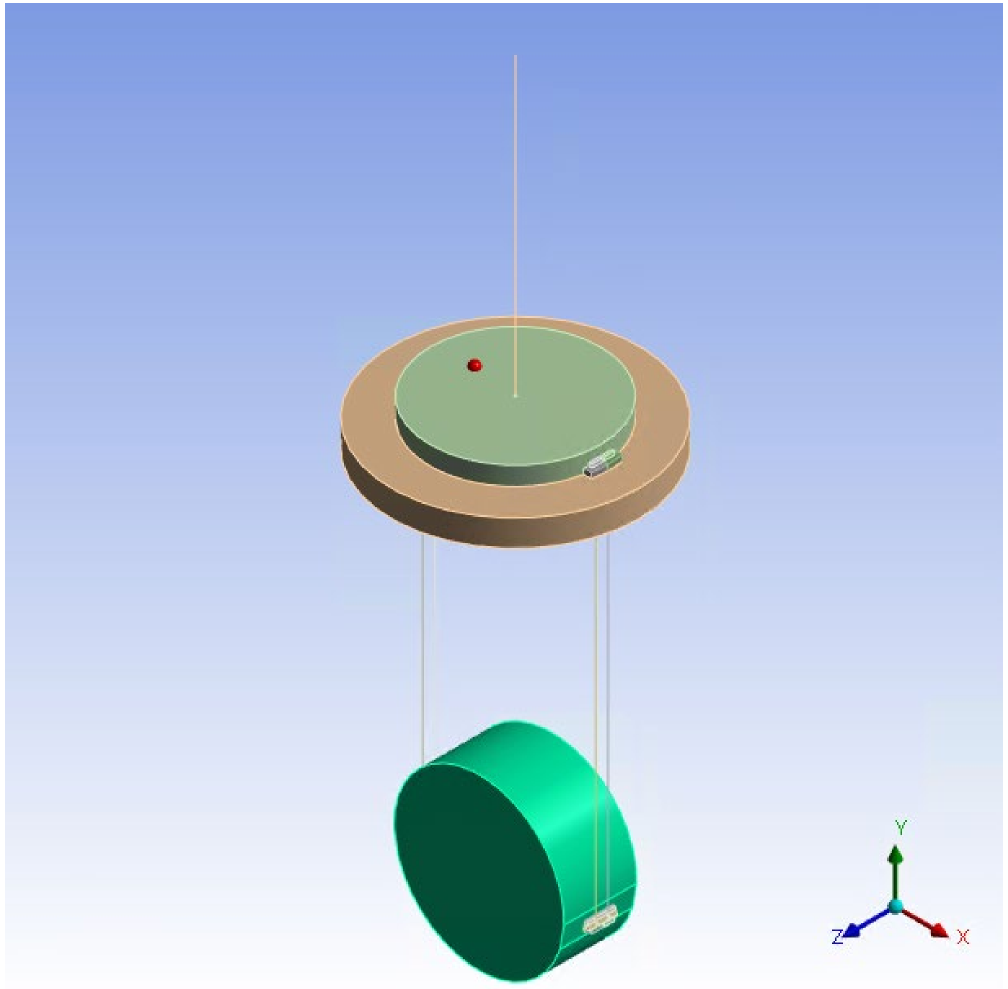
A conservative heat value of **500 mW** is used for the payload design.

These aspects have a strong impact on the choice of the cryostat dimensions
(see S. Grohmann presentation)

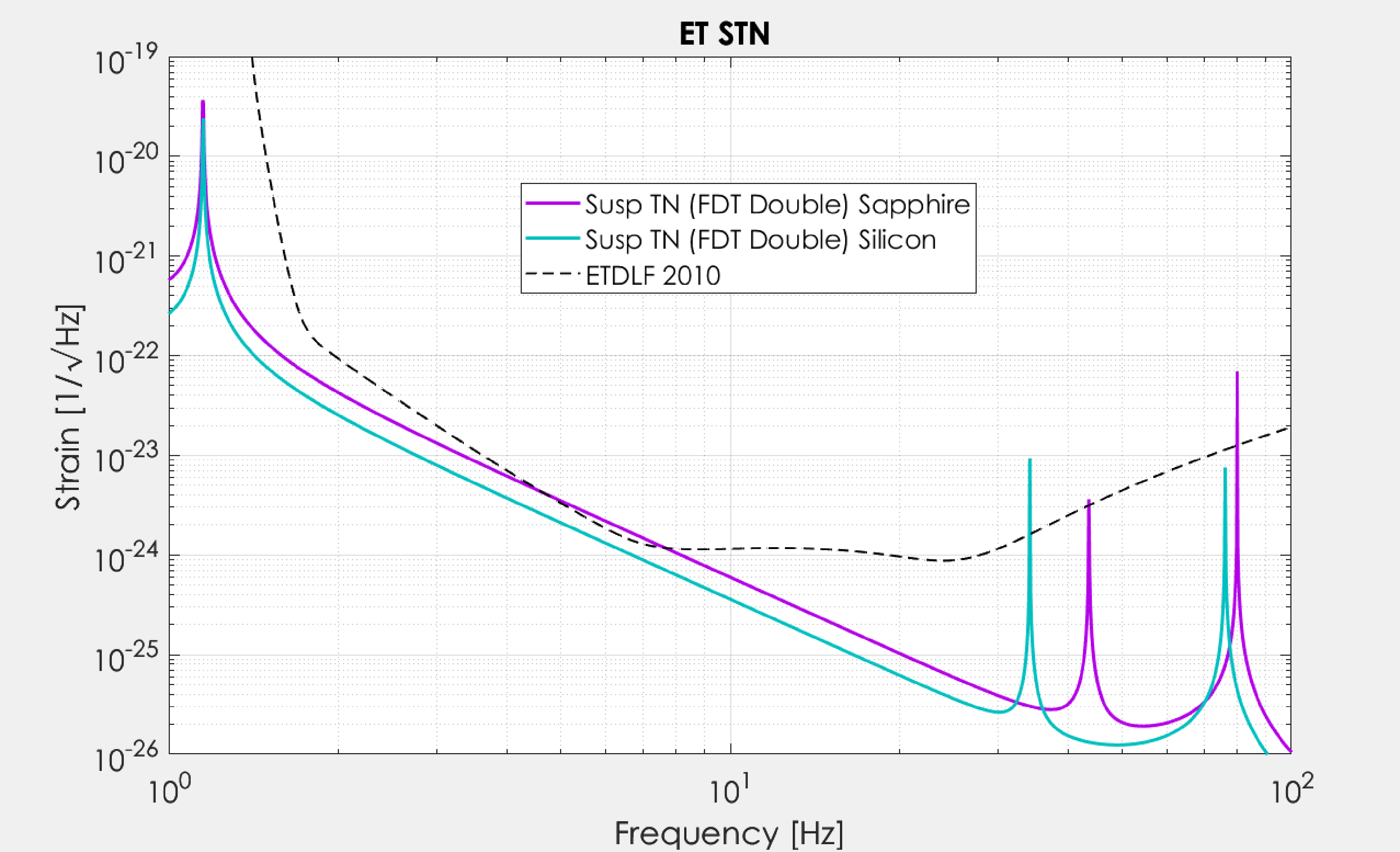
Close integration between suspension and cryogenics necessary

Silicon / Sapphire payload (double)

	Silicon	Sapphire
Mirror and Marionette Mass (kg)	200	220
Mirror thickness(mm)	360 (diam 550mm)	350 (diam 450mm)
Mirror wire • **diameter (mm)** • **length (m)**	 3.0 1.2	 2.3 1.2
Marionetta wire • **diameter (mm)** • **length (m)**	 8.4 1.0	 6.4 1.0
Losses	10^{-9}	$5.6\ 10^{-9}$
Temperature (K)	20	20
Wire Tension (Mpa)	77	130
Breaking Strength (Mpa)	200	400



