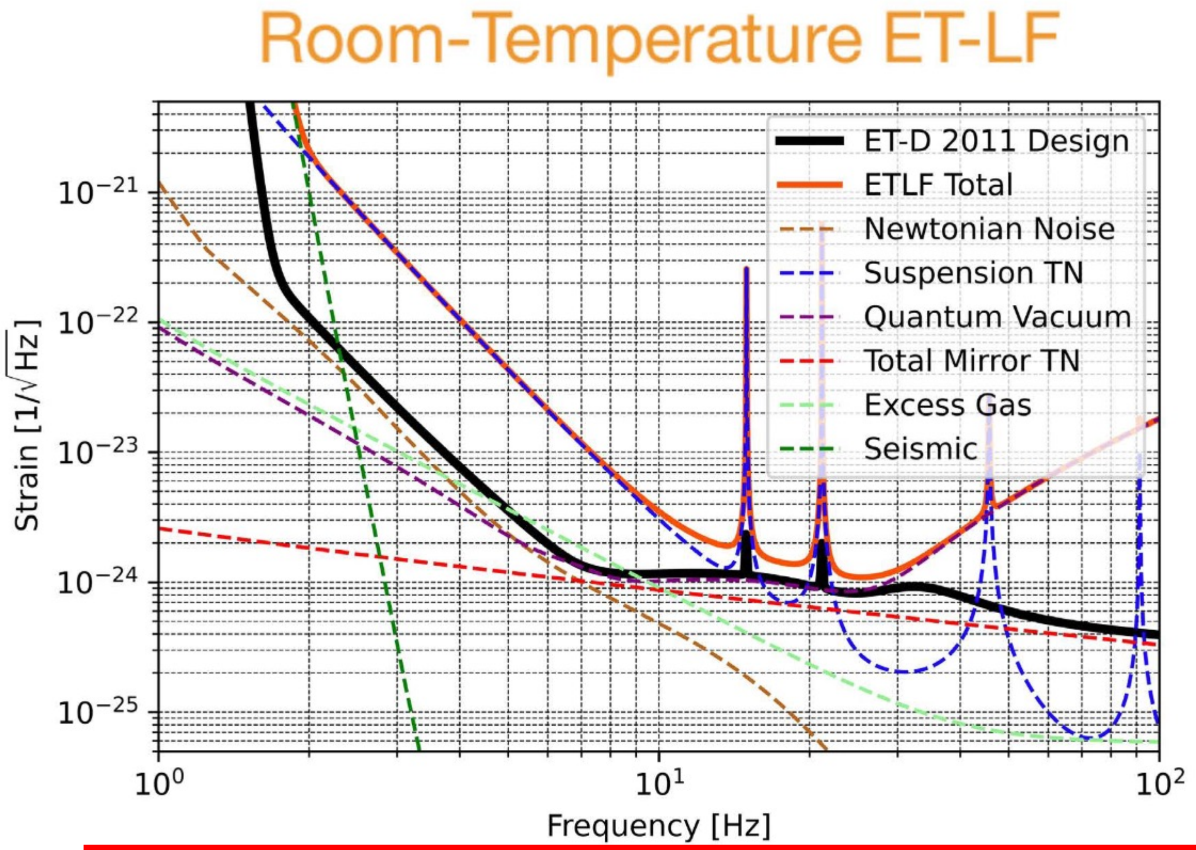
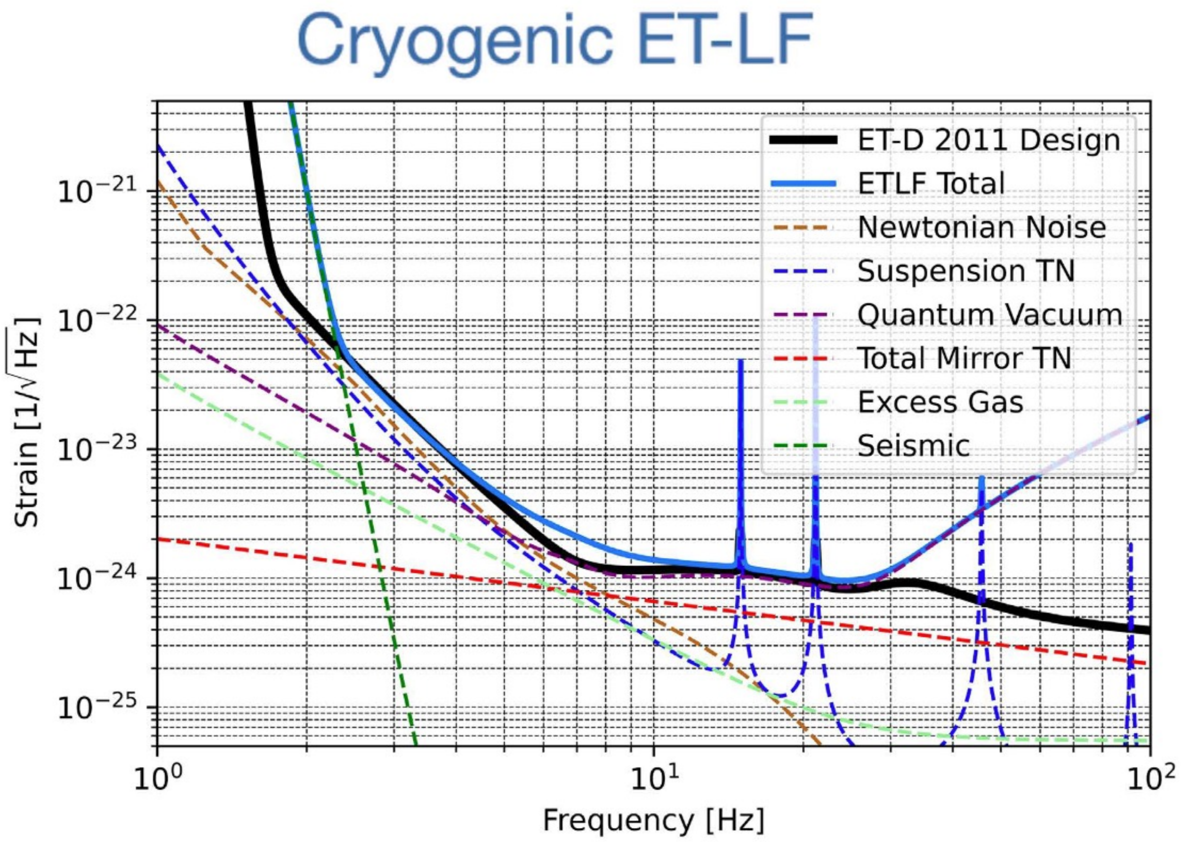
Cryogenis for ET

and the need for an integrated test of ET-LF experimental configuration

Fulvio Ricci

Cooling is better: Cryogenics for ET



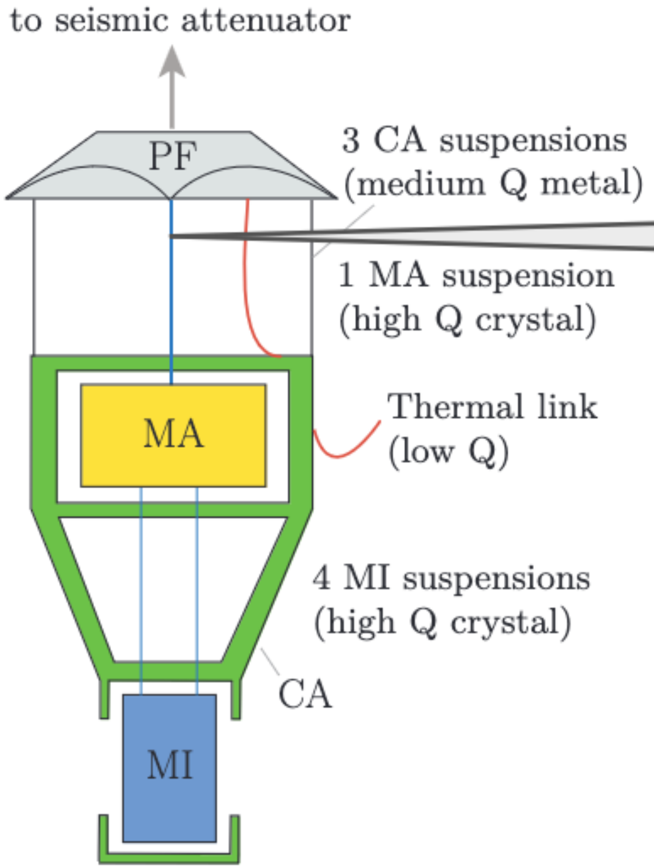


Two types of advantages emerge from cooling at very low temperature, one based on macroscopic quantum effect, namely superconductivity and superfluidity, and the other based on the general reduction of the k T thermal noise, thermal expansion, thermal electromotive force, creep, etc...

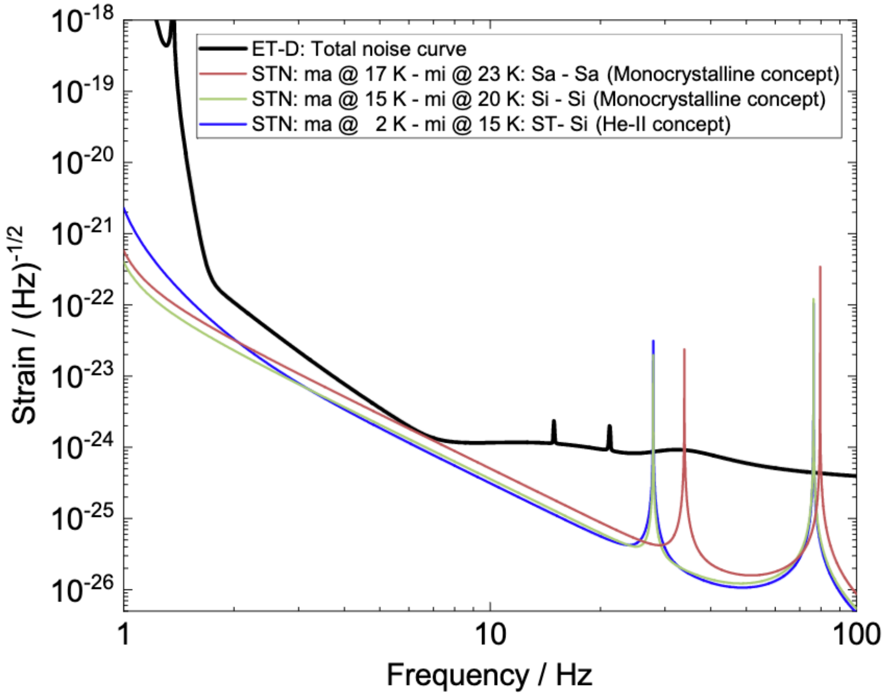
(W. M. Fairbank *The Use of Low Temperature Technology in Gravitaitonal Experimennts*, in Exprimental Gravitation , Proceedings of the International School of Physics "E. Fermi" – 1972 , LVI course B. Bertotti editor,)

Mirror cooling: two configurations under study

The robust solution ➔ R&D in Roma Sapienza…



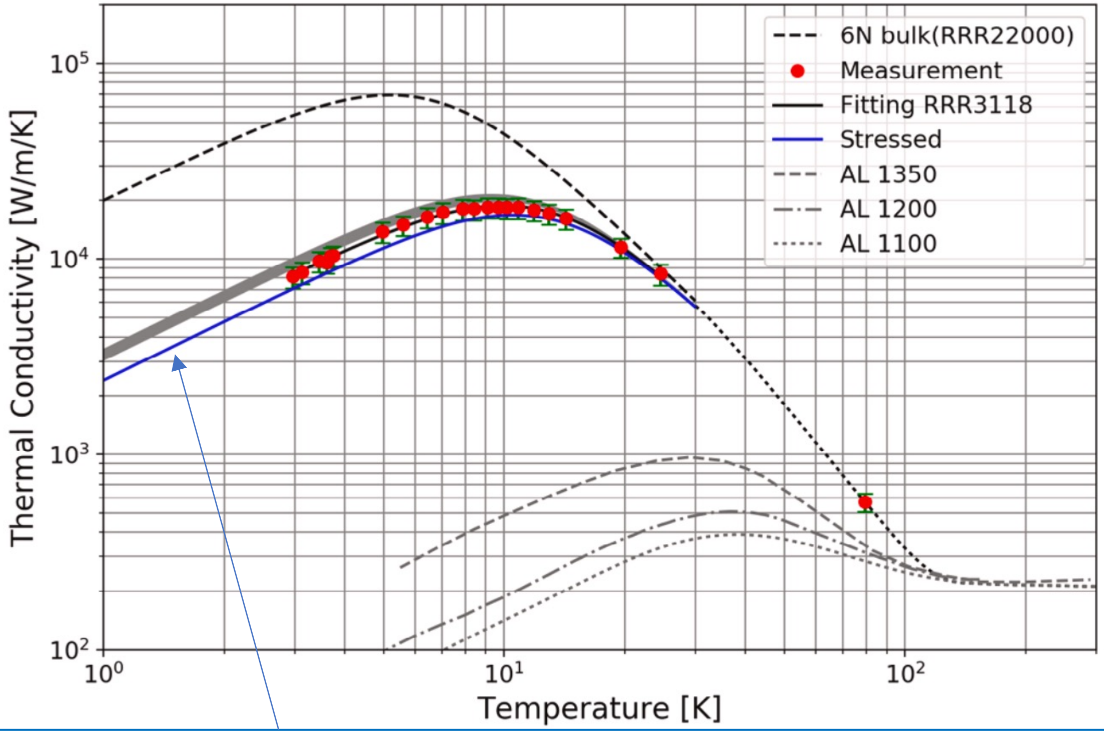
Monocrystalline
MA suspension
(silicon or sapphire)



KAGRA lesson

Tomohiro Yamada Et al. *High performance thermal link with small spring constant for cryogenic applications,* Cryogenics Volume 116, June 2021, 103280

Stress changes the thermal conductivity



The blue line is an estimated thermal conductivity curve for the case of deformation given by wrapping around a cylinder 10 cm diameter .

Smaller spring constant k reduce overall vibration transfer.

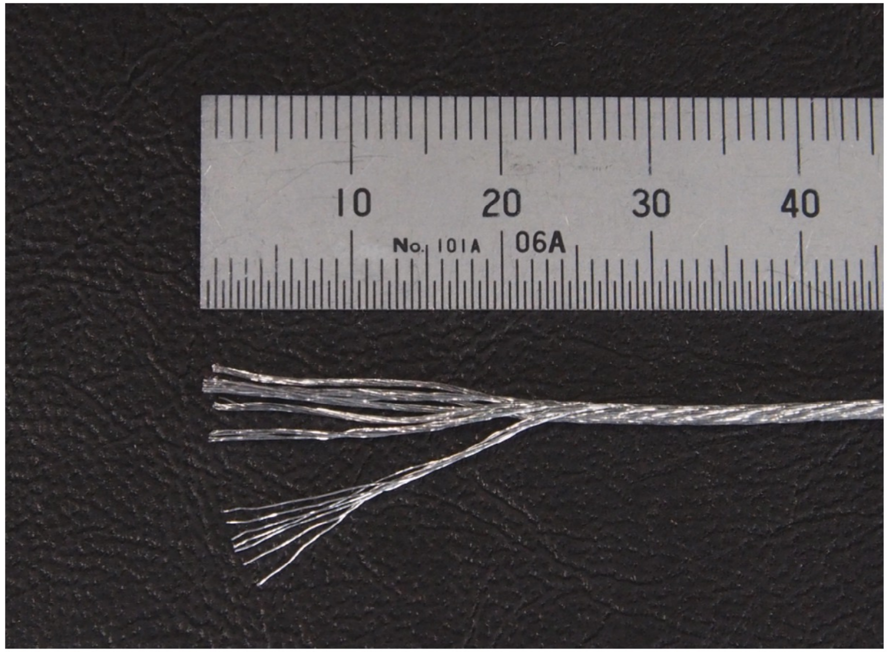
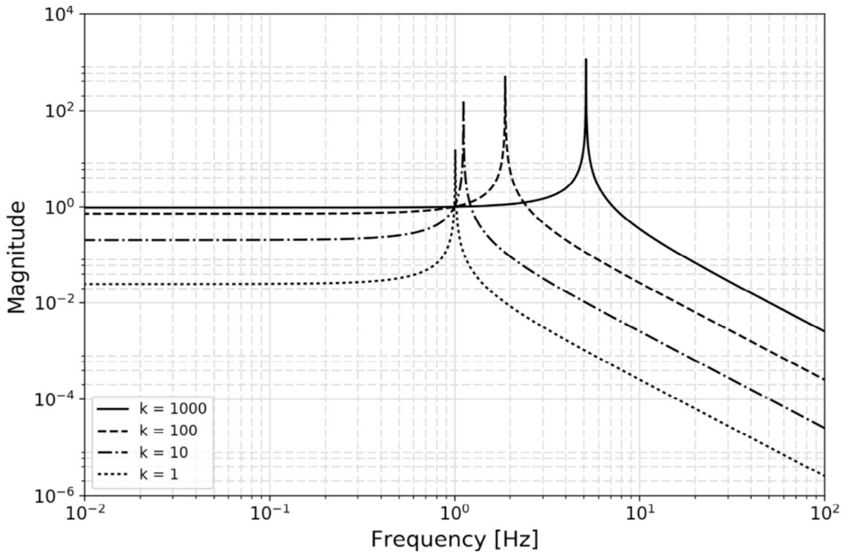
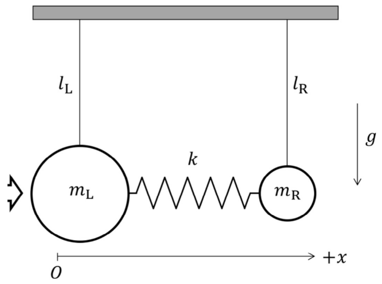


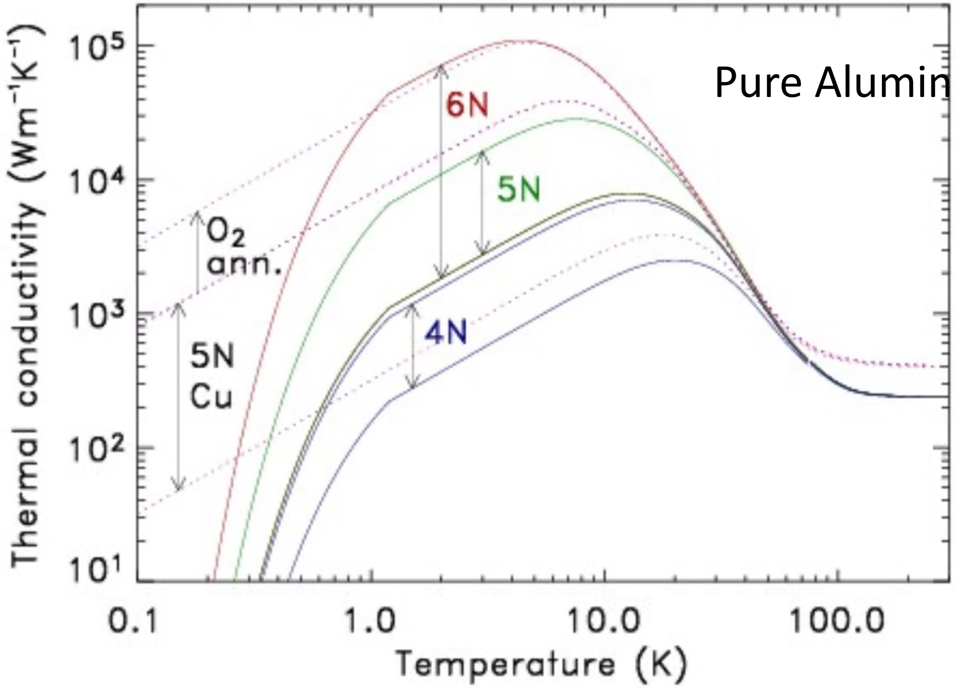
Fig. 1. Details of the developed thermal link. Outer diameter of the strand approximately 1 mm. Left tip is loosened to show details.



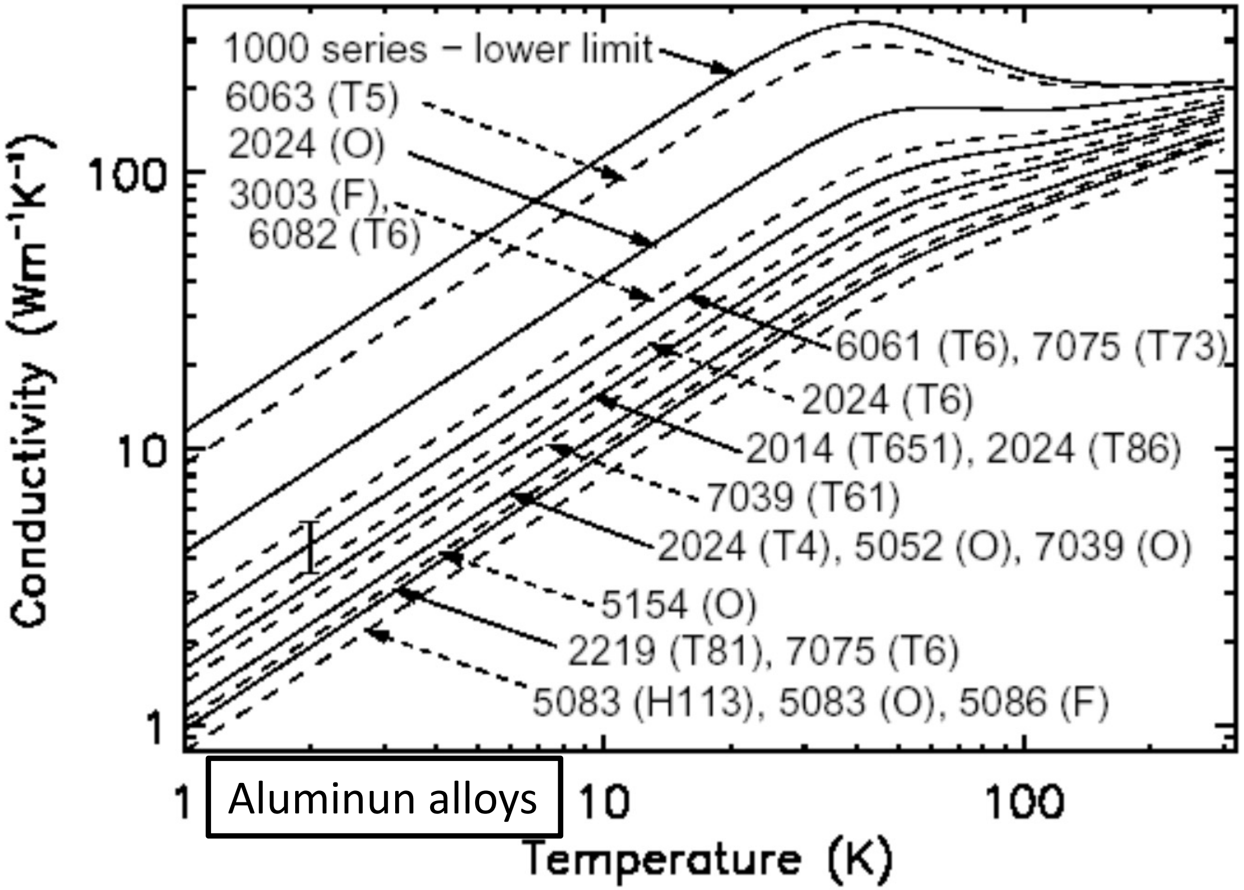


Thermal conductivity for cryo shields and thermal links

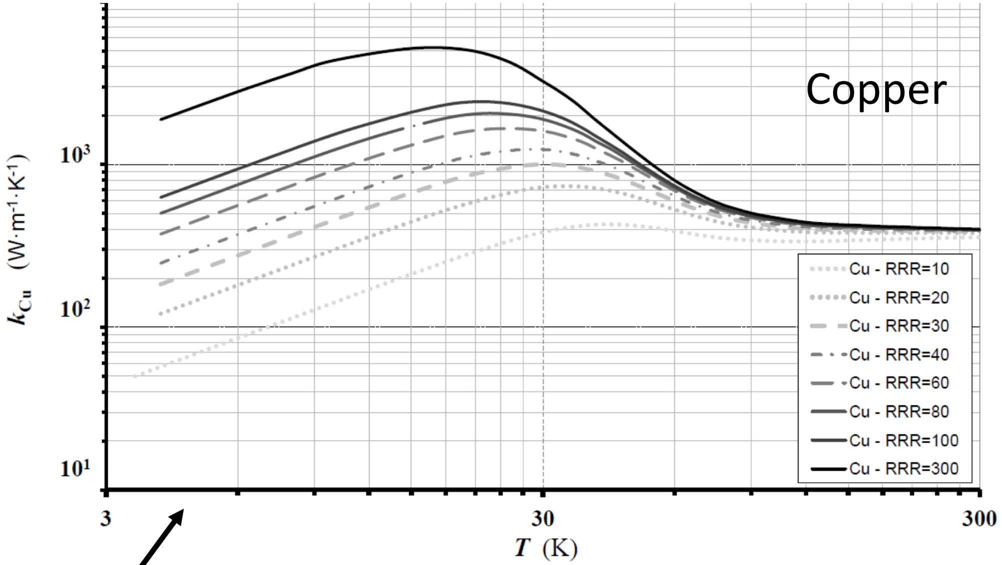
http://reference.lowtemp.org/alkappa.html