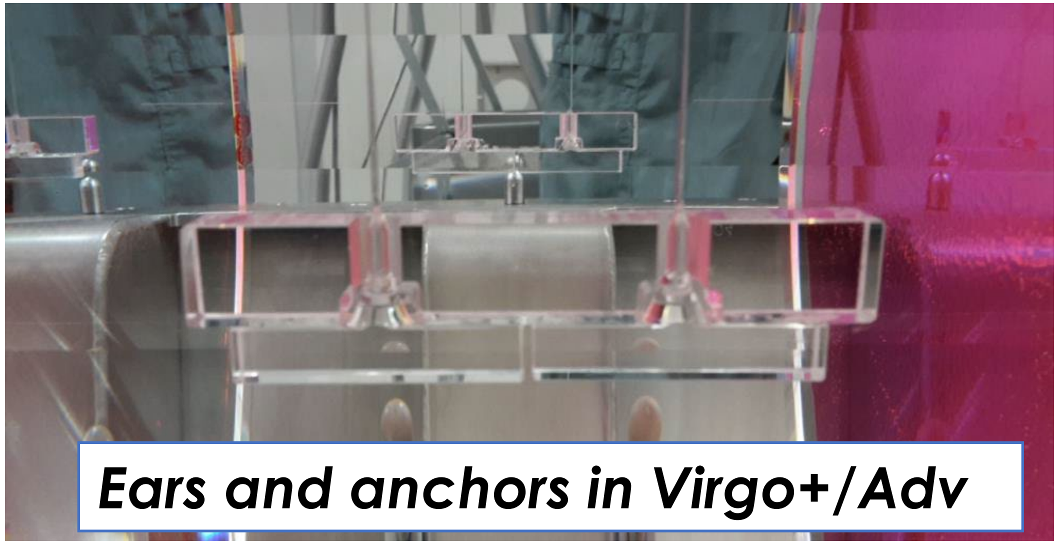
STN from analytical model



FEA Models

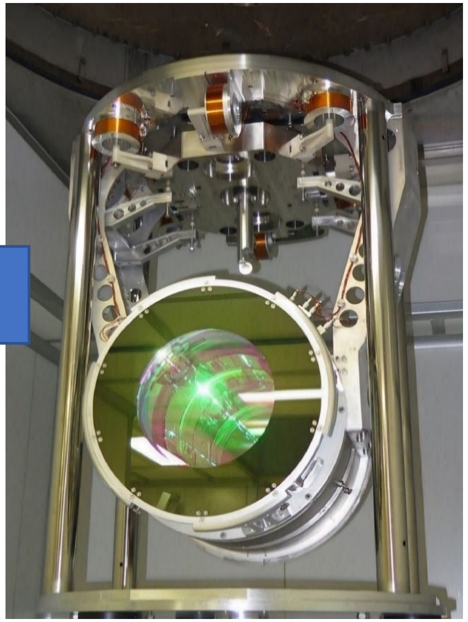
- FEA model of the mirrors payload using ANSYS;
  - elastic properties, losses
  - real shape of the payload system
  - Interfaces can be included
- Calculation of the expected modal frequencies and quality factors;
- Calculation of thermal noise using the Levin method;
- Calculation of temperature distribution with a thermal load

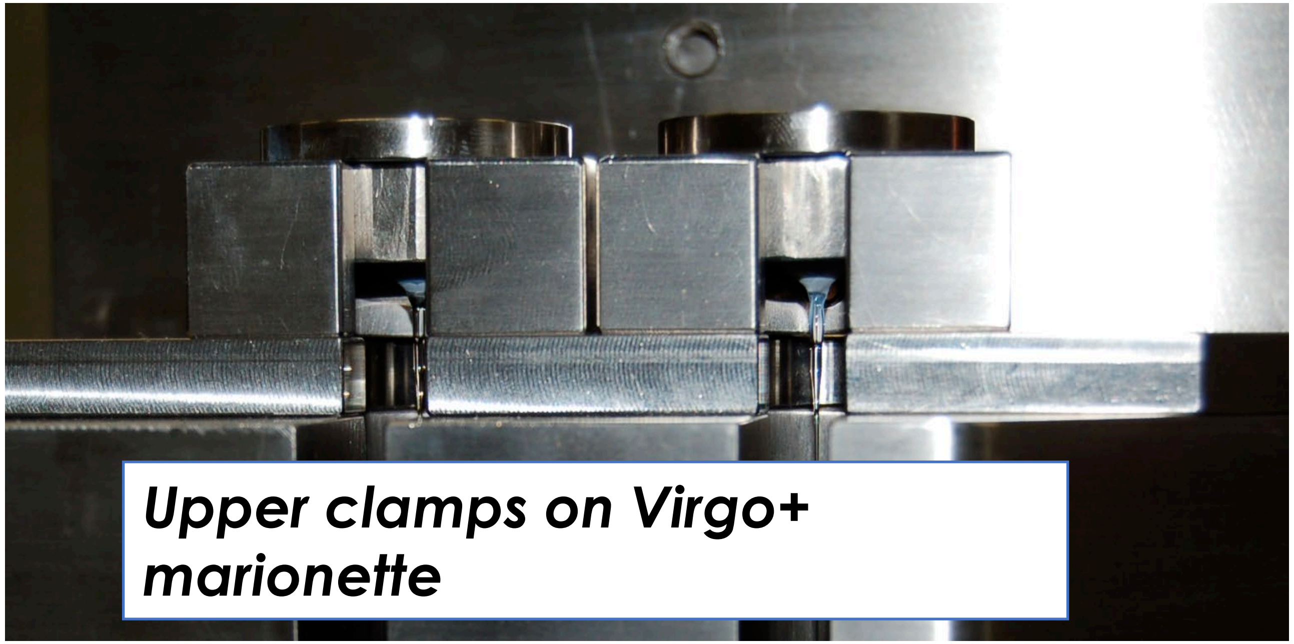
INTERFACES must be included in the computation this is not possible with analytical models