Pure Aluminun



Aluminun alloys

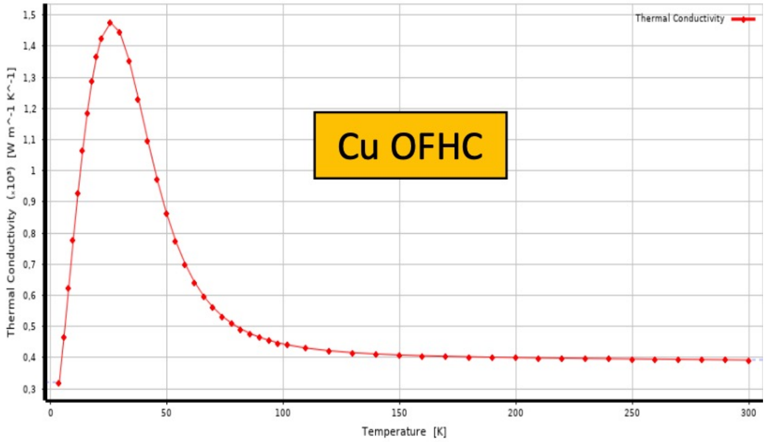
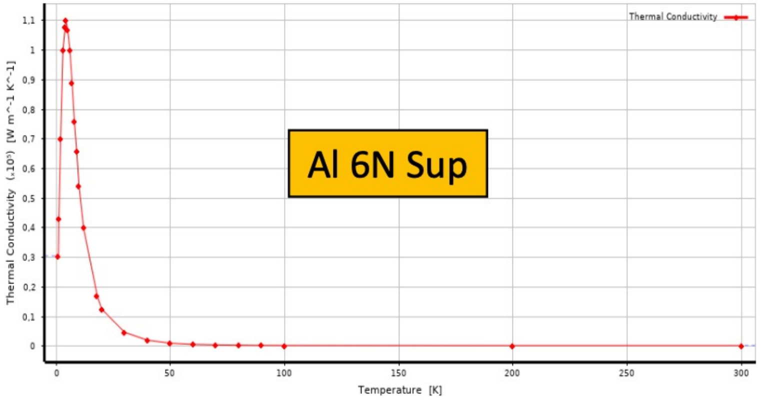


Copper

https://cds.cern.ch/record/1973682/files/arXiv:1501.07100.pdf

R&D on thermal links

ET-0375A-23 - *Progress at the Amaldi Research Center in Rome*

	Target Temperature	Design	Thermal Conductivity
1 stage	~ 60 – 80K		
2 stage	~ 4 – 10K	FOUR9 DESIGN ultRRRaSTRAPS 	

Few numbers to keep in mind

Pulse Tube refrigerators. Examples of nominal performances - CRYOMEC

PT407 - 0.7 W@4.2 K -- 25 W @55K
+ compr. CPA 2870 ➔ 7 kW
PT410 - 1.0 W@ 4.2 K -- 40 W @ 45 K
+ compr. CPA 289 C ➔ 7.9 kW
PT420 – 2W@ 4.2k – 55 W @45 K
+ compr. CPA1114 – 11.4 kW
PT425 – 2.7W@4.2 K – 55W@45 K
+ compr. CPA1114 ➔12kW
PT450 -- 5 W @ 4.2K – 65 W@ 45 K
+ compr. CPA3027 ➔ 25 kW

COP_r ~ 10^{-4}@4 K ➔ ~ 3 x10^{-3}@50K
(COP_r - Coefficient Of Performance$_{\text{refrigeration}}$)

Thermal input per unit surface due to radiation: the order of magnitude

$$(1/S)\, dQ/dt \simeq \varepsilon\, \sigma\, (T_a^{\,4} - T_b^{\,4})$$
$$\sim 0.2 \times 5.68 \times 10^{-8}\, (T_a^{\,4} - T_b^{\,4}) \quad \mathrm{W\ K^4/m^2}$$

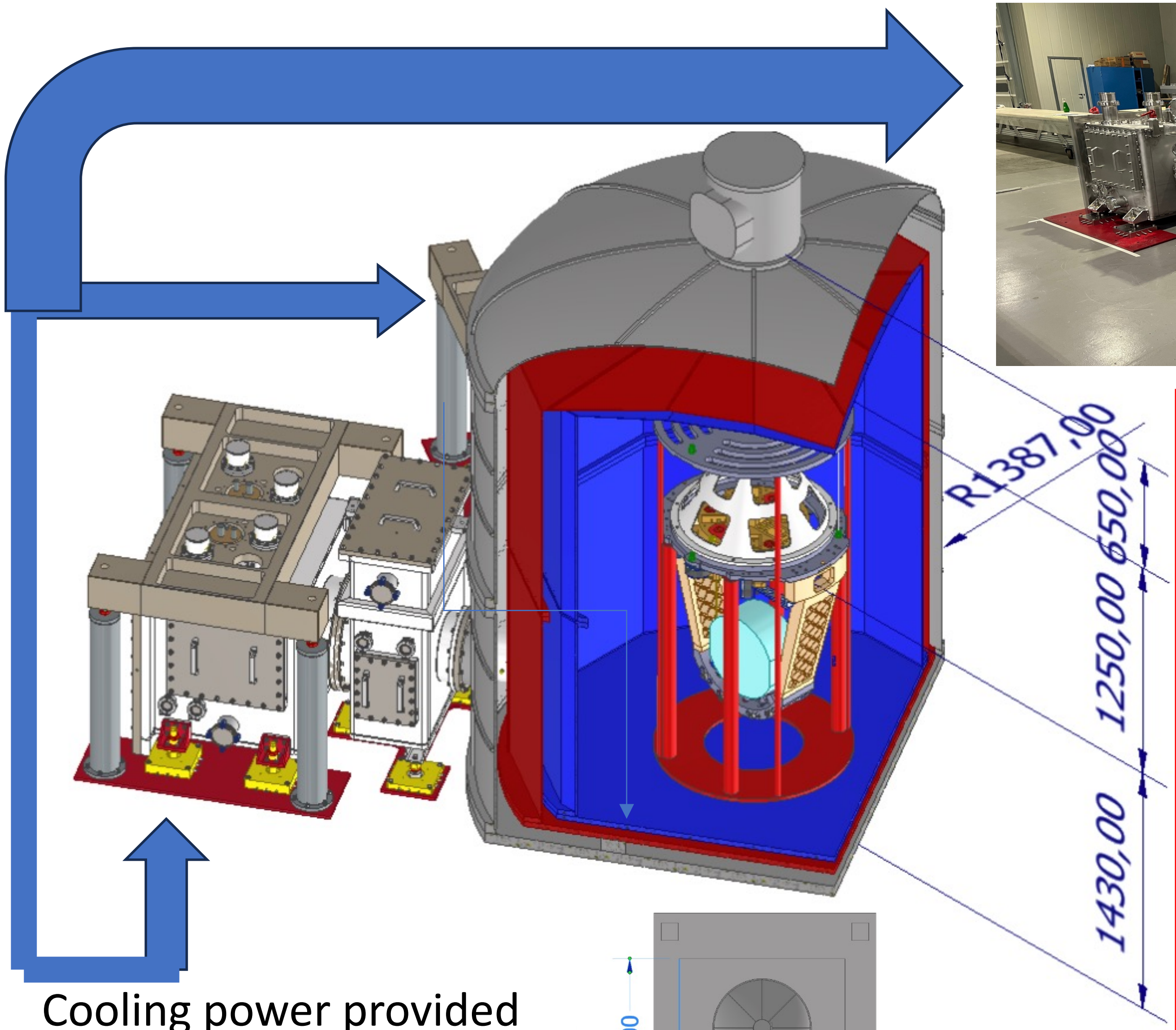
T_a =300 K *T_b= 50 K*

(1/S) dQ/dt ~ 100 W/m² (ε =0.2)

First thermal shield ➔ S ≳ 50 m²
We should provided a refrigeration power of ~ 5 kW
(electric power in the cavern of ~1.7 MW)

Standard solutions
- *Super-insulation ➔ High risk of pollution*
- *Liquid Nitrogen ➔ safety issues in cavern*
- *Enthalpy of the cold helium gas*

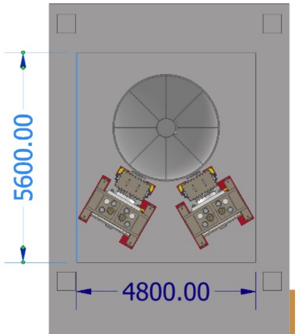
R&D in Rome: C75 cryostat to test the payload



E. Majorana, F. Van Long Hoang, E.Benedetti, V. Mangano, M. Ricci

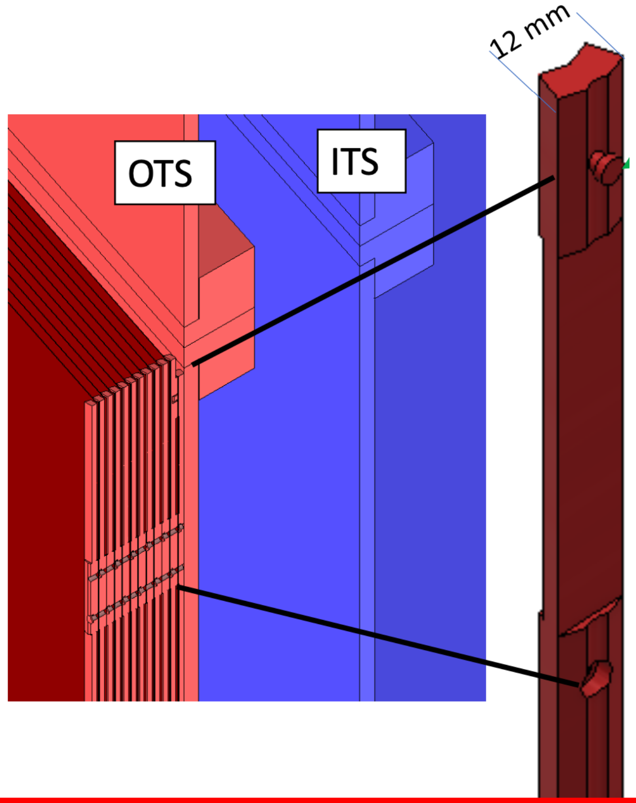
ET-0356A-23

Cooling power provided by 2 refrigeration lines
- 2 PTs for the cryostat
- 2 PTs for the payload



Cryostat Superinsulation–Rigid Multi Layer

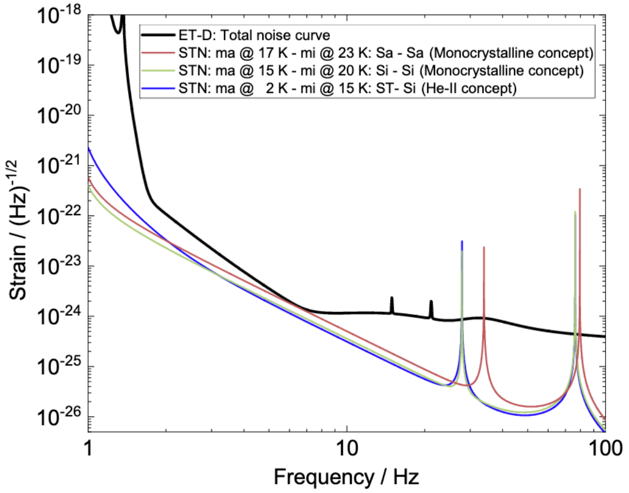
- *Multiple low emissivity aluminum foils* supported by *insulating rods* at each corner ($n_{layers} > 15$).
- Distance between each foil 4 mm



Mirror cooling: two configurations under study

Quantum fluid payload ➔ R&D at Karlsruhe Inst. Tech. - KIT

$$\vec{v}_{nor} + \vec{v}_{super} = \vec{0}$$

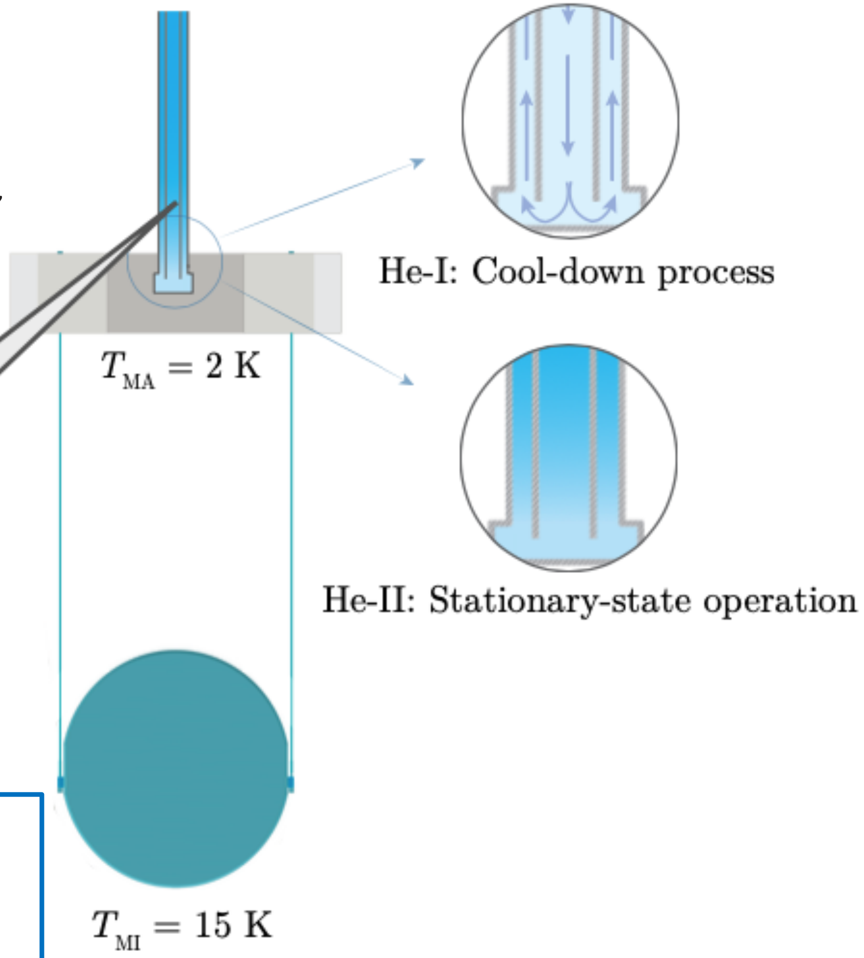


- L. Landau, Theory of the superfluidity of helium II, Phys. Rev. 60, 356 (1941).

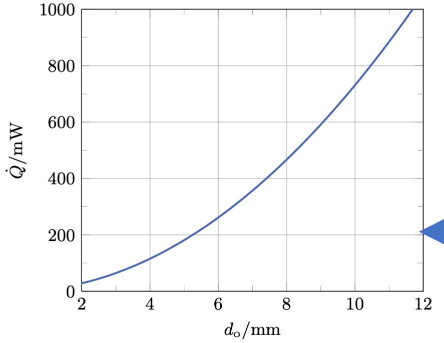
- S. W. Van Sciver, Helium Cryogenics, 2nd ed., International Cryogenics Monograph Series (Springer, New York, NY, 2012)

- P. Puppo and F. Ricci, Cryogenics and Einstein telescope, Gen. Relativ. Gravit. 43, 657 (2011)

- X. Koroveshi et al. Physical Review D 108.123009



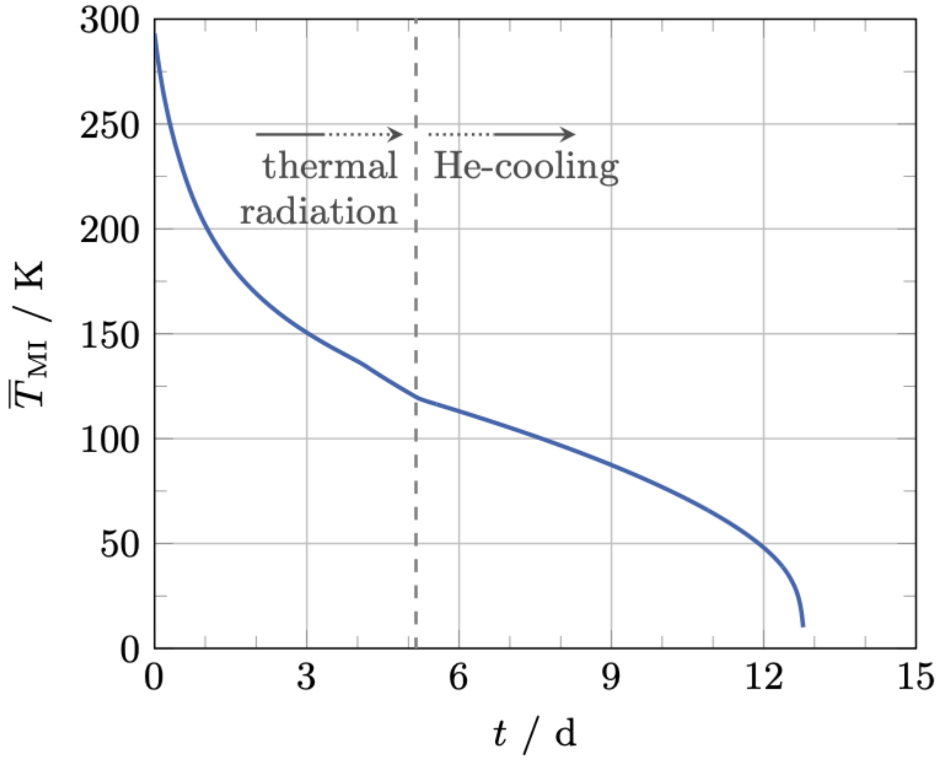
He-II filled MA suspension tube (titanium)



Cooling capacity of the He-II suspension as function of the outer tube diameter.

R&D in Karlsrhue: quantum fluid payload

Cooling time drastically reduced
Lower termal gradients



Open points to be studied on a dedicated R&D:
- payload control (tube stiffeness too high)
- sound transmission via fluid
- residual losses in the normal component of HeII fluid at T≠ 0
- residual dissipation of the metallic tube
- killing vortex formaton in the He II

TABLE IV. Suspension tube design parameters.

Parameter	Value
L_{ma}	1.0 m
M_{MA}	200 kg
M_{MI}	200 kg
Constraints:	
Mechanical SF	3.0
$T(y = L_{ma})$	1.9 K
$p_{He\text{-}II,in}$	1.2 bar(a)
ΔT_{ma}	50 mK
$\dot{Q}$	0.5 W
Design results:	
d_o	8.30 mm
s_o	0.36 mm
d_i	5.80 mm
s_i	0.05 mm

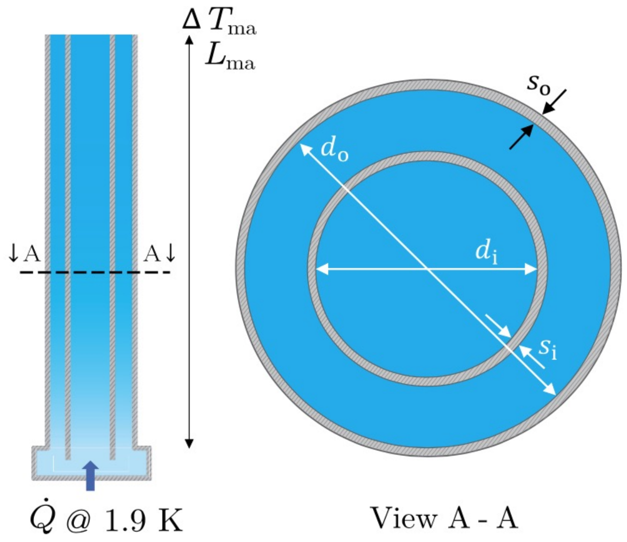
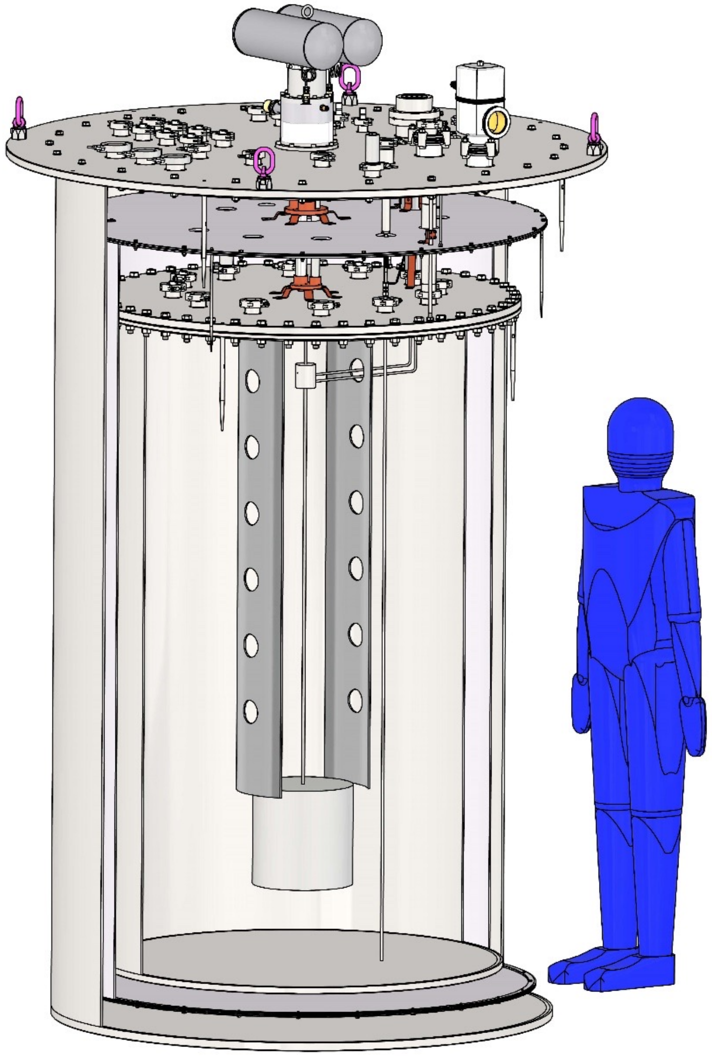


FIG. 8. Suspension tube design.

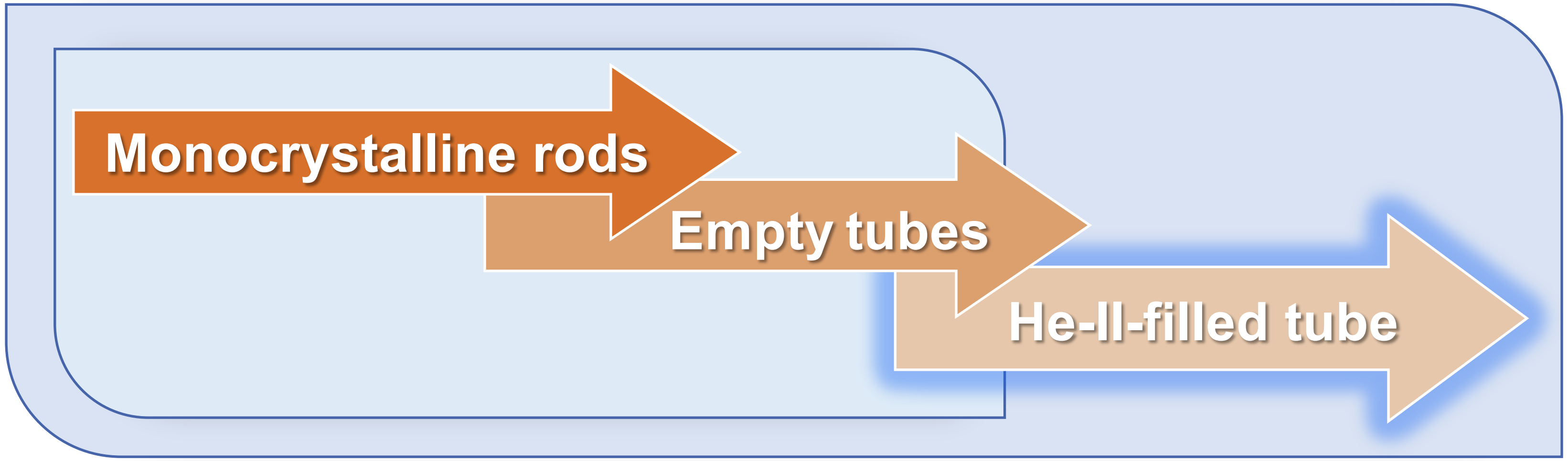
See X. Koroveshi et al. Physical Review D 108.123009