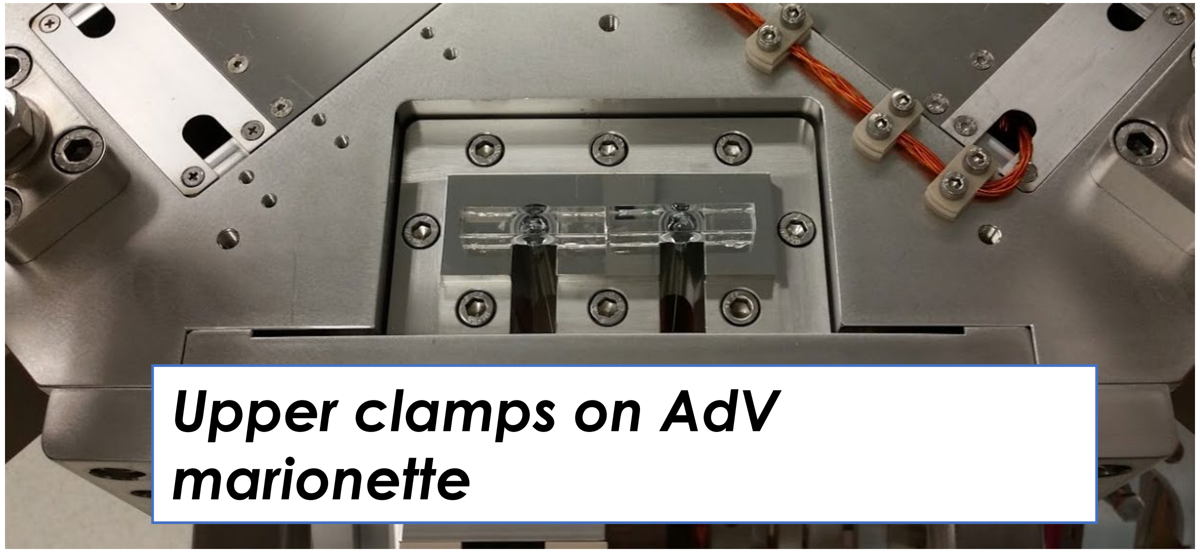
Ears and anchors in Virgo+/Adv

Monolithic suspension





Upper clamps on Virgo+ marionette



Upper clamps on AdV marionette

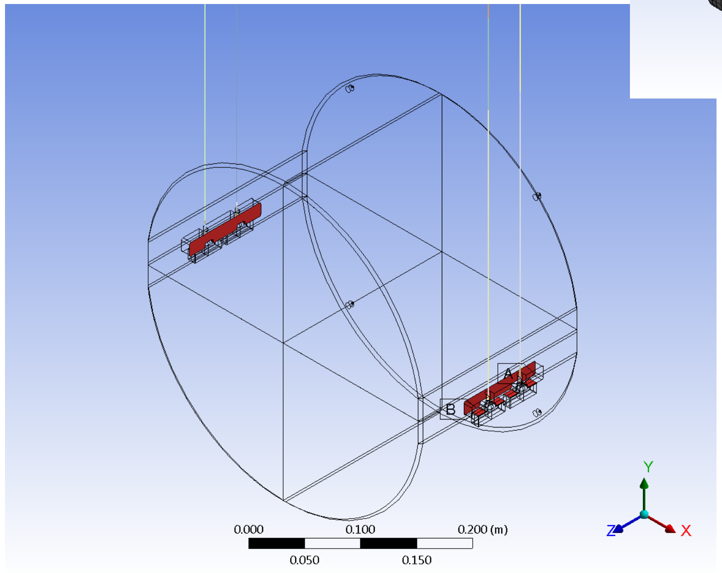
Silicate Bonding Layers for sapphire

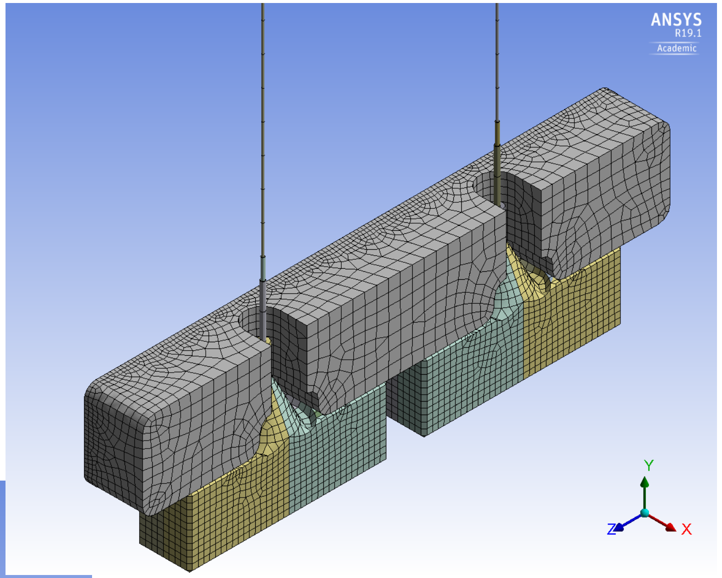
Thickness=60 nm
Young Modulus=18.5 GPa
poisson ratio=0.17
density=2201 kg/m^3

loss angle 1.8e-3 @ 20 K; sapphire

loss angle 2.25e-3 @ 20 K; silicon

from Phelps, Margot Hensler (2018) Hydroxide catalysis and indium bonding research for the design of ground-based gravitational wave detectors. PhD thesis.

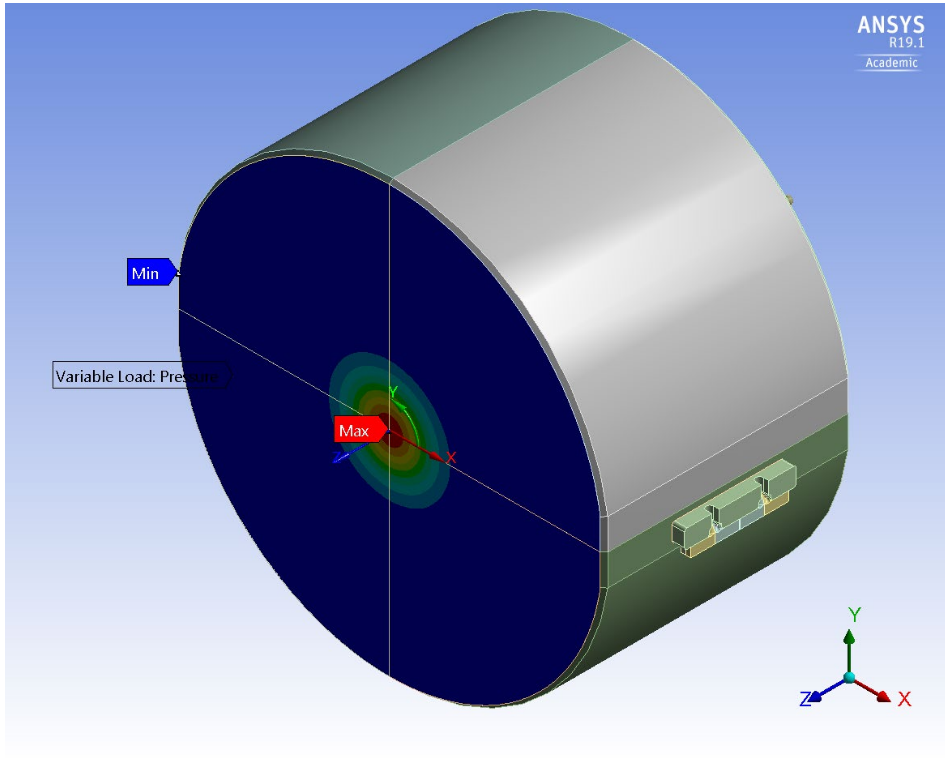




Suspension Thermal

(Levin Formula)

$$S_X^{FEM}(\omega) = \frac{4\,k_b T}{\omega\,F_o^2} 2 \left(\phi_{wires}E_{wires}(\omega) + \phi_{layers}E_{layers}(\omega) + \phi_{Mario}E_{Mario}(\omega) + \phi_{\substack{Silica\\parts}}E_{\substack{Silica\\parts}}(\omega) + \phi_{\substack{Mario\\Cable}}\,E_{\substack{Mario\\Cable}}(\omega) \dots\right)$$



Strain energies $E_i(\omega)$ from the FEM applying a unitary gaussian force on the suspended mirror face.

Dealing with temperature gradients

- Modal approach:
  - **For branched:** The Twelfth Marcel Grossmann Meeting, pp. 1732-1734 (2012) A thermal noise model for a branched system of mechanical harmonic oscillators: some issues for the test masses suspensions, P. Puppo https://doi.org/10.1142/9789814374552_0311
  - **For double pendulum:** Mechanical thermal noise in coupled oscillators, Y. Ogawa, E. Majorana, Physics Letters A, Volume 233, Issue 3, 25 August 1997, Pages 162-168, https://doi.org/10.1016/S0375-9601(97)00458-1

- FDT with different temperature input noises

- Direct approach for the fluctuation-dissipation theorem under nonequilibrium steady-state conditions, Kentaro Komori, Yutaro Enomoto, Hiroki Takeda, Yuta Michimura, Kentaro Somiya, Masaki Ando, and Stefan W. Ballmer, Phys. Rev. D **97**, 102001 – Published 3 May 2018

- Levin method with different temperatures with FEM

Temperatures distribution

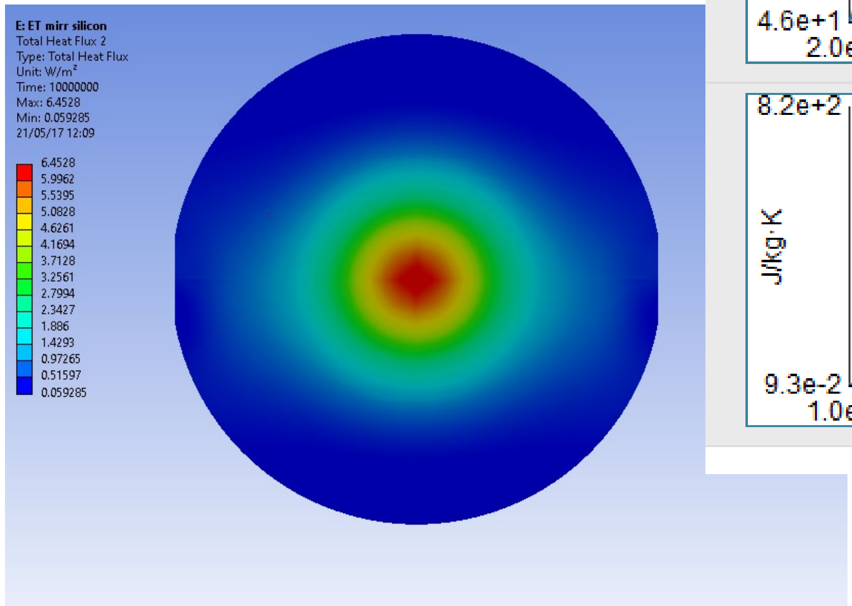
Sapphire Test Mass: 222 kg
Sapphire wires: 2.3 mm diam
Length: 0.8 m + 2* bending point (73 mm)