Test facility for cryogenic suspension studies for the Einstein Telescope

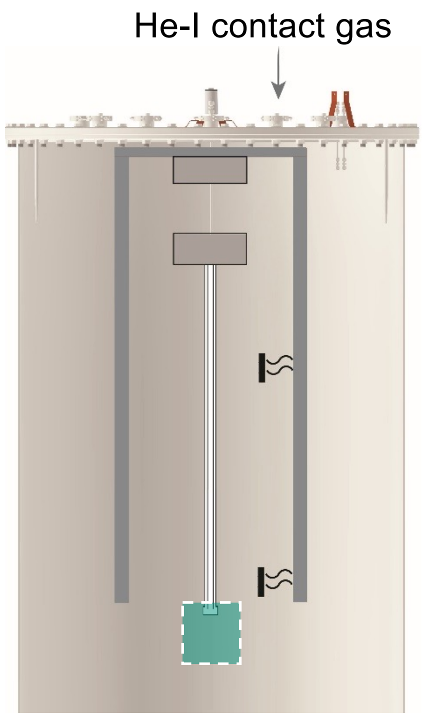
Karlsruher Institut für Technologie



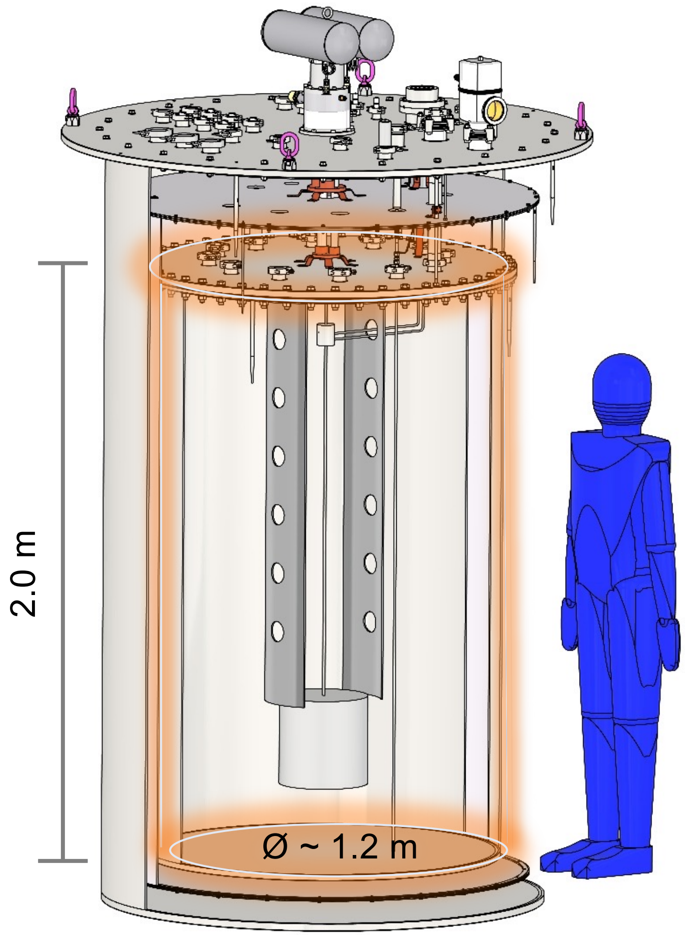
- Gravitational wave detectors cooled with superfluid helium
- <u>Q measurement test facility for:</u>
  - Full-size suspension fibers/rods and tubes
  - Investigation of loss contributions in suspensions
  - He-II integration in Q measurements
  - Proof of concept for He-II based payload cooling for ET-LF



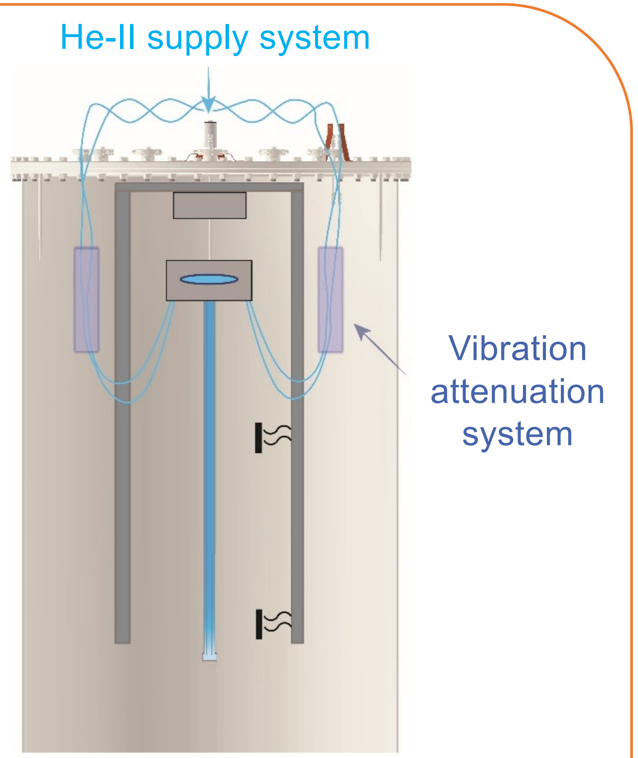
Cryogenic payload suspension studies [*]



Phase 1:
He-II free campaigns



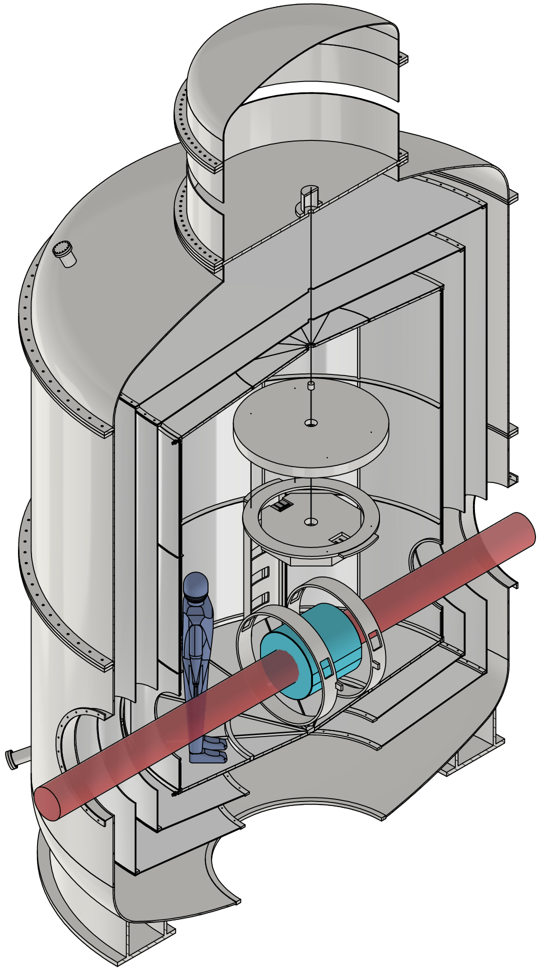
Know-how transfer

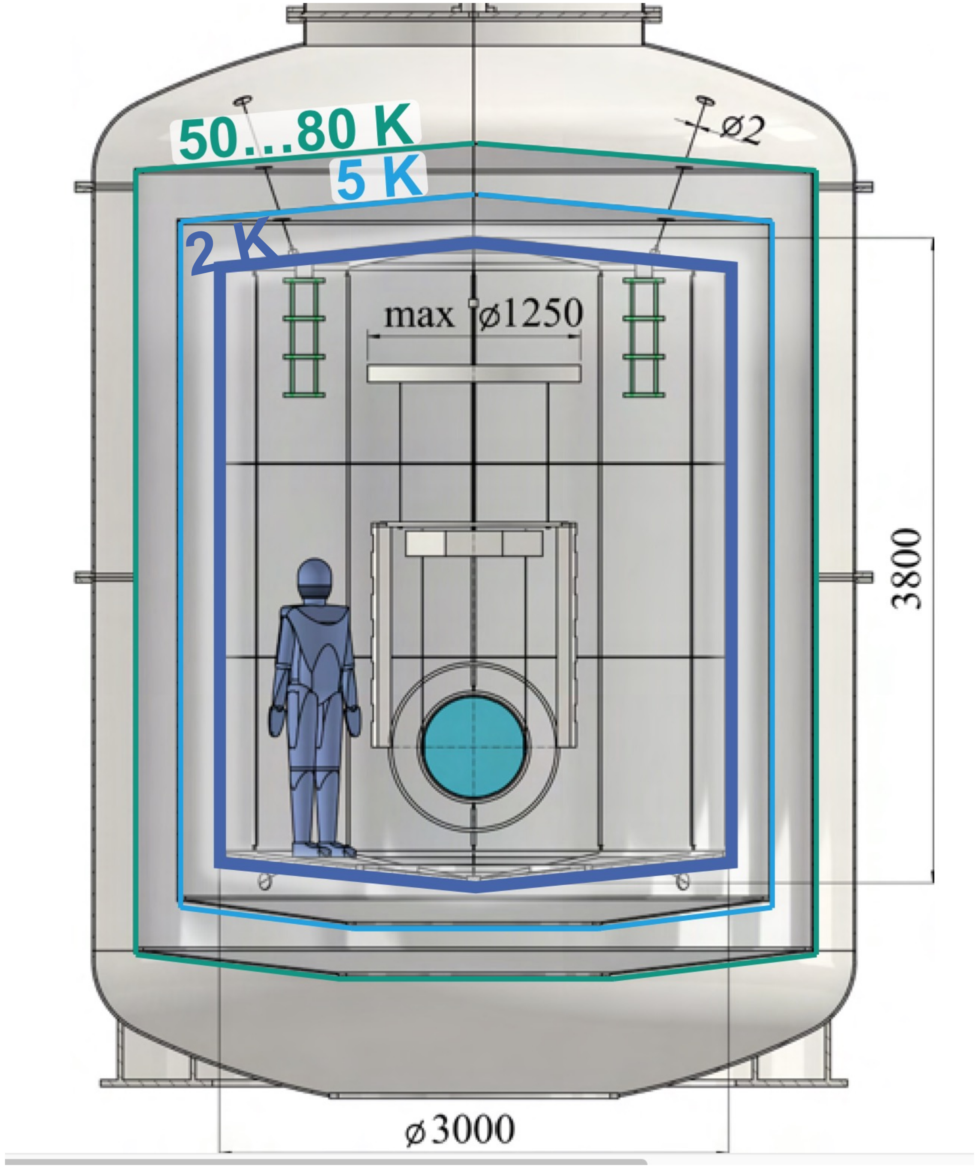


Phase 2:
He-II filled tube campaigns

[*] Koroveshi X, Rapagnani P, Mangano V, Stamm M, Grohmann S, 2024 *IOP Conf. Ser.: Mater. Sci. Eng.* submitted

The most quiet cryostat for ET: a provisional design





Key features of the cryostat

- Bottom access
- Several layers of thermal shielding
- Vacuum separation between the upper warm tower and the beam pipe vacua

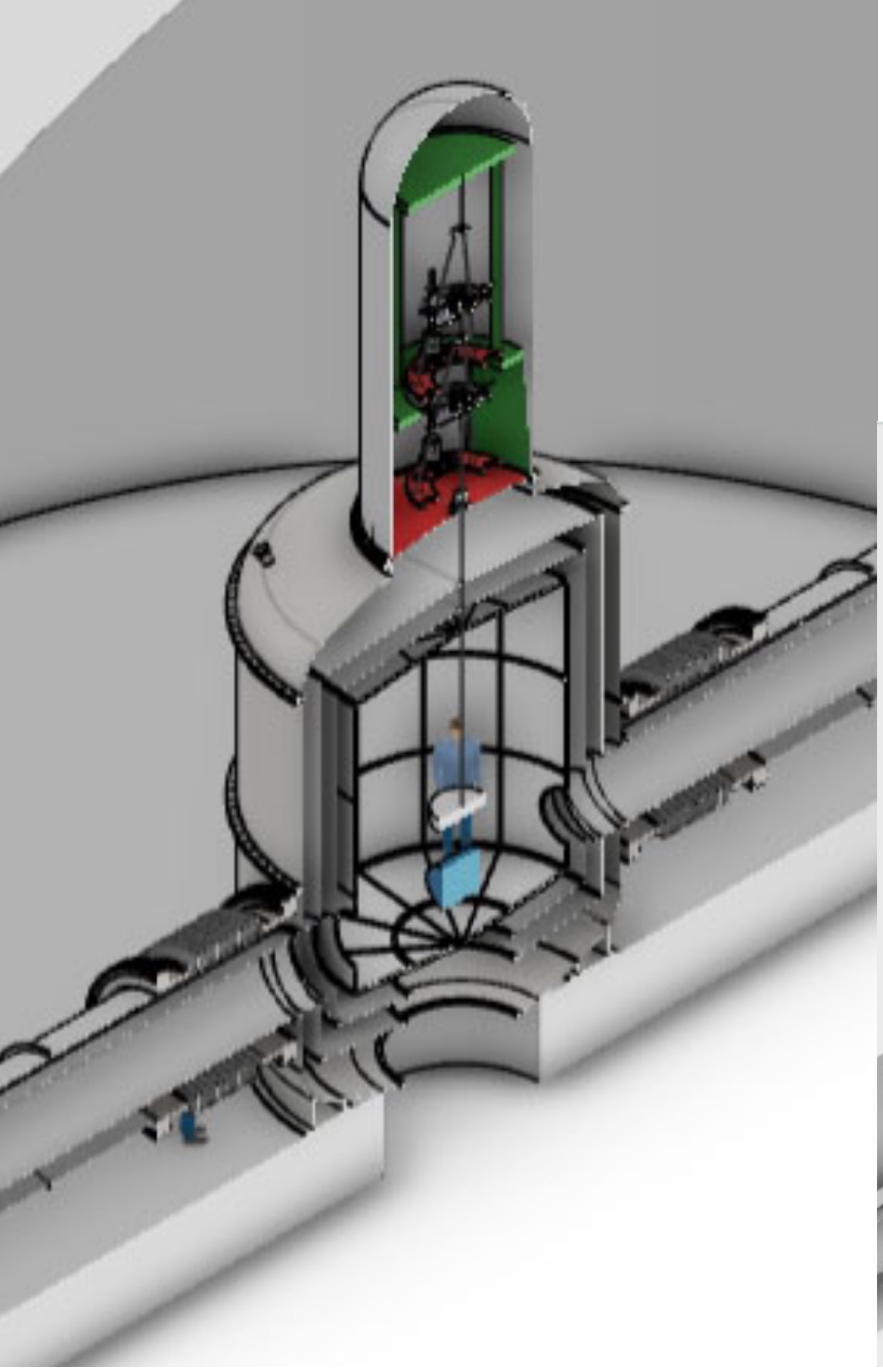
External dimensions

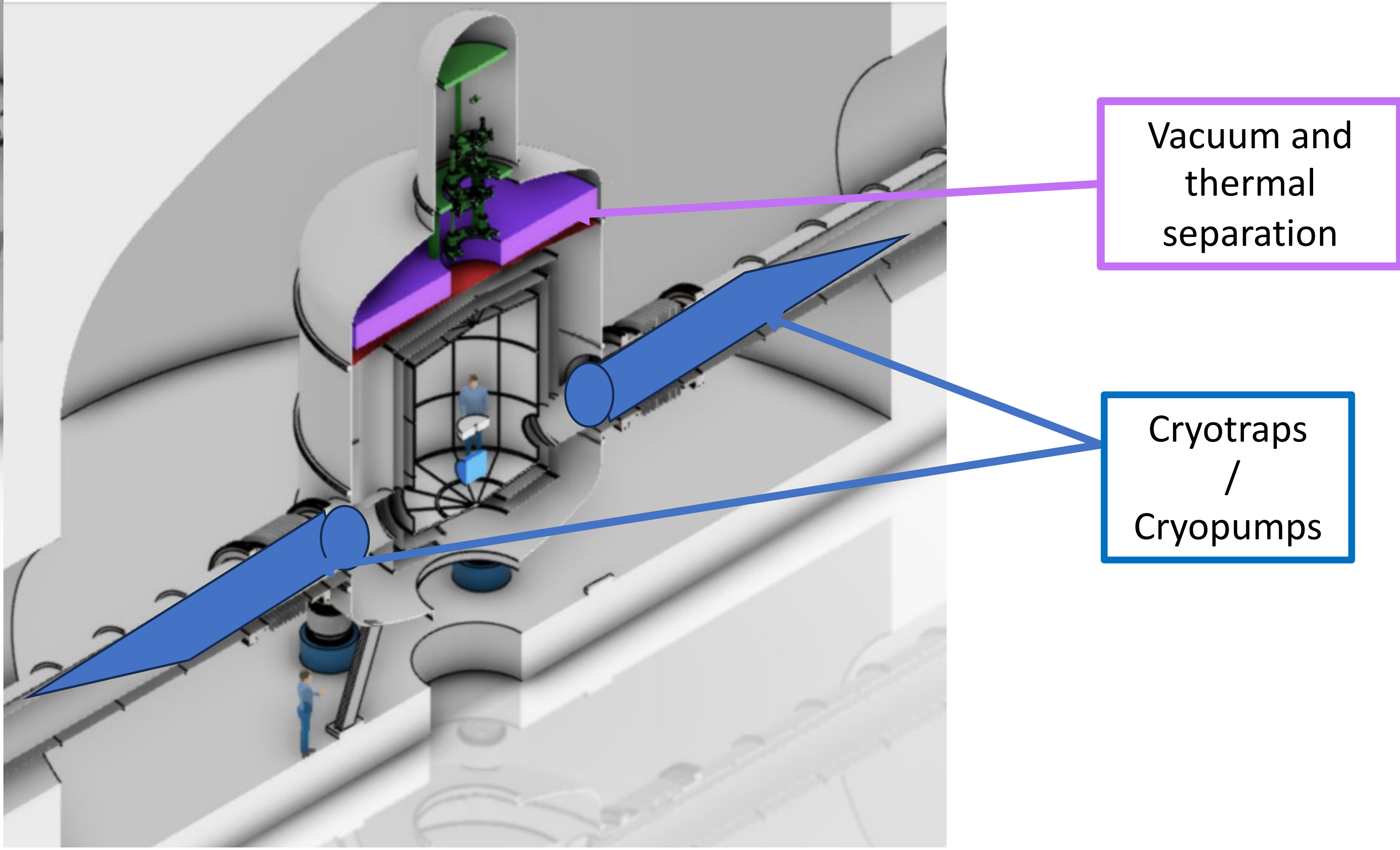
$\phi \approx 4.5$ m $h \approx 6.4$ m

Innermost shield h=3.8 m , ϕ =3.0 m @ 2K
Hosting a payload up to a 1250 mm height with a 600 mm mirror

Cooling the shields
2 K ➔ He II
5 K ➔supercritical He^4
50 - 80 K ➔ Helium Gas exchange
Extra shields to insure superinsulation

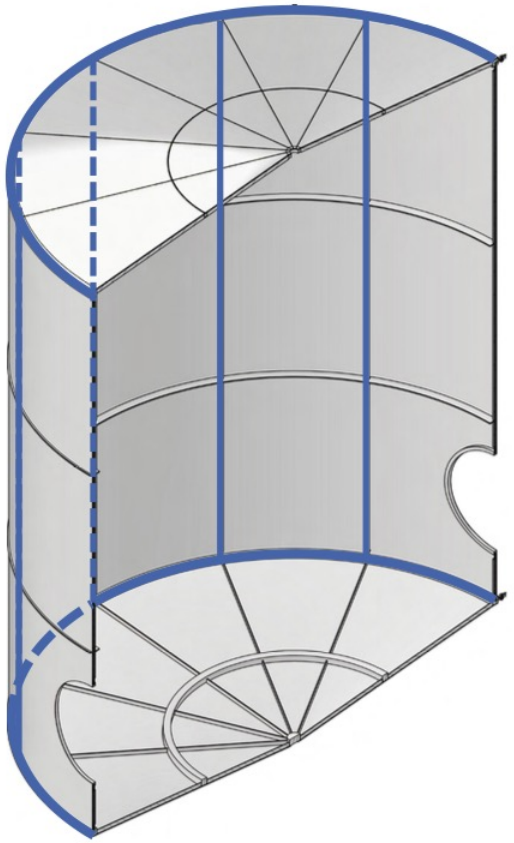
A provisional rendering of ET-LF cavern with Cryostat, Cryotraps and Suspension

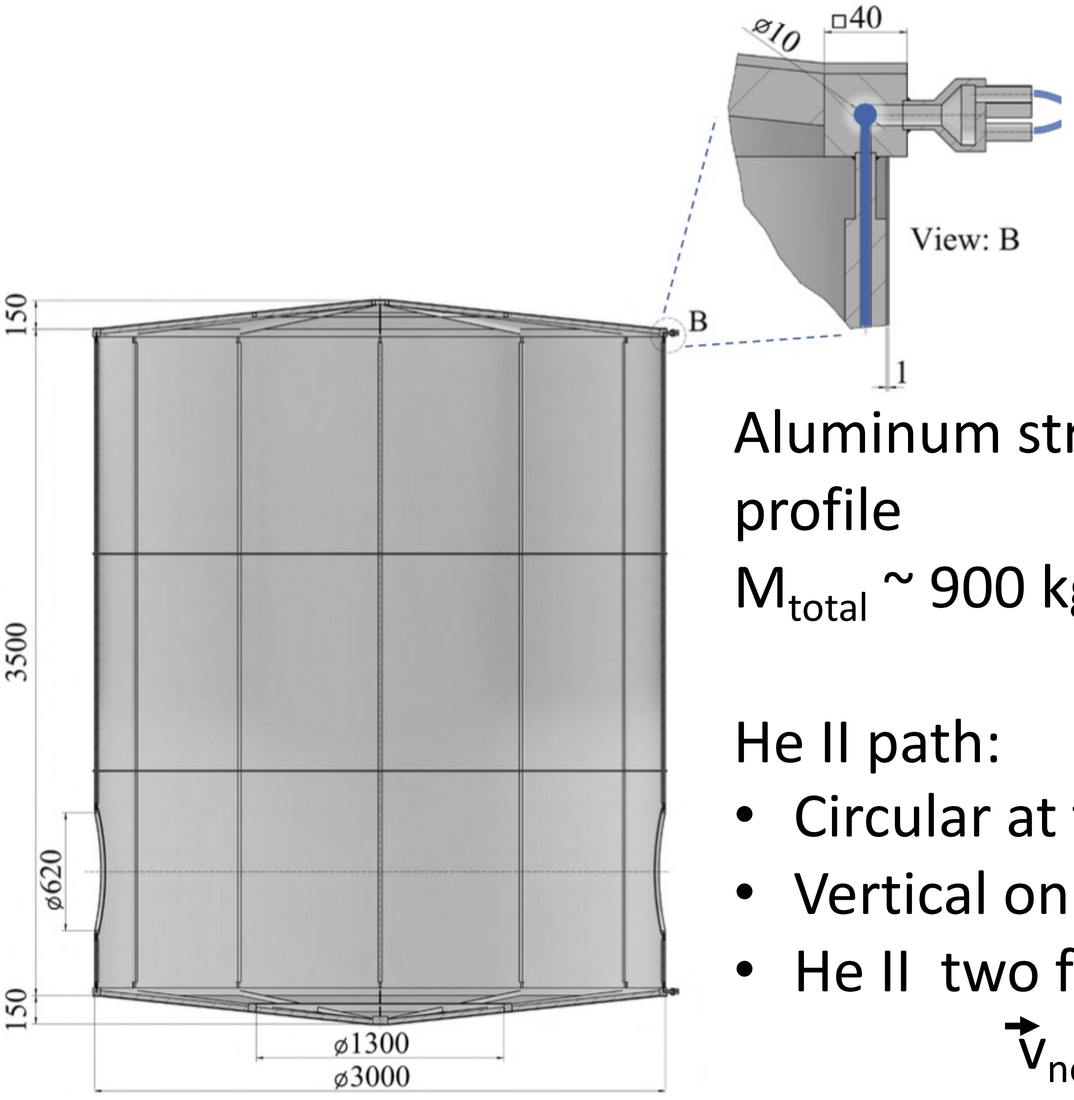




The 2 K shield geometry

L Busch, G Iaquaniello, P Rosier, M Stamm and S Grohmann - ET 0297A -23





Aluminum structure with hollow profile

M_{total} ~ 900 kg

He II path:

- Circular at the top and bottom
- Vertical on the lateral surface
- He II two fluids model (Landau)

$$\vec{v}_{nor} + \vec{v}_{super} = \vec{0}$$

Innermost shield:
Temperature distribution and Refrigeration power

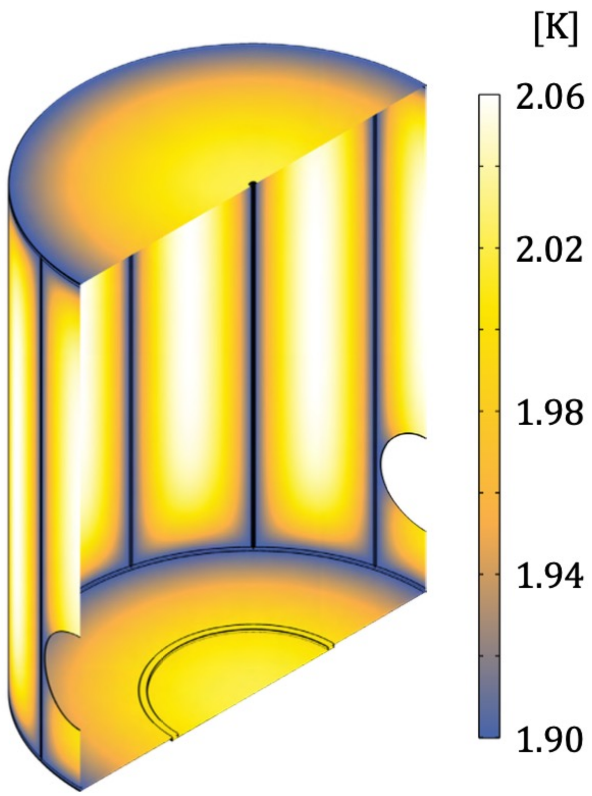
L Busch, G Iaquaniello, P Rosier, M Stamm and S Grohmann - ET 0297A -23