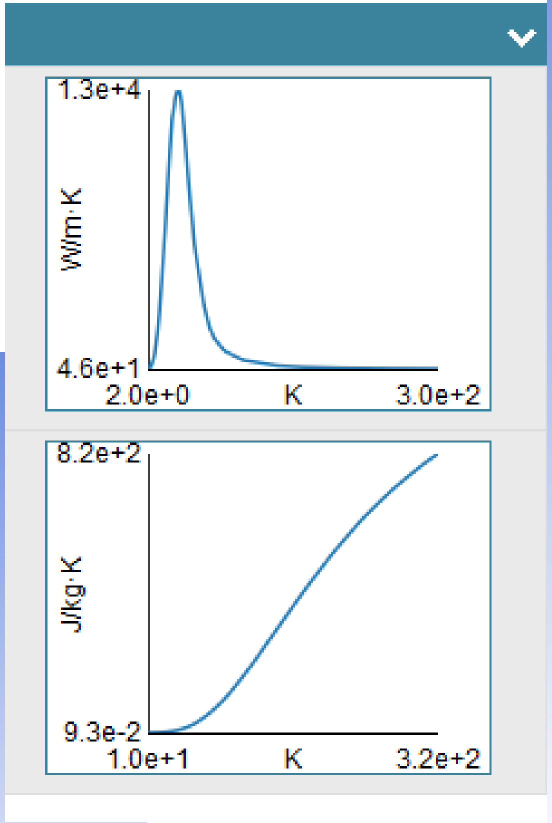
Marionette Wire: Sapphire
Diam 6.4 mm

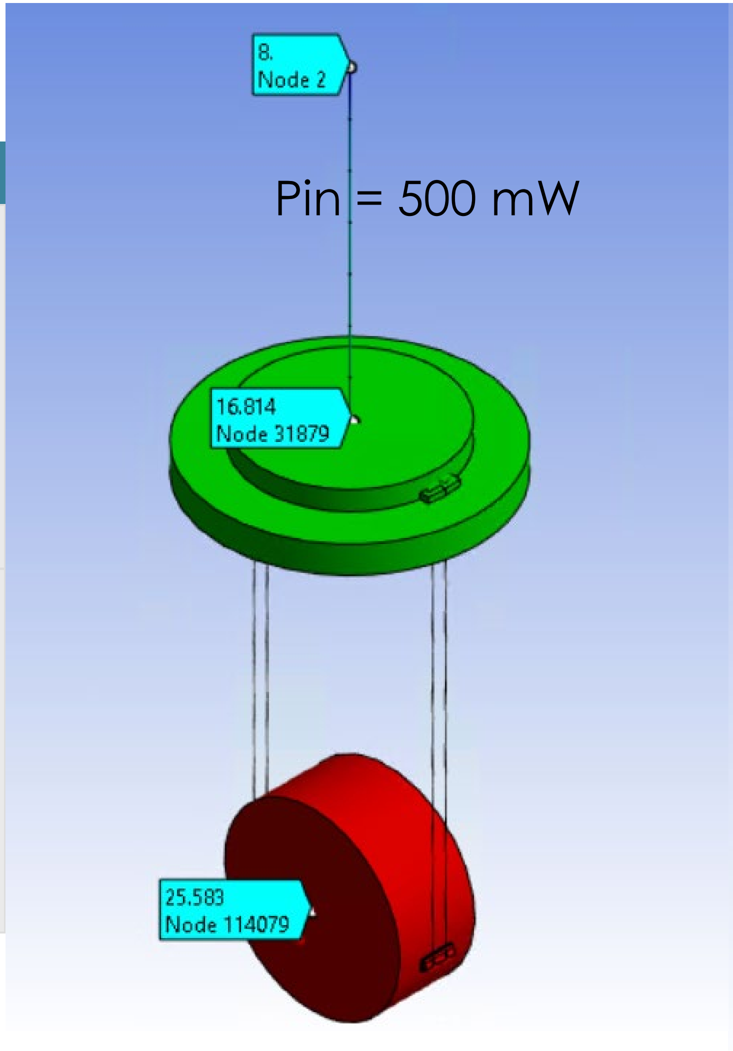
Upper point: 8 K

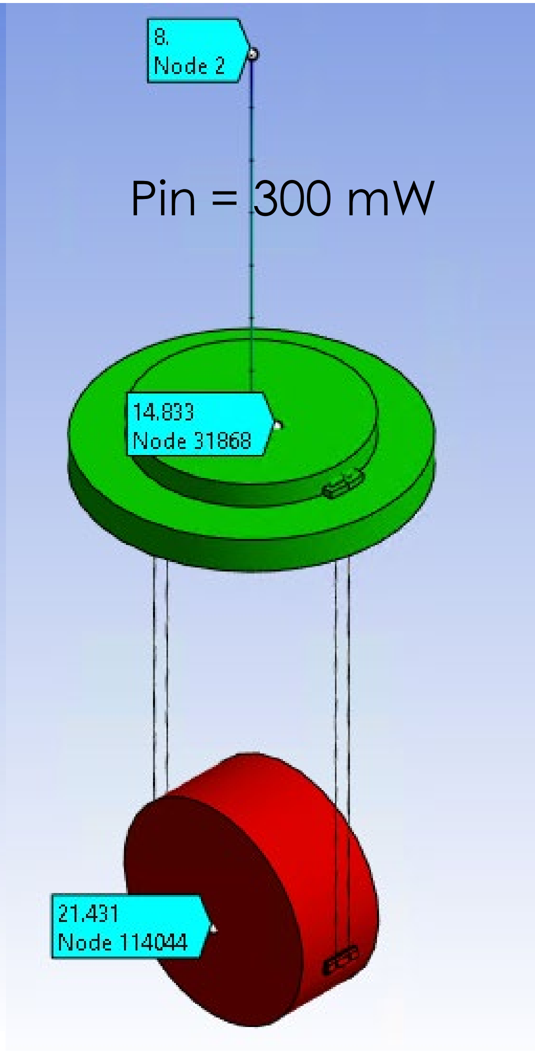
Steady State Thermal for sapphire

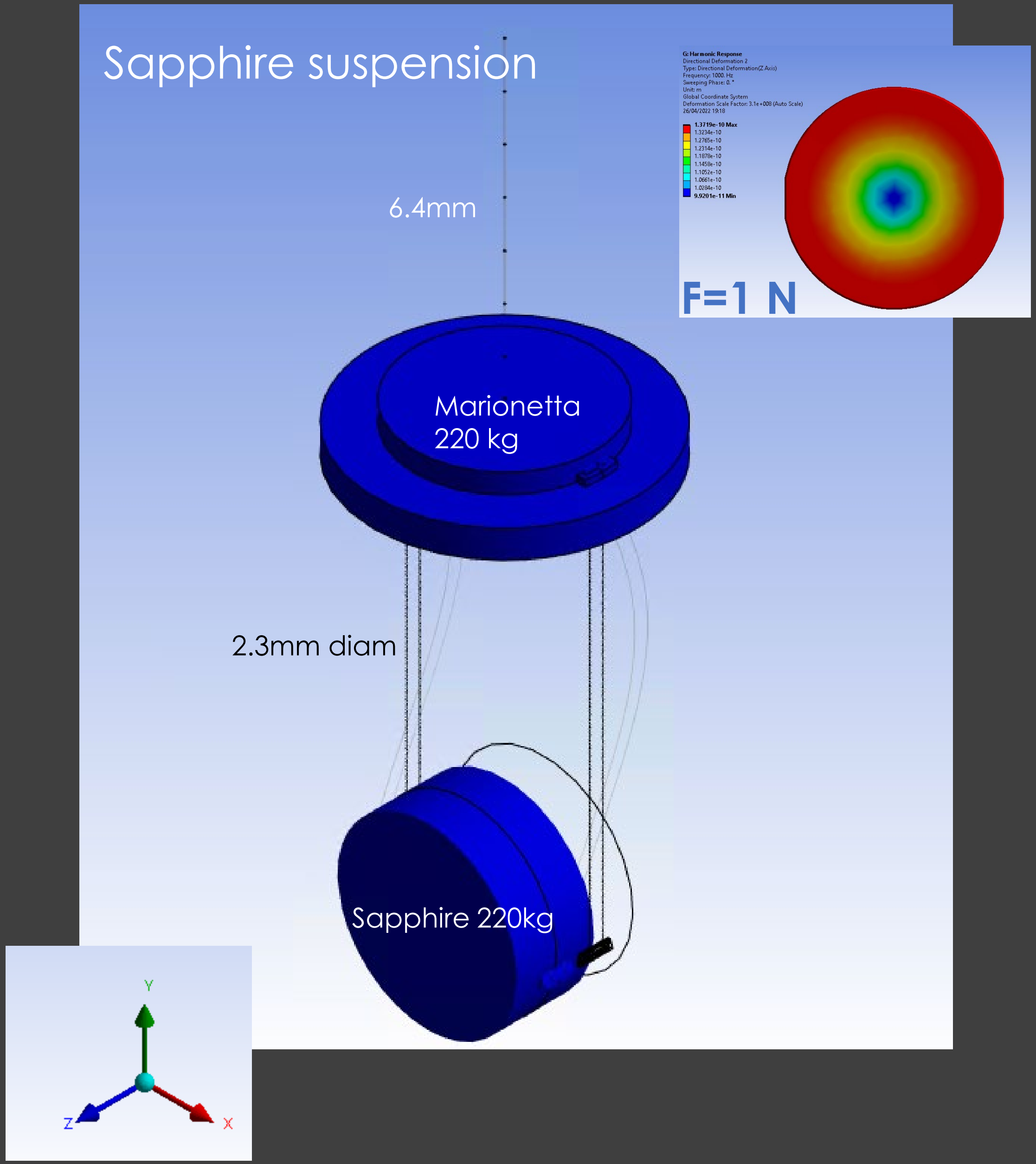
(similar results fo silicon)











Suspension Thermal with FEM

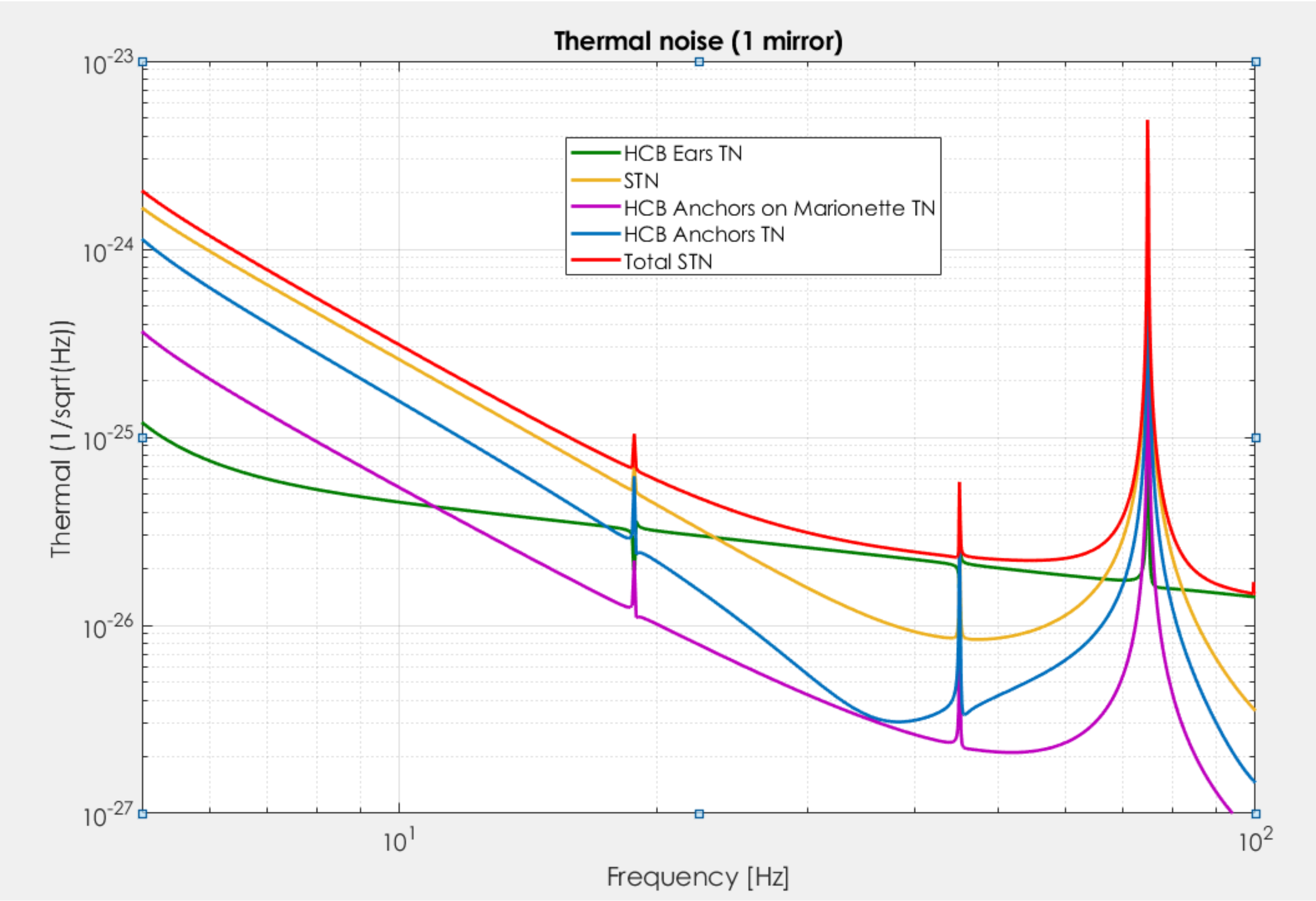
- $S_{Bulks}^{FEM}(\omega) = \frac{4\,k_b T}{\omega\, F_O^2} 2\, \sum_i \phi_i E_i T_i \qquad (T_{mario} \quad T_{mirror}\ .....)$

- $S_{Wires}^{FEM}(\omega) = \frac{4\,k_b T}{\omega\, F_O^2} 2\, \sum_i \phi(T_i, y_i) E_i(y_i) T_i$

  $\phi(T_i, y_i) = \phi_{thermo}\,(T_i, y_i) + \phi_{material} + \phi_{extra}$

$E_i(y_i)$ from Mechanical
$T_i(y_i)$ from Thermal Steady

Pendulum thermal for sapphire suspension (interfaces not optimized)



The TN of the interface on the marionette is reduced.

The link effect is reduced

The interface (anchors and ears are the bottleneck of the STN, the optimization is important)

Pin=300 mW	Sapphire
STN (10^{-25}/sqrt(Hz))	5.0
Ears HCB (10^{-25}/sqrt(Hz))	0.43
Anchors HCB (10^{-25}/sqrt(Hz))	3
Anchors on marionette HCB (10^{-25}/sqrt(Hz))	0.53
Total STN (with/without temperature distributions)	6.0/6.8

Comments and Outlook

• Presented the criteria designing a cryogenic payload

• We use a recursive method dealing with mechanical and thermal requirements in order to obtain a thermal noise compliant with the sensitivity curve;

• We have seen the cooling scheme based on the use of soft heat links cooled with PT cryocoolers and we have shown the parameters for a suspension with cylindrical fibers made of silicon or sapphire;

• With a conservative heat input on the system, the presented schemes are within the requirements for thermal noise and set an acceptable configuration for cryogenic system.