FEM results:

$\dot{Q}_{\mathrm{total}} = 2.0\ \mathrm{W}$

(full shield)

- Viewports
- Beam pipe
- Scattered light
- Shield suspensions



- $\Delta T_{\mathrm{shield,max}} < 100\ \mathrm{mK}$
- $\dot{Q}_{\mathrm{total}}$ distribution to thermal reservoir:
  - c. $^5/_8$ to vertical profiles
  - c. $^3/_8$ to header profiles

Analytical approximation of static 1D temperature profiles in He-II channels:

$$\frac{\mathrm{d}T}{\mathrm{d}x} = \frac{-\dot{q}_{\mathrm{HeII}}(x)^m}{k_{\mathrm{eff}}(T(x), p)}$$

- Example:

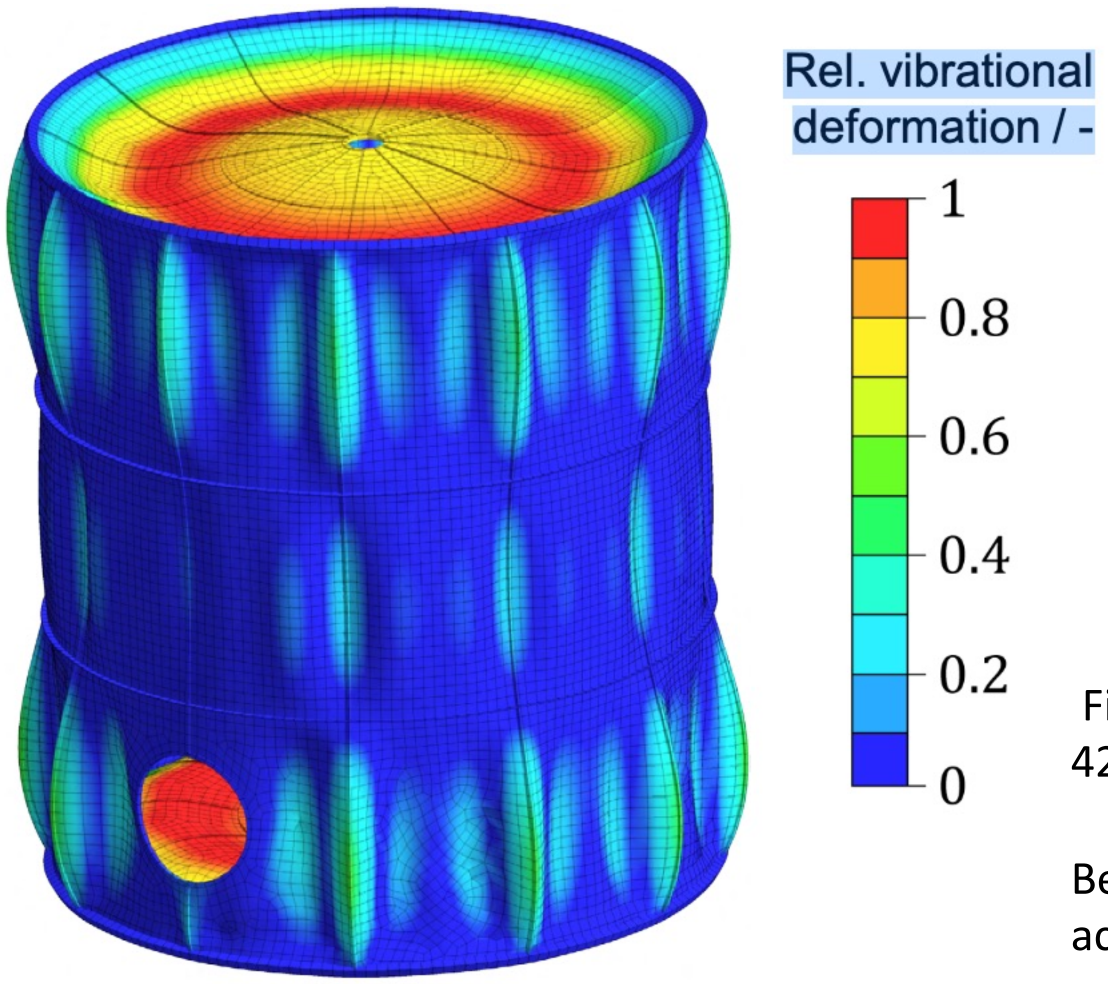
  $d_{\mathrm{i,He-channels}} = 5 \ldots 10\ \mathrm{mm}$:

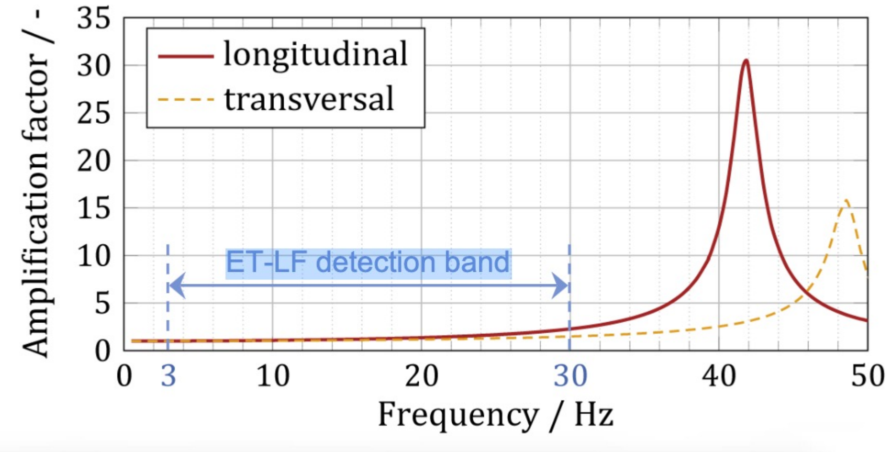
  $\rightarrow T_{\mathrm{HeII}} \approx 1.85 \ldots 1.87\ \mathrm{K}$ ✓

  supply...farthest point

Mechanical resonances of the inner shield

Free modal analysis results (credits G. Iaquaniello and P Rosier from IjClab-CNRS



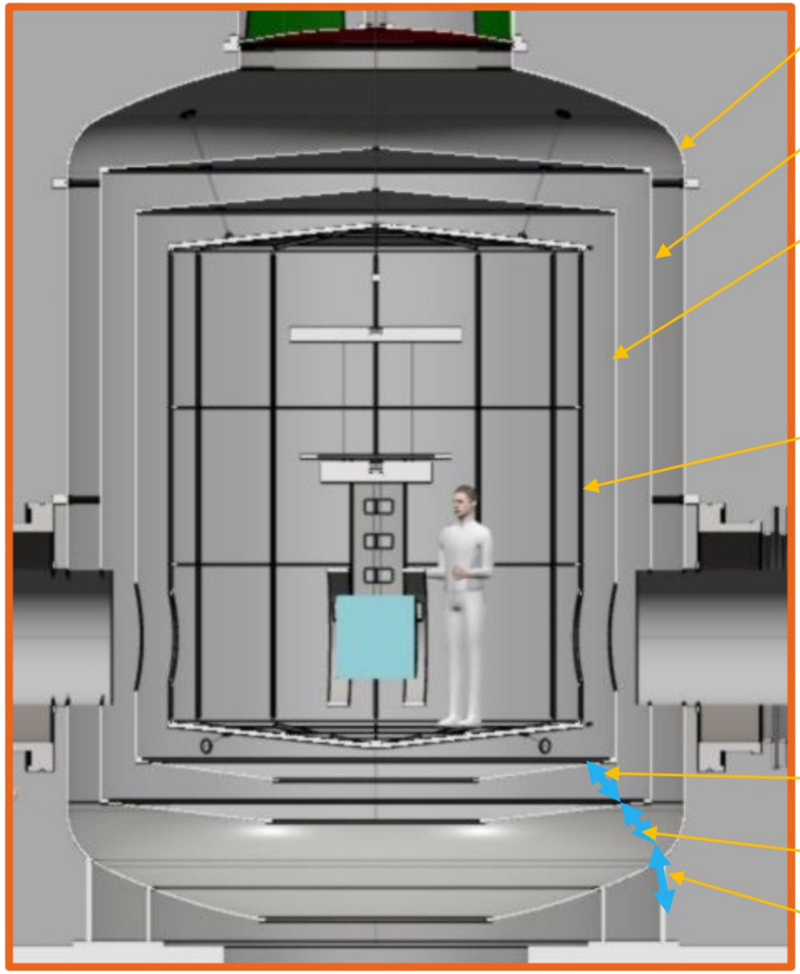


First resonant modes:
42 Hz (longitudinal) and 48 Hz (transversal)

Below 30 Hz: very low amplification factors achieveable

F.E.M. mechanical simulation

Summary of the CAD from KIT



19,467 T / Stainless Steel = after check

80K / 1526 Kg / alu = after optimization

5K / 1240 Kg / alu = after optimization

2K / 816 Kg / alu = already optimized end 2023

Total : 21,8 T

240 mm

270 mm

270 mm

Cryotraps / Cryopumps

S. Hanke, X. Luo, K. Battes, C. Day - ET-0417A-23

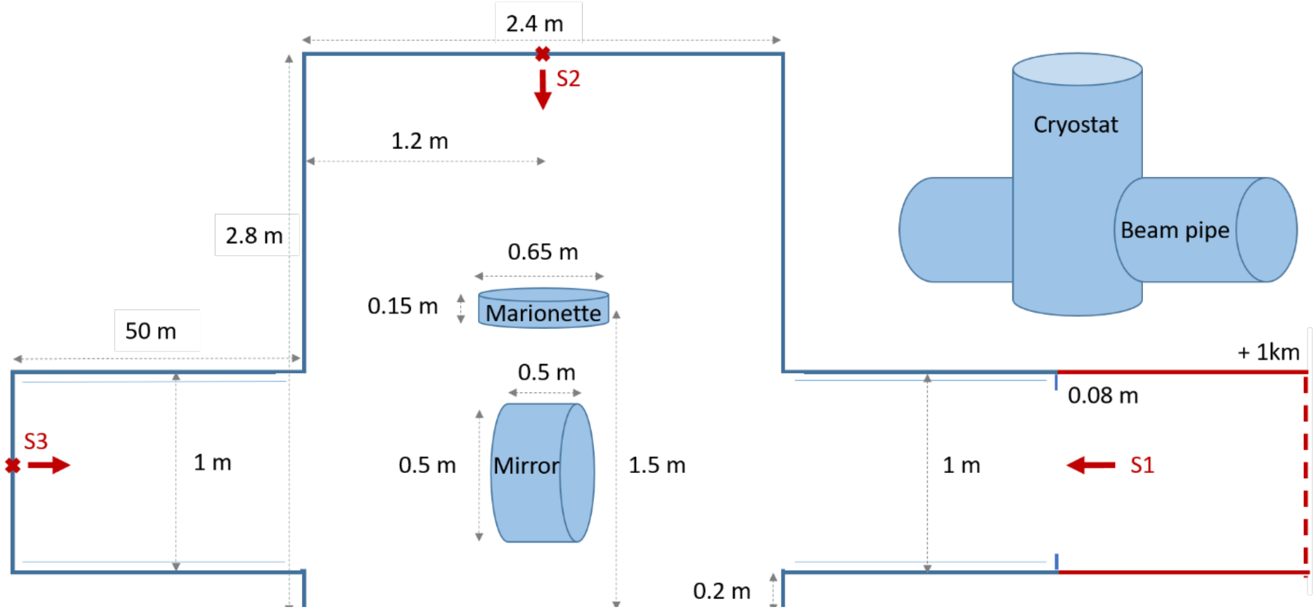
Proposed cryopump concept to fulfil
- all vacuum requirements
- slow frost formation on mirror (up to 2 years for one ML)