•<u>Close integration between suspension and cryogenics necessary</u>

Second part from Xhesika **Koroveshi**

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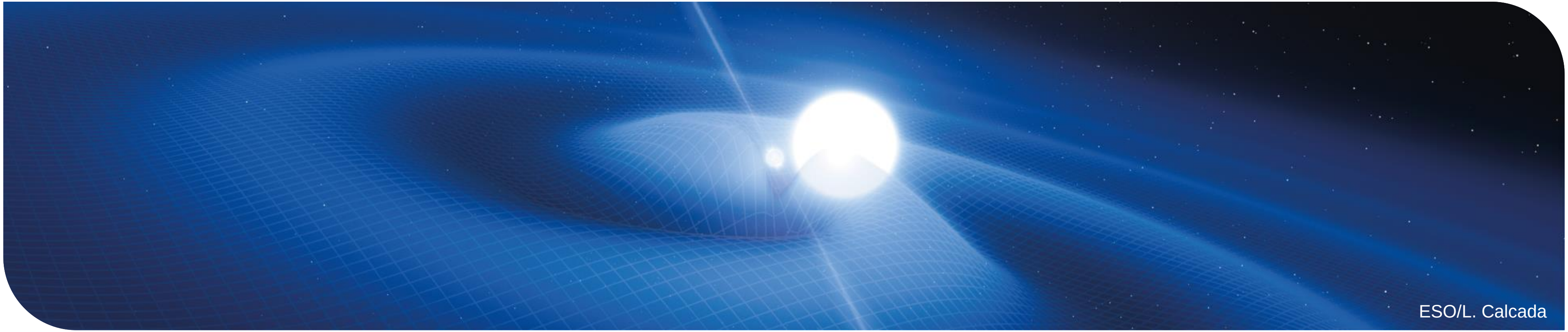
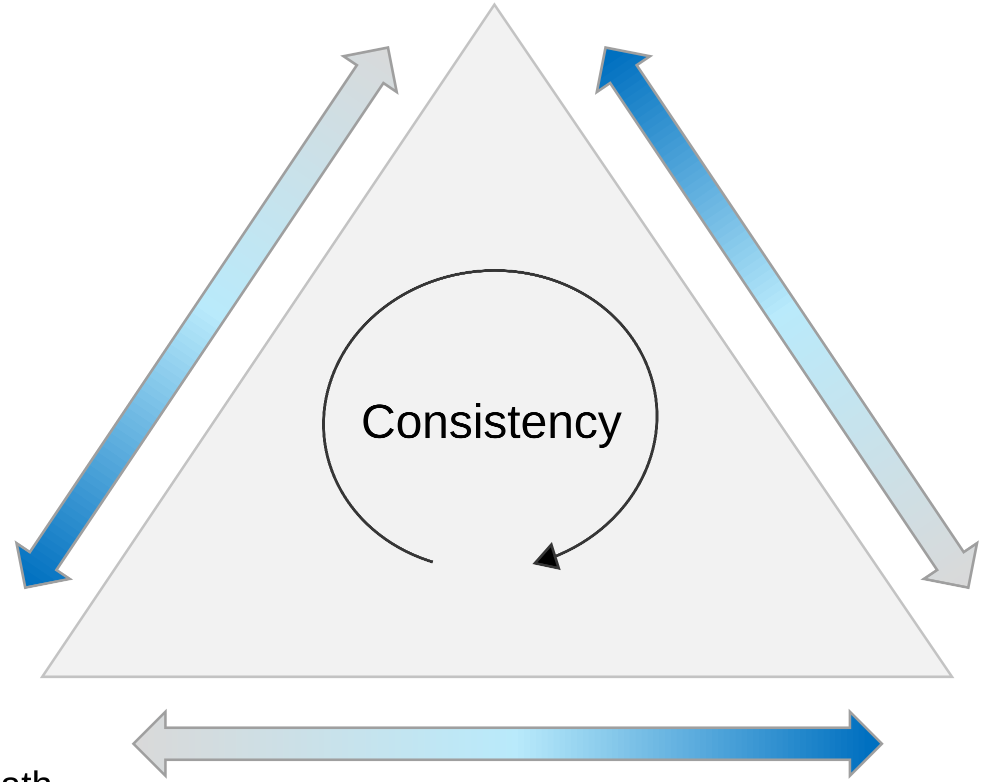
Part II on Update of STN modelling for the cryogenic payload of the ET-LF



Suspension Thermal Noise (STN)

- ET Sensitivity curve



Thermal Design

- Heat extraction path
- Interfaces & Temperatures

Mechanical Design

- Materials
- Dimensions

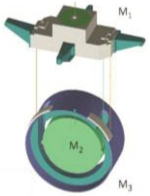
Outline

- Inconsistencies in current ET-LF Payload design
- Cooling concepts
- Impact of Test mass suspension design on STN
- Impact of Marionette suspenion design on STN
- Summary of updated Payload design parameters

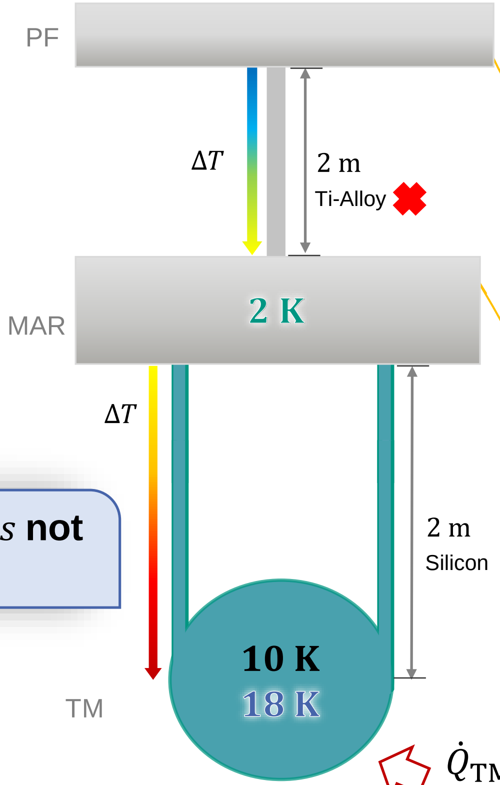
Inconsistencies in Current ET-LF Payload Design

ET-LF Payload

	Marionetta	Recoil Mass	Mirror
Masses for ETDLF (kg)	422	211	211
Wire Diameter (mm)	3	3	3
Wire length (m)	2	2	2
Wire Material	Ti6Al4V	Silicon	Silicon
Loss Angle	10^{-5}	10^{-8}	10^{-8}
Temperature (K)	2	10	10



Source: ET Design Report (2011)



Heatlink on PF

- Cooling interface on PF completely ineffective due to Ti-Alloy fiber [2]
- Consideration of $\Delta T s$ in fibers

How? $T_{\mathrm{MAR}} = 10\ \mathrm{K}$ with heatlink connection to heatsink?

- No! → Heatlink on MAR not possible due to STN, cooling interface muss be on PF [1]

Heatlink on MAR

Interface temperatures and $\Delta T s$ not yet consistently implemented

$\dot{Q}_{\mathrm{TM,total}} = 0.1\ \mathrm{W}$ ✖
$\dot{Q}_{\mathrm{TM,total}} = 0.5\ \mathrm{W}$

Conservative value due to size and complexity of ET-LF cryostat

[1] P.Puppo (2022) - ET-D: FEA models for the ET Payload: status and preliminary results
[2] L.Busch (2022) - ET-D: Payload cooldown studies

Conclusions I

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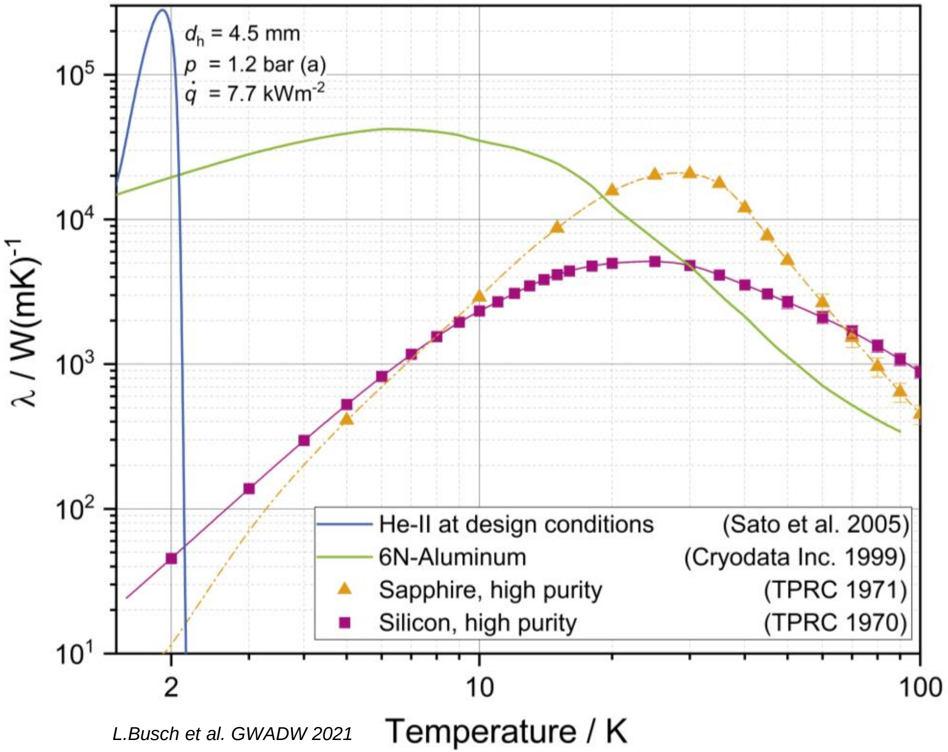
- $\dot{Q}_{\mathrm{TM,total}} = 0.5\ \mathrm{W}$ as conservative value due to size and complexity of ET-LF cryostat
- T_{TM} defined from $\dot{Q}_{\mathrm{TM,total}}$ and T_{MAR}
- T_{MAR} dependant on cooling concept, $2\ \mathrm{K}$ not achievable via solid conduction cooling
- Cooling interface should be implemeted on the platform (PF) due to STN
- Heat extraction path for ET-LF payload to be described correctly

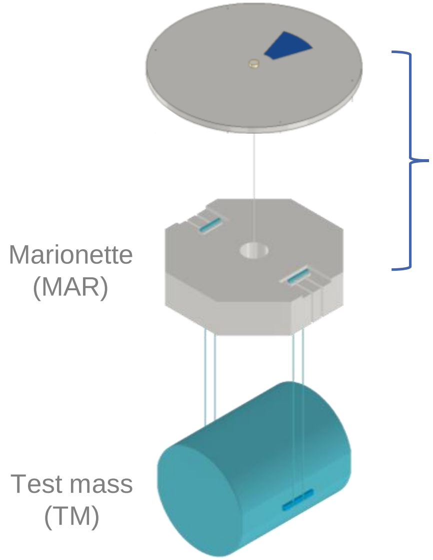
ET-LF payload cooling concepts

Thermal conductivity



L.Busch et al. GWADW 2021

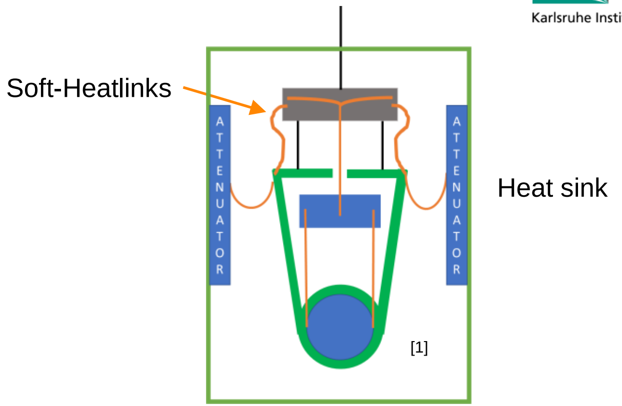
Cooling interface on platform



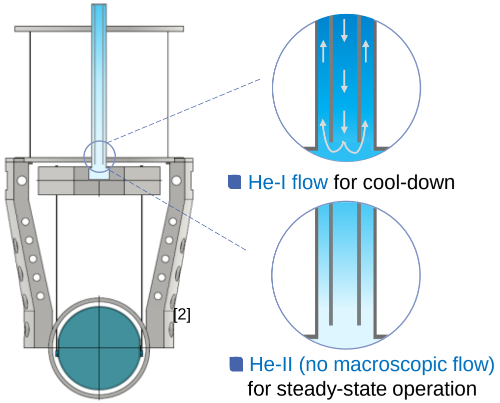
Thermal conductivity of Marionette suspension crucial for cooling!

ET-LF Payload Cooling concepts

- <u>Detector cooling with PT cryocoolers</u>
  - **Sapphire or silicon** marionette suspension fiber
  - Cooling interface: Soft-Heatlinks
  - $T_{\mathrm{MAR}} \approx 14 - 20\ \mathrm{K}$
  - R&D @ INFN Roma



- <u>Detector cooling with superfluid He-II</u>
  - **He-II-filled** marionette suspension tube
  - Cooling interface: He-supply capillaries
  - $T_{\mathrm{MAR}} \approx 2\ \mathrm{K}$
  - R&D @ Karlsruhe Instiute of Technology



[1] P.Puppo (2022) - FEA models for the ET Payload: status and preliminary results
[2] X. Koroveshi (2022) - Feasibility of He-II suspensions based on thermal noise modelling

STN modelling

Impact of Test mass suspensions

Test mass suspension

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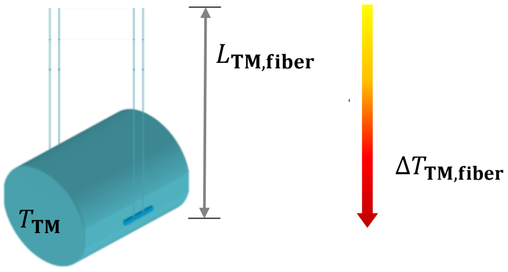
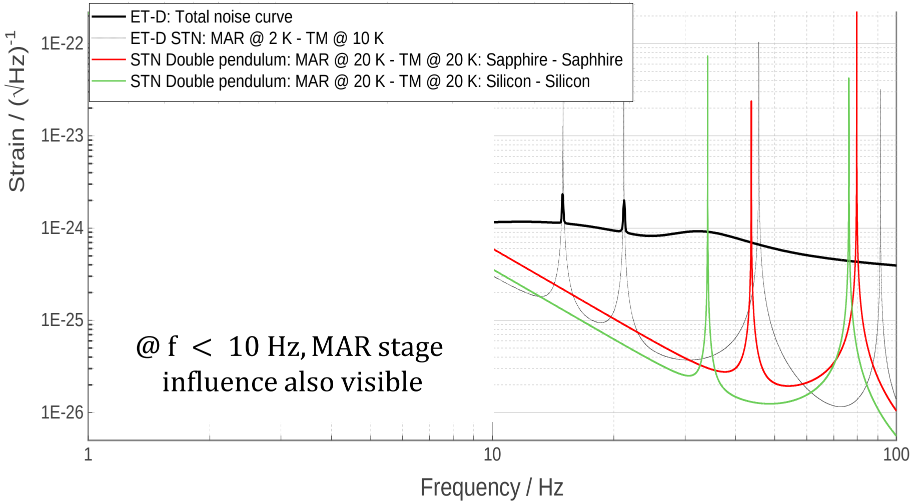
- Material choice: <u>Sapphire or Silicon</u>



$L_{\mathrm{TM,fiber}}$	$d_{\mathrm{TM,fiber}}$
STN @ LF : $L \uparrow$	Mechanical structure $(SF = 3)$: $d \uparrow$
Manifacture of fibers : $L \downarrow$	STN @ LF : $d \downarrow$
$\Delta T_{\mathrm{TM,fiber}}$: $L \downarrow$	Efficient heat extraction : $d \uparrow$
Reduced cryostat height : $L \downarrow$	

Possible parameters for mirror suspensions:

- ✓ $T_{\mathrm{TM}} = 14 - \mathbf{20\ K} = f(\dot{Q}_{\mathrm{TM,total}}, \text{cooling concept})$
- ✓ $M_{\mathrm{TM}} = 211 - 220\ \mathrm{kg}$
- ✓ $L_{\mathrm{TM,fiber}} = \mathbf{1.2\ m}$
- ✓ $d_{\mathrm{TM,fiber}} = \mathbf{2.3\ or\ 3.0\ mm}$