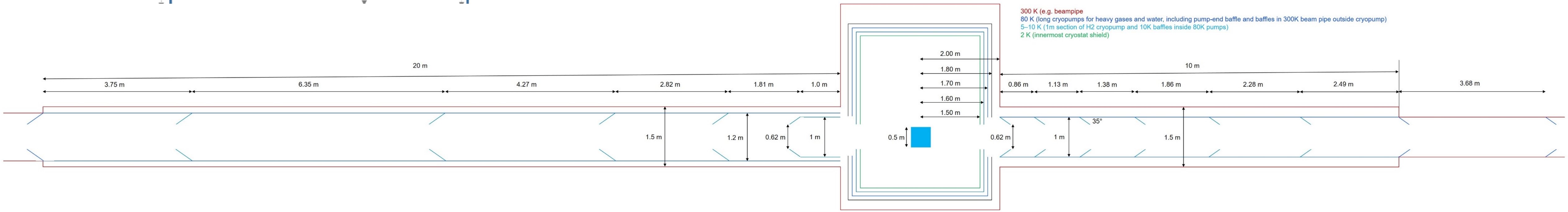
Temperature of the cryopumps
- for hydrogen ➔ section @4 K
- for heavy gases (water & co) ➔ section @ 80 K

On one side of the cryostat hosting the mirror
10 m lenght @80 K seems enough

On the other side where we have an adjacent tower
we need more pumping @ 80 K (20 m) and
1 m long section @ 4K

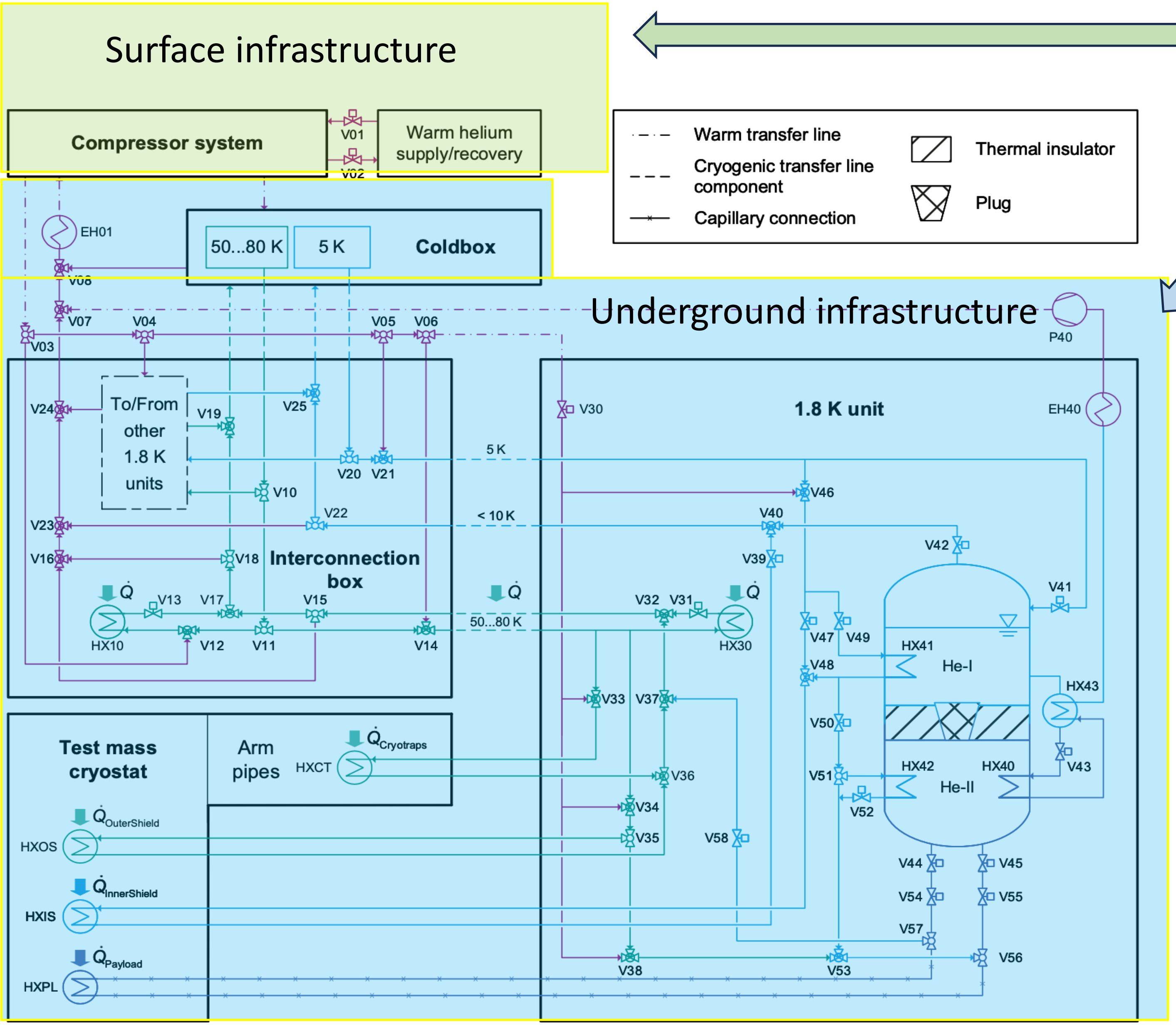
Compatibility check of this solution with a reduced thermal radiation load on the mirror is on going





Cooling Infrastructure based on Cryogenic fluids

Lennard Busch, Steffen Grohmann - ET-0376A-2



Noise generators:

Level of noise to be evaluated by measring similar systems installed In Hep laboratories

IOP Conf. Series: Materials Science and Engineering 1240 (2022) 012095 doi:10.1088/1757-899X/1240/1/012095

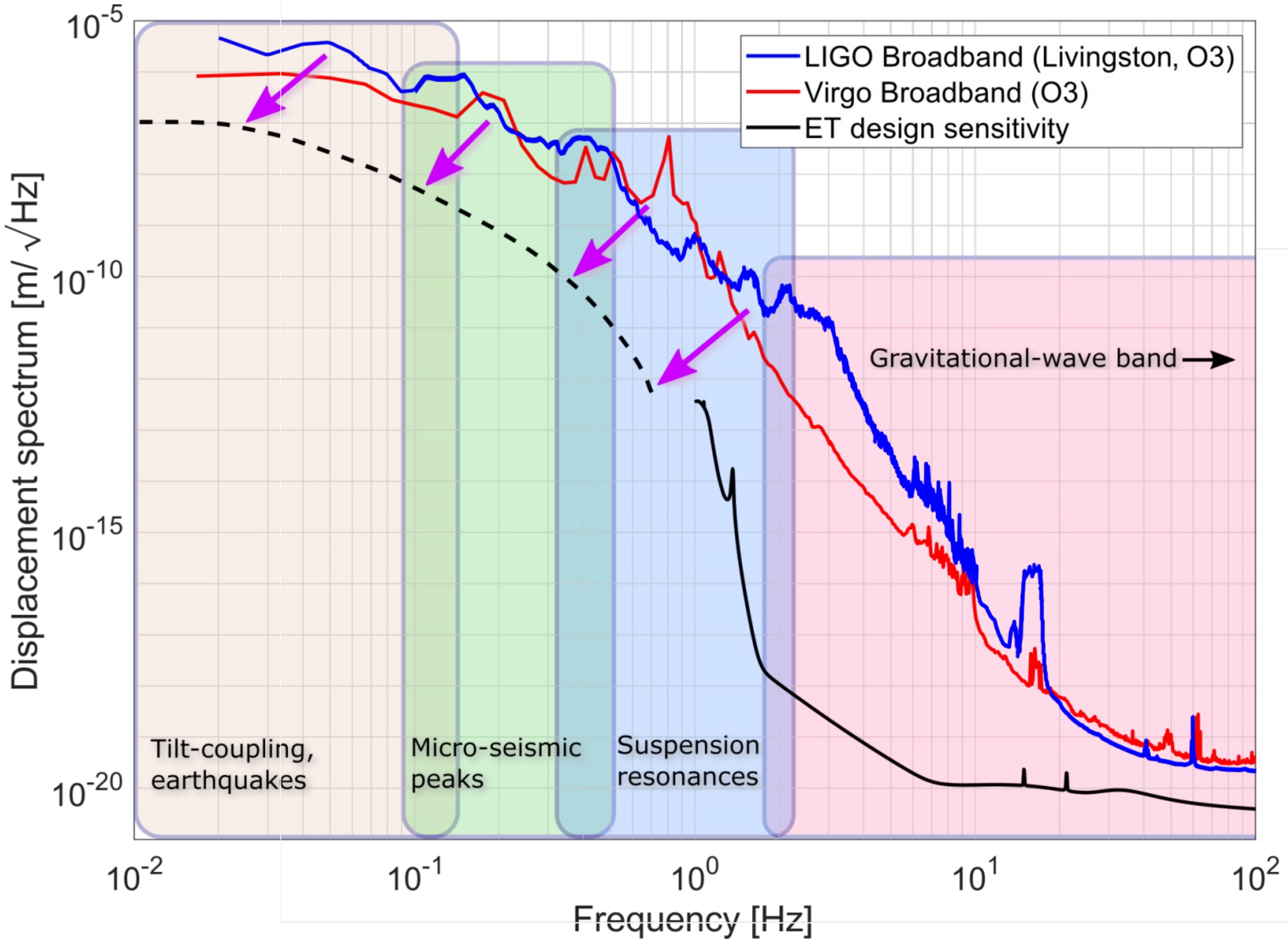
Does this cryo design add extra noise at low frequency?

- Is the Landau model good enough to predict the He II behavior in the innermost shields?

- If any, what is the He II residual motion compatible with the experiment? (Newtonian coupling)

- Can we limit the circulation of the supercritical He^4 to laminar regime providing enough refrigeration power and avoiding the exitation of the screen mechanical resonances?

- Is a potential source of noise the supercritical helium used to cool the 5 K shield?



LIGO Broadband (Livingston, O3)
Virgo Broadband (O3)
ET design sensitivity
Gravitational-wave band
Tilt-coupling,
earthquakes
Micro-seismic
peaks
Suspension
resonances
Displacement spectrum [m/ √Hz]
Frequency [Hz]
10^-5
10^-10
10^-15
10^-20
10^-2
10^-1
10^0
10^1
10^2

To-do list for achieving the 2 Hz sensitivity goal of ET

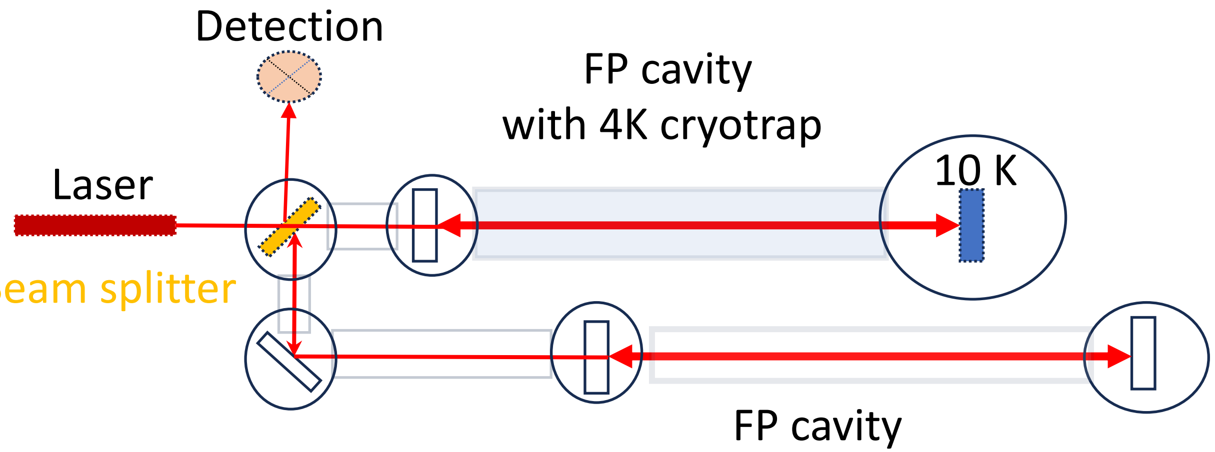
- New sensors and actuators compatible with the cryogenics environment
- Control models

======================

- Finalise the design the silent cryostat + Cryogenic infrastrucutre
- Develop an efficient cooling procedure with soft suspensions of the payload
- Integrate the solutions with the suspensions and the upper vacuum chambers at room temperature
- Final test

Longer term R&D: full scale cryo-protoytype in an undeground environment to test the performqnce

- Interferometer with suspended mirrrors:one of them cooled at low temperature by a <u>cryo infrastructure with surface and underground sections</u>



- Suspended mirrors
- Cryotrap long enough to reduce the thermal radiation heat

Thanks for the attention!