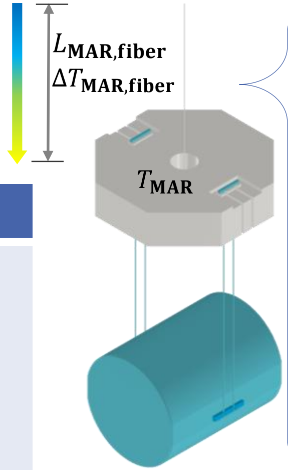
STN modelling

Impact of Marionette suspension

Marionette suspension

- <u>Possible design</u> based on **cooling concept**:
  - Sapphire or silicon fiber ($T_{\mathrm{MAR}} \approx 20$ K)
  - He-filled suspension tube ($T_{\mathrm{MAR}} \approx 2$ K)

$L_{\mathbf{MAR,fiber}}$	$d_{\mathbf{MAR,fiber}}$
STN @ LF : $L \uparrow$	Mechanical structure ($SF = 3$) : $d \uparrow$
Manifacture of fibers : $L \downarrow$	STN @ LF : $d \downarrow$
$\Delta T_{\mathrm{MAR,fiber}}$: $L \downarrow$	Efficient heat extraction : $d \uparrow$
Reduced cryostat height : $L \downarrow$	

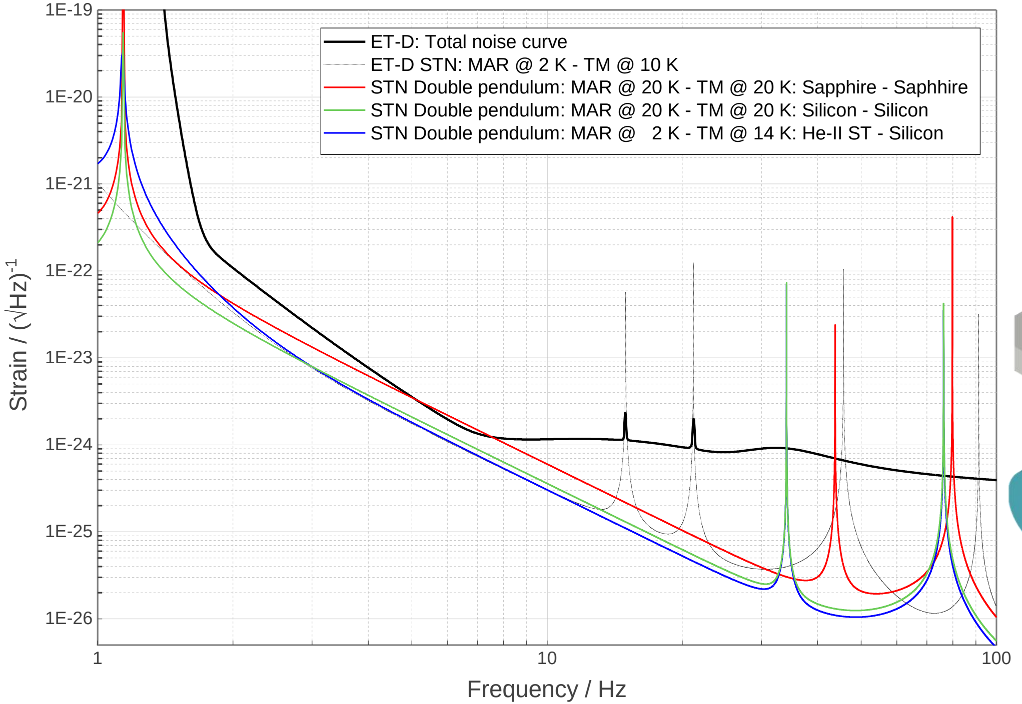


Sapphire or Silicon marionette fiber:
- ✓ T_{MAR} @ 20 K ($\Delta T_{\mathbf{fibers}}$ **to be implemented**)
- ✓ $M_{\mathrm{MAR}} = 100 - 110$ kg
- ✓ $L_{\mathrm{MAR,fiber}} = 1.0$ m
- ✓ $d_{\mathrm{MAR,fiber}} = 5.6$ or 7.0 mm

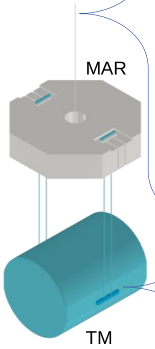
He-II-filled marionette suspension tube:
- ✓ T_{MAR} @ 2 K
- ✓ $M_{\mathrm{MAR}} = 100 - 110$ kg
- ✓ $L_{\mathbf{MAR,fiber}} = 1.0$ m
- ✓ $d_o = 8.3$ mm, $d_i = 4.1$ mm, $s_o = 0.25$ mm

STN with updated ET-LF payload parameters

Karlsruhe Institute of Technology



Possible ET-LF suspension design parameters



Concept: Sapphire or Silicon marionette fiber:

- ✓ T_{MAR} @ 20 K (ΔT_{fibers} to be implemented)
- ✓ $L_{MAR,fiber} = 1.0$ m
- ✓ $d_{MAR,fiber} = 5.6$ or 7.0 mm
- ✓ $M_{MAR} = 100 - 110$ kg

Concept: He-II-filled marionette suspension tube:

- ✓ T_{MAR} @ 2 K
- ✓ $L_{MAR,fiber} = 1.0$ m
- ✓ $d_o = 8.3$ mm, $d_i = 4.1$ mm, $s_o = 0.25$ mm
- ✓ $M_{MAR} = 100 - 110$ kg

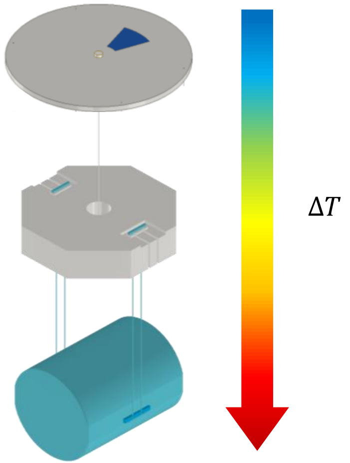
Mirror/Test mass suspensions:

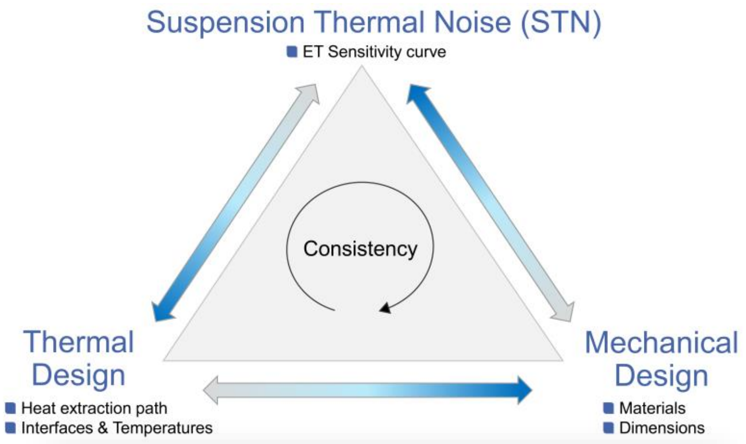
- ✓ Sapphire or silicon
- ✓ $T_{TM} = 14 - 20$ K $= f(\dot{Q}_{TM,total}$, cooling concept)
- ✓ $L_{TM,fiber} = 1.2$ m
- ✓ $d_{TM,fiber} = 2.3$ or 3.0 mm
- ✓ $M_{TM} = 200 - 220$ kg

Conclusions & Outlook

- Two concepts for marionette suspension based on cooling concept
- One concept for mirror suspension

- Implementation of heat extraction path with corresponding temperatures in STN model essential:
  - Heat sink
    - $\Delta T_{\text{thermal links}}$
  - Platform
    - $\Delta T_{\text{MAR suspension}}$
  - Marionette
    - $\Delta T_{\text{TM suspension}}$
  - Mirror





- Implementation of conservative loss angles

To be updated in each design iteration

Thank you for your attention

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